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# HIGHLIGHTS OF SPILL OPTIMIZATION SYSTEM USAGE AT GSI AND PROGRESS OF CONTROLS INTEGRATION

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*Abstract*

At the GSI SIS18 synchrotron, the Spill Optimization System (SOS) has been established as a key tool to improve spill quality during resonant slow extraction. During the 2025 beam times, the SOS was routinely used with the radio frequency knock-out (RF-KO) method for several experimental campaigns, enabling improved spill stability and more efficient beam delivery to users under various operational conditions. The experience gained during these runs has also guided the ongoing integration of the SOS into the FAIR control system environment. This integration enables time-multiplexed operation of the system for multiple experiments running in parallel, leading to more efficient operation. It also aims to streamline the setup and monitoring of slow extracted spills through tighter coupling with accelerator controls and unified human and machine interfaces. This contribution summarizes the operational highlights from the 2025 beam times and discusses observed improvements in spill stability and beam usability for the experiments. In addition, the current status and outlook of the full control system integration efforts are presented.

## INTRODUCTION

The heavy ion synchrotron SIS18 at GSI provides beams up to uranium to a broad experimental program [1]. Thereby, resonant slow extraction is used to drive particles into the extraction beam lines, either controlled by a quadrupole ramp or by a knock-out excitation (RF-KO). Controlling the temporal structure of the resulting particle spill is crucial to provide high-quality beams to experiments, avoiding pileup and maximizing the experimental yield. In particular, typically observed spill intensity fluctuations and drifts are detrimental to the efficient beam usage.

The Spill Optimization System (SOS) [2–4] was developed to optimize the extraction process using a combination of online feedback and iterative spill-by-spill optimization. Therefore, it digitizes detector signals, determines the average spill rate and the amount of spill intensity fluctuations (spill quality), and produces a tailored multi-band RF signal for the knock-out excitation system [5]. In the case of a quadrupole-driven extraction, it produces a tune ramp with a modulation [6] for the quadrupole power supply. As a result, the system improves the stability and reproducibility of spills, reduces intensity spikes causing pileup, and enables dynamic spill intensity control as required for ion therapy applications. A detailed description of the Spill Optimization System can be found in [2].

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## OPERATIONAL HIGHLIGHTS

During the 2025 beam times the Spill Optimization System was used as a standalone system for RF-KO extraction. As the control system integration was still ongoing, the system was set up by an expert and operated only for selected experimental campaigns spanning multiple days. In total, the new system was used for 114 shifts, delivering optimized beams to different user communities, including the NUSTAR, R³B and HADES collaborations, bio physics groups and detector research programs [7–11].

### *HADES FAIR Phase 0 Gold Run*

From 26. April through 5. May 2025 the HADES collaboration [12] continued its energy scan of gold collisions for the energy range of $\sqrt{s_{\mathrm{NN}}} = 1.96$ to $2.23\,\mathrm{GeV}$. A beam of $^{197}\mathrm{Au}^{65+}$ ions was delivered from SIS18 using the Spill Optimization System at a spill rate of $3 \cdot 10^6$ ions/s. This corresponds to an event rate recorded by the HADES detector of up to 12 kHz at the energy of $600\,\mathrm{MeV/nucleon}$. Among other factors, the increase compared to previous beam times with only 8 kHz [13] is possible because of the spill quality optimization, which reduces the probability of event pile-up. With the feedback system ensuring the delivery of the desired intensity throughout the full 10 s spill duration and considering 1.4 s spill breaks for injection and acceleration, a duty cycle of 88 % was achieved. Overall, a total of 6 billion events and 260 TB of data were recorded during the 216 hours of the beam time (Fig. 1). The collaboration reports that this is almost the number of anticipated events in the original beam time proposal, even though only about half of the requested beam time was granted.

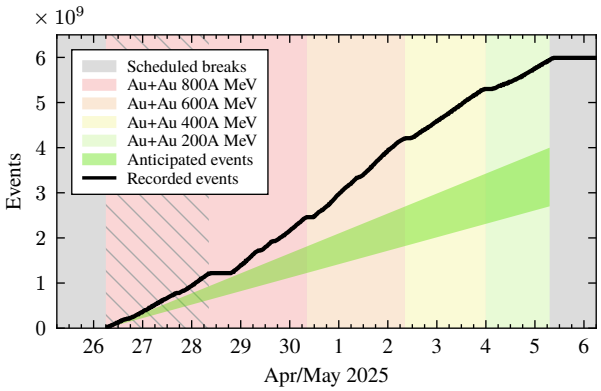



Figure 1: Events recorded by the HADES detector at several energies during the 2025 gold beam time. The hatched area marks the early start on the weekend before the scheduled beam time. The green wedge marks the event rate assumed in the experiment proposal without consideration of the SOS.

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### *Dual Ion Beam Therapy Study*

In May 2025 studies on the spill properties of a beam consisting of the two ion species $^{12}C^{3+}$ and $^{4}He^{+}$ were conducted at SIS18 [11]. Such beams have applications in ion therapy, where carbon treatment of the tumor is combined with in-situ monitoring by detecting the helium fraction passing through the tissue [14]. In the experiment at GSI, the RF-KO extraction of the dual ion beam from the synchrotron was controlled with the Spill Optimization System based on the measured carbon signal (Fig. 2). Keeping the carbon intensity in the spill at a constant value enabled studies on the time curve of the helium fraction over the course of a spill in order to understand how the beam, optics and extraction parameters influence the extraction process of the carbon and helium fractions in the dual beam.

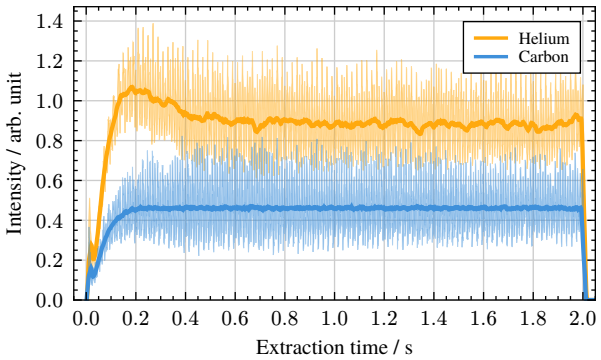



Figure 2: Intensity of carbon and helium contributions in the extracted spill. The intensity feedback control uses the carbon signal. Shades indicate the minimum and maximum intensities at 100 µs resolution; solid lines show the averaged signal. Depicted signal levels are not to scale; the helium fraction is only a few percent of the total intensity. [11]

## CONTROL SYSTEM INTEGRATION

To enable operating personnel to use the Spill Optimization System on a regular basis without the need for expert interventions for setup, a full control system integration of the system was required. This includes implementing essential user functionalities like multiplexed operation for multiple experiments running in parallel, features like spill pause and spill abort, legacy operation modes without feedback, and interfaces to different control system components providing information about beam destinations, beam parameters and detector calibration factors. In addition, an integrated user interface (GUI) for the operating personnel and persistent storage of all relevant parameters in the accelerator database were required.

In the course of the integration project, the system was deployed on a standardized front-end computer to ensure high performance and long-term maintainability. The underlying software-defined radio (SDR) based implementation was extended with new functionality: online dynamic intensity control and spill pause for biophysical applications, spill abort for machine and detector safety, and a parametrized control curve to enable operation when no active feedback can be used. A dedicated implementation of a front-end software architecture (FESA) class was developed as an interface between the SDR and the accelerator control system, including timing and a link to the detector framework providing calibration data. A pulse multiplexer was build to dynamically route signals from various beam-line and experiment detectors to the feedback system. In combination with the FESA implementation, this enables multiplexed operation, allowing to supply multiple experiments in parallel. An option to combine SOS-controlled RF-KO extraction with quadrupole-controlled slow extraction was added, enabling operating scenarios ensuring full extraction under various conditions. Finally, the development of a dedicated GUI (Fig. 3) with built-in expert-knowledge (presets, sanity checks) together with comprehensive documentation enables routine operation by non-expert operating personnel.

With the dry commissioning on 2. February 2026 the control system integration project of the Spill Optimization System for RF-KO extraction from SIS18 has been successfully completed. A hands-on training for the operating personnel will follow.

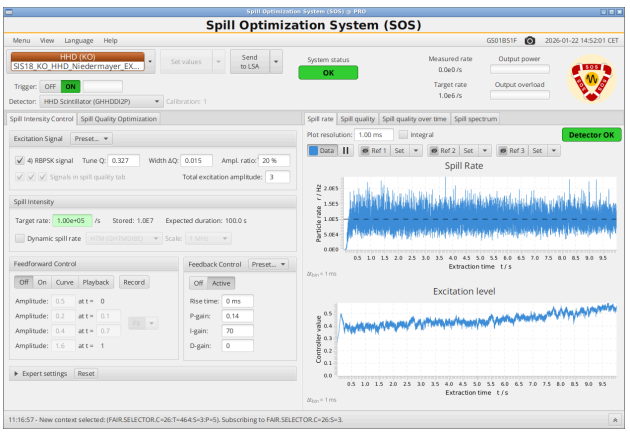



Figure 3: Screenshot of the GUI for operating the SOS

## OUTLOOK

Following the successful utilization of the Spill Optimization System for RF-KO extraction from SIS18 during the 2025 beam times and the recent completion of its control system integration, we are now working on also integrating the second Spill Optimization System for quadrupole-driven slow extraction from SIS18. In the future, additional copies of these systems are planned to be installed also at SIS100.

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