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LLRF OPERATION AND PERFORMANCE 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 providing ultra-short hard and soft X-ray flashes with a high brilliance. All low level radio frequency (LLRF) stations of the injector, covering the normal conducting RF gun, A1 (8 1.3 GHz superconducting cavities (SCCs)) and AH1 (8 3.9 GHz SCCs), were successfully commissioned by the end of 2015. The commissioning of LLRF stations A2 to A23 (32 1.3 GHz SCCs each) in the XFEL accelerator tunnel (XTL) was concluded in June 2017. Self-amplified spontaneous emission (SASE) light was produced in undulator section SA1 and delivered to the first users in September 2017, marking the beginning of regular user operation. The current state of the LLRF systems, the experience gained during operation and the performance achieved in terms of stability and energy reach are presented.

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) [1] is operated at the Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany. Currently up to 300 coherent laser pulses per second with a duration of less than 100 fs and with a wavelength down to 1.3 Å are delivered to the experiments. In future the number of pulses will increase to the design value of 27000 per second. For the production of these laser pulses, electrons have to be accelerated using a 2 km long accelerator based on superconducting radio frequency (RF) technology. The maximal design energy is 17.5 GeV [1]. In order to provide a highly reproducible and stable electron beam, a precise regulation of the RF fields within the superconducting cavities (SCC) is required. The hardware standard in which the low level radio frequency (LLRF) systems are realized is Micro Telecommunications Computing Architecture (MicroTCA.4) [2]. The RF stations in sections L1 to L3 have a master-slave configuration. For further information on the system architecture see [3,4]. As high power RF sources 10 MW multi–beam klystrons are used. Figure 1 shows a schematic of the RF stations along the accelerator sections.

LLRF SYSTEM STATUS

Since the conclusion of the basic LLRF commissioning [5,6] at the end of March 2017, the linac was operated with 19 (A2 to A20) and from middle of June 2017 with 22 RF stations (A21 to A23 in addition). Currently the advanced LLRF commissioning is on-going. This covers the following system components and algorithms, which will improve long and short term RF field regulation stability:

- Piezo driver electronics [7],
- Drift calibration modules (DCM) [8],
- Beam-loading compensation (BLC),
- Output vector correction (OVC).

Once the piezo driver electronics is installed, it will be possible to operate the piezos, which are acting on the SCCs. The goal is to counteract and compensate for the Lorentz force detuning, which can be even a limiting factor in closed-loop vector-sum operation of multiple high gradient cavities.

The DCMs allow a recalibration of the probe signals for every pulse. By this long and short term drifts of the cables from the top patch panel to the MicroTCA.4 crate and of the detection electronics due to temperature and humidity variations can be compensated for. The majority of the DCMs are already active. Minor software and configuration optimizations are on-going.

The BLC modifies the feedforward table in such a way, that RF field disturbances caused by beam loading are compensated. The input for the BLC algorithm is beside others the charge information for every bunch in the bunch train. This information is provided for every RF station by the beam position monitor (BPM), which is located upstream of the respective RF station. Currently the BLC is operational

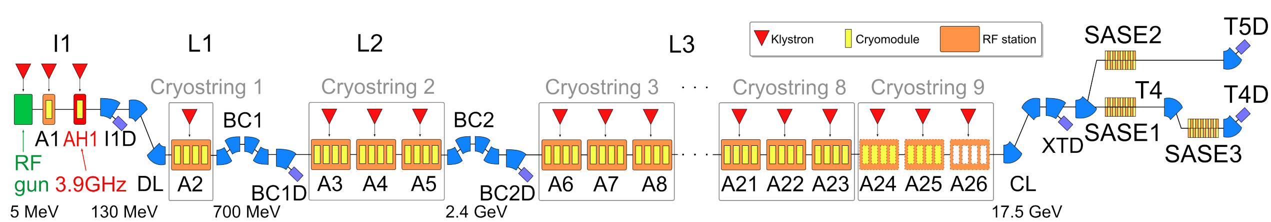

Figure 1: Schematic of the RF stations, the cryostrings and the accelerator sections of the European XFEL.

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at 8 RF stations. Once the optical cable connection between the BPMs and the LLRF systems has been established for the remaining RF stations, the algorithm can be used throughout the entire accelerator.

The goal of the OVC is to keep the loop phase and loop gain always constant. Currently a rework of the underlying algorithm is on-going, which will ensure high reliability and robustness both in open and closed-loop operation.

EXPERIENCE GAINED DURING OPERATION

During six user blocks in 2017 the self-amplified spontaneous emission availability was about 91% [9]. A preliminary evaluation of finite-state machine (FSM) [10] log files has indicated a mean time between trips of the RF stations of about 1.13 hours. A trip is an event in which the RF at an RF station cannot be maintained. Typically the downtime created by such an event is less than two minutes. The FSM is the software used for starting and stopping the RF stations. It also detects via interlock signals and an internal algorithm, if an RF trip occurred. In some conditions (e.g. for a large mismatch between vector sum (VS) voltage read back and set point values) it triggers a trip, meaning shutting off the RF. After such an event, it tries to recover the RF operation three times, otherwise it gives up. Furthermore, if an RF station trips, the electron beam is blocked in order to prevent unintended beam loss. These events are logged in a log file. At the European XFEL a very flexible timing system allows to set the pulse start trigger for every RF station individually. This is used to operate RF station on and off the beam. At the moment, typically one RF station in section L3 is shifted off the beam serving as a spare station in case another RF station fails. In the preliminary trip evaluation both operative and spare RF stations are included. In order to reduce the number of trips the root cause for every single trip has to be identified. Tools for supporting this work and ideally automating it are under development.

PERFORMANCE ACHIEVED

LLRF In-Loop Stability

The requirements for the in-loop amplitude and phase stability over the flattop is 0.01% and 0.01°, respectively [1]. Figure 2 shows the amplitude and phase stability reached at the XTL RF stations. The achieved performance in amplitude and phase are up to a factor of 2.4 more stable than required. Even the worst performing RF station performs well below the requirements. The differences in stability from station to station result from differences in the detuning of the cavities. The presented data was taken during nominal operation without beam. Algorithms such as the multiple input multiple output-based feedback controller [4] and the learning feedforward [11] were active. The pulse-to-pulse stability is in the same order of magnitude fulfilling the requirements.

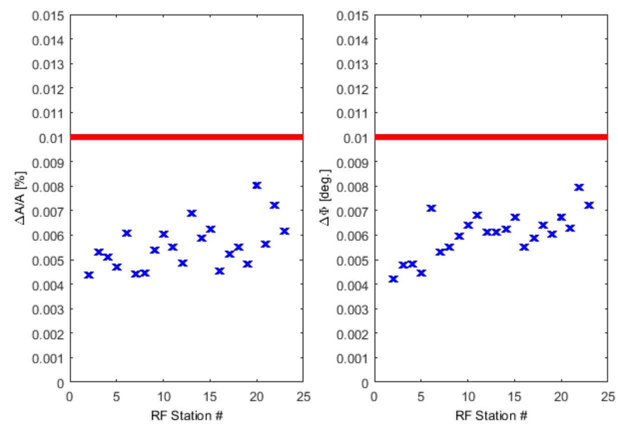

Figure 2: In–loop intra–pulse amplitude (left) and phase (right) stability of the XTL RF stations averaged over 1000 pulses as of 23rd of June 2017. The red line indicates the required stability level.

Electron Beam Energy Stability

The requirement for the electron beam energy stability is 0.01% [12]. The electron beam energy stability can be measured in all sections of the accelerator using the Beam Energy Measurement Server [13]. In the following data taken at the collimation section (CL), the T4 section (T4), which is located after the SASE1 undulators, and the T4D section (T4D), which is located after the SASE3 undulators and includes the electron beam dump, is discussed. Table 1 shows the measured stability over a 4 hour period of time. The average energy stability is a factor 1.5 to 1.8 higher than the requirement. It is believed that with the system improvements, which will be implemented in the near future, the required beam energy stability will be met.

Table 1: Electron Beam Energy Stability As Measured On The 1st Of February 2018.

Time [hh:mm]	CL [E-4]	T4 [E-4]	T4D [E-4]
18:45	1.5	1.5	1.7
19:45	1.7	1.5	2.0
20:45	1.5	1.5	1.9
21:45	1.7	1.5	1.7
22:45	1.8	1.5	1.6
Mean	1.6	1.5	1.8

Maximal Energy Reach

The maximal design electron beam energy is 17.5 GeV [1]. After the commissioning of RF stations up to A23 the maximal reachable energy was 14.7 GeV. Based on the module tests at the Accelerator Module Test Facility (AMTF) [14,15] it should have been possible to reach a theoretical electron beam energy of about 17.9 GeV. In reality the AMTF test values can never be reached due to imperfections in the

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waveguide systems and to the fact that 11 cavities have been detuned after the modules were installed in the tunnel due to high field emission or to coupler issues. Still, these arguments cannot account for the too high gap. In order to reach and exceed the design energy of 17.5 GeV investigations are on-going. As of the 28th of March 2018, 13 (A10 - A22) of 20 (A6 - A25) L3 RF stations have been tested. 8 of the 13 tested RF stations reached their final maximal VS voltage. The investigations on the other 5 RF stations have to be continued. The projection suggests that the testing of all RF stations in L3 may be finished by the end of summer 2018. During the investigations, the RF station is ramped up slowly while monitoring all important signals (RF waveforms, coupler temperature, helium level, radiation level, etc.). This is done until a limit is reached. The nature of the limit and possible counter measures are then investigated. In some cases cavities showed multipacting, which then was conditioned away. In other cases the initially limiting cavity was detuned, allowing the maximal VS voltage to increase. These investigations are typically done on the spare RF station parallel to nominal beam operation. Figure 3 shows the maximal VS gradients of RF stations A6 to A23 estimated from AMTF tests, measured at XFEL on the 23rd of June 2017 and on the 28th of March 2018 during the maximum energy reach investigations. The current maximal electron energy is 16 GeV, which still has to be demonstrated with beam operation.

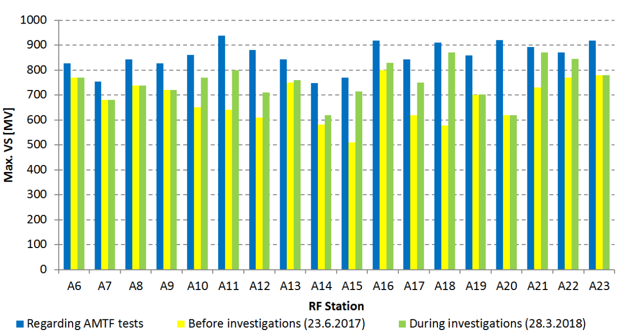

Figure 3: Maximal VS gradients of L3: estimated from AMTF tests (blue), measured at XFEL on the 23rd of June 2017 (yellow) and on the 28th of March 2018 (green) during the maximum energy reach investigations.

SUMMARY AND OUTLOOK

The basic commissioning of the LLRF systems at the European XFEL went very smoothly and was finished up to RF station A23. RF stations A24 and A25 will follow around May 2018. The advanced LLRF commissioning is on-going. The operation during user runs in 2017 yielded a SASE availability of about 91%. A too short mean time between RF station trips (about 1.13 hours) triggered investigations in order to improve the situation. The LLRF in-loop amplitude and phase stability is about a factor of 2 better than the requirement. The electron beam stability is about a factor of 1.6 above the requirement. It is believed that after system improvements the requirements will be met. The maximal design energy of 17.5 GeV has not been reached yet. In order to reach and exceed it, every RF station in L3 is investigated individually and optimized. Until now the maximal possible energy was increased by 1.3 GeV to 16 GeV. Also the imminent commissioning of RF stations A25 and A26 will help to reach the goal of 17.5 GeV.

REFERENCES

[1] "The European X-Ray Free Electron Laser Technical Design Report," Jul. 2007, http://xfel.desy.de

[2] MicroTCA® is a trademark of PICMG, "MicroTCA.4 specifications," Sep. 2006, http://www.picmg.org

[3] H. Schlarb, "Overview on the LLRF and MicroTCA developments at DESY," presented at LLRF'13, Lake Tahoe, USA, Oct. 2013.

[4] S. Pfeiffer *et al.*, "Design of an Optimal and Robust Controller for a Free-Electron Laser Exploiting Symmetries of the RF-System," in *Proc. CDC'12*, Maui, USA, Dec. 2012, pp. 4253–4258.

[5] J. Branlard, "LLRF Commissioning and First Operation of the European XFEL," presented at 6th MicroTCA Workshop for Industry and Research, Hamburg, Germany, Dec. 2017.

[6] M. Omet *et al.*, "LLRF Commissioning at the European XFEL," in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, paper FRXBA01, pp. 941–943.

[7] M. Grecki *et al.*, "Piezo Control for XFEL," presented at LLRF'17, Barcelona, Spain, Oct. 2017.

[8] J. Piekarski *et al.*, "Phase and Amplitude Drift Calibration of the RF Detectors in FELs LLRF Systems," presented at RT'16, Padova, Italy, Jun. 2016.

[9] M. Scholz, "FEL Performance Achieved at European XFEL," presented at IPAC'18, Vancouver, Canada, Apr. 2018.

[10] O. Hensler, "Progress in Finite State Machine Developments at FLASH," presented at the FLASH Seminar, Hamburg, Germany, Oct. 2010.

[11] S. Kirchhoff *et al.*, "An iterative learning algorithm for control of an accelerator based Free Electron Laser," in *Proc. CDC'08*, Cancun, Mexico, Dec. 2008, pp. 3032–3037.

[12] W. Decking, "Private communication," Deutsches Elektronen–Synchrotron, May 2017.

[13] L. Fröhlich, "Private communication," Deutsches Elektronen–Synchrotron, May 2017.

[14] J. Branlard *et al.*, "LLRF Test of XFEL Cryomodules at AMTF: First Experimental Results," in *Proc. SRF'13*, Paris, France, Sep. 2013, paper THP087, pp. 1132-1134.

[15] J. Swierblewski *et al.*, "Large Scale Testing of SRF Cavities and Modules," in *Proc. LINAC'14*, Geneva, Switzerland, Sep. 2014, paper TUIOC01, pp. 426-430.