SIMULATION BASED MACHINE PROTECTION FOR THE Super-FRS

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Abstract

Starting in 2027, the Super-FRS will produce and separate rare isotopes for nuclear physics experiments at the Facility for Antiproton and Ion Research (FAIR). To reach isotopes further toward the nuclear drip line, the separator uses heavy-ion beams of higher energy (>1.5 GeV/u) and intensity ($>3 \cdot 10^{11}$ ^{238}U/s) compared to previous facilities. These primary beams, as well as the secondary fragment beams produced in reaction targets, can damage detectors along the beamline and may cause quenches in the superconducting magnets. To prevent such scenarios, it is essential to ensure that all beams are correctly separated and stopped in dedicated beam dumps. For this purpose, a machine protection system is being developed to verify every new machine setting required during diverse experimental campaigns. To avoid slowing down machine operation, the system simulates, in near real time, all (fragment) beams for different magnet settings, targets, degraders, and detectors throughout the entire separator. The planned capabilities of this machine protection system and the currently achieved prototype are presented.

INTRODUCTION

Exotic nuclei are produced at in-flight fragment separators by the fragmentation and fission of relativistic heavy-ion beams. To meet the demand of nuclear physics research for increasingly rare nuclei, the Super-FRS (Superconducting Fragment Separator) is currently being installed as part of FAIR (Facility for Antiproton and Ion Research) in Darmstadt, Germany [1]. Compared to the previous GSI fragment separator FRS [2], the new separator can handle higher primary beam intensities and has larger momentum- and angular acceptances to catch more fragments. The Super-FRS will receive primary beams from the SIS18 and SIS100 synchrotron, which can accelerate ions ranging from protons to Uranium up to magnetic rigidities of 100 Tm [3]. For the Super-FRS intensities of $5 \cdot 10^{11}$ Uranium ions per cycle of between 0.4 and 2.7 GeV/u are expected. Depending on experimental needs, these ions can be extracted either fast in ~ 70 ns or slow in 1–10 s. In the former case this translates to an instantaneous power shortly exceeding 500 GW and even in the latter case corresponds to more than 20 kW of average beam power.

In the Super-FRS these intense primary beams are used to produce exotic nuclei in a graphite target wheel of up to 8 g/cm^2 thickness. Behind the target, a cocktail beam, consisting of the degraded primary beam and more than 3000 different fragments for the heaviest beams (as simulated in Fig. 1) enters the separator. It is the purpose of the separator to filter for exotic fragments of interest while preventing other, multiple orders of magnitude more intense beam components from overwhelming detector systems. The Super-FRS, presented in Fig. 2, uses a combination of magnets, degraders, and slits to achieve this separation. It will usually be operated as a double stage $B\rho$-ΔE-$B\rho$ separator [7]. In this setting the fragments of interest will be achromatically focused both after the pre- and main-separator, while fragments of different charge or mass number are horizontally separated. For different experiments the main-separator can serve three different branches dedicated to low-energy, high-energy and storage ring experiments.

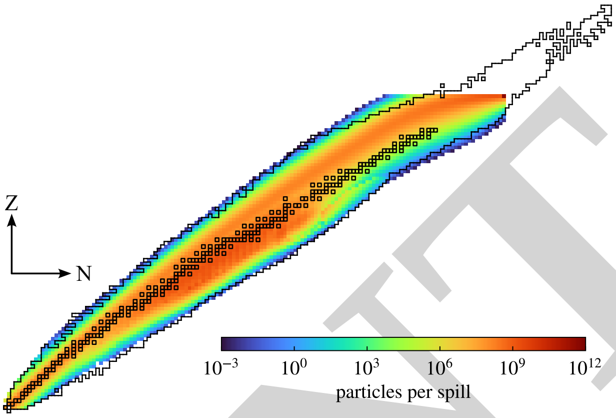

Figure 1: Fragments produced by a 1.5 GeV/u $5 \cdot 10^{11}$ ^{238}U spill on 8 g/cm^2 C simulated with Mocadi [4] and cross sections from [5, 6].

MACHINE RISKS

The target area of the Super-FRS is designed to receive beams of the highest intensities from the accelerator. The first eight magnets after the target are radiation-resistant normal-conducting magnets, unlike the remaining superconducting magnets. Dedicated beam catchers are installed behind the first three dipoles to absorb the most intense beam components. Other sections further downstream of the separator are not designed to handle these high intensities.

Superconducting Magnets

The superconducting NbTi coils in the Super-FRS are cooled to 4.5 K by liquid helium and will quench if they exceed a temperature of about 7 K [8]. A misguided beam locally depositing >1 mJ/g into the coil could induce a quench and a beam depositing >10 W into the 4.5 K cryostat could

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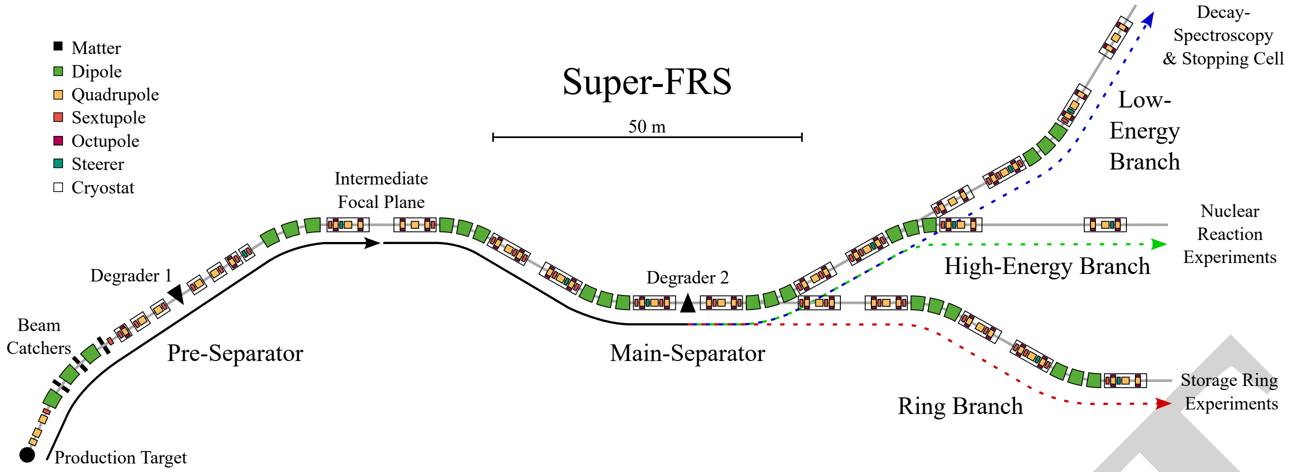

Figure 2: Layout of the Super-FRS at FAIR.

exceed its cooling power. While a quench protection system is in place to avoid damaging the magnet in such a scenario, the recovery from such an accident may interrupt an experiment for multiple hours. Significantly higher intensities could even lead to irreversible damage to the magnets.

Detectors

Multiple detector systems can be inserted into the beamline which allow an in-flight identification of the fragments. Specifically, the single-particle detectors are supposed to operate at most with intensities around 10^6 particles/s and can be damaged by higher intensities. During the first year of operation both position and timing information will be measured at the Super-FRS using scintillator detectors. The plastic scintillators used are known to become increasingly opaque from irradiation, reducing their detection efficiency and leading to wrong particle identifications [9].

Dangerous Settings

To avoid both of these scenarios the separator should only be operated with settings where all high intensity beam components are safely stopped before reaching these sensitive devices. During experimental campaigns the Super-FRS will be switched between many settings for different tasks, including for example beam alignment, detector calibration, or fragment identification. Each setting may vary in primary beam (type, energy, spot size, emittance), magnets (currents), target (material, thickness), slits (position), degraders (thickness, angle), and inserted detectors (material, thickness). It is not feasible to verify all possible setting combinations prior to each beamtime, so each new setting needs to be validated online.

To illustrate the risk associated even with small setting changes, as an example a possible Super-FRS setting to produce the exotic isotope ^{212}Pb is simulated in Fig. 3. The most intense contributions which reach the last beam catcher are fully stripped ^{238}U^{92+} and the two charge states ^{238}U^{91+} and ^{238}U^{90+}. The magnetic rigidity of the ^{212}Pb fragments is exactly between these intense components although its intensity is about 7 orders of magnitude lower. To capture ^{212}Pb and prevent ^{238}U$^{92+/91+}$ from reaching sensitive devices the beam catcher needs to be positioned as indicated in the upper part of Fig. 3. During a beamtime an operator may decide to remove seetram detectors in front of the target, which are intensity detectors of in total 60 µm Ti thickness. The impact of this setting change, assuming the magnets are not adjusted accordingly, is shown in the lower part of Fig. 3 and for the full separator in Fig. 4. While the setting was previously safe, this removal of a thin detector increases the downstream intensity by more than an order of magnitude and poses a risk to superconducting magnets and detectors.

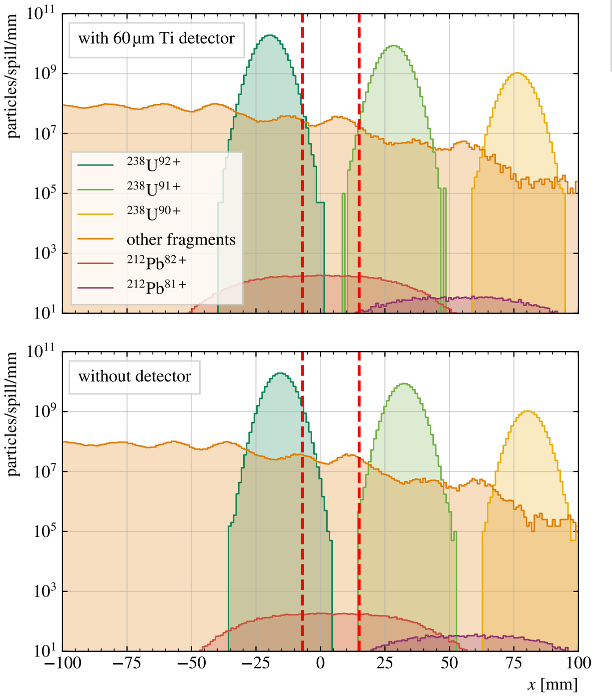

Figure 3: Transversal intensity distribution produced by a ^{238}U (1.5 GeV/u) impinging on a 3.2 g/cm^2 C target, separator centered on ^{212}Pb. Distribution simulated infront of the third beam catcher whose absorbers are positioned to stop everything outside the red dashed lines.

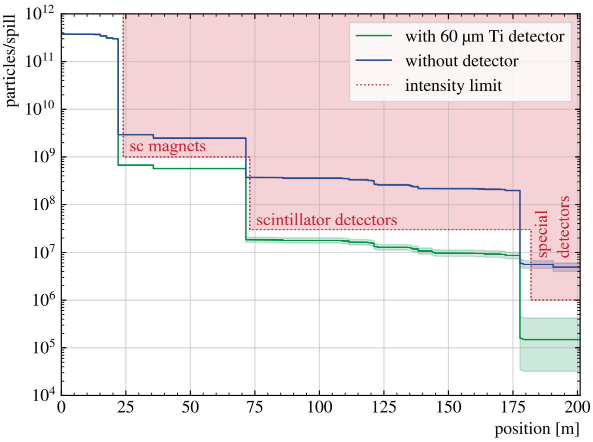

Figure 4: Beam intensity throughout the high-energy branch of the separator in the ^{212}Pb setting, depending if the detector is inserted. In red are the different devices indicated that can limit the intensity.

VALIDATION SYSTEM

To ensure a safe machine operation every new machine setting will be automatically validated to pose no risk for any subsystem of the separator. The large number of components, >100 magnets and >50 drives, together with diverse experimental demands exclude simple logic interlock systems from fulfilling this task. Only a complete simulation considering degraded primary beam, charge states, and intense fragments, as shown in Fig. 3, can reliably predict all beam intensities along the full separator. To avoid excessively interrupting the machine operation a time limit of about 2 minutes, comparable to the magnet cycle time, was set for this validation system.

Existing programs optimized for simulating fragment separators are Mocadi [4, 10] and LISE^{++} [11]. LISE^{++} does currently not meet the time-requirement (for heavy-ions including charge-states, secondary reactions, and rates at all positions) and is difficult to modify for simplification and integration into our control system. The other program, Mocadi, is a Monte Carlo ion tracking code originally developed for the design and operation of the FRS. It tracks heavy-ions through ion optical systems with higher-order image aberrations and through matter layers with atomic and nuclear interactions [10]. The underlying interaction physics have been extensively validated in experiments with conditions similar as expected at the Super-FRS, making this the ideal starting point for the setting validation system.

Current Mocadi simulations are performed for a given list of fragments created in a target, so the Monte Carlo generation is biased to produce a given number for each of these fragments. This feature allows simulating rare events with short computation time but is not well suited for a general purpose machine protection, where only the primary beam is known before. Instead, a new routine for the target (and matter layers in general) is needed which performs unbiased, random nuclear reactions, weighted according to the respective cross-sections. This was implemented in a validation system prototype to simulate in Figs. 3 and 4 the fragment background produced by projectile fragmentation based on the EPAX cross section model [5]. The final system will include additional models to also simulate fission and the fragmentation of very light and heavy projectiles more precisely.

With this unbiased event generation the Monte Carlo simulation yields at every point along the separator a number of n_i hits which is divided by the number of simulated primary events N an estimate for the true relative rate r_i at the i-th position. The observed hits n_i are approximately Poisson distributed around the expectation value $\lambda = r_i \cdot N$. To decide if a setting is safe the confidence interval for the mean of a Poisson distribution can be used [12], quantified by

$$\frac{1}{2}\chi^2\left(\frac{\alpha}{2}; 2n_i\right) \leq \lambda \leq \frac{1}{2}\chi^2\left(1-\frac{\alpha}{2}; 2n_i+2\right).$$

Given a confidence level α, for example 1%, a setting is deemed safe if the intensity limit $r_{\max}$ is above the left endpoint, unsafe if it is below the right and requires more events if neither is fulfilled. In Fig. 4 for example $N = 10^7$ events were simulated and 5 hits reached the end of the separator with the detectors inserted. This yields a 99% confidence interval of $[0.5, 7] \cdot 10^5$ particles/spill which is below the lowest expected intensity limit $r_{\max} \approx 10^6$ particles/s for detectors. Simulations of other settings confirmed that at most around 10^7 primary events are needed to validate a setting for such limits. So, to meet the time limit the validation system must be capable of simulating at least 10^5 events/s.

For the setting validation a new program is being developed that is based on the physics routines of Mocadi introducing unbiased event generation and parallelization to achieve the performance goal. The validation system will be systematically tested against Mocadi and LISE^{++} as well as previous experiments conducted at the FRS. The current prototype was able to simulate for the machine setting shown in Fig. 3 10^7 primary events in 50 s on a 12-core desktop computer. This performance corresponds to $2 \cdot 10^5$ events/s although tests with simplified physics models show that more than 10^6 events/s should be achievable with the final system. For settings with less intensity or less stringent limits much less events and computation time is required. In most situations, the system can distinguish between safe and dangerous settings within a few seconds.

CONCLUSION

Protecting the Super-FRS from damage caused by intense heavy-ion beams requires an automatic setting validation system. This system will be integrated into the FAIR control system to simulate every new setting applied to the Super-FRS, ensuring that all dangerous beam components are correctly separated and stopped before reaching sensitive devices. The system will be based on a performance-optimized reimplementation of Mocadi routines and will be ready for the upcoming commissioning of the Super-FRS.

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