

LLRF COMMISSIONING AT THE EUROPEAN XFEL

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Abstract

The European X-ray Free-Electron Laser (XFEL) at Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany is a user facility under commissioning, providing ultra-short X-ray flashes with a high brilliance. All LLRF stations of the injector, covering the normal conducting RF gun, A1 (8 1.3 GHz superconducting cavities (SCs)) and AH1 (8 3.9 GHz SCs), were successfully commissioned by the end of 2015. The injector was operated with beam transmission to the injector dump since then. After the conclusion of the construction work in the XFEL accelerator tunnel (XTL), the commissioning of 22 LLRF stations (A2 to A23) started with the beginning of 2017. At every station the LLRF system is organized in a master-slave configuration, controlling 32 1.3 GHz SCs. Stable operation with beam transport to the main dump (TLD) was achieved. The commissioning procedure applied, experience gained and performance reached are described.

INTRODUCTION

The Deutsches Elektronen-Synchrotron (DESY) in Hamburg is currently commissioning the European X-ray Free Electron Laser (E-XFEL) [1]. Once finished, up to 27000 coherent laser pulses per second with a duration of less than 100 fs and a wavelength down to 0.05 nm will be generated. For this, electrons have to be accelerated using a 2 km particle accelerator based on superconducting radio frequency technology. The maximum design energy is 17.5 GeV [1]. Precision

regulation of the RF fields inside the accelerating cavities is essential to provide a highly reproducible and stable electron beam. The RF field regulation is done by measuring the stored electromagnetic field inside the cavities. This information is further processed by the feedback controller to modulate the driving RF source. The standard in which the low level radio frequency (LLRF) systems are realized is Micro Telecommunications Computing Architecture (MicroTCA.4) [2]. Figure 1 shows a schematic of European XFEL, focusing on the accelerator sections, cryostrings (CS) and RF stations. Every RF station has its own power source and LLRF system. In the case of the XTL, the LLRF systems have a master-slave configuration [3].

COMMISSIONING OF THE LLRF SYSTEM

The following commissioning denominates the procedure necessary to ready an RF station from a finished pre-commissioning for beam acceleration. For a detailed description of the installation and first commissioning see [4]. Due to the large number of RF stations to be commissioned, a commissioning team of 14 members of DESY personal was established. This team was supported by five guests from the SLAC National Accelerator Laboratory and one from the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The work was organized in two 8-hour shifts per day. It was planned to commission the RF stations SC-wise. The estimated required time was two weeks for L1 (one RF station), two weeks for L2

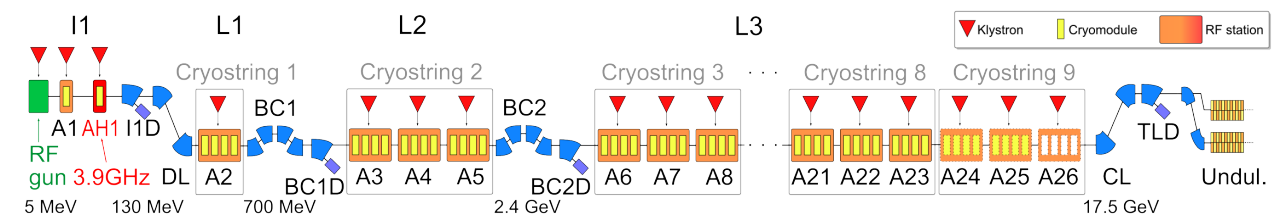


Figure 1: Layout of the European XFEL.

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(three RF stations) and two months for L3 (15 RF stations, A6 to A20). In order to assure a systematic and homogeneous commissioning of all RF stations, a check list with precisely defined commissioning steps was established and used.

The commissioning of the XTL LLRF systems started on January 2nd 2017. In practice, the majority of the commissioning was performed during day time and during weekdays. The required time for the commissioning of L1 was 3.4 weeks and for L2 1.4 weeks. The time required to finish the commissioning of an RF station depended strongly on the condition of other subsystems, such as e.g. cavity frequency tuner driver electronics and cabling. Furthermore, other subsystems also required commissioning and beam operation had a high priority. The combination of tunnel access only once per week and the need of a few iterations fixing frequency tuner subsystems in some cases lead to idle times in the LLRF commissioning. This was also the reason to move away from a CS-wise commissioning strategy at L3 (CS3 to CS7). There the commissioning of the RF stations was highly parallelized. Thus only 1.6 months were required for the commissioning of L3, even including all idle time. Due to delayed construction work, CS8 commissioning started over a month later in May 2017. Due to the above described problems with the cavity frequency systems in combination with less tunnel access possibilities due to a highly prioritized beam operation, the LLRF commissioning of CS8 took 1.1 months. The evaluation of cable issue tracking showed that 35% of all identified cabling issues after the cool down were located at CS8. This was the cryostrapping, at which the cabling work was performed with the highest time pressure.

PERFORMANCE REACHED

Maximum Gradients

All cryo modules, which are installed at the European XFEL, were intensively tested at the Accelerator Module Test Facility (AMTF) [5,6], which is located at DESY. There the maximal operational cavity gradients for every cryo module were measured. Based on this, a waveguide distribution was tailored for every cryo module, in order to provide an optimal level of driving power to every single cavity. The measured waveguide distribution attenuations in combination with the assumption of perfect power sources (same power at the two multi beam klystron output ports) yield the maximal estimated vector sum (VS) gradients for every L3 RF station. These are shown in Figure 2. One should note that a) these values cannot be achieved in the accelerator due to waveguide and power source imperfections and b) these values are defined by break down limits or radiation limits. Stable operation is only possible below (typically 1 MV per individual cavity) these limits. Otherwise the probability of quenching a cavity due to an externally induced gradient fluctuation (e.g. detuning change due to helium pressure fluctuation) and consequently interrupting beam acceleration would be too high. Thus the maximal operational VS gradient achievable is always lower than the VS regarding

the AMTF tests.

Figure 2 shows the stable operational gradients in L3 reached so far during operation. These yielded a maximal stable beam energy of 14.1 GeV. In this case all RF stations were operated with a safety margin below their limits, which corresponds to the maximal stable vector sum voltages.

Typical limitations were klystron saturation or cavity quenching. Where necessary, the klystron high voltage was increased in order to deliver enough power. The current quench limits as well as the actual waveguide distributions are under investigation. So far cavity degradation was not observed, but also cannot be excluded yet. One should further note that the calibration methods at AMTF and at XFEL were different. At AMTF no beam was available. Thus the only way of calibration was the usage of power meters (about 10% precision). At XFEL a beam based calibration was performed (about 2% precision).

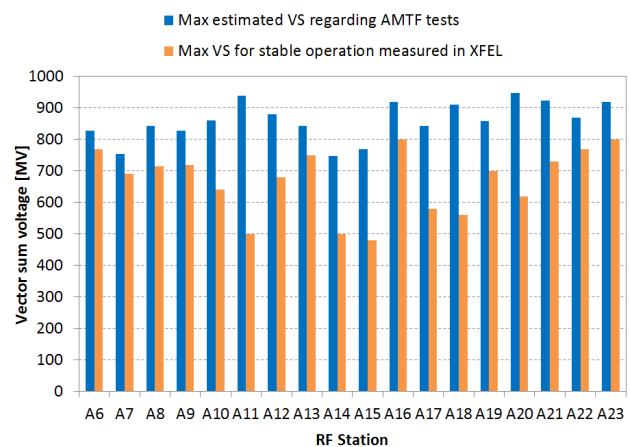


Figure 2: Maximum vector sum gradients of L3 as of 22.06.2017: estimated from AMTF tests and measured at XFEL.

In-loop Stability Measurements

Figure 3 shows the in-loop measured intra pulse stabilities in amplitude and phase for all XTL RF stations. The red bar in both plots at 0.01% and 0.01°, respectively indicates the stability requirements [1]. One can see that the achieved performance in amplitude and phase are up to a factor of 2.4 more stable than required. Even the worst performing station performs well below the requirements. Detuning of cavities leads typically to a decrease in amplitude and phase stabilities.

Beam Energy Stability Measurement

In order to quantify the beam energy stability, the beam energy was measured over 1000 pulses at the collimation section (CL) via the Beam Energy Measurement Server [7]. This method utilizes beam position monitors (BPM) and the corresponding magnet currents. At the time of the measurement 1 bunch with a charge of 0.5 nC was accelerated. The

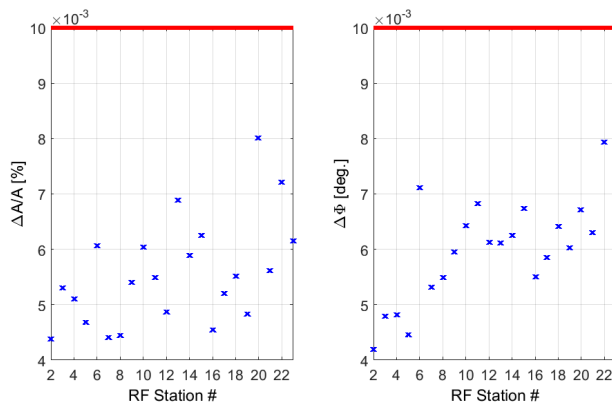


Figure 3: In-loop intra-pulse amplitude (left) and phase (right) stabilities of the XTL RF stations averaged over 1000 pulses as of 23.06.2017. The red line indicates the required stability level.

resulting beam energy stability is shown in Table 1. It is well below the initial performance goal of 0.1% [1] and the final performance goal of 0.01% [8].

Table 1: Beam Energy Stability Measurement at CL

ΔE [MeV]	E [MeV]	$\Delta E/E$
0.310	13489	0.0023%

EXPERIENCE GAINED DURING OPERATION

A problem which occurred during operation was module-wise 240° phase jumps on the probe, forward and reflected channels after crate restarts. This increased the start-up time of the accelerator, since the phase jumps had to be corrected cavity by cavity. The issue was caused by the incorrect triggering of the frequency dividers for the generation of the LO in the LLRF system in combination with temperature induced drifts in the master timing system. On both sides the firmware was fixed and an initialization script for the accelerator start-up was prepared for deployment. The implemented Output Vector Correction (OVC) algorithm, whose purpose is the compensation of amplitude and phase drifts of the plant, led to instabilities during closed-loop operation. It is in the process of revision and optimization.

The general operation of the MicroTCA.4-based LLRF systems is very stable and reliable. So far no radiation related failures were seen. A key for smooth operation is an appropriate set of scripts for automation as well as sufficient diagnostics.

SUMMARY AND OUTLOOK

At the European XFEL the commissioning of all LLRF system of RF stations up to A23 was concluded. This allowed stable beam acceleration to energies up to 14.1 GeV. Investigations to push the maximal operational beam energy to the design value of 17.5 GeV are ongoing. The vector sum intra-pulse amplitude and phase stabilities are about a factor two better than specifications. The beam energy stability was measured at the collimation section and is well below requirements. In the first quarter of 2018 it is planned to commission CS9, which at the moment comprises RF stations A24 and A25. Furthermore the advanced commissioning of the LLRF systems is ongoing. This includes further commissioning of the Drift Calibration Module (DCM) [9], installation and commissioning of piezo drivers and Optical Reference Modules (REFM-OPT) [10]. In addition, it is planned to repeat at XFEL the LLRF tests which were performed before at AMTF. By this, any changes of e.g. Q_L ranges, fundamental modes, etc. can be quantified.

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