COMMISSIONING AND OPERATION EXPERIENCE OF THE 3.9 GHz SYSTEM IN THE EXFEL LINAC

C.G. Maiano*, J. Branlard, M. Huening, M. Omet, E. Vogel, DESY, Hamburg
A. Bosotti, R. Paparella, D. Sertore, P. Pierini†, INFN/LASA, Segrate (MI)
†on leave at DESY, Hamburg

Abstract

The European X-ray Free Electron Laser (EXFEL) injector linac hosts a 3.9 GHz module (AH1) for beam longitudinal phase space manipulation after the first acceleration stage, in order for the linac to deliver the high current beams with sufficiently low emittance for the production of 1 ÅFEL light to the experimental users. The module was technically commissioned in December 2015 and operated well above its nominal performances during the Injector Run from January to July 2016. Its operation has restarted in January 2017 with the startup of the whole facility, and the system met the design beam specifications after the bunch compression stages. A brief review of the commissioning and first operation experience of the RF system are presented here.

THE EUROPEAN XFEL 3.9 GHz SYSTEM

The EXFEL linac delivers the low emittance-high peak current beams, which will in the near future produce the 1 Å FEL radiation for the experimental users [1, 2]. The high quality beam is generated in the injector complex by a laser-driven L-Band Radio-Frequency (RF) photocathode gun and pre-accelerated to energies in the 130-200 MeV range by a single standard EXFEL 8-cavity module. At the injector the bunch length is diluted to mitigate the space-charge effects occurring at high beam currents, and three bunch compressor stages along the linac (after the injector, at ≈600 MeV and at ≈2.4 GeV) provide the necessary peak current needed for FEL emission.

The RF curvature induced by the long bunch length (with an approximate fwhm of 20 ps, corresponding to ≈ 9 degrees of the RF phase) at the injector needs to be corrected by a special module operating at three times the main RF system and at ≈180° phase with respect to the beam. The EXFEL third harmonic system, a single module with 8 superconducting cavities at 3.9 GHz) was jointly provided by INFN and DESY as an In-Kind contribution to the EXFEL. Table 1 summarizes the design parameters for the EXFEL third harmonic system.

After the module (AH1) preparation and assembly, its integration at the EXFEL injector started in September 2015, with the transport to the underground building. The EXFEL superconducting accelerating modules contain all the cryogenic distribution lines, thus the completion of the cryogenic installation necessary for its cold operation started with the welding of all the process pipes to the neighboring 1.3 GHz injector module (A1) and the cryogenic feed box .

* cecilia.giovanna.maiano@desy.de

[1] Without taking into account RF distribution losses in operation

Table 1: EXFEL Third Harmonic Section Design/Parameters

Module	
Maximum Design Energy Gain	40 MeV
Number of Cavities	8
Operating Phase	180°
Coupler orientation in string	Alternating for dipole kick cancellation
Cavities	
Active Length	0.346 m
R/Q	750 Ohm
Maximum Gradient (tuned)	≈ 14.5 MV/m
Tuners	
Tuning Range	>750 kHz
Tuner Type	ILC-type blade tuner
Couplers	
Design Q_L	3.2×10^6
Type of antenna	Fixed
Max Forward Power[1]	3.75 kW
RF source	
Type	Klystron
Max req Power for operation	≈ 50 kW
Nominal RF pulse structure	
Filling time	750 μs
Flat-top length	550 μs
Pulse Repetition rate	10 Hz

The System Components

The 3.9 GHz RF structures used in the EXFEL third harmonic module derive from the system developed by FNAL and successfully operated in FLASH [3, 4]. Several adaptations to the concept were needed to fit the different beam parameter and beam line requirements and the different cryogenic environment of the EXFEL accelerating modules [5,6]. The cavity RF geometry is the same as the FLASH 3.9 GHz cavities, with design changes to the cavity and cryomodule components in order to: 1) standardize the flanging system of all RF antennas to those of the EXFEL main linac cavities; 2) achieve compliance to the pressure vessel norms [7] for operation in the EXFEL facility; 3) use the recent INFN developments of the International Linear Collider slim Blade Tuner design [8]; 4) adapt the mechanical design of the dressed cavity to the different support and transverse cross

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sections of the EXFEL modules with respect to the existing modules of the FLASH injector; 5) implement a cavity string layout which minimizes the emittance growth due to coupler dipole kicks [9]; 6) include a magnet package (consisting of quadrupole, beam position monitor unit and corrector coils) at the module beginning. Figure 1 shows a cavity with all its ancillary components, briefly described in the following.

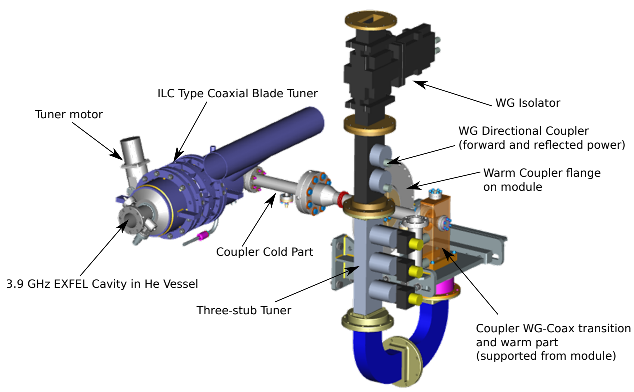

Figure 1: A cavity with all its main ancillary components.

Cavities The EXFEL 3.9 GHz cavities were procured as part of the Italian In-Kind contribution to the project and characterized to the project specification in the INFN-LASA vertical test facility before their integration in the helium vessel. All cavities were successfully tested above the EXFEL accelerating gradient specification of 15 MV/m with a Q_0 greater than 1×10^9. Most of the cavities reached accelerating fields in the 20 MV/m range with no appreciable slope of the Q_0 curve and quenched at the limiting field, with dissipated power in the 20-100 W levels [10].

Couplers AH1 was equipped with FNAL fixed antenna couplers, successfully used for the FLASH ACC39 module [11]. Since the coupling specifications for the FLASH beam structure were different, the FNAL data was extrapolated to determine the correct coupling value as required for the EXFEL beam structure. A final trimming operation to a new cold antenna length was sufficient to adjust to the lower coupling value foreseen by the EXFEL. Coupler conditioning and antenna trimming was performed by FNAL under a Work for Others agreement between DESY and FNAL.

Tuners A cold tuning system is needed for the fine frequency adjustment of the SRF cavities to the frequency provided by the linac timing and synchronization system. AH1 uses a scaled version of the coaxial ILC-Slim type blade tuner [8]. Two assemblies of three Ti half-rings joined by e-beam welding with Ti blades at an angle transform the rotation of the central ring into a longitudinal movement of the outer rings. These are fixed to the two sides of the cavity helium tank, divided by a soft Ti bellow. The same motor and gearbox package used for the 1.3 GHz EXFEL cavity tuners and mounted between the two half-tuner assemblies

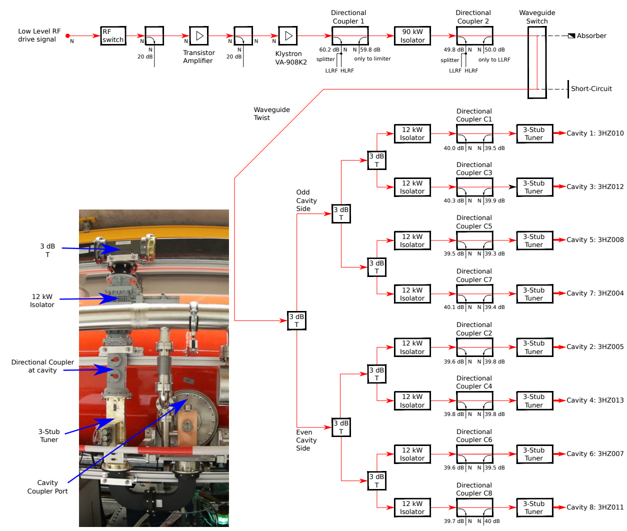

Figure 2: Power RF generation and distribution in AH1.

actuates the rotation of the central ring. Due to the moderate operational gradient of these structures and their relatively high stiffness, the tuner has no fast piezo action for Lorentz Force compensation.

Cold mass and vacuum vessel The cavities are integrated into a cryostat derived from the TTF design [12], updated with the modifications performed for the EXFEL series mass production. The cavity string is suspended from the He Gas Return Pipe (GRP), the structural backbone of the module. The GRP is suspended from the vacuum vessel (≈ 6 m long) . Two thermal shields at 5-8 K and 40-70 K protect the low temperature environment from the ambient temperature. The shields are cooled by cryogenic lines at intermediate temperatures.

High Power RF and RF distribution A single 3.9 GHz klystron (CPI, model VA-908K2), with a maximum peak power rating of ≈ 80 kW drives RF in AH1. A fixed waveguide distribution system splits the klystron output into two lines on either side of the module, which are then split into two further stages to provide RF power to the 4 couplers at each side. Each splitting stage is achieved with a 3 dB magic T divider. Close to each cavity a directional coupler allows the monitoring of the forward and reflected power from the cavity and a three-stub tuner is used to achieve the nominal Q_L value and adjust the cavity relative phases for correct beam acceleration. Isolators at the klystron output and at each cavity arm prevent possibility of damage due to full power reflection at the cavities. The RF scheme is shown in Figure 2.

LLRF control The LLRF system for the third harmonic is a modified version of the standard 1.3 GHz system used in the rest of the linac [13]. The 3.9 GHz reference is based on a dielectric resonator oscillator (DRO) from Rupptronik

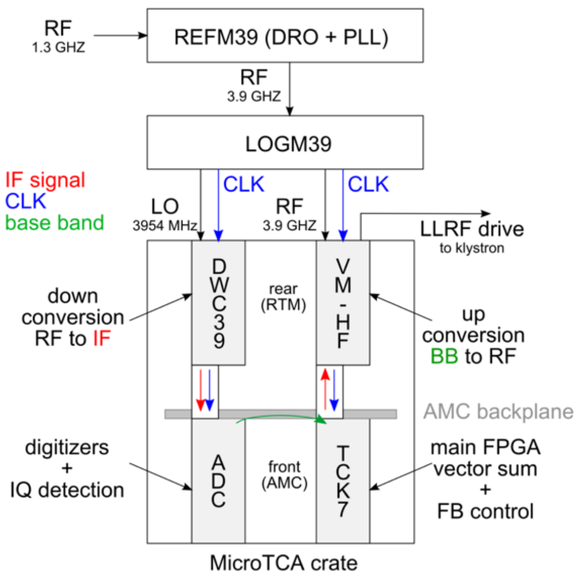

Figure 3: Scheme of the EXFEL 3.9 GHz LLRF signal flow.

locked onto the 1.3 GHz signal from the master oscillator inside the reference module (REFM39). This reference is used by the local oscillator 19″ module (LOGM39) to generate and distribute local oscillator (LO =3954 MHz), clocks (CLKs =81.25 MHz) and reference (RF = 3900 MHz) signals. Forward, reflected and transmitted signals are then down converted and digitized within a MicroTCA-based LLRF system. The 1.3 GHz down converter (DWC39) front ends have been modified to handle 3.9 GHz signals, the digitizers (ADC) are identical to the 1.3 GHz. The main feedforward and feedback computation is taking place inside the TCK7, the main FPGA board based on a Kintex 7 which is used in all 1.3 GHz LLRF systems. The in-phase and quadrature LLRF drive signal is up-converted back to 3.9 GHz using a high-frequency version of the vector modulator MicroTCA board (VM-HF). Figure 3 shows the signal flow.

System Validation Test of a Single Cavity

The characterization and technical commission of the 3.9 GHz module occurred only after its installation in the accelerator tunnel. Due to this fact, a validation test of the cavity package concept was needed before the module assembly. All subsystems under test (coupler, tuner, waveguide tuners, LLRF system) were qualified above their design performances [14].

RF COMMISSIONING EXPERIENCE

The module assembly started in July 2015 and required 14 weeks at the DESY module assembly facility in Halle III [15]. AH1 was brought to the underground injector building in late September 2015 for the installation and the start of the technical commissioning. Cooldown started on December 10th and beam transport was estabilished on December 18th.

Incoming RF Checks on Cavities

At arrival in DESY, the cavity transmission through all antennas on the fundamental passband was monitored and verified with the outgoing measurements at INFN-LASA.

RF Controls During Module Preparation

After the string assembly, the installation of the tuner and magnetic shielding was performed under frequency control from a Vector Network Analyzer (VNA), to preserve the fundamental mode frequency within approximately 100 kHz. Before the closure of the inner thermal shield, the fundamental mode rejection capability of the HOM coupler was measured and the notch filter tuned.

RF Operation of the Module in the Injector

RF operation started after reaching 2K stable conditions.

Cavity pretuning after cooldown The cavities were tuned cold in the tunnel with a VNA, to bring them close to the operation frequency (which is 200-500 kHz higher than the natural frequency at cold). A check that the tuner delivers the nominal $\approx$ 170 $\pm$10 kHz/turn was also performed. The final fine tuning was performed with the LLRF system by maximizing the cavity transmitted power and using a real-time Fast Fourier Transform (FFT) analysis.

RF Calibration The measure of the Q_L from the probe signal decay time and the computation of field level at the end of the fill time with analytical formulas for the cavity driven by the measured forward RF level provided the initial calibration.

Cavity phasing and Q_L tuning Motorized 3-stub tuners allow the alignment of all relative cavity phases for the vector sum operation and the setting of the nominal Q_L value. Beam-induced cavity gradient changes with a train of 30$\times$0.5 nC bunches allowed the determination of the relative cavity phases and the adjustment of the field calibration constants. Maps of the phase-Q_L reach as a function of the stub positions enabled to find the correct setting to achieve the nominal operation point. For three cavities, where the goal was outside of the stub tuner reach, it was sufficient to use waveguide spacers to perform the large needed phase shift and bring the operation point within the regulation reach.

Beam based calibration Beam based calibration in the dispersive sections of the injector beam line allowed to adjust the relative calibration of the A1 and AH1 modules, in order to enable the use of physics-based operational control knobs for the longitudinal phase space control.

CONCLUSION

The third harmonic section of the EXFEL accelerator was successfully commissioned during the injector run in 2016 and is in regular operation up to its nominal performances since the start of the operation of the facility.

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