LLRF AND TIMING SYSTEM INTEGRATION AT ESS

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Abstract

The Low-Level Radio Frequency (LLRF) system is an important part of an accelerator as the linear accelerator from the European Spallation Source (ESS). LLRF is commonly used with many different setups depending on the aim: preparation, calibration, conditioning, commission, and others. These different setups are connected to the ESS Timing System (TS).

This paper presents the control system integration between LLRF and TS. The integration of these two systems provides different and important features as allowing different ways to trigger the RF system (synced or not to other systems), define how the RF output will be defined (based on the features of the expected beam), re-configure LLRF depending on the timing setup and more. This integration was developed on both ends, LLRF and TS, and is mostly concentrated on the control system layer based on Experimental Physics and Industrial Control System (EPICS). Dealing with the different scenarios, synchronicity, and considering all the software, hardware, and firmware involved are some of the challenges of this integration. The result of this work was used during the last two ESS accelerator commissionings in 2022 and 2023.

INTRODUCTION

The ESS [1] is on the path to deliver the proton beam up to the target where the neutrons will be produced. The ESS linac is shown in Fig. 1. In 2022 [2] and 2023 two beam commissionings on the ESS accelerator covering up to the RF Quadrupole (RFQ) and the Drift Tube Linac (DTL) 4 were performed. To assure a stable commissioning with different setups and also allow the conditioning of different cavities in parallel a special integration between the RF systems and the timing system was needed. This integration allows the RF expert or Cavity specialist to control the RF repetition rate from one cavity independently of the others. It allows also the LLRF to have different automatic behaviors over the feed-forward correction depending on the expected beam (information delivered by the timing system).

The next sections present the details of this implementation and its challenges.

ESS TIMING SYSTEM

The main role of the ESS TS is to generate, acquire, and distribute RF $\approx$ 704.42 MHz based timing signals, with the topology in Fig. 2. The timing hardware is based on Micro Telecommunications Computing Architecture (MTCA) and the detailed concept was described in [3]. The Timing Master (TM) is the main TS gateway for the operation control while event receivers (EVRs) embedded within the timing distribution to machine subsystems (TDMS) perform synthesis of the received information into the timing signals required by a particular subsystem.

RF Events

The TM produces different events that are used to trigger actions on different subsystems (TDMS from Fig. 2). Specifically for RF subsystems, there is one main event called RF Start which is used to trigger the following actions at one RF station:

- Start Modulator,
- Start LLRF (which will generate the initial RF pulse),
- Start Local Protection System (LPS) data acquisition.

Besides the RF Start event, the RF EVR is configured to look into Beam Start and Beam End events, although these events are used only as marker points for LLRF (beam envelope).

Data Buffer

Another important piece of information that is distributed by the timing system is the data buffer information, a deterministic set of data. The data contains information about the next beam pulse, and it will be used to allow different systems to prepare themselves before the proton beam pulse is transported along the linac. The data used by a RF system for example:

- Beam Present, i.e. is there a beam expected,
- Beam Destination,
- Expected Beam Current.

The data information is provided for the subsystem (e.g. RF system) by the EVR EPICS Input/Output Controller (IOC).

ESS RF SYSTEM AND ESS LOW-LEVEL RF

The RF systems at ESS are composed of different elements, most of which are illustrated in Fig. 3. This figure shows some of the main elements as the LLRF, pre amplifier, klystron, and modulator for a generic cavity. For different cavities, the elements can change a bit. Each of these components, responsible for producing RF for one cavity, is called an RF station.

At ESS there are two types of RF stations, the ones using modulators and klystrons, and the lower power stations, where modulators are not required. The RF systems using klystrons share the same modulator [4] (2 or 4 klystrons per modulator). From the ESS sections, the ones following this topology are RFQ, DTLs, Medium Beta Linac (MBL), and High Beta Linac (HBL). The topology of these systems is illustrated in Fig. 4. That figure presents also a new element from an RF station - EVR. The EVR is the component responsible for connecting the RF station to the ESS TS.

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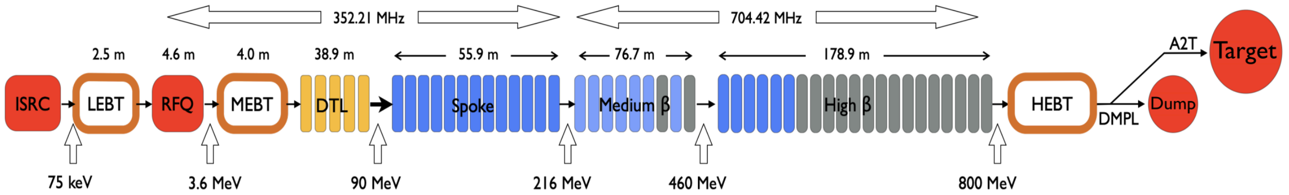


Figure 1: Block view of the ESS linac. The LLRF and timing integration were tested on 2023 beam commissioning up to DTL-4. The two colors (blue and grey) highlight the two energies that different periods of commissioning will bring in the future. Picture courtesy Mamad Eshraqi.

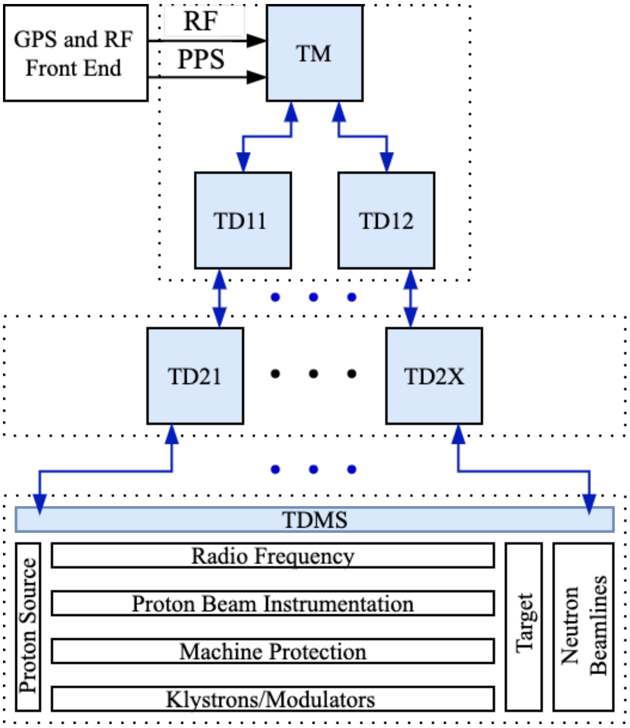


Figure 2: ESS timing network - tree topology. Timing Master (TM); Timing Distribution (TD); TDX_1X_2: X_1 - tree layer, X_2 - ID, TD2X contains X = 22 currently; Timing Distribution to Machine Subsystem (TDMS).

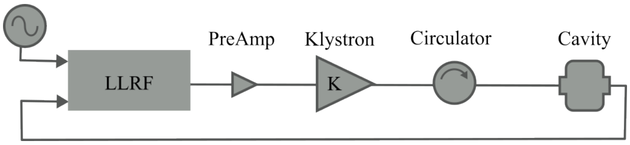


Figure 3: Overview of one RF station.

LLRF

The ESS Low-Level RF [5] is responsible for controlling the field phase and amplitude of the ESS accelerating cavities. The ESS LLRF controls 6 types of cavities: RFQ, Medium Energy Beam Transport (MEBT) Buncher, DTL, Spoke, MBL, and HBL. The control of the cavity field is done by a PID controller implemented in the LLRF firmware.

In order to correct repetitive disturbances, beam loading, and high voltage ripple the LLRF also implements an adaptive feed-forward (AFF) algorithm (or iterative learning control (ILC)), this algorithm is implemented in the software layer. As demonstrated at [6] for long beam pulses both feedback and AFF should be used.

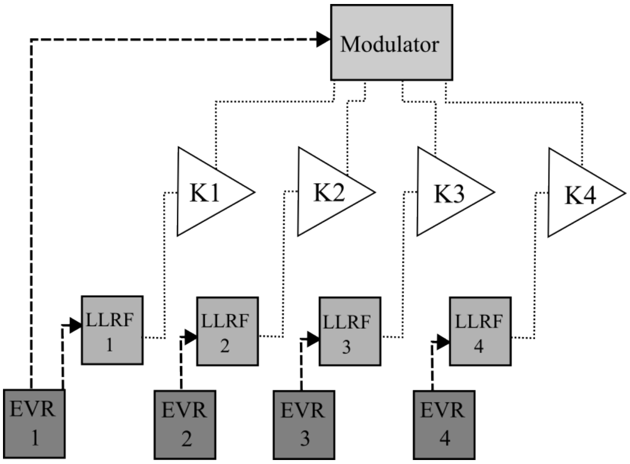


Figure 4: Topology of 4 RF stations using klystrons. The dashed lines with the arrow indicate the trigger line from EVR to LLRF and to the modulator.

Another method implemented in LLRF to correct the beam loading during the RF pulse is the static feed-forward (SFF) [6]. This technique adds a “counter-beam” signal in LLRF feed-forward to cancel out the beam loading effect from the real beam.

The implementation of ESS LLRF is based on MTCA and it is split into two main blocks: FPGA-based firmware and software controller. The FPGA-based firmware is implemented in the Struck SIS8300 digitizer card. The software side of LLRF is implemented using EPICS [7] and it runs on a Concurrent Technologies computer (CPU) on the same MTCA system as the Struck card. The EVR is within the same setup. The hardware communication is implemented via the MTCA backplane: using Peripheral Component Interconnect (PCI) Express for data transfer between SIS8300 and CPU, and the trigger lines to trigger acquisition and interlocks between SIS8300 and EVR.

Other systems that are also relevant to ESS LLRF are the Local Protection System (LPS), the Local Oscillator, and the Piezzo Driver Controller. All of them are composed of hardware located in the same MTCA system. The LPS for example can interlock LLRF when some of the monitored signals (e.g. RF power forward to klystron) are above a defined threshold.

LLRF AND TIMING INTEGRATION

This section describes the main work on the specialized integration between ESS LLRF and TS. Like other systems, LLRF benefits from the common features provided by TS: events, triggers, time reference, etc. However, due to the different ESS operation modes needed for the RF operation, there is a need for a special integration that is not available to other ESS systems so far.

Timing Modes

As shown in Fig. 4, the RF stations using klystron have a dependency between the 1*st* RF station and the others due to the modulator. As the modulator should run at one specific repetition rate this might be a limitation when the other "dependent" klystrons that are running at different repetition rates.

The ESS proton beam accelerator is designed to produce the beam at 14 Hz, but during conditioning and commissioning campaigns different cavities might be running on different repetition rates, e.g. to ramp the RF power. The RF stations can then operate in 2 scenarios: following the global TS and independent of the global TS. These scenarios are detailed below:

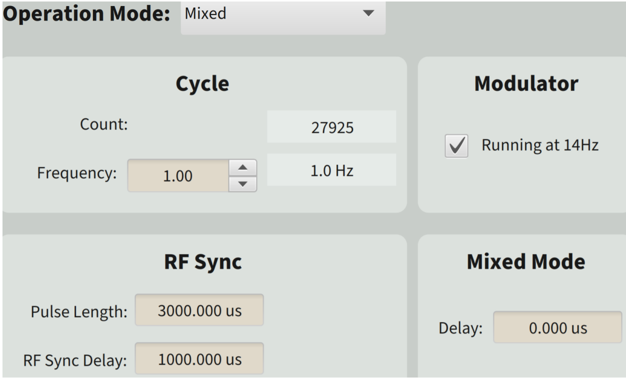
- **Following global timing** - This happens when the RF station in question is being used to accelerate the beam, in that scenario, all the cavities accelerating the beam will operate at the same repetition rate. In the last beam commissioning for example, if the beam is produced up to DTL-4, all the cavities before and including DTL-4 would be following the global timing in sync.
- **Independent of the global timing** - This is used when the cavity is being conditioned or its power is being ramped up. In that scenario, the repetition rate can be changed even if the global timing is locked in a specific one (e.g. 14 Hz).

The first scenario does not present great challenges but the second one main challenge is to keep the RF station synced with the modulator. One example would be 2 cavities using the same modulator, one operating at 1 Hz and another at 7 Hz. In order to address this scenario, an additional timing mixed mode was implemented.

The mixed mode scheme is implemented in two pieces. In the timing distribution system, special events are generated at specific repetition rates and are synced to the 14 Hz event: 0.5 Hz, 1 Hz, 2 Hz, 3.5 Hz, and 7 Hz. In the EVR client, when the user wants to operate a specific rate, the EVR should be reconfigured to follow the desired repetition rate event (e.g 1 Hz) instead of the RF Start one. The timing mixed mode implementation allows the RF station to run on its own repetition rate but still synced with the global timing system. This feature also allows other subsystems of the machine to synchronize with the RF activities. For example a Proton Beam Instrumentation (PBI) sensor that wants to detect interference of the RF power in a cavity while in conditioning campaign.

The remaining point to be addressed was to define the modulator repetition rate, for that we include the possibility of triggering the modulator at 14 Hz. Using this repetition rate the modulator can be used by klystrons operating on any of the mixed mode frequencies and also by the klystrons following the global time. When not needed this option can be disabled to save energy.

Another part of the timing mode implementation is focused on making the user interaction with the TS simpler. To have the different modes in place, a different set of EVR parameters should be changed. A simple EPICS module was implemented that reconfigures the EVR depending on the selected mode and provides a set of PVs used to control that specific mode. The operator graphical interfaces (OPIs) used to control the timing modes in RF system are shown in Figs. 5 and 6.



Operation Mode: Mixed

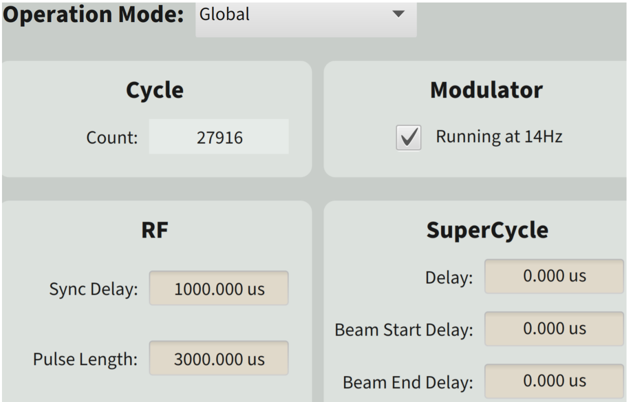
Cycle
Count: 27925
Frequency: 1.00 1.0 Hz

Modulator
☑ Running at 14Hz

RF Sync
Pulse Length: 3000.000 us
RF Sync Delay: 1000.000 us

Mixed Mode
Delay: 0.000 us

Figure 5: User interface to control the timing mixed mode.



Operation Mode: Global

Cycle
Count: 27916

Modulator
☑ Running at 14Hz

RF
Sync Delay: 1000.000 us
Pulse Length: 3000.000 us

SuperCycle
Delay: 0.000 us
Beam Start Delay: 0.000 us
Beam End Delay: 0.000 us

Figure 6: User interface to control the timing global mode.

Each of them controls the possible parameters for the different modes. As shown in Fig. 5, there is the possibility to select the repetition rate, different from Fig. 6, where the repetition rate is controlled by the global timing. The OPIs also present other parameters related to the control of the RF pulse length and position.

Beam Operation Mode

The LLRF implementation used during the proton beam commissioning in 2022 [2] had the features described before to keep the cavity field stable: PID controller, AFF, and SFF compensation. However, during that commissioning phase, some missing features were noticed:

- **FF compensation attached to beam pulses** - During the commissioning not all RF pulses have the beam. Before starting producing the beam or when the cavities are warming up the FF corrections should not be applied.
- **Beam position should be updated into FF compensation automatically** - As the beam position in the cycle can be moved on a pulse-to-pulse basis, this should be taken into account on the FF table as well.
- **Allow RF and the beam pulse to run at different repetition rates** - Similar to the first point, LLRF should be able to apply correction only on RF pulses with the beam.
- **Automatically enable/disable different FF corrections** - All the FF corrections should be automatically controlled (e.g. enabled and disabled).
- **Ignores pulses with interlock in AFF** - When an interlock happens, AFF should ignore that pulse.

To address the missing features a special beam operation mode "Beam Operation" was implemented, using the information from the timing data buffer to address all points listed above. The aim of this integration was to let LLRF deal with different compensations as automatically as possible based on the intended beam information. Most of the automatic actions implemented resulted in enabling or disabling the SFF and the AFF compensation, it also could remove the FF for scenarios where there is no beam.

The beam operation mode adds automatic behavior for different scenarios considering the information of the past beam and the expected information of the next beam. The considered scenarios and the actions, LLRF should take are described below:

- **From no beam to beam** - in the first pulse: enable SFF, next pulses: disable SFF and enable AFF.
- **From beam to no beam** - disable AFF and SFF.
- **Ramp up the beam current with small steps** - no action, AFF should handle it.
- **Change the beam current with a big step** - disable AFF and go to the first scenario.
- **Hard interlock from LPS** - disable AFF and SFF.
- **Fast recover interlock from LPS** - AFF should just ignore the pulse, and everything should continue without any change.
- **Post Mortem event** - LLRF goes to its error state (no RF), AFF and SFF should be disabled.

All these scenarios were implemented on the software level into the LLRF control system, more specifically this integration was mostly done using the EPICS database layer as all the important information, including the timing data buffer, was available as PVs. Besides the automatic transitions, the beam operation mode also sets automatically the beam position on LLRF algorithms, this way if the beam is moved LLRF will know where to position the FF correction.

RESULTS / SUMMARY

During the proton beam commissioning in 2022 [2], the different LLRF timing modes were used and allowed to condition cavities at the same time as the beam commissioning happened. This saved much time for the beam commissioning. The timing modes have also been extensively used for the RF conditioning procedures done on all klystrons.

The beam operation mode was tested in our lab setup using a cavity simulator and demonstrated promising results. During the 2023 beam commissioning, it was possible to test the beam operation mode for a short period of time and the results indicated good improvements. Using the beam operation mode it was possible to have the RF pulses operating at a higher repetition rate than the beam pulses. It also allowed a smoother transition between the different scenarios reducing the number of trips during the beam commissioning.

NEXT STEPS

To allow a stable operation of the cavities during the next beam commissioning phase there are some steps to be done described below:

- **Runs more extensible tests with beam operation mode**
- **Drop FF correction when the beam drops** - This feature will avoid an overshoot of RF power when there are beam trips. It is implemented in the LLRF firmware.
- **Integrate LLRF with other support IOCs** - In order to have a more automatic operation of the RF systems some automation between different supportive IOCs should be done. For example, the IOC responsible for ramping up the RF power could be triggered by LLRF in some scenarios.

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