ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-TUPDP018

ABOUT THE NEW LINEAR ACCELERATOR CONTROL SYSTEM AT GSI

P. Gerhard*, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

Abstract

The first accelerator at GSI, UNILAC, went into operation in the early 1970s. Today, UNILAC is a small accelerator complex, consisting of several ion sources, injector and main linacs comprising 23 RF cavities, several strippers and other instrumentation, serving a number of experimental areas and the synchrotron SIS18. Three ion species can be provided at different energies simultaneously in a fast time multiplex scheme, two at a time. The UNILAC is going to be the heavy ion injector linac for FAIR currently under construction next to GSI, supported by a dedicated proton linac. The current linac control system dates back to the 1990s. It was initiated for SIS18 and ESR, which enlarged GSI at the time, and was retrofitted to the UNILAC. The linear decelerator HITRAP was added in the last decade, while an sc cw linac is under development. Today CRYRING, SIS18 and ESR are already operated by a new system based on the LHC Software Architecture LSA and other developments from CERN, as FAIR will be. In order to replace the outdated linac control system and simplify and unify future operation, a control system on the same basis is being developed for all GSI linacs. Recently the first data supply tests were performed during a dry run.

INTRODUCTION

The GSI Helmholtzzentrum für Schwerionenforschung was founded in 1969 [1]. Its mission is to develop, build and operate heavy ion accelerators and conduct research with heavy ions. Starting with the UNIversal Linear ACcelerator UNILAC (as shown in Fig. 1) in the 1970s [2, 3], the heavy ion synchrotron SIS18 [4] and the experimental storage ring ESR were added around 1990 [5]. In the context of this major extension of the facility, a highly sophisticated control system was developed in order to run the different accelerators in a well coordinated and highly efficient way. This system made extensive use of then state-of-the-art digital equipment and techniques, for instance data bases, computers with OpenVMS for the high level operation with programs written in Fortran, FPGAs for the complex online timing generation and device control by front end computers connected via MIL field buses.

Today, the construction of FAIR (Facility for Antiproton and Ion Research) [6, 7] is about to multiply the size and capabilities of the heavy ion accelerator facility on the Darmstadt site again, using the existing accelerator complex as its injector. A completely new control system for FAIR was developed in close cooperation with CERN. It is based on the LHC Software Architecture LSA [8] and the Front End Software Architecture FESA [9], while the new General Machine Timing is based on White Rabbit [10] to enable accurate timing over the enlarged facility. The new control system was developed using the versatile CRYRING accelerator [11] as a testbed [12], and was put into regular operation for the ring machines SIS18 and ESR and the High Energy Beam Transport HEBT since 2016 [13, 14]. For the UNILAC, this has not been achieved so far.

The main feature of the facility, which is also reflected in the control system, is the efficient operation of the whole complex. The key is a virtual parallel operation of different ion beams, serving several users individually by a time multiplex operation. The increased number of storage rings for FAIR with their long cycle times adds a new dimension to this, while the UNILAC still has to be operated in the same manner on a cycle time of 20 ms.

End of 2019 a dedicated project was started to migrate the UNILAC to the new FAIR style control system, notwithstanding that some actions were already started earlier.

LEGACY CONTROL SYSTEM

The legacy control system still in use today for UNILAC was introduced some 40 years ago. Some major upgrades and modernizations have taken place, for instance switching from OpenVMS to Linux as the underlying operating system, moving the production server cluster to virtual machines and recently replacing obsolete thin clients. But some outdated hard- and software components still remain and may be replaced or modernized only with large efforts or by replacing the control system completely. Among those are the front end computers and the corresponding software, software services not available for current operating systems, and operating software written in Fortran.

The current upgrade project aims at retrofitting the UNILAC to the modern FAIR control system standard. Because

Figure 1: The Alvarez type main linear accelerator of the UNILAC went into operation in 1975.

* p.gerhard@gsi.de

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of the limited resources and time available, this is for the time being limited to the high and middle tiers of the control system. The front end replacement will be tackled independently and in large part later. Therefore, the new control system has been enabled to work together with the old front ends. To this end, also the interfaces of the individual device front end software has to be adapted to be accessible from LSA. While the retrofit is prepared, the existing control system has to be maintained in order to ensure beam operation of the facility. This task becomes increasingly challenging as the expert knowledge is draining due to aging staff.

MAIN CONTROL ROOM MODERNIZATION

The main control room is the most visible part of the control system. Figure 2 shows the UNILAC domain, which still comprises many analogue features like hardware switches, signal lights, oscilloscopes and low level interfaces.

Figure 2: The UNILAC domain of the current main control room.

The modernization of the main control room therefore is a major subproject of its own. It has three main objectives: ensuring future operation by relieving obsolete, unserviceable hardware and systems, establishing compatibility with the new control system, and enabling moving the main control room to the new FAIR Control Center (FCC) building, where no analogue signals will be provided. The complete digitisation of the operating is a prerequisite to this and involves also a large contribution of the beam diagnostics and operations departments.

MIGRATION STRATEGY

Recently, the migration strategy to the new control system was thoroughly reviewed. This had become necessary because of the evolution of various boundary conditions since the project had started. The main point was to ensure the support of the already allocated user beam times and the upcoming commissioning of FAIR in the next years. Prolongation of the operation of the legacy control system and availablity of the new control system had to be balanced in terms of risk and effort. Three general operating scenarios were analysed[1]. It was finally decided to prolong operating the legacy system until 2025 and then switch to the new control system in one step. This puts a well known risk on the expected performance during the beam time 2026. In order to handle and mitigate this, the strategic planning of operations and FAIR commissioning and the beam time coordination were involved in the decision. They were asked to account for the commissioning of the new control system and its foreseeable teething problems. Recently, an overall planning proposal for the next years was presented internally, providing a promising perspective for the successful development and commissioning of the new control system.

Despite the new control system being in operation for CRYRING, SIS18 and ESR since several years, all building blocks need extensive further development in order to operate UNILAC. Based on the overall planning for the next years, a development schedule is being worked out to coordinate the tasks for the many different groups and departments involved. Necessary dry runs and engineering machine beam times will be scheduled to provide adequate testing opportunities for the developers. At the same time, the maintenance effort for the legacy system has to be accounted for.

TIMING

The use of the FAIR timing system for the operation of the comparatively fast linear accelerator and the necessary steps to achieve this are one of the major challenges of the implementation of the new control system for UNILAC.

Legacy Timing: Pulszentrale

Proper acceleration of the beam is accomplished by the synchronized cooperation of hundreds of devices spread over the campus. This synchronization was achieved to an accuracy of about 1 µs by a central timing system called *Pulszentrale* (pulse center), which generates and distributes timing events in realtime via a MIL field bus to the front end systems. The *Pulszentrale* integrates realtime scheduling of different ion beams, event generation for producing each beam, beam chopper control, fast and slow interlock systems, beam request handling and individual experiment trigger signal generation. The time multiplex operating scheme of the UNILAC requires one full acceleration cycle (i. e. one beam pulse) every 20 ms synchronized to the 50 Hz of the electrical grid. For every cycle it has to be decided which beam will be produced. This decision is based on availability of ion sources, rf cavities, beam lines and other resources necessary, and takes into account the different priorities and beam time shares given to the different users. The decision process is based on a set of rules and counters, which are implemented in FPGA logic to enable fast realtime execution. Real parallelism is added by executing secondary tasks like rf

[1] The three scenarios are: using (1) the legacy or (2) the new control system alone or (3) a combination of the new data supply together with the *Pulszentrale*.

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conditioning or even another beam in otherwise unused parts of the UNILAC, thereby increasing the operating efficiency. This yields a highly intricate FPGA logic implementation, and expert knowledge is necessary to maintain and debug the system. This approach results in a (limited) flexible but undeterministic beam scheduling. It enables handling of ad-hoc beam requests, but is unsuited for taking into account long term constraints and may lead to long waiting times for requests to be executed. Advance planning by more than a few cycles is unfeasible or at least hard to implement in most cases.

New Beam Scheduling Paradigm

While the *Pulszentrale* made excellent use of the UNILAC capabilities and provided highly efficient operation especially for the UNILAC users, it was not really optimised to serve the synchrotron, although beam requests from SIS18 are granted highest priority. With UNILAC becoming the injector for FAIR, beam scheduling and resource management at the UNILAC have to be aligned to achieve optimal efficiency for FAIR. Therefore, the ad-hoc scheduling will be replaced by a predetermined schedule, based primarily on the FAIR beam requirements. All resources of the UNILAC will be aligned to guarantee on time beam delivery without any waiting times, minimizing idle time for FAIR. Only after this is achieved, other users will be integrated in the schedule as before. This planning will be implemented in a high level programming language, facilitating a much higher level of complexity to take into account more and more challenging boundary conditions.

New Timing System

The new timing system for the UNILAC will make use of FAIR technologies and standards for reasons of maintenance and uniformity. The FAIR General Machine Timing (GMT) system uses White Rabbit (WR), a fully deterministic Ethernet-based field bus for clock transfer and synchronization. The key components of the GMT are a so-called Data Master (DM) [15, 16] that schedules actions by broadcasting messages, a WR network and Timing Receiver (TR) nodes executing machine relevant actions on time. It is an alarm based system, in contrast to the *Pulszentrale*, and was invented primarily with synchrotrons in mind. The fast, repeating cycles of the UNILAC and the requirement, that there must be no interruption in the sequence of cycles, result in very high event message rates, network traffic and CPU load in the DM. The timing graph representing the schedule has to include the event sequences for all possible variants of the cycles to enable switching between different operating modes for the UNILAC, e. g. with and without beam or pilot beam. Conditional branching nodes and wrapping of the different cycles will be used to reduce the size of the timing graph.

The UNILAC is represented in the new timing system by 44 timing groups. Including the FAIR pLinac and future extensions, some 60 groups will be necessary. Figure 3

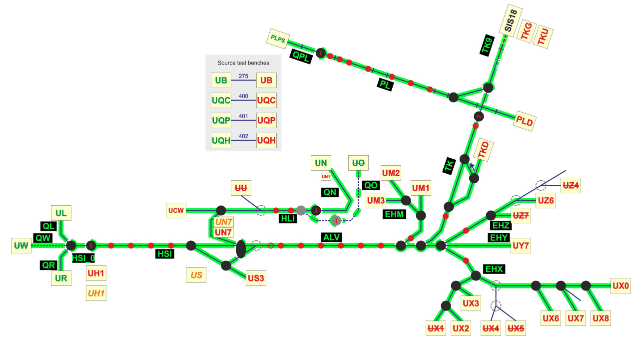

Figure 3: Schematic representation of the UNILAC and pLinac facility for the control system.

shows the diagrammatic representation of UNILAC, including pLinac.

For every timig group involved in a beam production chain, up to 25 events have to be distributed. The event sequence together with their dependencies are shown in Fig. 4.

LSA

The LSA framework provides for settings generation and management for the devices making up the accelerator. This includes managing information on the beams to be provided, called beam production chains (BPC or simply chain), and their scheduling in so-called patterns. This constitutes the basic context, to which every data and action is linked.

Patterns and Chains

The present concept for defining and scheduling beams was primarily inspired by synchrotron operation. It allows for several patterns executed round robin, each containing a single chain. Each chain can only be incorporated once, but may be repeated nonintermittent. The general timing

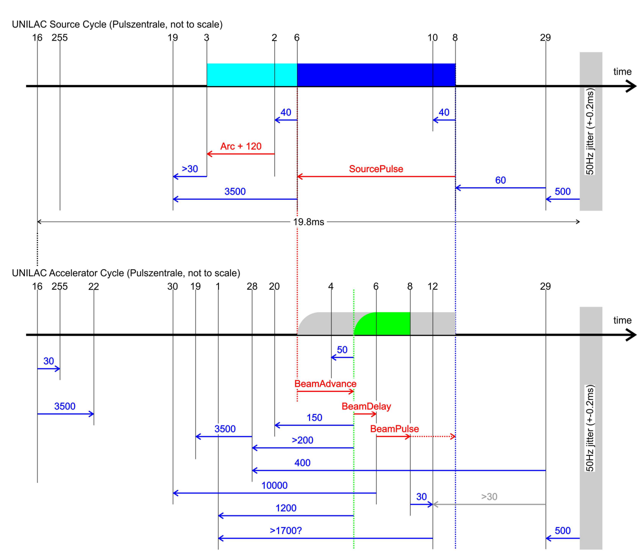

Figure 4: Event sequence for one UNILAC cycle for ion sources (top) and general accelerator sections (bottom).

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concept adopted for UNILAC calls for many repetitions of different chains in arbitrary order as well as execution of more then one chain in one cycle. To date, this is not possible within the LSA framework at GSI. A new concept for beam scheduling was devised to enable the execution of one chain identity alternating with other chains in any order, and several chains being executed in arbitrary combinations. The new concept, called stand-alone chains, is now being implemented for UNILAC and will later also be used for FAIR.

Settings Generation

The settings generation and data supply to the UNILAC devices benefits strongly from the work already done for CRYRING including its local injector linac, SIS18 and especially the HEBT. Settings are managed by parameters connected via makerules, which define how a parameter is derived from others, resulting in a full parameter hierarchy. For UNILAC, this hierarchy is rather simple as there is no abstract, high-level model involved. The challenge in implementing the UNILAC hierarchy is more related to necessary data structures being unsuited or unavailable. This results from the existing settings generation being developed for ring machines.

At first, the implementation of the UNILAC settings generation focused on the completion of the full parameter hierarchy for a limited set of standard devices. This included the setup of all necessary data structures to supplement the framework. Accordingly, to date most standard magnets are covered. Magnets necessitating more sophisticated calculations, like phase advance magnets, or special settings management, like the slow magnets in the Alvarez, are left out for the time being. Figure 5 shows the current parameter hierarchy for the UNILAC.

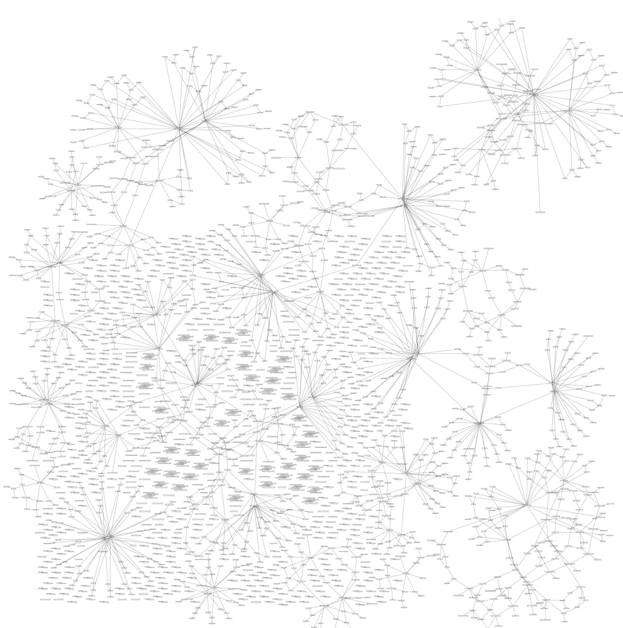

Figure 5: Current parameter hierarchy for the UNILAC.

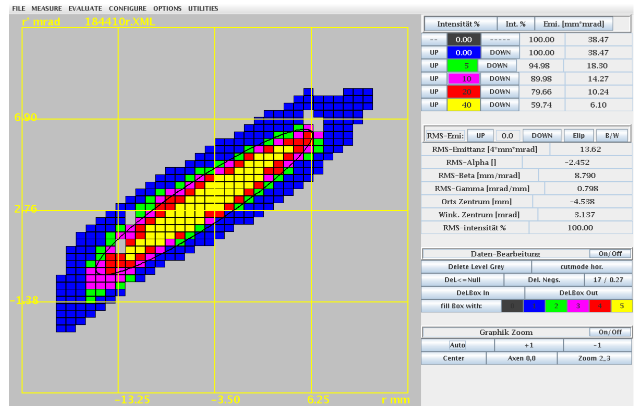

Figure 6: Screenshot of the new emittance measurement and anlysis application PROEMI.

Recently, the first data supply test with the new settings generation and management based on LSA was successfully conducted on the real devices. Because the new control system for UNILAC is still far from being complete, the high current injector HSI of the UNILAC was initialized using the old control system. Then magnet settings for a $^{6}Li^{1+}$-beam were sent to about 40 magnets by the new system, followed by systematically modified settings, changing isotope, charge state and energy settings of the HSI. All data sent were read from the devices and recorded using the old system for later analysis.

APPLICATIONS

As for the settings management, several applications have already been developed for the operation of the GSI facility, which can also be used for the UNILAC. While some only need adequate configuration or are generic enough to be used right away, e. g. the main operating applications ParamModi and Device Control, other applications need more adaptation because requirements are quite different. Finally, a number of custom-made operating programs of the legacy control system have to be re-developed. Among them are the applications to setup and control the ion sources, the linac rf systems, measuring of charge state and mass spectra, emittance measurements (Fig. 6), and energy and bunch shape measurements. The emittance measurement application has already been upgraded to the new control system, and the ion source application is in a very advanced stage with commissioning for routine operation expected during the next beamtime. This was possible because they can be used while the legacy control system is still in charge. Other applications depend on the new control system deployed, at least for testing and developing purposes, and will be implemented in the near future.

CONCLUSION

A migration strategy to move the UNILAC from the current, outdated control system to a new one based on FAIR technology within the next three years has been decided on.

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The schedule accounts for the limited possible prolongation of the old control system, the development time needed for the new system, the allocation of beamtimes and FAIR commissioning planning, and the move of the main control room to the FCC. Arrangements have been made to allow for a successful commissioning of the new control system at the UNILAC and a smooth beamtime 2026. The associated upgrade project runs since 2019 and has made significant progress. After a period of preparation and planning, the modernization of the main control room significantly gained momentum during this year. The basic modeling of the UNILAC is complete. The parameter hierarchy for most magnets has been established, the rf settings generation is in progress. More complex parts of the data supply are still to be done. The preliminary creation of Patterns and Chains for the UNILAC was implemented in the Scheduling App, enabling testing of the settings generation. This was recently achieved successfully for the high current injector. Testing with beam is scheduled during the engineering run end of the year. Fundamental decisions on the new timing system were taken, including the mapping of the UNILAC and the future way to synchronize to the 50 Hz of the grid. This allows for the start of the development of the Data Master and the timing generation according to the requirements of the UNILAC operation, taking advantage of several DM developments of the last years. The implementation of the new scheduling algorithm is one of the major challenges and has just started. Development of the applications is in progress, with some being rolled out already or in the near future. Other applications still need to be designed or are ready to be realized.

ACKNOWLEDGEMENTS

This report is given on behalf of all the colleagues who are contributing to this project, in particular from the controls and system design departments at GSI.

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