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INTRODUCTON OF KEY PERFORMANCE INDICATORS FOR THE GSI ACCELERATOR FACILITY

O. Geithner†, W. Geithner, N. Kehl, V. Rapp, S. Reimann, F. Herfurth, R. Assmann[2]
GSI, Darmstadt, Germany
[2] also at JWGU, Frankfurt, Germany

Abstract

The GSI Facility consists of several accelerators, offering the distinctive capability to provide different ion beams with varying characteristics to a range of experiments simultaneously. In order to facilitate the monitoring of machine performance across diverse beam production chains and experiments, a Key Performance Indicator (KPI) metrics has been introduced. The CRYRING@ESR team has completed an initial KPI assessment of the ion storage ring and developed procedure to analyse beam diagnostic data offline. Initial analysis has identified lacking information and features in the FAIR Archiving System (FAS) and data structures to support automated tracking of machine performance. This paper will present detailed definitions of KPIs to enable quantitative, beam-based accelerator performance measurement, an assessment of their implementation and an outline of future developments.

INTRODUCTION

Key Performance Indicators have proven to be an indispensable tool in industry for transforming abstract goals into concrete, measurable outcomes. By defining clear metrics - whether for machine up-time, production throughput or failure rates - organization can recognize bottlenecks, benchmark performance against references or past periods and drive continuous improvement. Regular monitoring of KPIs creates transparency, aligns teams around shared goals and enables data-driven decision-making.

With the IT Infrastructure available at GSI/FAIR, availability and beam quality tracking and monitoring can be performed on the level of manual logbook (OLOG) entries or beam-based by analysing data from beam instrumentation devices (Fig. 1). Beam-based metrics can currently be performed only offline, but our goal is to make the tools online capable in the future.

DEFINITIONS

In our accelerator facility we intend to implement this methodology by establishing three core KPI performance components (PC):

Accelerator Availability (A_{avail})

The fraction of Scheduled Beam Time (SBT), during which the accelerator delivers beam to the experiment versus fraction of beam time, where the beam was not available for the experiment. This component highlights failure patterns, maintenance gaps, refurbishment project requirements and potential design improvements.

Beam Intensity (I_{norm})

The beam intensity, normalized against a target value I_{target}. It enables tracking if an accelerator delivers the committed numbers and represents the quality of the beam setup and losses along the production chain (transmission). We define the Beam Intensity metric as:

$$I_{norm} = \begin{cases} I_{meas} \,/\, I_{target}, & I_{meas} < I_{target} \\ 1, & I_{meas} \geq I_{target} \end{cases} \tag{1}$$

Beam Quality (Q_{norm})

Depending on the specific requirements of each experiment, certain beam parameters such as beam brilliance, energy spread, emittance, luminosity, beam spot size or other relevant quality metrics, normalized against a respective benchmark, can be used to ensure the consistent delivery of the desired characteristics.

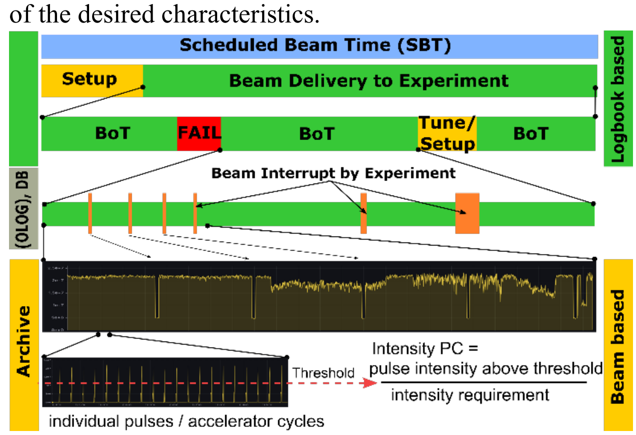

Figure 1: Levels of tracking accelerator performance.

The overall performance of the accelerator facility is then consolidated into a single composite KPI - the Accelerator Performance Index (API) - as the product of these three components:

$$API = A_{avail} \cdot I_{norm} \cdot Q_{norm}. \tag{2}$$

Each factor is dimensionless and scaled between 0 and 1. An API of 0.8, for example, indicates that the accelerator is achieving 80% of the requested output.

† o.geithner@gsi.de

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IMPLEMENTATION AT CRYRING@ESR

CRYRING@ESR is a low energy ion storage ring, a Swedish in-kind contribution to FAIR and the first FAIR accelerator to become operational [1]. CRYRING@ESR is able to receive beams either from GSI's Experiment Storage Ring ESR - highly charged ions with energies of some MeV/u [2] or from CRYRING@ESR's local ion source - lowly charged ions with energies of keV/u (directly from the source) or 300 keV (pre-accelerated with a local RFQ LINAC) [3]. CRYRING@ESR itself can be operated in an accelerating or in a decelerating regime, depending on the specific needs of the experiment.

In close collaboration with the GSI/FAIR control systems department, we established a prototype IT infrastructure for collecting, storing, and visualizing data from beam diagnostics. This setup allows us to explore both the potential and the challenges of using this data for real-time accelerator performance monitoring.

As a first step towards this goal, we extracted data for one beamtime from the FAIR Archiving System FAS [4], where CRYRING@ESR received beam from ESR. On this data we performed offline analyses looking at rather simple performance indicators: beam intensity, extracted from ESR, intensity at injection into CRYRING@ESR, intensity after reaching nominal energy as well as beam line transport efficiency from ESR to CRYRING@ESR.

ANALYSIS

For this study, we analysed data from the experiment, which ran at CRYRING@ESR in March 2025 using a $^{197}Au^{75+}$ beam [5]. The ions were first accelerated through the UNILAC–SIS18–ESR chain and then injected into CRYRING@ESR, where the experiment was conducted. In Fig. 2 an example of measured intensity in CRYRING@ESR is plotted, where different marker colours indicate different beam-process indices. As I_{meas}, we use the mean of a sample of data points from the phase of the accelerator cycle, where the intensity is maximum (Fig. 2, pink colour).

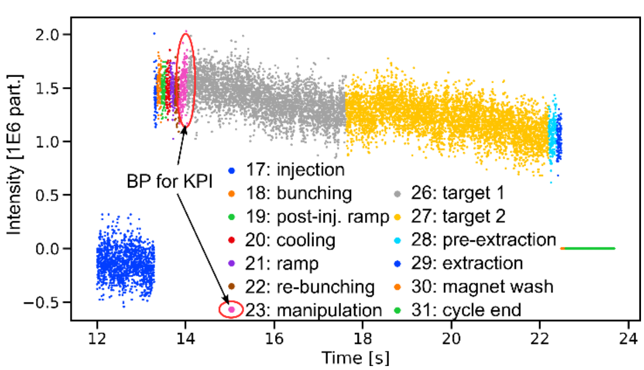

Figure 2: Example of beam intensity measured with a DC beam transformer in CRYRING@ESR monitored over one cycle. Colours indicate different beam-process indices.

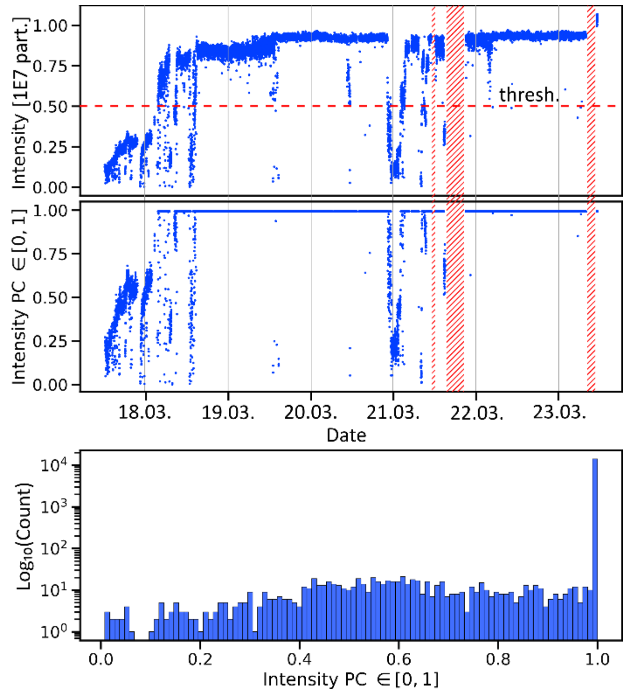

Figure 3: Result of intensity PC analysis for the CRYRING@ESR beamtime. Top: intensity for each individual cycle. Middle: intensity PC based on formula (2). Bottom: Histogram of intensity PC.

For the experiment, the threshold for performance analysis was set at an intensity of 2×10^6 particles per ring filling. This intensity was defined as I_{target}. Under these assumptions, the beam-based, per-cycle performance was extracted from the data available and is plotted in Fig. 3.

Beam intensity gaps are visible in the two upper time series plots. These gaps are caused by discriminating ESR and CRYRING@ESR intensity values smaller or equal to zero, which are treated as non-physical. A more careful treatment of the data should correlate these gaps with failure events, logged in the GSI OLOG logbook or with accelerator cave openings.

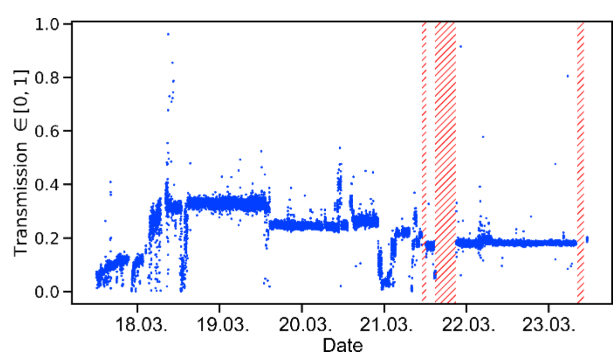

Figure 4: Transmission quality PC calculated as $\frac{I_{meas,CRYRING}}{I_{meas,ESR}}$. Each data point represents one accelerator cycle.

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We also calculated the transmission through the beam line between ESR and CRYRING@ESR - a quality PC for beam transport efficiency. The transmission was optimized in the beginning of the run to the typically achievable 35%. During the run, the focus was on stability of operation, and since the experiment still got the requested intensity, no further efforts were made to maintain the high initial transmission. Figure 4 shows the results as time series data for each accelerator cycle. Only cycles with an ESR intensity of at least 5×10^6 particles were included in the plot.

ROOM FOR IMPROVEMENT

Currently, a number of shortcomings make the analysis of time-series data, available from the FAIR Archiving System, challenging:

- Lack of a unique bunch identifier: today, we correlate individual ion bunches across accelerator stages via time stamps of sequential extraction / injection events. This approach is rather error-prone and requires clumsy custom logic. Assigning a unique identifier for each bunch - from ion source to target - would greatly simplify tracking.
- The FAS keeps only numeric beam-process indices; it does not store what each index means (e.g., injection, extraction). This mapping must be done by hand and the task is made difficult because the indices themselves change over time.
- Lack of generic data-writing interface (GDWI): Currently, the FAS can only ingest data through internal Java interface sources, that are part of the FAIR control system. Hence, integrating data analysis tools in popular environments like Python is not easily possible. This absence of a writing interface requires to persist performance-analysis data outside of the FAS remains impractical.
- Beam interruptions during BoT, caused by the experiment (e.g., personnel accessing the accelerator cave), are only available from specific data sources outside of FAS. The same is the case for machine failures, which are tracked via the OLOG logbook tool. Both need to be handled manually during data analysis.
- Undocumented detector settings: Not all critical detector settings with impact on the measurement – e.g., gain, sample rates, offsets, etc. - are persisted in FAS.

NEXT STEPS

As a first step we plan to refactor existing intensity and transmission routines - currently tailored to offline analysis - into modular, streaming-capable components. This will enable online monitoring, threshold-based alerts and immediate operator feedback.

Next, the analysis shall be applied to other properties, which are available from the FAS. As an example, the longitudinal beam spread is an important property, qualifying beam cooling by the electron cooler, installed in CRYRING@ESR.

As soon as the tool of beam-based performance analysis and monitoring becomes an established tool, it can be expected, that requests and ideas for more performance components will develop.

CONCLUSION

The beam-based, per-cycle analysis of performance components offers high-level but valuable insights into the state of an accelerator during operation. Furthermore, it makes machine performance quantifiable and provides numbers for future machine operation. Instead of occasional and error prone logging of offline information on PCs in logbooks, an automated PC analysis provides a more transparent and unbiased online view on accelerator performance.

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