GSI OPERATION STATISTICS IN THE FAIR CONSTRUCTION PHASE (2012 – 2025): TRENDS, FAILURES AND LESSONS LEARNED

O. Geithner*,[1], M. Klich[1], M. Vossberg[1], A. Bloch-Spaeth[1], H. Stemmler[1], R. Assmann[1,2], S. Reimann[1]
[1]GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany
[2]JWGU, Frankfurt, Germany

Abstract

We present operational statistics for the GSI accelerator complex during the FAIR construction phase from 2012 to 2025, covering UNILAC, SIS18, ESR, HEST and CRYRING@ESR. The analysis is based on beam-time schedules, availability monitoring, and fault annotations from the Operator Logbook (OLOG). During the last five years, failure entries were systematically reviewed and reclassified to ensure consistent data quality and enable reliable long-term trend evaluation. The main performance indicator discussed is accelerator availability, determined from scheduled operation periods and fault-related downtimes. The evaluated data were used as a quantitative input in the recent POF-5 evaluation process (2028-2034), where they clearly supported refurbishment and consolidation needs at GSI. A technical roadmap was established this year to prioritize these measures according to their impact on stable beam delivery towards FAIR accelerators.

INTRODUCTION

During the FAIR construction phase, the GSI accelerator complex continued operating as a user facility while simultaneously preparing for FAIR integration. This dual role created significant operational challenges.

Many technical systems exceed their original design lifetime, while resources must be shared between maintaining current operation and supporting the FAIR project. Beamtime for experiments must be balanced against shutdown periods required for upgrade [1] and maintenance activities

This paper presents a quantitative analysis of operational statistics from 2012 to 2025 based on beamtime records and operational logbook (OLOG [2]) fault annotations. The goal is to identify key reliability trends and structural limitations during the FAIR transition. The results form the basis for a data-driven prioritization of refurbishment measures summarized in the Technical Roadmap [3].

ACCELERATOR COMPLEX AND DATA SOURCE

The analysis covers the main machines of the GSI accelerator complex that contribute to routine beamtime. The focus is on their role in the beam production chain and correspondent reliability burden.

- UNILAC – linear accelerator forming the backbone of the injector chain.
- SIS18 – main synchrotron providing beam for downstream rings and experiments.
- ESR – experimental storage ring with electron and stochastic beam cooling.
- CRYRING@ESR – low-energy storage ring with electron beam cooling.
- HEST – transfer and extraction beamline systems linking synchrotron, storage rings and experimental caves.

These machines form a strongly coupled production chain; failures in upstream systems frequently propagate downstream, influencing global availability.

DEFINITIONS

The availability calculation is based on operational periods documented in OLOG, which is continuously updated during beamtime. Instead of using the originally scheduled times from long-term planning, the analysis relies on the dynamically adapted beamtime record in OLOG, reflecting the actual operational conditions on daily base. Setup periods include machine preparation, beam tuning and ion source service times. Accelerator availability is defined as the ratio of effective beam-on-target time to the sum of beam-on-target, setup and failure times, summarized over all experiments [4].

LONG – TERM OPERATIONAL TRENDS

Figure 1 shows the evolution of GSI performance between 2012 and 2025. The time values are aggregated over all experiments operated in parallel, which explains the high total number of operation hours per year. The data do not follow a simple linear trend but rather reflect changing operational boundary conditions over time.

The years 2012–2014 represent relatively long beamtime blocks. In 2013, no user beamtime took place due to extensive shutdown activities. During these early FAIR construction years, operation was driven by experimental demand and beamtime scheduling was comparatively continuous.

From 2015 onward, a clear operational shift can be observed. FAIR project activities required longer shutdown periods, infrastructure access, and coordination with civil construction. In addition, personnel resources were increasingly shared between FAIR construction and ongoing GSI

* o.geithner@gsi.de

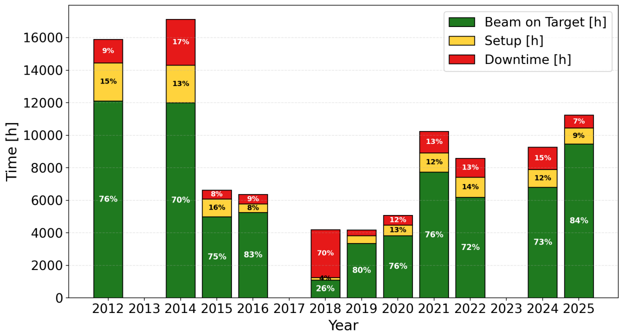

Figure 1: Evolution of GSI accelerators performance (2012 – 2025) based on OLOG – classified operational time.

operation. As a result, beamtime blocks became shorter, and user beamtime decreased in several years. The accelerator complex was no longer operated as a stand-alone facility but was strongly influenced by the FAIR project.

Another important transition started in 2018 with the roll-out of the new FAIR control system for the accelerators (except UNILAC). However, the operational statistics of 2018 and 2019 are limited due to very short beamtime periods and interrupted operation. The immediate impact of the new control system therefore cannot be directly seen in these years.

From 2020 onward, the influence of the new control system becomes visible. Setup times increased, reflecting slower response times for simple machine parameter changes as well as the additional effort required for operating procedures in the new control environment. To mitigate this, a dedicated task force team was established to improve control system performance and usability [5]. This led to systematic performance improvements and better collaboration between operators and control system experts.

Starting in 2021, setup times gradually decreased again. This was mainly due to improvements of the control system and the growing experience of the operators with the new tools and interfaces. After the initial adaptation phase, operation became more routine and tuning could be performed more efficiently despite higher system complexity and the steadily increasing degree of parallel operation.

In the most recent years (2022–2025), the statistics indicate a stabilization of operation at a high operational performance level. Parallel operation increased, with the accelerator complex supplying beam to up to three experiments simultaneously (parallel factor ≈ 3). Effective beam-on-target fractions reached their highest values, while setup times continued to decrease. This suggests that the accelerator complex has successfully adapted to the combined challenges of ageing infrastructure, FAIR construction constraints, and the transition to a new control system. A notable outlier in the long-term trend is the year 2018, when a fire incident in the UNILAC RF gallery forced an early termination of the beamtime. The event underlines the critical role of UNILAC as the future FAIR injector, which currently has no redundancy; prolonged failures therefore lead to a complete stop of the whole accelerator chain. A more detailed discussion of these downtime contributions and their technical origin is given in the following failure statistics section.

FAILURE STATISTICS

The failure analysis shows that downtime of the GSI accelerator complex is influenced by a combination of short-term subsystem effects and structural weak points typical for an ageing facility operated during an ongoing construction phase.

A significant improvement in the quality of the analysis was achieved from 2020 onward with the establishment of the Availability Working Group (AWG). Since then, OLOG failure entries have been systematically reviewed, cleaned, and reassigned to harmonized categories, enabling a consistent and structured long-term evaluation. Figure 2 presents a bump chart of the globally defined top ten downtime categories for 2020–2025 based on this AWG-reclassified dataset. The top ten categories were first identified according to their cumulative downtime impact over the last five years, followed by their yearly ranking (rank 1 = highest impact). This representation allows the identification of systematic weak points while reducing the influence of stochastic yearly events.

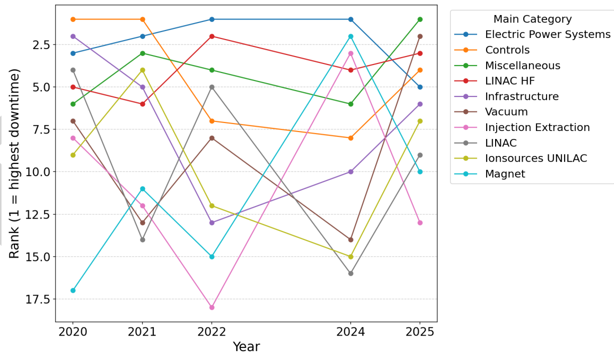

Figure 2: Bump chart of the top ten downtime categories for the period 2020–2025 based on AWG-reclassified OLOG data. The top categories were identified according to their cumulative downtime impact over the last five years, followed by a yearly ranking (rank 1 = highest impact).

The evaluation shows that short-term trends appear in individual subsystems such as controls, magnets and injection/extraction devices (e.g., septa), which temporarily move to higher ranks during control system transitions or due to ageing components. These categories fluctuate over time and are usually linked to local technical issues rather than long-term structural limitations.

In contrast, the long-term analysis shows a small set of categories that regularly dominate the downtime. Electric power systems, LINAC and LINAC RF, infrastructure-related failures, and the miscellaneous category form a stable top 5 of the downtime statistics. The latter includes external effects such as high summer temperatures, grid power interruptions and heavy rainfall, which cannot always be fully handled by the existing buildings and cooling systems, as well as a fraction of "unknown" events where the root cause cannot be fully reconstructed from logbook data. Their systematic high ranking reflects the limits of the ageing UNILAC equipment and the overall GSI infrastructure, which are increasingly challenged by weather conditions and the growing accelerator complex.

Another important aspect is the role of the injector chain for FAIR commissioning [6] and future operation. UNILAC and SIS18 are the main injectors for the FAIR accelerator complex, so their availability is essential for the overall facility performance. The failure statistics show that LINAC and LINAC HF repeatedly appear among the main downtime drivers, indicating that the injector systems are a critical weak point from a high-availability perspective.

This sensitivity was clearly illustrated by the 2018 UNILAC HF gallery fire, which led to an early termination of beamtime and highlighted the strong propagation of injector-related failures through the entire accelerator chain.

Overall, the statistics show that downtime is not driven by more major failures, but mainly by many recurring interruptions in ageing core subsystems. Distinguishing between short-term fluctuations and consistently dominant categories makes it easier to identify the main weak points and to prioritize refurbishment and consolidation measures. In particular, the repeatedly high impact of power systems, LINAC-related hardware, and infrastructure provides an important input for the POF-5 evaluation and the Technical Roadmap, aiming at high injector availability and stable beam delivery for future FAIR operation.

LESSONS LEARNED

The long-term operational analysis of the GSI accelerator complex during the FAIR construction phase provides several key lessons relevant for large accelerator facilities operated under transition conditions.

First, availability figures alone are not sufficient to assess the reliability state of a complex accelerator chain. Stable global availability can hide continuous structural weaknesses, especially in ageing injector systems and infrastructure-related subsystems. A differentiated analysis of downtime categories is therefore essential to identify true long-term limitations.

Second, systematic and harmonized failure classification is a prerequisite for meaningful trend analysis. The introduction of regular AWG reviews and the cleaning of OLOG entries significantly improved data quality and enabled reliable identification of dominant downtime drivers over many years. Without such structured data consolidation, long-term statistics remain biased by inconsistent logging practices.

Another important lesson concerns the limitations of the current failure documentation. As mentioned above, the miscellaneous category includes a fraction of "unknown" events where the exact root cause cannot be reconstructed from standard logbook information. This highlights the need for a dedicated post-mortem system that records interlocks, machine states, and relevant signals with higher time resolution in the minutes before a failure. Such data would enable a more reliable root cause analysis and improve the interpretation of downtime statistics.

Finally, for future FAIR operation, the injector chain (UNILAC and SIS18) emerges as the most critical element from an availability perspective. Failures in injector-related subsystems propagate through the entire accelerator complex and can dominate global downtime, as illustrated by the premature termination of beamtime after the UNILAC HF gallery incident in 2018. Ensuring high reliability of ageing injector and infrastructure systems is therefore a key prerequisite for stable beam delivery in the FAIR era. However, the limitation of operating with a single injector can only be fully mitigated by introducing a second injector option. In this context, developments such as the HELIAC superconducting linac and the planned FAIR proton linac represent important steps toward improving the robustness of the injector chain [7–9]

CONCLUSION

This paper presented a harmonized long-term analysis of operational statistics of the GSI accelerator complex from 2012 to 2025 during the FAIR construction phase. The results show that global availability remained at a stable and partly improved level despite ageing infrastructure, shortened beamtime windows, and increasing construction-related constraints.

The systematic evaluation of AWG-reclassified failure data reveals that downtime is not dominated by isolated events but by persistent contributions from ageing core subsystems, in particular power systems, LINAC/LINAC HF, and infrastructure. Short-term fluctuations related to controls, magnets, and injection/extraction devices are visible but do not represent the primary long-term limitations.

A key outcome of the analysis is the critical role of the injector chain (UNILAC and SIS18) for future FAIR operation, where failures propagate through the entire accelerator complex and directly impact global beam delivery.

REFERENCES

[1] U. Scheeler, W. A. Barth, M. Miski-Oglu, H. Vormann, M. Vossberg, and S. Yaramyshev, "Recent UNILAC Upgrade Activities", in *Proc. HIAT'22*, Darmstadt, Germany, Jun.–Jul. 2022, pp. 166–169. doi:10.18429/JACoW-HIAT2022-TH3C3

[2] P. Schuett *et al.*, "Operation LOGbook OLOG", presented at WAO 2010.

[3] R. Aßmann *et al.*, "Consolidation of the Existing GSI Accelerator Complex - A Prioritized Technical Roadmap to Support the Operational Goals of FAIR and GSI", Oct. 28, 2025, unpublished internal document.

[4] O. Geithner *et al.*, "Introduction of key performance indicators for the GSI accelerator facility", in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 604–606. doi:10.18429/JACoW-IPAC2025-MOPS008

[5] A. Schaller, "Full Stack Performance Optimizations for FAIR Operation", Unpublished.

[6] S. Reimann *et al.*, “FAIR commissioning - Towards first science”, in *Proc. IPAC’25*, Taipei, Taiwan, Jun. 2025, pp. 2495–2498. doi:10.18429/JACoW-IPAC2025-THBN2

[7] W. Barth *et al.*, “Heavy ion linac as a high current proton beam injector”, *Phys. Rev. ST Accel. Beams*, vol. 18, p. 050102, 2015. doi:10.1103/PhysRevSTAB.18.050102

[8] J. List *et al.*, “Beam commissioning of the first HELIAC cryomodule”, in *Proc. LINAC’24*, Chicago, IL, USA, Aug. 2024, pp. 295–298. doi:10.18429/JACoW-LINAC2024-TUAA004

[9] C. M. Kleffner *et al.*, “Status of the FAIR Proton LINAC”, in *Proc. IPAC’19*, Melbourne, Australia, May 2019, pp. 889–891. doi:10.18429/JACoW-IPAC2019-MOPTS020