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SPILL OPTIMIZATION SYSTEM IMPROVING SLOW EXTRACTION AT GSI

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Abstract

Resonant slow extraction is routinely used to provide ion beams to various users. At GSI SIS18, two extraction methods are implemented: quadrupole-driven and radio frequency Knock Out (RF-KO) extraction. In either case, delivering a defined beam intensity (spill) without fluctuations or drifts is desired for an efficient beam usage. The Spill Optimization System (SOS) was developed to address this demand and improve the spill quality based on online spill monitoring. Developed using software-defined radio technology, it comprises a feedback controlling the spill rate and an optimization algorithm to improve the spill quality. In the case of RF-KO extraction, it controls the spill by generating tailored excitation signals for the KO exciter. For quadrupole-driven extraction, it produces a control signal for the tune ramp including tune wobbling to improve the spill quality. This contribution gives an overview on the systems and compares different usage scenarios.

SLOW EXTRACTION AT GSI

The Heavy Ion Synchrotron (SIS18) at GSI Helmholtzzentrum für Schwerionenforschung (GSI) provides a broad range of ion beams ranging from protons with a maximum energy of 4.5 GeV up to uranium $^{238}U^{73+}$ with a maximum energy of 1 GeV/u [1]. The accelerated beam is extracted and delivered to the downstream users (Fig. 1) either within a few microseconds (fast extraction) or as a spill with a certain intensity of up to 20 seconds duration (slow extraction). Slow extraction is the main operation mode and in 2024 was used for 94 % of the beamtime.

Resonant Slow Extraction

Resonant slow extraction utilizes a horizontal betatron tune close to a sextupole driven third-integer resonance [2]. The resulting non-linear particle dynamics is governed by amplitude detuning effects where the resonance emerges as a triangular separatrix in transverse phase space (Fig. 2) [3]. By slowly moving the beam into the resonance, particles cross the separatrix and become unstable. The resulting rapid increase of their betatron amplitude allows these particles to jump over the blade of a septum where they are deflected into the extraction beam line.

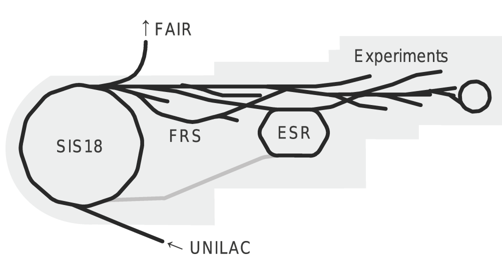

Figure 1: Accelerator SIS18 with beamlines to the Facility for Antiproton and Ion Research (FAIR), fragment separator (FRS), experiment storage ring (ESR) and experiments.

For SIS18, two methods are used routinely to drive the resonant slow extraction process in a controlled manner as depicted in Fig. 2: The first method, quadrupole-driven extraction, uses a dedicated quadrupole to slowly move the machine's tune to the resonance, which effectively shrinks the separatrix below the beam emittance [4]. While operationally simple, this method results in a systematic drift of the beam on the target due to the ramped beam optics. For the second method, radio frequency Knock Out (RFKO) extraction, a static optics with constant separatrix is used [5]. Here, the beam emittance is increased beyond the separatrix size by exciting the stored beam with a transverse RF field. While this method provides a stable beam spot on the target, it requires compensation of the chromaticity to ensure that the separatrix size is independent of the individual particle's momentum deviation.

Spill Quality

A major challenge in resonant slow extraction are drifts of the extracted particle rate over the course of several seconds and intensity fluctuations on timescales of milliseconds and below. For quadrupole-driven extraction, these fluctuations are the result of tune variations dominantly caused by current ripples and noise on the magnet power supplies in the order of 10^{-5} [6]. For RF-KO, artifacts of non-optimal excitation signal are known to cause similar fluctuations of the spill intensity [7]. Together with a varying extraction rate, these fluctuations are detrimental to the efficient usage of the beam by experiments. Therefore, the aim is to deliver spills of high quality in terms of the lowest possible intensity fluctuations and smallest deviation from the spill rate requested by the users.

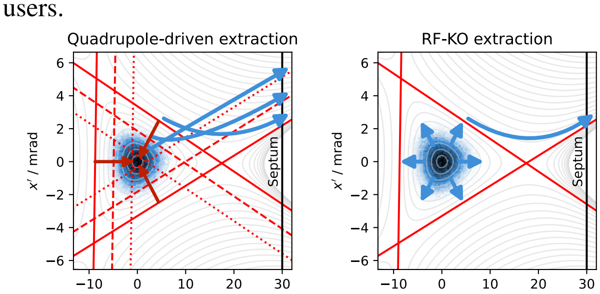

Figure 2: Phase space scheme of quadrupole-driven (left) and RF-KO resonant slow extraction (right).

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SPILL OPTIMIZATION SYSTEM (SOS)

The Spill Optimization System (SOS) was developed as a flexible tool to control and optimize the slow extraction process. Build as software-defined radio (SDR) [8], a universal software radio peripheral (USRP) is used as commercial front end to digitize signals at 200 MHz and generate signals from DC to 30 MHz. The digital signal processing is implemented using GNU Radio [9] and RFNoC [10]. These open source frameworks enable a flexible design using flow graphs and are being used increasingly in the accelerator community [11–14]. A detailed technical description of the flow graphs and implementations used is given in Ref. [15].

Working Principle

Figure 3 shows a schematic of the two Spill Optimization Systems for the two extraction methods. In either case, a particle detector monitors the extracted beam intensity, providing the measured spill rate as a signal consisting of logic pulses to the system. While this signal is usually provided by the beam user, a variety of permanently installed detectors can also be used, including indirect measurements of the spill rate obtained from beam loss monitors (BLMs) or the beam current transformer (BCT). The input signal is digitized, pre-processed on the field-programmable gate array (FPGA) and subsequently analysed using GNU Radio. This yields the extraction rate averaged on the millisecond-level on the one hand and the spill quality by means of the coefficient of variation c_v at a sub-ms resolution on the other hand. A twofold spill optimization approach is implemented: First, the averaged spill rate is processed by a digital feedback controller which regulates the output signal amplitude in realtime, thereby controlling the extraction rate to closely follow the target rate. Depending on the user's request, the target can be a fixed rate or a dynamically controlled intensity. Second, the spill quality is used by an optimization algorithm iteratively adjusting the signal parameters such as frequencies, bandwidths and amplitudes to improve the spill quality. For this purpose, the bound optimization by quadratic approximation (BOBYQA) algorithm [16, 17] is used as a robust, derivative-free global optimizer. The typically required 50 to 100 iterations can be performed intra-cycle for faster results, and/or cycle-by-cycle for a higher precision. Based on the controller output and the signal properties defined by the optimization algorithm, the system produces a control signal for the respective actuator controlling the extraction process, as explained in the following sections.

System for RF-KO Extraction

For RF-KO, the extraction process is controlled by the transverse RF field exciting the beam, which is generated in a stripline exciter powered by RF amplifiers. The Spill Optimization System produces dedicated excitation signals comprising multiple RF bands matched to the betatron sidebands of the stored beam [7, 18, 19]. Here, the SDR based approach offers a large flexibility in the composition of the excitation signal. While the amplitude of the excitation signal is controlled by the feedback controller, its properties such as frequencies, bandwidths and amplitude ratios between bands are tuned with the optimization algorithm minimizing intensity fluctuations.

System for Quadrupole-Driven Extraction

In the case of a quadrupole-driven extraction, the Spill Optimization System generates a voltage signal controlling the power supply of a dedicated fast quadrupole magnet (see Fig. 3, right). Here, the extraction process is driven by the tune change induced through the changing DC component of the quadrupole field. The feedback therefore controls the slope of the voltage signal. To reduce intensity fluctuations, the signal is modulated with a swept RF frequency of a few kHz referred to as tune wobbling [20]. The exact modulation frequency and amplitude are optimized using the aforementioned algorithm.

IMPROVEMENTS FOR USERS

The feedback control increases the stability of the delivered spills by compensating drifts and cycle-to-cycle fluctuations of the intensity and ensuring that the users receive precisely the requested spill rate. Compared to the previ-

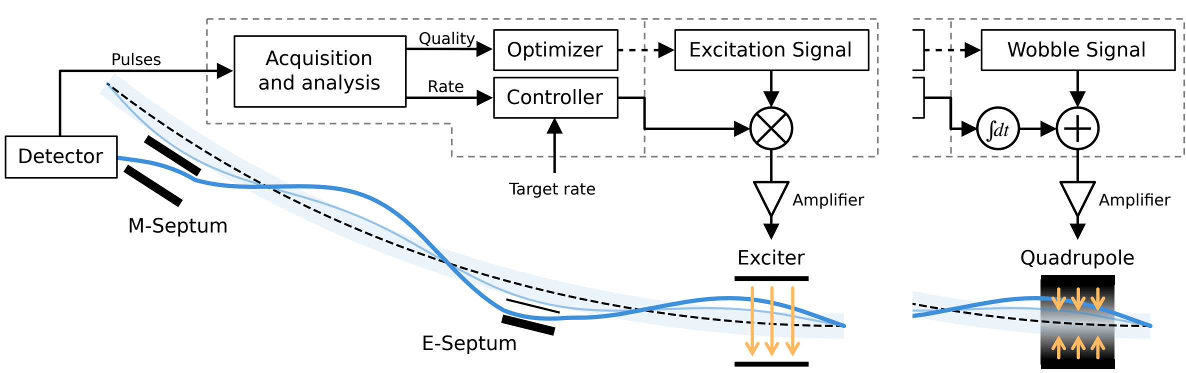

Figure 3: Schematic of the spill optimization system with signal processing parts for RF-KO extraction (left, framed part). For quadrupole-driven extraction, only the signal generation part is modified (right). A part of the beamline with exciter or quadrupole, magnetic septum and electric septum and the trajectory of particles being extracted is indicated.

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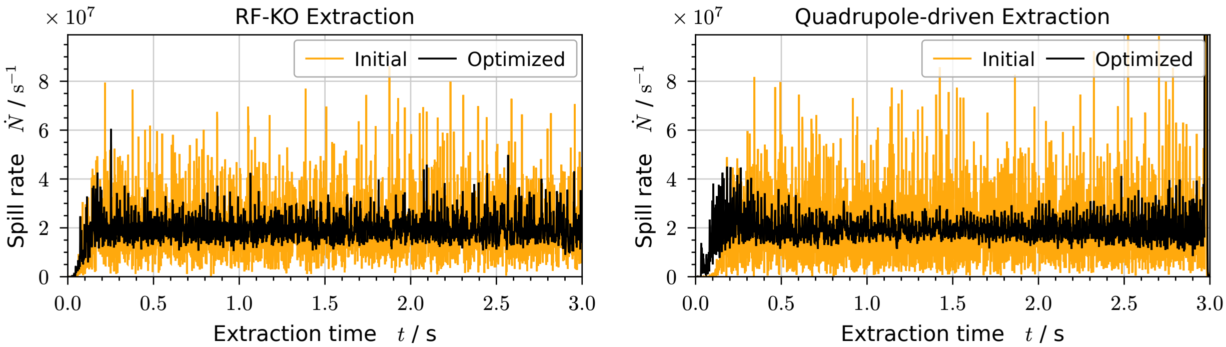

Figure 4: Measured spill rate (1 ms time resolution) for either extraction method using the respective feedback system for full extraction of the $^{238}U^{73+}$ at 500 MeV/u. Optimized refers to a combination of multi-sine excitation and tune wobbling.

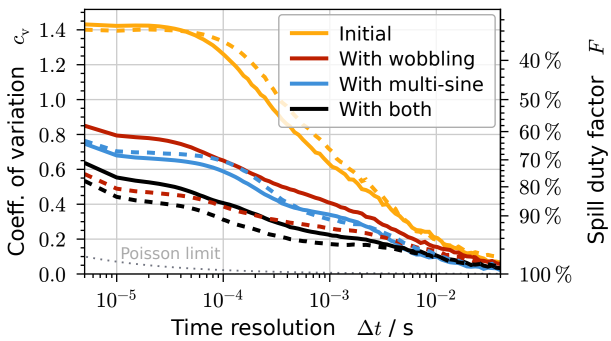

Figure 5: Spill quality obtained for RF-KO (solid) and quadrupole-driven extraction (dashed) using wobbling, multi-sine, and both of these optimization techniques.

ously typically observed curved spill shape, the rectangular spill increases the duty cycle and results in a statistics gain for experiments. Furthermore, the feedback system enables dynamic control of the spill intensity including spill pause, which is relevant for bio-physics applications [21]. Figure 4 shows spills obtained with SOS for RF-KO and quadrupole-driven extraction under comparable beam conditions in alternating machine cycles (multiplexed operation). For RF-KO, the initial setting uses a standard band-filtered noise excitation.

Spill intensity fluctuations are reduced using the aforementioned optimization techniques: A multi-sine excitation signal is applied with the RF-KO exciter and a tune-wobbling signal is applied with the extraction quadrupole. Multi-sine excitation applied to noise-driven RF-KO extraction is also referred to as Noise++ excitation [7]. Figure 5 shows the resulting spill quality observed by applying these techniques individually as well as in combination for either extraction method. Thereby, the coefficient of variation c_v is the standard deviation of the spill rate normalized to its average and is based on measured data binned to the given time resolution. The best spill quality is obtained with a combination of both optimization techniques (tune wobbling and multi-sine excitation) as depicted in Fig. 4. By minimizing intensity spikes, pile-up and detector saturation can be reduced, which allows experiments to use higher average beam intensities. This results in a gain of statistics for particle physics experiments or shorter treatment times in medical applications, fostering an efficient beam and detector usage.

For low energy, low intensity beams, the RF-KO extraction can also be driven by a pure multi-sine excitation, for which very high spill qualities approaching the Poisson limit can be achieved. Such a spill is shown in Fig. 6 as measured during a dedicated machine study in March 2024. The spill rate was set to 500 kHz, corresponding to about 5 % of the intensity stored in SIS18 during the 10 s extraction. In daily operation, multi-sine excitation is combined with band-filtered noise (Noise++) and optimized as a trade-off between spill quality and extraction efficiency.

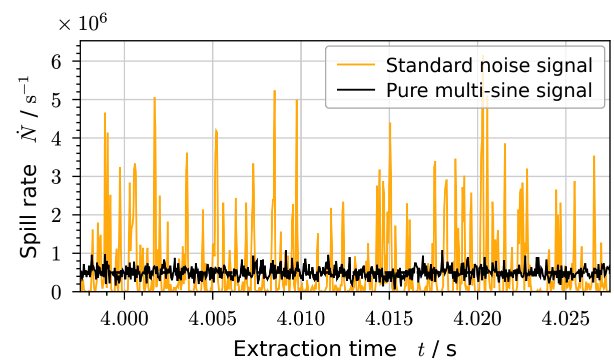

Figure 6: Measured spill rate (50 µs resolution) for an RFKO extracted coasting $^{197}Au^{65+}$ beam at 800 MeV/u using the standard band-filtered noise signal and an optimized, pure multi-sine excitation signal.

STATUS AND OUTLOOK

The system was implemented as a portable solution comprising a USRP X310 and an industrial PC. It has been used for RF-KO extraction studies at GSI, at the Heidelberg Ion Beam Therapy Center (HIT) [19] and for regular user operation at the Cooler Synchrotron (COSY) in Jülich [22]. The system for RF-KO is currently used at GSI SIS18 for selected users; multi-user operation is being implemented along a full control system integration. The system for quadrupole-driven extraction has been tested successfully at SIS18 and its control system integration is foreseen too. The custom firm- and software of the SDR based Spill Optimization System is published in Ref. [23]. It comes with a GUI and an API for programmable control. With the commercial USRP as front-end and the open-source GNU Radio framework, it is available for use at other facilities.

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