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SUPPORTING FLEXIBLE RUNTIME CONTROL AND STORAGE RING OPERATION WITH THE FAIR SETTINGS MANAGEMENT SYSTEM

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Abstract

The FAIR Settings Management System has now been used productively for the GSI accelerator facility operating synchrotrons, storage rings, and transfer lines. The system's core is being developed in a collaboration with CERN [1], and is based on CERN's LHC Software Architecture (LSA) framework [2].

At GSI, 2018 was dedicated to integrating the Beam Scheduling System (BSS). Major implementations for storage rings were performed in 2019, while 2020 the main focus was on optimizing the performance of the overall Control System.

Integrating BSS allows us to configure the beam execution directly from the Settings Management System. Defining signals and conditions enables us to control the runtime behavior of the machine.

The Storage Ring Mode supports flexible operation with features allowing to pause the machine and execute in-cycle modifications, using concepts like breakpoints, repetitions, skipping, and manipulation.

After providing these major new features and their successful productive use, the focus was shifted on optimizing their performance. The performance was analyzed and improved based on real-word scenarios defined by operations and machine experts.

PREFACE

Patterns and Beam Production Chains (Chains) are the central technical concepts within the new LSA-based Settings Management System at GSI [3,4]. Chains are foreseen to provide a beam-oriented view on the facility from source to target, for now this is not utilized and they still represent an accelerator-oriented view. To be able to coordinate multiple beams traversing the facility in parallel, Chains are grouped into Patterns. See Fig. 1.

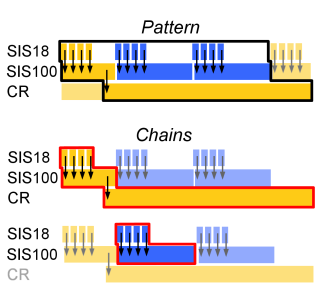

Figure 1: Patterns and Beam Production Chains as concepts for scheduling beams.

The term LSA will be used throughout this paper when the FAIR Settings Management System business logic is referenced.

RUNTIME CONTROL THROUGH BSS

Conceptually, LSA is an offline system which has no information about real-time scheduling, issued beam requests or machine status. BSS is an online system that, at runtime, processes scheduled event sequences and their dependencies on beam requests, accelerator status and beam modes.

Figure 2 shows an overview of the data that is exchanged between the systems.

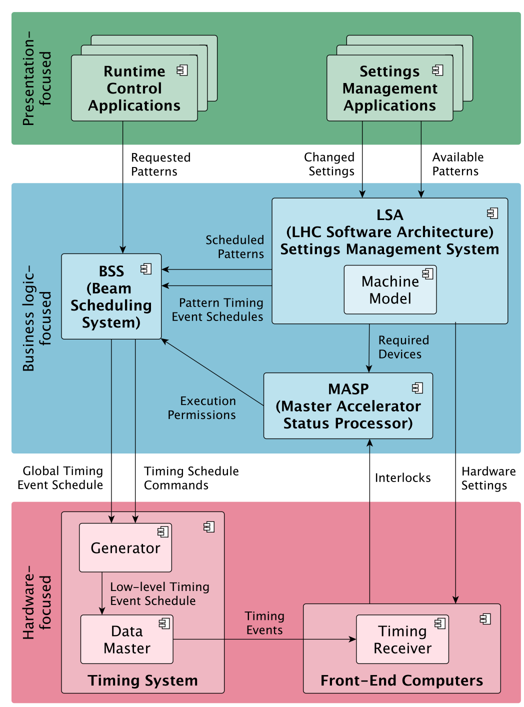

Figure 2: Control system interaction diagram.

The BSS's beam scheduling description is using LSA's own concepts like Patterns, Chains and additionally generated scheduling information like

- description of alternative timing event sequences
- definition of synchronization points
- causal description of branching depending on beam requests, accelerator status and beam-mode
- signal definitions that are used to switch between the aforementioned points

For a detailed description of BSS see [5].

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A major effort was to implement the foundation that all the information needed by BSS can be generated in LSA.

Originally at CERN, LSA only has the concept of resident contexts. A resident context represents a corresponding set of set-values, that are loaded into the devices and the Timing System could potentially send events to execute them.

At first the machine model at GSI, like the one at CERN, only contained set-values for devices. In discussion with the machine experts it was decided to introduce an additional hierarchy into the model that also calculates tables of timing events that are needed to execute the settings.

Figure 3 shows a part of the timing hierarchy that is used to calculate the timing event sequences.

LSA at GSI now has full control over the series of timing events which can be adapted depending on factors like element, isotope, energy, ramp speed/length, number of injections, etc.

The calculations lead to a series of timing events (see Table 1) that are converted into a DOT graph [6] description and sent to BSS (see Fig. 4).

Table 1: Simplified Event Sequence as Generated by the LSA Model

Timing Group	Chain	Chain Start	Event Id	Event Time µs	Comment
300	1	1	256	0	Start of sub-sequence
300	1	0	512	0	Prepare Function Generators (FG)
300	1	0	352	0	Request beam transfer
300	1	0	256	16000	Start of sub-sequence
300	1	0	351	16000	End beam transfer
300	1	0	513	16000	Start FGs and Ramp

Patterns were extended by the possibility to add execution conditions and a repetition count. Both are used by LSA to generate branching conditions. First LSA determines which branches exist and generates BSS Signals to enable switching between branches. These Signals are then used at runtime to determine the branch that should be taken for this Pattern execution.

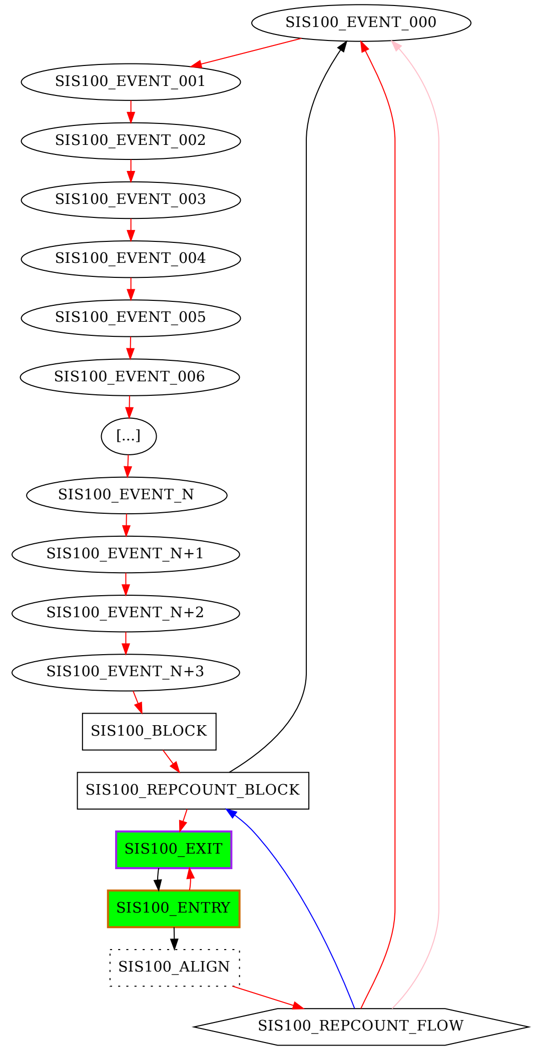

Figure 4: Schematic timing graph that is sent to BSS as DOT.

As an example Fig. 5 shows a simplified graph that allows to repeat or skip a Pattern.

Since setting manipulation happens per Pattern, the schedule graph information sent is also strictly per Pattern. Only BSS has an overview of the whole schedule.

On top of the resident concept from CERN, the concept of "Pattern Groups" has been introduced into LSA at GSI.

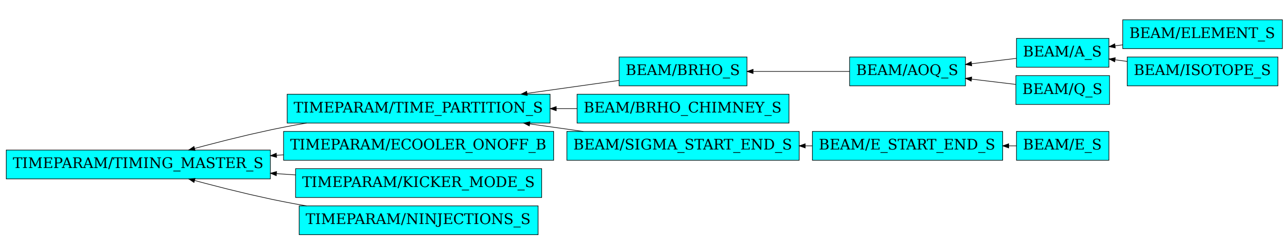

Figure 3: Simplified timing hierarchy to calculate the timing event sequence.

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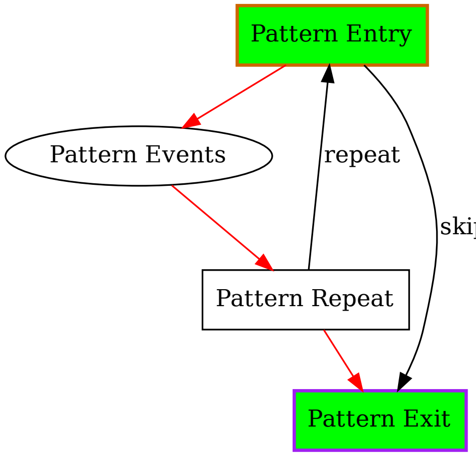

Figure 5: Simplified Pattern repetition and skip graph.

They tell BSS which Patterns can run alternately and which can be executed concurrently.

To describe that a beam is transferred between Patterns from different Pattern Groups, a concept that is called "coupling" is used. If *Pattern B* is coupled with *Pattern A*, *Pattern B* halts at injection level, requesting that *Pattern A* is executed. Once *Pattern A* is ready to transfer the beam, it signals for *Pattern B* to continue its execution. The extraction from *Pattern A* and the injection in *Pattern B* is now executed synchronously. The whole process, its timing schedule and conditions, are pre-planned offline using LSA and sent to BSS. At runtime, everything is handled at the lower-level Timing System. Figure 6 shows a simplified coupling graph.

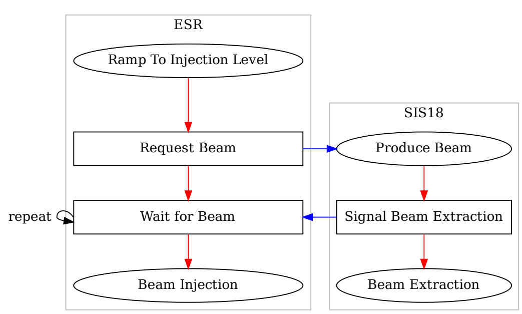

Figure 6: Schematic SIS18<->ESR coupling graph.

Realizing these features enables runtime control through BSS's signals and the timing event graph without the need of further interaction with LSA. It can be prepared beforehand what is possible at runtime.

The integration of BSS was also a precondition for Storage Ring Mode features that require manual user input at runtime to control the beam execution interactively.

STORAGE RING MODE

Ever since the commissioning of the heavy ion storage ring ESR in 1990, storage ring operation has been a regular, routine mode of operation at GSI. A second, smaller heavy ion storage ring called CRYRING [7], which had previously been installed at Stockholm University, became a part of the GSI facility in 2016.

LSA already supported fully pre-planned, usually short contexts used for synchrotron operation. As some of the storage rings can store a beam for several days, a more flexible, interactive approach that allowed certain in-cycle modifications was required.

Based on the experience of the ESR and CRYRING experts and the requirements for future storage rings at FAIR, a suitable concept for the new GSI Accelerator Control System was subsequently developed and implemented in 2019. It introduces smaller building blocks within the Chain that represents the full storage ring cycle. The desired functionality is provided by four key features for flexible operation that affect the building blocks: breakpoints, skipping, repetitions, and manipulations (see Fig. 7). Apart from manipulation, the other features can be combined with each other in a single building block.

All features can be configured and triggered by operators using a specialized Storage Ring Mode application (see Fig. 8).

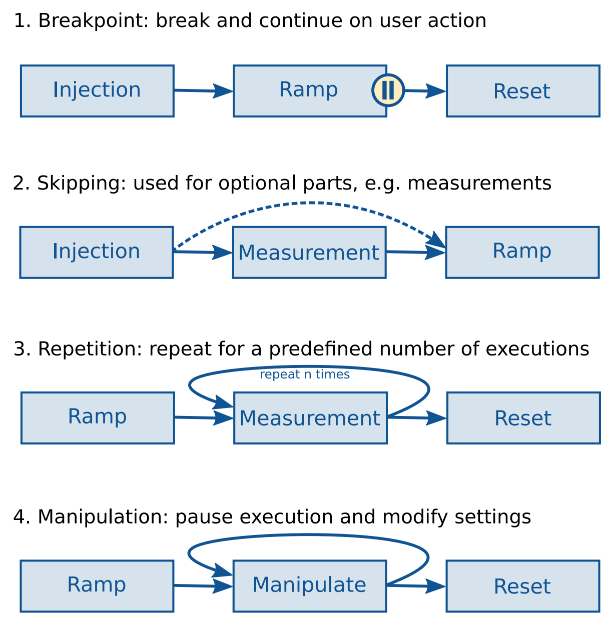

Figure 7: The four key features of the Storage Ring Mode.

Breakpoint

Breakpoints are pre-defined points at the end of a block in a storage ring Chain at which the execution can be interactively paused while the beam is still circulating in the ring. Using the specialized application, the operator can activate a breakpoint. The next time the Chain execution reaches this point, it will halt there until the operator deactivates the breakpoint and execution resumes.

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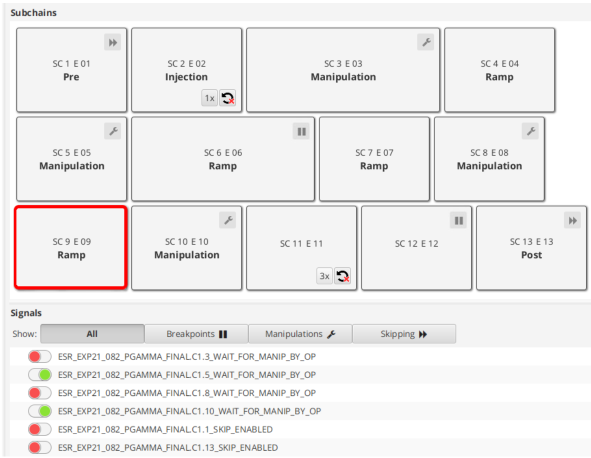

Figure 8: Partial screenshot of Storage Ring Mode application.

This feature can be used for example to pause for an indeterminate time while performing measurements, until sufficient data has been collected.

Skipping

For blocks of the storage ring Chain that are skippable, the operator can configure whether these blocks are executed or skipped.

Skipping can be used e.g. to quickly reach the end of a Chain execution and start from the beginning, for example in case of unexpected beam loss. This feature is currently also utilized to execute optional parts at the very beginning and end of a Chain. These parts bring the ring devices from their initial state up to an operational level and down again, and only need to be performed when the storage ring operation is started and stopped, but not between shots. This saves time, reduces energy consumption, and reduces the load on the devices.

Repetition

Blocks of the storage ring Chain can be repeated for a well-defined amount of repetitions. The operator can define that amount, and can decide to abort currently executed repetitions.

Repetitions are used to perform certain parts of the storage ring Chain multiple times, e.g. to take a certain number of measurements. They can also be useful to have a pre-planned way of "stalling" the execution for a pre-determined amount of time while beam is circulating – in contrast to breakpoints, which are used interactively and for an indeterminate time.

Manipulation

The most complex Storage Ring Mode feature is the manipulation. Similar to breakpoints, they offer the possibility to not only pause at certain points in the storage ring Chain, but also to modify certain settings in this state, until the operator decides to leave the paused state.

The manipulation feature is used to influence the beam while it is stored in the machine, e.g. by slightly changing its orbit. This provides the operators with a lot of flexibility to interactively find good settings by performing multiple small trims on stored beams.

Storage Ring Mode in Production

The Storage Ring Mode comprised of the features described above was successfully used in production during the beamtimes in 2020 and 2021 at ESR and CRYRING. Using this new flexibility allowed for multiple machine and science experiments.

Once Storage Ring Mode operation had been established, the performance of the Control System became the new center of attention.

PERFORMANCE OPTIMIZATION

During beamtime 2019/2020, operating identified massive performance problems with the Control System, some of which were intensified by the new features. With the system's increasing functional range and complexity, especially due to in-cycle modifications, the importance of performance as a Control System feature became apparent.

To improve the overall performance, a full stack scenario-based approach was defined [8].

Real-world scenarios that fit common use cases and are used frequently were defined, as well as very complex use cases that are not used often. A baseline measurement was performed after the beamtime for each scenario to compare the efforts that were made during shutdown 2020, see Fig. 9.

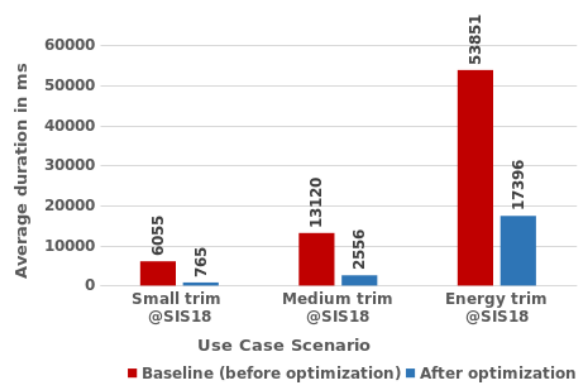

Figure 9: SIS18 scenario measurements – Total before and after optimization.

Each scenario has then been performed with applied diagnostic logging to find the parts in the stack that took a long time (see baseline in Fig. 10).

The identified long running parts were then revised by the domain experts and developers across departments working together. In addition to internal optimizations within the individual components, interfaces and APIs were redesigned to make the whole process more efficient. This full stack approach allowed precise identification of affected parts, e.g. database, BSS or LSA. In LSA, the main performance issues

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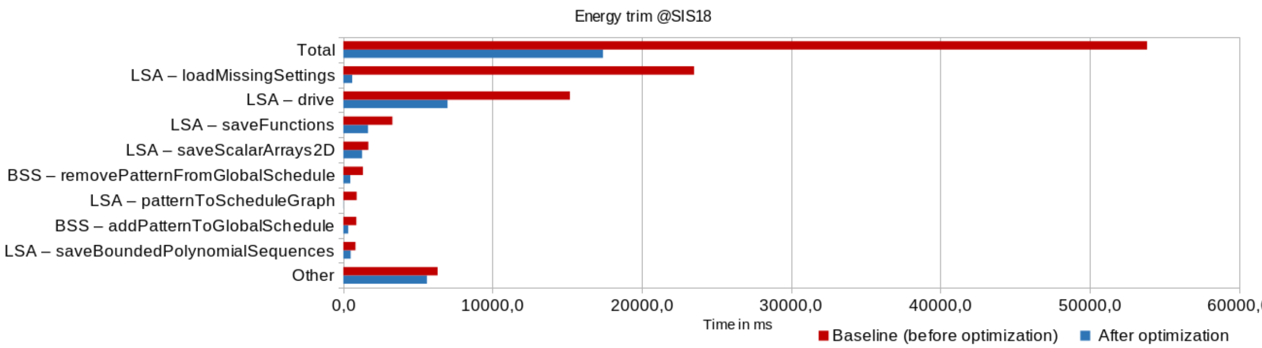

Figure 10: SIS18 scenario measurement – Critical data points before and after optimization.

were located in looking up data from and writing data to the database, and calculating new set-values. The database parts led to new and more efficient queries that were partially merged back to CERN's code base. During the trim, values were kept with higher precision than needed, leading to more complex calculations. Also more data points were kept for further calculations than needed. By reducing them to a minimum, the calculation was sped up as well as the database performance since less points have to be persisted. Also the interaction with BSS was optimized so that Patterns can be supplied more efficiently after calculating new set-values. After all optimizations had been applied through the entire Control System stack, a final measurement was made and compared to the baseline, see Fig. 10.

The overall speedup is between 7.91 for the 'Small trim' scenario down to 3.1 for the 'Energy Trim' scenario. During beamtime 2020/2021, the optimizations have been used productively and operation reported a noticeable speedup [9].

OUTLOOK

Focus is now more on features for FAIR, further discussing the general concept of "Patterns" and also reviewing the existing concepts. Other topics are requirements for upgrading the UNILAC and integrating it into the new Control System.

Current Development

Booster Mode Support Booster Mode in SIS18 is needed for FAIR. It is used for beam accumulation by stacking four SIS18 cycles into SIS100 using bunch-to-bucket transfer. At the moment, UNILAC is operated in a different way than the rest of the facility and needs to be synchronized with SIS18.

For this purpose, it was decided to introduce the possibility to start a set of timing events asynchronously in the Timing System. This way, UNILAC's deviation can be taken into account.

First tests with a first implementation that does not cover all corner cases and requires specific setup are expected during machine experiments in 2022.

Injector Controls Upgrade Project UNILAC is operated at 50 Hz, which means a cycle is only 20 ms and we can switch between cycles on this timescale. The current UNILAC Supercycle needs to be integrated into the LSA concepts, we have to make it possible to derive a current UNILAC schedule taking into account the beam requests that are expected from SIS18. Possibly the current concept of having Chains, Patterns and Pattern Groups has to be reworked.

Rework of Pattern Concept The current operating is done by executing different Patterns that each contains only one Chain while one Chain describes the beam from a source to a target. A source in this case may be an ion source or another linac or ring and a target also may be another ring or an experiment.

For the future FAIR Facility this concept needs to be developed to be more flexible. The focus will switch from machine-oriented point of view like it is now to a beam-oriented view. This means that a Pattern should contain all Chains from ion source via all participating rings and transfer lines to an experiment.

With the background of the "Injector Controls Upgrade Project" the current idea is, that there are only loosely coupled Chains within a Pattern while one Chain now describes the beam from an ion source to an experiment.

There may be multiple Patterns, but in this case, they all do different things, e.g. providing beam for an experiment on request or executing a Storage Ring Mode Chain in parallel. Ultimately, the Pattern Groups will then no longer be needed, and the Pattern itself will no longer be a context in the sense of LSA's context grouping set-values.

This allows to fulfill the special needs for the UNILAC as well as a beam-oriented view on the facility. Discussion on these concepts is ongoing.

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