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COMMISSIONING OF THE TIMING SYSTEM AT ESS

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Abstract

The European Spallation Source (ESS), currently under construction and initial commissioning in Lund, Sweden, will be the brightest spallation neutron source in the world, when its driving proton linac achieves the design power of 5 MW at 2 GeV. Such a high power requires production, efficient acceleration, and almost no-loss transport of a high current beam, thus making design and beam commissioning of this machine challenging. The commissioning runs of 2021 and early 2022 were the first where the master timing system for the linac was fully available. As a consequence of that, the beam actuators and beam monitoring equipment relied fully on timing events sent across the machine, not only to be triggered to act but also to get the configuration. In this paper, we describe the timing system as available today, present how we define and create the beam pulses using the available parameters. We also present planned future upgrades and other outlook for the system.

INTRODUCTION

ESS is a collaboration of 17 European nations and its objective is to be the world's most powerful spallation neutron source [1]. The neutrons are produced by a 5 MW proton beam hitting a solid, rotating tungsten target at a distance of 600 m from the ion source. The ESS linac, the driver of the protons onto the target, requires site-wise synchronisation in order to accelerate the desired beam through its components. The production of the proton beam begins with the ion source providing the pulse of protons with an optimized current and of a given length [2]. Later, the two choppers (LEBT and MEBT) shape the pulse to the desired pulse length. The acceleration is given by the radio-frequency cavities pulsing at the correct moment. The overall repetition rate is a consequence of the definition of the arbitrary number of consecutive set of timing events (cycles), that are pre-loaded before the ion source starts producing the beam. Last but not least, the beam pulse current is primarily controlled by the IRIS settings, and does not belong to the timing system.

The combination of the three beam parameters, i.e. beam repetition rate, beam pulse length and beam current defines the envelope of the accelerator working point defined as a beam mode. At any time of the machine operation, the Fast Beam Interlock System (FBIS [3]) with Beam Current Monitors (BCMs) is supervising the compliance to the beam mode, i.e. asserting if the produced beam pulse belongs to the allowed parameter space. Pulse timing information distributed to the BCMs containing the planned beam pulse position in the cycle has therefore also a machine protection purpose.

Figure 1 shows schematic of the ESS linac. The actuators are located within the beginning of the line (e.g. source and choppers), at the very end of the line (target raster magnets), and along the full linac (RF stations). The proton beam instrumentation devices, e.g. Beam Current Monitors (BCMs), Beam Position Monitors (BPMs), Faraday Cups (FCs) and Beam Loss Monitors (BLMs) are located along the line.

The ESS distributed control system is based on Experimental Physics and Industrial Control System (EPICS [4]). The full synchronisation is provided by a distributed timing system with its own network infrastructure, and it is operated within a *Beam Production* environment. The entire timing system is configured with the pre-created timing tables, that consists a definition of supercycles, namely sequenced definitions of what the RF/actuators and instrumentation do in the given cycle. This paper summarises the efforts put in the beam commissioning of the Normal Conducting Linac, i.e. from the ion source to the DTL1 FC.

TIMING SYSTEM

The main role of the ESS timing system is to generate, acquire and distribute RF ≈ 704.42 MHz based timing signals:

- Synchronous clock, mostly RF/8 = 88 MHz.
- Machine synchronous and asynchronous events.
- Trigger events as a derivative of timing events.
- Data bus (a.k.a. data buffer) with beam and machine parameters.
- Absolute time reference.
- Orchestrate EPICS record processing and acquisition.

In addition, those features are utilized for troubleshooting of different distributed subsystems. The timing hardware is based based on Micro Telecommunications Computing Architecture (MTCA [5]). The detailed concept was described in [6]. Figure 2 presents the timing system topology. The Timing Master (TM) is the main timing system gateway for the operation control while event receivers (EVRs) embedded within TDMS perform synthesis of the received information into the timing signals required by a particular subsystem.

Supercycle Engine

The ESS machine ticks in ≈ 71.43 ms cycles (≈ 14 Hz). The cycles can be added together making a meaningful supercycle, so a collection of cycles. The operation team defines each supercycle and a certain supercycle is played during different site acceptance tests, or site integration tests, or the ESS production operation. The ESS machine ticking is produced by the ESS in-house EPICS module called Supercycle

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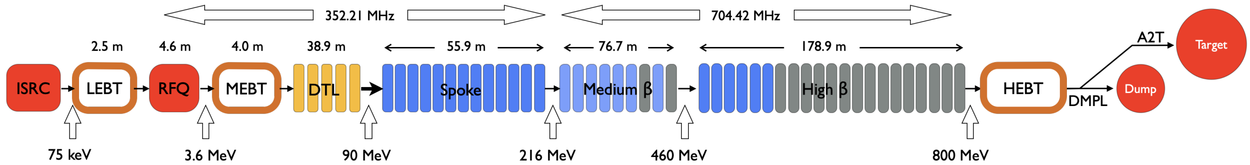

Figure 1: Block view of the ESS linac. First commissioning of the timing in 2021 and 2022 covered the Ion Source, LEBT, RFQ, MEBT and the first DTL1 tank. The two colour (blue and grey) highlight the two energies that different periods of commissioning will bring in the future. Picture courtesy Mamad Eshraqi.

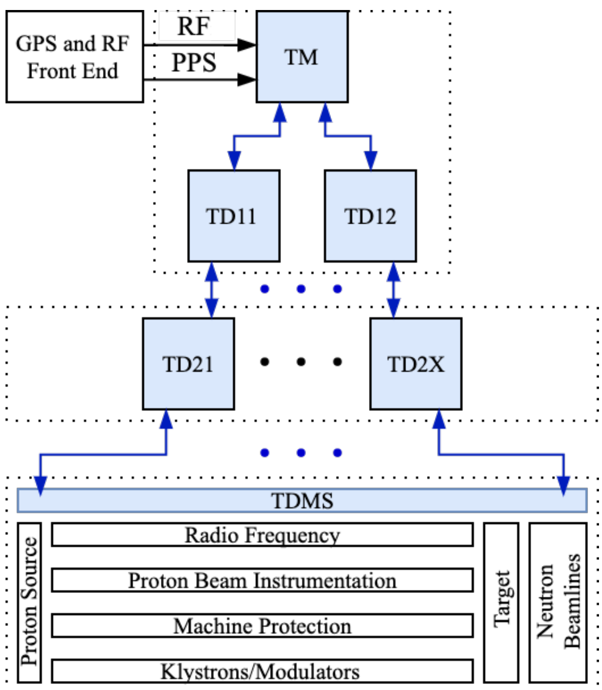

Figure 2: ESS timing network - tree topology. Timing Master (TM); Timing Distribution (TD); TDX_1X_2: X_1 - tree layer, X_2 - ID, TD2X contains X = 22 currently; Timing Distribution to Machine Subsystem (TDMS).

Engine (SCE) which is an extension of mrfioc2 [7] EPICS driver running on the Timing Master. In addition, the engine runs routines supporting asynchronous and synchronous management, safety (inhibiting required ESS actuators), the data bus and the overall system status.

Timing Events

Within the arbitrary defined timing events for the accelerator use, three main groups can be isolated:

- Longitudinal beam shaping: Ion Source Magnetron; LEBT chopper; MEBT chopper,
- Beam pulse: Beam pulse position; RF start,
- Beam monitoring: Acquisition.

These events are used as a base for the cycle definition. Along the cycle, a dedicated data buffer is sent, it contains the beam mode and beam destination, and also dedicated cycle dependent beam parameters like intended beam energy and current for the purpose of the beam loading compensation provided by the LLRF. All of the events definitions and data buffer definitions are kept as the configuration of the *Supercycle Engine* in the dedicated git repository [8].

BEAM PRODUCTION

Figure 3 illustrates the time-in-the-cycle distribution of the events and the data buffer along with the actual beam window. The fixed beam window is established for protection purposes, i.e. there shall never be a beam outside that window. The delays between the events are part of the design such that the dedicated equipment has enough time to configure itself before the beam arrives [9]. Those delays between the events consist of three contributions: the HW network (e.g. cables), the device processing time and the Time of Flight (ToF) between the different positions. The aim of the general commissioning is to identify all three groups and distribute (include) at different levels, i.e. EVRs configuration and/or a supercycle definition.

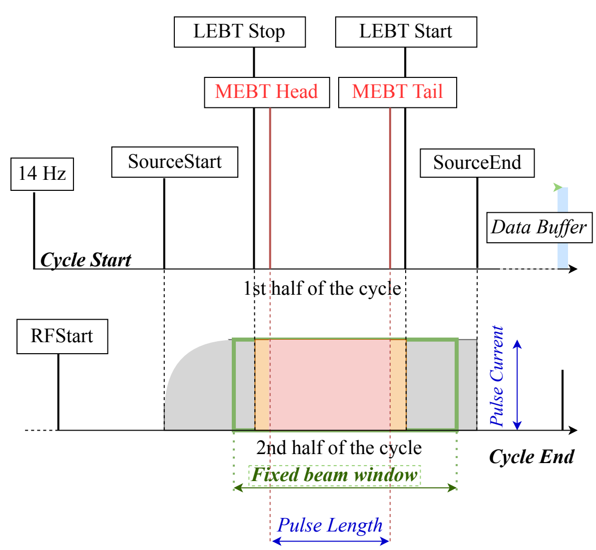

Figure 3: The schematic breakdown of the ESS beam pulse (≈ 71.43 ms) that consists: the events available for each cycle (solid squared black labels) the reserved; source pulse (grey), the fixed beam window (green region); the chopped beam (orange/red) of a given pulse length will be placed inside the fixed beam window. The pulse current is not a parameter of timing and it is shown only for the illustration.

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From the control room perspective, the whole timing system is controlled via the *Beam Production* layer that interfaces more than only timing ecosystem via EPICS through the CSS Studio Phoebus suite [10]. The *Beam Production* operator interface (BP OPI) allows to control the Beam Mode and the Beam destination. Whereas both of them are part of the data buffer being sent to all EVRs they are set via BP OPI from the control room only. All receivers can read that and setup their configurations according to the selected mode and destinations (see commissioning section). The BP OPI allows to load the intended super cycle definition and (though at the time of the tests it was not available) setup the beam current settings, via a separate EPICS channel. The timing tables (in the first iteration) are persisted as CSV files and stored in the shared file repository. Figure 4 illustrates the front panel of the BP OPI, where most of the controls to set and prepare the machine and send beam pulses are available. Dedicated top-level overview that includes status from the FBIS and status of the magnetron are highlighted to simplify troubleshooting.

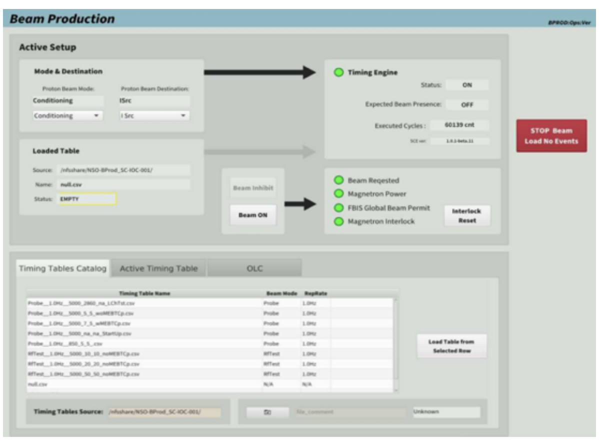

Figure 4: Front panel of the *Beam Production* OPI. It allows to control the Beam Mode and Destination (top left) the loaded timing tables (bottom) and switch ON/OFF beam.

Between the control room screens and timing system, there is another layer of *Beam Production* suite that provides all the advanced logic. As part of the internal checks, the intended (loaded) timing table can be checked if it fits the currently set beam mode in order to avoid the violation of the allowed parameters envelope. A pre-warning is visible for the operator, indicating that the intended configuration may not be supported by the FBIS. The *Beam Production* consists of ESS dedicated Input/Output Controller (IOC). Contrary to the timing engine, this controller has ESS-specific implementation of the beam mode compatibility. The main further improvements that were prototyped and tested in the later commissioning were: (a) to include the control on over the IRIS via dedicated calibration curves, (b) move the timing tables definition into the EPICS layer using the normative types, namely the NTTables. Both of these features will become operationally available in the future commissioning periods in 2023.

COMMISSIONING IN 2021/2022

Recently three designated periods of hardware and beam commissioning were assigned [11]. The timing system was available for the first of them for the first time at ESS and it is when most of the initial dry runs and setup took place. The following milestones were achieved:

1. *October 2021 - December 2021*, the MEBT FC commissioning with small current beam, first time with the timing system available,
2. *February 2022 - March 2022*, MEBT FC, commissioning with high current beam,
3. *May 2022 - July 2022*, DTL1 FC commissioning, low and high current beam.

Managing the Timing Tables

Throughout the commissioning phases the creation of the timing tables was done using the automated tool (external python notebook). The generated setup files were then sent to the shared repository and available for the system to pick up and load upon request.

The creation, the storage, the file format, and the bug fixing were heavily practiced and revision during all three periods of the commissioning. Throughout the commissioning and as an outcome we allocated resources to build a dedicated tool for editing (aka. Supercycle Editor), storing and verifying the available timing tables. While the prototypes were available during the 3rd commissioning phase, the production tool will come later in the future commissioning phase in early 2023. The validation (semantic and numeric) was implemented at the end of 1st commissioning period in the *Beam Production* IOC and it was extended during the later commissioning.

Ion Source, Choppers and RF Systems

The initial setup of the ion source timing was handled within the pre-commissioning dry runs. The magnetron timing interface setup went smooth and the timing signals were properly propagated from day one of the beam commissioning.

The LEBT Chopper works with a gate trigger type, in which the output trigger rising edge is generated by a dedicated event and the falling edge is generated by another event. This feature was configured in the EVR with the flip-flop resource. For the MEBT Chopper, a different setup is needed, as two trigger pulses must be generated for every cycle: one at the beginning (head) of the proton pulse and another one at the end (tail). On the EVR side this is implemented by using two different events to trigger the same delay generator (pulser). As the MEBT Chopper is powered by two units of high-voltage power supplies, special output modules with sub-nanoseconds delay tuning are used in the EVR. This is required in order to properly match the arrival of both high-voltage pulses on the MEBT Chopper striplines in the tunnel. The setup of the timing for both choppers was handled in the pre-commissioning dry runs and everything worked fine after the calibration of the delays in the EVRs.

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The setup of the LLRF (and the RF in general) required a bit more follow up. Main issue that was isolated was related to the fact how ESS cavities are powered. The NCL's cavities share the modulator (i.e. one modulator per two cavities), that receives the pulsing signal from the individual cavity's LLRF. We proposed disentangling and implemented this by allowing the modulator to pulse at 14 Hz independently of the selected supercycle, and produce RF power as requested by the super cycle. To achieve that, a concept of *Global*, *Mixed* and *Island* modes of EVRs was introduced. In *Global* timing the local EVR was entirely following the supercycle, in the *Island* mode the local EVR was running completely isolated and unaware of global timing. Extremely handful came the *Mixed* timing mode where EVR can follow specific frequency events: 1 , 2 , 3.5 , 7 and 14 Hz. This solution allowed for a simultaneous beam run and RF conditioning activities where both could progress at different effective frequency, i.e. provide beam tests at 1 Hz and push the RF conditioning at 14 Hz.

Beam Monitoring Devices

We isolated the BCMs that required an immediate, i.e. pre-commissioning runs, in order to get ready for the beam commissioning. During the dry runs we tested the response of the all chain for controlling the beam mode and destination, loading the test timing tables that contained the simple cycles on which we tested simple EVR responses.

In order to fulfill one of the requirements, i.e. all events should come early in the cycle to allow devices to load proper configuration [9], delays were implemented in the cycle definition as well as in the EVRs. Delays configurations are stored in the SaveAndRestore [12] application and are part of the pre-restart checks.

Further simplification in this configuration is foreseen, i.e. stepping away from the common delay in the EVRs and Supercycle Tables, and it is planned to be tested during the dry runs before the commissioning phases on 2023. ESS machine protection (FBIS) heavily relays on the BCM functionality where the beam mode and beam destination data allows to load the dedicated Look up Tables (LUT). As part of the dry run, this was verified for each available BCMs and FCs. The latter, as the commissioning was progressing, were successively added tested with similar dry runs before each commissioning run. Figure 5 shows one of the first beam pulses sent to the MEBT FC that was chopped using both choppers. More on the performance of the beam instrumentation can be found in [13].

Data Storage Concerns

During all three periods of the commissioning almost every day we experienced data acquisition and/or storage issues. Commissioning the timing events and triggering the data acquisition is subject to a constant analysis of the high resolution wave forms. This post analysis heavily relays on the availability of the proper time-stamping of the data. To solve the recurring issues the concept of the Synchronous data system was supported and re-introduced [14].

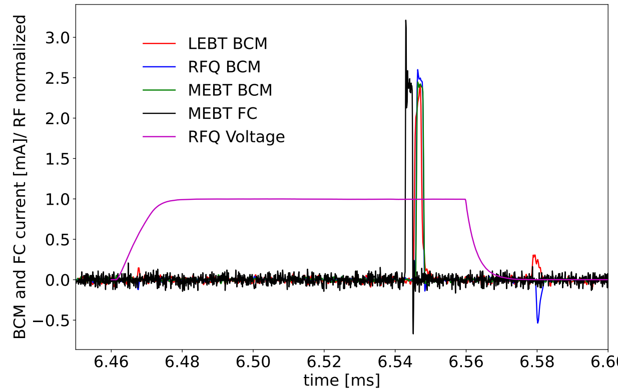

Figure 5: The aligned wave-forms triggered at the same acquisition event. All captured during one of the commissioning days in 2021.

SUMMARY

The beam runs and test with a configured timing system were performed for the first time at the ESS. The accelerator devices were configured, commissioned and handed over to operations. During tests we found few showstoppers that required in house adjustments. The outcome of these findings (i.e. event distribution, event delays or supercycle definitions) are identified and put in the list to improve before the next rounds of commissioning. There is an active effort put in consolidation of the scattered tools to manage and handle timing configurations. The beam commissioning activities will restart in the spring 2023 and many of the new top level features will be available for the commissioning and operation team.

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