OPERATION OF THE ESR STORAGE RING WITH THE LSA CONTROL SYSTEM

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Abstract

The LHC Software Architecture (LSA) framework developed at CERN has been applied as a core for the new control system of the accelerator complex GSI and the future facility FAIR, Germany.

The Experimental Storage Ring (ESR) at GSI was recommissioned with the LSA and different accelerator and physics experiments were performed in the recent years. The overview of the ESR performance will be presented here. The features and challenges of the operation with the LSA system will be outlined as well.

INTRODUCTION

The ESR [1] is the core instrument for unique physics experiments in the FAIR facility [2] (see Fig. 1) [3]. It is operated for accumulation, storage, cooling and deceleration of a wide range of heavy ion beams in the energy range from 4–400 MeV/u coming from the synchrotron SIS18 [4] via the FRagment Separator (FRS) [5] or a direct transport line. The ESR is a symmetric ring with two arcs and two straight sections and a circumference of 108.36 meters (see Fig. 2). It consists of 6 dipole magnets (deflection angle is 60°) and 10 quadrupole families (20 quadrupoles in total). For the second-order corrections 8 sextupole magnets are installed in the arcs. The ESR can be operated at a maximum magnetic rigidity of 10 Tm. For reducing transverse and longitudinal emittances of the stored ion beams, the ESR is equipped with the electron cooler which is installed in one of the straight sections of the ring. In another straight section the internal gas-jet target for in-ring reaction experiments is installed.

The ESR model for the control system is based on a generic circular accelerator hierarchical model, which was implemented into LSA [6] and features of the ESR were added on top of common structures.

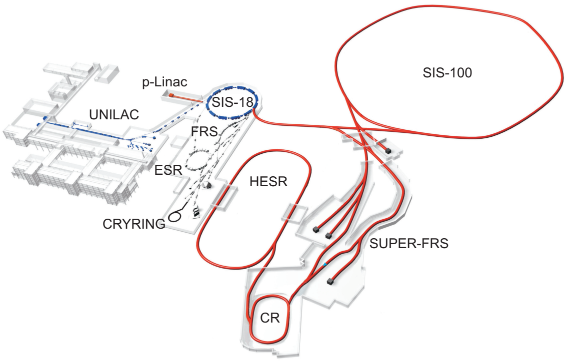

Figure 1: Layout of present GSI and future FAIR facility.

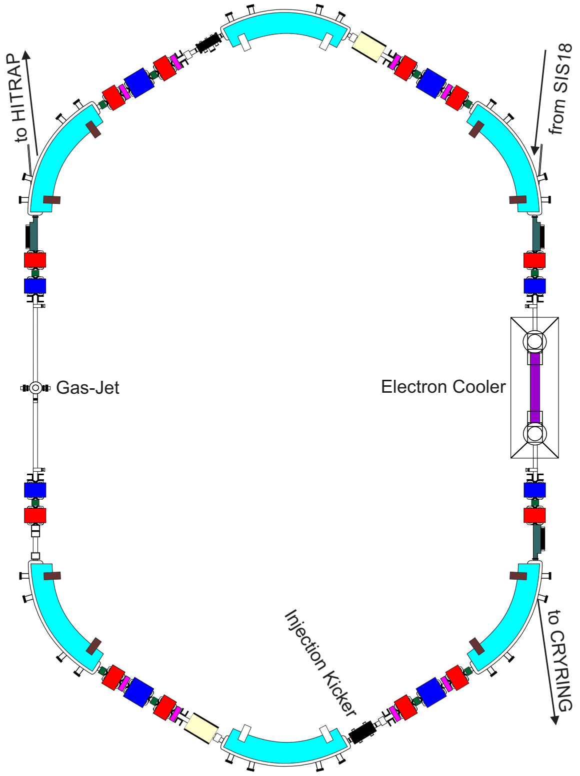

Figure 2: Layout of the ESR.

A generic model is a collection of all input parameters and algorithms based on the accelerator physics approach, which are needed to perform the calculation of hardware values according to the defined machine operation. Physics quantities and hardware set values are represented as parameters, which are grouped according to their parameter type, describing the physics category of the parameter. For each parameter there is a special make rule, which calculates its relations with other different parameters. Relations between parameters build a parameter hierarchy, which in turn form a accelerator hierarchy [7].

The ESR operational setting is called a pattern (see Fig. 3). It is a fully pre-planned chain of different subsequent blocks, named sub-chains, which consist of different beam processes arranged in a certain order. The beam process defines a special procedure of the machine, like the beam injection or the magnets' ramp. The order of beam processes in the certain sub-chain is built in such a way, to perform the corresponding beam procedure, pre-described in the sub-chain (e.g. beam deceleration). The sub-chains are also ordered in a certain way, required by the user to perform a full machine cycle. So, one has to carefully consider all user requests in order to make a pattern, since once the pattern is created its structure of chains, sub-chains and beam processes cannot be changed online during the run and should be replaced by a new updated version, which takes time and resources. Presently, due to old hardware devices (devacc), the ESR control system is limited to a maximum of 16 sub-chains, which restricts the pattern flexibility. With update to FESA [2] this limitation will be gone.

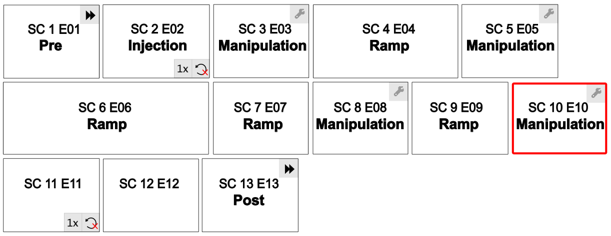

Figure 3: Visualization of the ESR pattern with 13 sub-chains in the Storage Ring Mode application. It is a cycle for the beam accumulation in repeatable sub-chain 2 (Injection) with subsequent deceleration to the low energy in sub-chains (Ramp) and the data collecting in repeatable sub-chain 11. The sub-chains 1 and 13 (Pre and Post) were skipped. Number of repetitions in repeatable sub-chains can be changed or aborted during the cycle. The width of sub-chain blocks represents their length in time.

To realize storage ring properties of the ESR a special "Storage Ring Mode" concept was developed and implemented in 2019 [8]. There are three pre-defined functions provided to the sub-chains: *breakpoints*, *skipping* and *repetition*, which can be combined with each other. The fourth function, namely *manipulation*, should be created as a single sub-chain. These features can be triggered using a dedicated Storage Ring Mode application (see Fig. 3).

Breakpoints are the points which can be added at the end of a sub-chain and pause the cycle, while the beam is circulating in the ring. Usually, it is used manually during the experiments in the sub-chain where the data taking occurs.

A repetition feature can be added to a sub-chain in advance and this sub-chain can be repeated a certain amount of times, defined by a user. The repetition can also be aborted, if necessary and the cycle will be continued. Recently, the repetition is used for the beam accumulation in the ESR (see below) and during experiments for the data collection in a pre-determined amount of time.

Certain sub-chains of a complicated pattern can be predefined as skippable, in order to have possibility skip them and shorten the cycle time during the ESR adjustment. Two necessary special sub-chains, namely *Pre* and *Post* at the beginning and the end of any storage mode pattern, ramp the ring's magnets up to the injection level and down to the initial state. The skipping both of these two sub-chains, while the beam is in the ring, prevents the ESR from ramping down, so that the next injected beam will be stored with previous one. This is an absolutely necessary condition for the beam accumulation.

With the manipulation function one can modify the ESR settings with the stored beam, which gives a great opportunity for interactive beam study and finding best experimental conditions. Based on experience, manipulation sub-chains are placed after each sub-chain where the ESR adjustment is needed (as one can see in Fig. 3).

RECOMMISSION OF THE ESR

In 2019 the ESR was recommissioned with the LSA for the first time. That time only the so-called synchrotron mode was available for the operation, where the magnets were ramping up and down and the beam could be stored only for a short time of about 1 minute maximum, during the cycle. Within the synchrotron mode, it was not possible to use the ESR as the storage for dedicated physics experiments. However, the functionality of the ESR model according to the hardware settings was experimentally proved and the timing coupling concept [8] between the SIS18 and the ESR was successfully tested.

The Storage Mode feature was available since late 2019 and its first test was successfully performed by storing the stable argon beam with an energy of 250 MeV/u in the ESR for about fifteen hours. Later, the rather complex laborious modes of the ESR were achieved.

Accumulation and Deceleration

Modern nuclear astrophysics experiments on exotic nuclei are often limited by the available intensity and purity of the ion species. A secondary rare ^{118}Te^{52+} beam was produced in the FRS beryllium target from ^{124}Xe primary beam with an energy of 550 MeV/u from the SIS18 and then stored, accumulated (with intensity of about 10^6 ions) and decelerated in the ESR for the measurement of nuclear proton-capture at energies of 6 and 7 MeV/u [9]. The accumulation of a beam is a special stacking technique consisting of several steps, which is usually done with a high intensity primary beam [10]. Firstly, the injected beam is stochastically precooled at the fixed energy of 400 MeV/u at the injection orbit of $\Delta p/p = +1$ % and then bunched. After that, it is moved to the inner orbit of about $\Delta p/p = -1$ % by the radio frequency (RF) cavity, where the electron cooling was continuously applied. The steps are repeated several times until the desired intensity of accumulated beam is reached. RF amplitude and frequency must be matched for better accumulation and the ESR is in the skippable mode always. An example of the beam accumulation is illustrated in Fig. 4.

After accumulation the bunched beam is decelerated to the intermediate low energy of about 30 MeV/u. There the beam is electron cooled and further decelerated to the very low requested energy with changing the harmonic number of the RF cavity. In order to cool the beam at low energies the magnets of the cooler must also be ramped down. The limiting factor is the high voltage supply of the electron cooler. It needs more time to ramp down and stabilize than the magnets. Therefore, the beam is already on the desired energy, while the cooler is not yet ready to cool which leads to additional beam losses. In order to avoid it, an additional

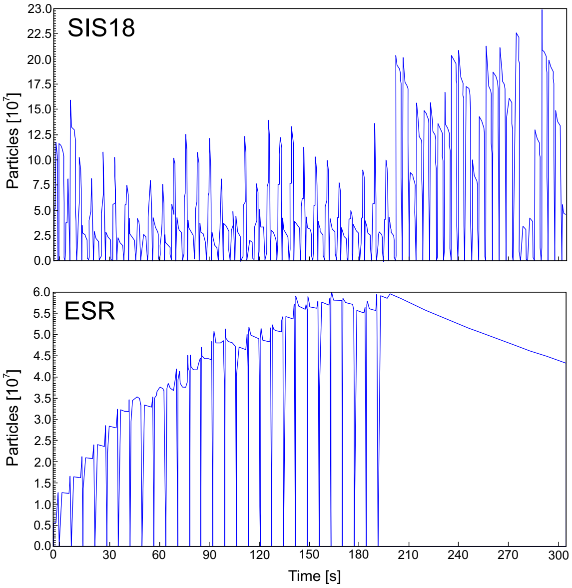

Figure 4: Bottom: Intensity of the ^{124}Xe primary beam during its accumulation in the ESR for about of 3 minutes (29 injections). Top: The corresponding beam intensity of SIS18 at extraction to the ESR.

"Ramp" sub-chain was created where only the cooler ramped down, but the magnets are not (sub-chain 6 in Fig. 3). The electron cooler of the ESR has its own model and hierarchy, which is integrated with the ESR and implemented in the LSA.

The ESR can also provided decelerated beams to the low-energy ring CRYRING@ESR [11] or to the ion trap facility HITRAP [12] using the injection kicker magnet for the fast extraction. With a new barrier bucket cavity the beam can be extracted as a single bunch. A typical deceleration cycle for the extraction to CRYRING@ESR is shown in Fig. 5.

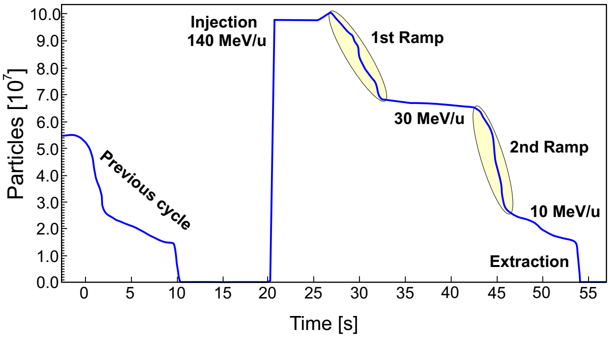

Figure 5: Deceleration cycle of ^{107}Ag^{47+} beam, injected with an intensity of about 10^8 particles and energy of 140 MeV/u, with 2 subsequent deceleration ramps to 30 MeV/u and 10 MeV/u correspondingly, and final extraction to CRYRING@ESR. The cycle time is about 35 seconds.

Outlook

A completely pre-planned patterns construction and an impossibility of editing them on-flight during the run restricts the flexibility of the control system. Nevertheless, after replacement of old devacc devices by FESA, the limitation of 16 sub-chains will be removed and patterns with different structures can be switched between each other, while beam is stored in the ring. A long time response by tuning the ESR limits machine availability and has to optimized. However, with the storage mode the LSA shows a great potential in functionality, stability and accuracy of the ESR operation.

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