AUTOMATED MINIMIZATION OF UNCONTROLLED BEAM LOSS FOR SLOW EXTRACTION FROM SIS18

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Abstract

The GSI heavy ion synchrotron SIS18 delivers ion beams via slow extraction to various experiments for a wide range of ion species, beam energies, and spill lengths. For the upcoming FAIR Early Science program, extraction intensities of more than 1E9 uranium ions per second are required at energies up to about 1 GeV/u. One of the most important tasks for the slow extraction is limiting uncontrolled particle losses. Limits arise from the requirement to avoid damage of the extraction septa and to minimize the activation of accelerator components. For the highest expected intensities, the limits are a few percent only. That requires a robust optimization of the machine settings. Therefore, automated schemes using numerical optimizers are developed at GSI and tested for quadrupole-driven and RF KO slow extraction, in simulation as in measurements. We will report on first results that demonstrate the fast convergence of the observed transmission toward similar values, both in simulation and in measurements. The validated simulation model allows for important insights into the optimized settings.

INTRODUCTION

The Facility for Antiproton and Ion Research (FAIR) is an international center of heavy-ion accelerators, designed to advance research in heavy-ion and antimatter physics [1]. The facility's complexity demands a high degree of automation for future operations [2]. As part of this effort, we developed a framework called Generic Optimisation Frontend and Framework (*Geoff*) [3], which allows machine experts and operators to solve concrete optimization problems and reuse these solutions in an operational context.

Many present and future experiments at GSI and FAIR use slow-extracted beams from the SIS18/SIS100 synchrotrons [4]. For the upcoming FAIR Early Science program, extraction intensities of more than 10^9 uranium ions per second are required at energies up to about 1 GeV/u from SIS18. A slow-extracted beam is also referred to as *spill*. Critical tasks during the slow extraction of heavy ion beams at SIS18 are to ensure a good spill quality achieved by a low spill structure level according to the requirements of fixed target experiments, and to minimize uncontrolled particle losses in order to avoid component activation and ensure stable operation. The losses are influenced by the tuning of nonlinear lattice elements and orbit parameters. Therefore, automated optimization approaches, as enabled by *Geoff*, provide a promising tool to improve extraction performance and reduce losses in a systematic and reproducible manner.

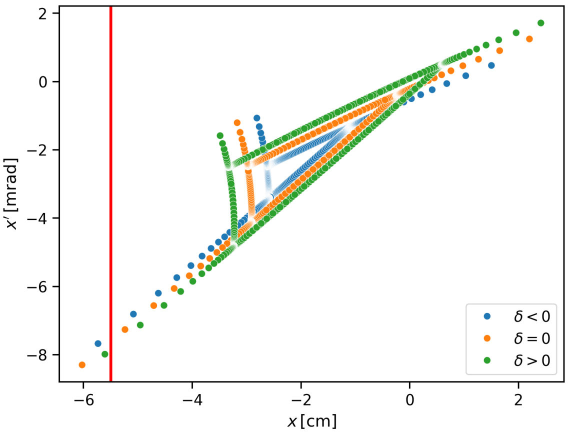

Figure 1: Simulated transverse phase space trajectories (x, x') of particles with different momentum offsets.

SLOW EXTRACTION IN SIS18

Slow extraction from ring accelerators is widely used for delivering hadron beams to fixed-target experiments and for tumor irradiation in hadron cancer therapy. Most schemes rely on the excitation of a third-integer lattice resonance with sextupoles. In SIS18, the resonance condition is given by $13 = 3Q_{x,\mathrm{r}}$, yielding a resonance tune of $Q_{x,\mathrm{r}} = 13/3 = 4.\overline{3}$. This creates a triangular stable phase-space area in the horizontal plane, bounded by separatrices, see Fig. 1. The betatron motion of particles is stable inside this region and unstable outside. The size of the stable phase-space area depends on the distance between particle and resonance tunes and is therefore sensitive to the particle momentum offset via chromatic tune shifts, as shown in Fig. 1. Slow extraction is performed by adiabatically approaching the resonance such that particles gradually become unstable, leave the stable phase-space region, and are extracted when reaching the electrostatic septum. Two standard extraction modes exist in SIS18: quadrupole-driven and RF knock-out [5]. The present work focuses on quadrupole-driven extraction, where the tune is swept across the third-integer resonance starting from $Q_{x,\mathrm{start}} < Q_{x,\mathrm{r}}$.

A key challenge in slow extraction is the minimization of uncontrolled particle losses, which cause irradiation, component damage, and increased operational costs. The electrostatic septum (ES) and magnetic septum (MS) are particularly sensitive to such losses and therefore require careful optimization. In general, losses should be kept below 5–10 %. Losses of low-energy particles need to be stronger suppressed, as their impact is greater and is not limited to slow extraction losses. The ES applies a transverse kick required for beam extraction using a high electric field. Its anode consists of an array of wires with a diameter of 100 µm

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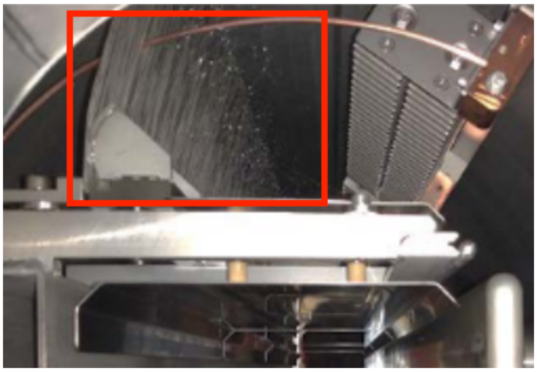

Figure 2: Zoomed view of the ES after operation, showing a representative section of the anode wire array with severe damage (about 50 % broken wires) [6].

and a spacing of 2 mm. Significant degradation of the anode structure was observed during operation, requiring substantially higher voltages than nominal to maintain efficient extraction. Subsequent inspection revealed severe damage to the wire array, with about 50 % of the wires found to be broken over a significant length, see Fig. 2 [6].

The resonance is excited with sextupoles, whose integrated strengths are defined by

$$(k_2L)_n = (k_2L)_\mathrm{a} \sin\left(2\pi\frac{n-1}{12} + \phi_\mathrm{sx}\right), \tag{1}$$

where the sextupoles of SIS18 are located in selected sectors $n = 1, 3, 5, 7, 9, 11$. The sextupole system is fully determined by two parameters: the *sextupole amplitude* $(k_2L)_\mathrm{a}$, which determines the size of the stable phase-space area, and the *sextupole phase*, which controls its orientation and thus the matching of the particle's divergences x' to the tilt angle of the ES at extraction. Additional optimization parameters include the closed-orbit (CO) bump amplitude at both septa, $x_\mathrm{CO,ES}$ and $x_\mathrm{CO,MS}$, as well as the ES deflection angle $\Delta x'_\mathrm{ES}$. Proper tuning of these parameters ensures correct transport of particles through the apertures of ES and MS into the extraction channel. The objective of the optimization is to minimize the relative extraction loss, which is given by $1 - f_\mathrm{ex}$, where the extraction efficiency f_ex denotes the fraction of particles which have reached the extraction channel.

Table 1: Optimization Parameter Ranges for Full and Reduced Space

Parameter	**Symbol**	**Full**	**Reduced**
Sextupole strength	$(k_2L)_\mathrm{a}$ [m^{-2}]	[0:0.25]	[0.02:0.08]
Sextupole phase	ϕ_sx [°]	[-180:180]	[-10:50]
CO bump ES	$x_\mathrm{CO,ES}$ [mm]	[16:30]	[16:30]
CO bump MS	$x_\mathrm{CO,MS}$ [mm]	[0:10]	[2.5:7.5]
ES deflection	$\Delta x'_\mathrm{ES}$ [mrad]	[-10:-3]	[-4.5:-3]

CONVERGENCE STUDIES

Geoff [3] provides a flexible and standardized interface for switching between optimization algorithms, including reinforcement learning (RL), enabling users to start with simple optimizers such as BOBYQA, which defines the search space via bounds and allows them to concentrate their initial efforts on problem formulation. Py-BOBYQA is a trust-region implementation using quadratic models that improves robustness for nonlinear and noisy problems, with strict bound handling and a heuristic for global optimization [7–9].

Automated optimization of slow extraction settings using Py-BOBYQA as the initial optimization for both reduced and full parameter ranges is shown in Fig. 3. The corresponding optimization parameter spaces are summarized in Table 1. The full scan covers wide physical ranges of sextupole settings and orbit parameters, while the reduced space restricts the search to regions expected to contain physically relevant solutions, in particular for the sextupole amplitude and phase. Convergence studies show that both parameter spaces reach the same maximum performance with loss around 10 %, see Fig. 3 (a). However, the full parameter scan exhibits a significantly larger spread and less stable convergence behavior across seeds, Fig. 3 (b). In contrast, the reduced parameter space yields similarly high performance with a more confined and robust optimization trajectory. This indicates that the reduced bounds still contain the rele-

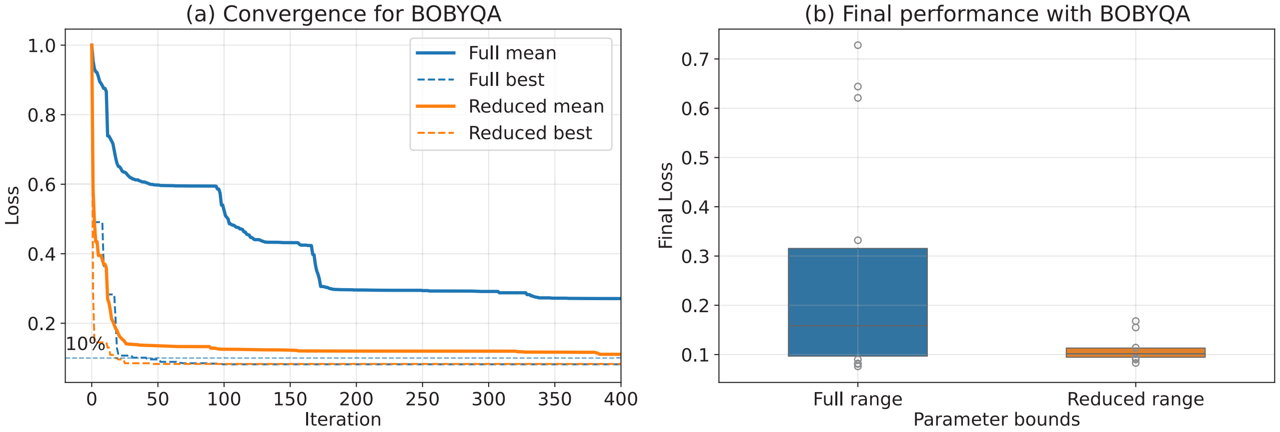

Figure 3: Optimization performance comparison between full and reduced parameter spaces from Table 1. Left: convergence of mean and best-so-far loss. Right: final loss distribution across seeds.

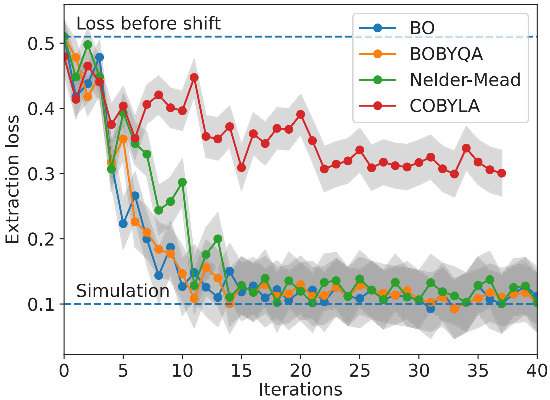

Figure 4: Automated slow-extraction optimization from identical initial conditions shows convergence within 15 steps except COBYLA; the gray region indicates uncertainty.

vant optimum region of the optimization landscape, while excluding non-informative parameter regions and thereby improving optimization efficiency.

ONLINE OPTIMIZATION

Automated optimization of slow extraction settings using various algorithms can significantly reduce beam losses in just a few iteration steps. Figure 4 demonstrates that serverless algorithms can deliver strong performance on this task. The optimization was performed within the reduced parameter ranges introduced in Table 1, which were identified from simulation studies and refined based on operational experience to contain the relevant optimum region. Bayesian optimization (BO) builds a probabilistic model (typically a Gaussian process) to predict the behavior of the objective function. Based on this model, it uses an acquisition function to decide where to sample next, balancing exploration and exploitation [10]. COBYLA (Constrained Optimization BY Linear Approximations) is a derivative-free algorithm that handles nonlinear constraints by iteratively approximating them with linear models [11]. The Nelder–Mead algorithm iteratively updates a simplex using reflection, expansion, contraction, and shrink steps to minimize an objective function [12]. Although the optimization techniques are conceptually distinct, all of them - except COBYLA - were able to identify machine settings that effectively reduce the losses to levels comparable to the 10 % achieved in simulation, likely due to the limited parameter range restricting the objective landscape to a comparatively convex region.

FURTHER IMPROVEMENTS

Usually, slow extraction is performed with static lattice settings, except for driving the fast quadrupoles to sweep the tune. This causes a continuous shrinkage of the triangular stable phase space (Fig. 1) as the machine tune approaches the resonance. Consequently, the particle divergence at the ES changes during the extraction in a range, determined by the initial phase space size, which can lead to additional particle losses at the septum. To mitigate these losses, we extend the simulation model by introducing more time-dependent lattice parameters. In the present study, the sextupole phase ϕ_{sx} in Eq. (1) is varied in time,

$$\phi_{\mathrm{sx}} = \phi_{\mathrm{sx}}(t), \tag{2}$$

resulting in a rotation of the stable phase space. This reduces the total particle loss from about 10 % to 6.5 % (Fig. 5).

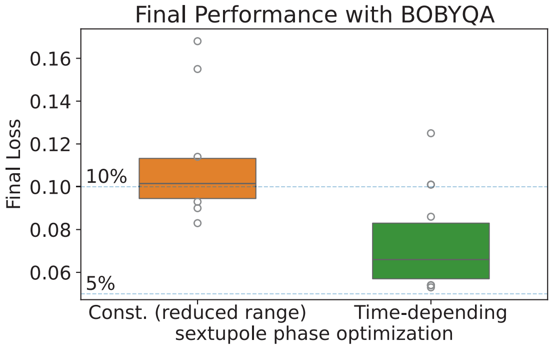

Figure 5: Time-dependent sextupole phase reduces particle losses to 6.5 %.

Further reduction is expected from optimizing the horizontal chromaticity, which would decrease the spread in phase space size due to momentum deviations.

SUMMARY AND OUTLOOK

An automated optimization approach for quadrupole-driven slow extraction was developed and validated in both simulation and experiment, yielding consistent loss levels of about 10 %. Simulations also show that introducing a time-varying sextupole phase can lower these losses to about 6.5 %.

Beyond losses, spill quality is a key requirement for experimental operation and can be improved via dedicated techniques (e.g., feedback systems or spill cavities) or optimized machine settings [5, 13–18]. A simultaneous optimization of losses and spill structure via multi-objective Bayesian optimization appears attractive, but it is computationally intensive and difficult because the loss and spill objectives impose different modeling requirements. Accurate loss prediction in simulations can be performed with relatively few particles and short time intervals but demands a detailed description of machine apertures. In contrast, spill quality is highly sensitive to the short temporal structures of the extracted beam and thus necessitates sufficiently large particle statistics and a realistic time interval.

The effectiveness of slow extraction and multi-turn injection (MTI) optimization [19] for SIS18 validates future autonomous tuning concepts at FAIR [20], including model-based and machine-learning-driven approaches for accelerator operation [21–23].

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