

INSTALLATION AND FIRST COMMISSIONING OF THE LLRF SYSTEM FOR THE EUROPEAN XFEL

J. Branlard*, G. Ayvazyan, V. Ayvazyan, Ł. Butkowski, M. Fenner, M. Grecki, M. Hoffmann, M. Hierholzer, M. Killenberg, D. Kostin, D. Kühn, F. Ludwig, U. Mavrič, A.S. Nawaz, M. Omet, S. Pfeiffer, H. Prysichelski, K. Przygoda, A. Rosner, R. Rybaniec, H. Schlarb, C. Schmidt, N. Shehzad, B. Szczepanski, G. Varghese, H. Weddig, R. Wedel, M. Wienczek, B. Yang, DESY, Hamburg, Germany
 K. Czuba, P. Jatczak, T. Leśniak, K. Oliwa, D. Sikora, M. Urbański, W. Wierba, ISE, Warszawa, Poland
 W. Cichalewski, D. Makowski, F. Makowski, A. Mielczarek, P. Perek, DMCS, Łódź, Poland

Abstract

The installation of the European X-ray Free Electron Laser (XFEL) is finished, leaving place for its commissioning phase. This contribution summarizes the low-level radio frequency (LLRF) commissioning with a special emphasis on the development of automation tools to support the commissioning of such a large scale accelerator. First results of the LLRF commissioning in the main linac are also given.

THE EUROPEAN XFEL AND ITS LLRF

The European XFEL is based on a 17.5 GeV pulsed superconducting accelerator, consisting of 101 cryomodels organized in 26 RF stations. Its injector has been commissioned and is in operation since December 2013 [1]. The installation phase for the main linac stretched between 2014 and 2016. A description of the LLRF system for the XFEL is given in [2, 3]. Reports of the installation planning and progress can be found in [4, 5]. It was decided not to install the last 4 cryomodels of the main linac (RF station 26), as they need to undergo substantial repair work which would delay the overall installation plan. The energy loss from the missing cryomodels is acceptable, since the target accelerator energy can still be reached with the installed cryomodels. LLRF systems were installed for all RF stations, but operation only up to A20 is allowed at this time.

INSTALLATION SUMMARY

The main LLRF installation steps are: crate preparation in the lab (≈ 1 month for 6 crates), rack preparation and inner rack cabling (1-2 weeks), installation of the LLRF racks inside the tunnel, external RF cabling (2 months), connection to mains, cooling water, Ethernet and LLRF pre-commissioning (2-3 weeks). The LLRF system is then ready to drive the klystron in open loop and monitor cavity forward and reflected signals. The installation of the first RF station started in January of 2015. Each subsequent installation followed a cryostring (CS) granularity (i.e. 3 RF stations at a time). The first complete CS installation took 250 days (including cryomodels, klystrons etc.), while the last one was completed in less than 150 days. Most of the tasks could

be performed in parallel, resulting in a total installation time just below 2 years. Although the LLRF installation itself only represents a fraction of that time, the cryostring installation dictated the LLRF installation schedule. The core LLRF installation team consisted of 6 people, sharing tasks related to infrastructure, MicroTCA.4 system setup, firmware and server installation, system integration and troubleshooting. Both inner- and outer-rack cabling was handed over to a professional cabling company. Basic LLRF checks could be performed parasitically during warm coupler conditioning, hence identifying hardware failures as early as possible, in order to minimize the cold commissioning time and best make use of open tunnel access times. At the end of the installation, the complete RF distribution chain was measured, from master oscillator down to each local reference distribution point along the tunnel. Power levels, insertion losses, and signal spectra were documented. Due to delays in the design and production, piezo drivers were not ready in time before tunnel closure and will be installed later in 2017.

COMMISSIONING OVERVIEW

From a LLRF point of view, commissioning of the injector covers the normal conducting RF gun, the first accelerating cryomodel A1, the third harmonic cryomodel AH1 and the normal conducting transverse deflective structure TDS. Commissioning of the first linac corresponds to RF station A2; the second linac comprises RF stations A3, A4 and A5, and the commissioning of the third linac consists of commissioning RF stations A6 through A20. The operation of RF stations A21-A23 was not yet approved by German authorities and was only scheduled for end of April 2017. Operation of the last installed RF stations A24 - A25 has no firm date at this time.

The commissioning of the LLRF system relies on many pre-commissioning steps performed during installation, at the board, crate, rack and system level. These steps are referred to as warm commissioning [6] since they are performed before accelerator cool-down. The LLRF cold commissioning can be subdivided into the following steps: 1) initial LLRF system verification, 2) LLRF signals dynamic range optimization, 3) cavity frequency tuning, 4) coupler

* julien.branlard@desy.de

tuning, 5) power-based calibration, 6) closed-loop operation, 7) cavity phasing and beam-based calibration.

Step 1: Initial LLRF System Verification

This preliminary step consists of checking that the LLRF system functions properly and is ready for commissioning. Boards are loaded with the correct firmware, all servers are properly running (LLRF control server and other supporting servers such as diagnostic, data acquisition, etc.) and all signals can be read. At this stage, all server properties are systematically initialized. Although obvious in appearance, this is a necessary step to guarantee that the starting point is identical for all stations. The installation phase was stretched over two years; getting a uniform firmware, software distribution across the accelerator is mandatory before starting any commissioning work.

Step 2: LLRF Signal Dynamic Range Optimization

Step 2) assumes that cold couplers can handle the nominal forward power. In almost all cases, warm coupler conditioning was enough, coupler conditioning was not repeated after cool down. The forward power is then increased up to the nominal power (i.e. corresponding to the nominal operation gradient, typically 150-250 kW per coupler). The adjustable attenuators are then automatically set for all forward and reflected channels so that the signal amplitude utilizes 75% of the digitizer dynamic range. In most cases, the 31.5 dB range of the programmable attenuators sufficed. When a signal reached 90% or more of the digitizer range despite the maximum adjustable attenuation, additional fixed-value attenuators had to be inserted manually upstream of the LLRF down-converters (less than 1 per mill of all cases).

Step 3: Cavity Frequency Tuning

Before tuning cavities to resonance, the tuner motor is moved by a complete turn. This initial check guarantees that the motor is working, that the cavity detuning is changing by the expected amount and in the expected direction. Cabling issues were hence identified (i.e. wrong polarity of the tuner driver or mis-cabling resulting in tuner of cavity i actually moving the tuner of cavity j). Issues with current settings were also encountered. The longer cables used in the tunnel resulted into higher inline cable resistance, which required new current limit settings. Once the proper functionality of the tuner is established, cavities are tuned from their parking position to resonance. This step is performed at a moderate forward power (≈ 10 kW per coupler corresponding to 5-10 MV/m per cavity) in order to avoid any potential quench once the cavity comes close to resonance. A so-called *far-detuning* measurement tool was developed to guide the operator through the initial tuner validation step and through the complete cavity tuning process. Looking at the probe signal in the frequency domain, the tool computes the cavity detuning at its parking position (typically 300-500 kHz away from 1.3 GHz) and tracks the detuning as the cavity is being tuned. One drawback is that this tool requires the klystron to be switched on but the obvious advantage is

that one can monitor the entire tuning process and catch any exception that might occur. A smooth tuning process (i.e. no cabling issues or motor driver failure) would allow tuning a complete RF station (32 cavities) in less than 2 hours.

Step 4: Coupler Tuning

The cavity coupling ratio is then adjusted to its target value $Q_L = 4.6 \times 10^6$. A middle layer server automates this step, moving the coupler motor until the target Q_L is reached [7]; this typically takes a few minutes per RF station. At this point, cavities are tuned to resonance and have the desired bandwidth. Before proceeding to the next step, a signal validation check is systematically performed. First, a waveform recognition algorithm verifies that forward, reflected and transmitted waveforms have the expected shapes. Typical issues where forward and reflected cables are swapped would be caught during this step. Second, the script exercises individual waveguide phase shifters back and forth while measuring the resulting phase shift on forward, reflected and probe signals. This step identifies cable issues where the forward signal of cavity i is swapped with that of cavity j . Overall, ≈ 20 such cable mistakes ($< 1\%$) were identified and could be corrected during maintenance days.

Step 5: Power-based Calibration

The LLRF system requires calibration of over 2400 RF signals. For cost-saving reasons, only the forward and reflected power signals at the output of the klystron (both arms) are measured using a power meter. The actual power at the input of each of the 32 cavity couplers is then calculated, based on the measured klystron output power and the attenuation of the waveguide distribution measured during assembly. The LLRF system needs to be calibrated so that the displayed waveforms show actual kW. This step is automated by retrieving the waveguide attenuation from the XFEL cryomodule database and scaling the LLRF waveforms to match the calculated power. The reflected and probe signals are then scaled using the calibrated forward power signal as reference and the following three statements: (1) the reflected power matches the forward power at the beginning of the RF pulse (2) the forward power is exactly zero at the end of the RF pulse (3) the cavity probe is a complex linear combination of the forward and reflected waveforms [8]. This approach, also referred to as *power-based* calibration as opposed to the *beam-based* calibration described in step 7), provides a first order cavity gradient calibration within 10-15% of the actual value.

Step 6: Closed-loop Operation

Having all cavity gradients calibrated, the phases are aligned (i.e. rotated to a common phase value, however, still arbitrary with respect to beam phase). The complete vector sum is computed, combining four cryomodule-wise partial vector sums. A system identification is performed following an automated procedure [9]. The multiple input multiple output (MIMO) controller is derived from this model and closed-loop operation can be engaged. A closed-loop system

model is computed to determine the learning feed forward coefficients [10].

Step 7: Cavity Phasing & Beam-based Calibration

Beam transmission is required for this last step; typically 0.5 nC, 30 bunches for a 4.5 MHz laser repetition rate. Beam induced voltage transients are measured to establish the phase relationship between cavities. Phase shifters, acting on the forward signals are adjusted in order to align all measured cavity phases. At this stage, the relative cavity phases are aligned with respect to beam, (i.e. cavity phasing is performed). This procedure initially relies on the gradient measurement of the first cavity. Absolute gradient calibration is performed by scaling the LLRF operating gradient to match the energy gain measured by the beam energy monitor. A global phase scan is also performed, measuring the beam energy as a function of operating phase to validate the 0 deg. on-crest setting. The LLRF system is then in a state, where all cavity phases are aligned with respect to beam, 0 deg. set point corresponds to on-crest acceleration and the RF station amplitude set point matches the measured energy gain. The forward and reflected signals are then adjusted in amplitude and phase, following the same principle described in step 5), this time however, using the probe as reference. This beam-based approach provides an absolute calibration within $\approx 1\%$ in amplitude and a few degrees in phase.

CHALLENGES AND ASSESSMENT

The complete commissioning of the XFEL accelerator is expected to last the major part of 2017, marked by several milestones. Cool down of the injector and the entire linac started in December 2016 and was finished in time for the beginning of the cold commissioning on January 2nd 2017. The injector had already been cold commissioned in 2016, so that the injector nominal energy was reached within a week. Commissioning of the first linac L1 (1 RF station) took two weeks, L2 (3 RF stations) another 2 weeks, and L3 (15 RF stations) roughly 2 months.

Typical Problems

Besides LLRF system troubleshooting, the error most commonly found was cable swaps but could be easily identified and corrected during the commissioning phase. One cryogenic incident was triggered due to undetected quenches, but not resulting in any down time. Cavity quenches due to multipacting appearing for gradients above 17-18 MV/m were observed on nearly all stations, affecting up to 50% of cavities in the worst case. The effect could always be processed away within 2-3 hours of conditioning (i.e. controlled quenches). 4 couplers out of 616 in use so far had to be shorted due to overheating, 5 cavities out of 616 had to be detuned out of operation due to field emission above the acceptance criteria (10^{-2} mGy/min). In total, 10 out of 19 RF stations commissioned so far have a complete 32-cavity vector sum. In all other cases, one cavity was removed from the controlled signal. During the early beam steering along the main linac, several electronic components were show-

ered and triggered false alarms due to beam losses: smoke and fire detectors, temperature sensors, ... Although some LLRF electronic failures remained unexplained and could be attributed to radiation, no LLRF component seemed to have suffered non-recoverable damage until now.

Lessons Learnt

The effort placed into testing components and performing system checks early on paid off, smoothing the way for the initial commissioning. The experience gathered at FLASH with the MicroTCA.4 LLRF system installed as a prototype for the XFEL also proved beneficial. A strong commissioning team, reinforced by external colleagues boosted the work force during the peak commissioning time. The large level of automation, organized as simple modular scripts, was a key factor to perform most of the commissioning tasks in a systematic and reproducible way. It proved to be essential to have easy access to the important information gathered during the cryomodule tests: maximum cavity gradient, expected number of tuner motor steps from parking position to resonance, which cavities should be payed special attention to in terms of radiation or low quench gradient... Some of the weaker points of the commissioning include the fact that many steps had to be repeated for diverse reasons: incomplete documentation, commissioning procedure revised or insufficiently explained, identified bugs resulting in a system upgrade thus voiding previous work. Finally, although the use of bug tracker tools such as Redmine proved very useful, a tool to measure and report the overall commissioning progress was missing.

CONCLUSION AND OUTLOOK

A overview of the LLRF commissioning tasks and first results were presented. Overall, the baseline LLRF commissioning went relatively smoothly. Standard accelerator operation could be handed over to XFEL operators after a couple of months, where RF station ramp-up, down and recovery after some trip events is handled automatically by a finite state machine; LLRF expertise and support being available as on-call service. Currently, one main effort consists of assessing the maximum operational gradients for every RF station, in comparison with expected individual cryomodule performance. A few other LLRF milestones also remain to be met. Installation and commissioning of the piezo driver modules, improving the system startup time after shutdown, and understanding the long term stability of the system; in particular measuring the performance of the optical RF synchronization and the drift compensation modules. Finally, a higher level of automation for LLRF operations, diagnostics and fault detection is also on the agenda.

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