

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

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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 Å FEL 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 $\approx 180^\circ$ 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 .

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 Power¹	3.75 kW
RF source	
Type	Klystron
Max req Power for operation	≈ 50 kW
Nominal RF pulse structure	
Filling time	750 μ s
Flat-top length	550 μ s
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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¹ Without taking into account RF distribution losses in operation

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.

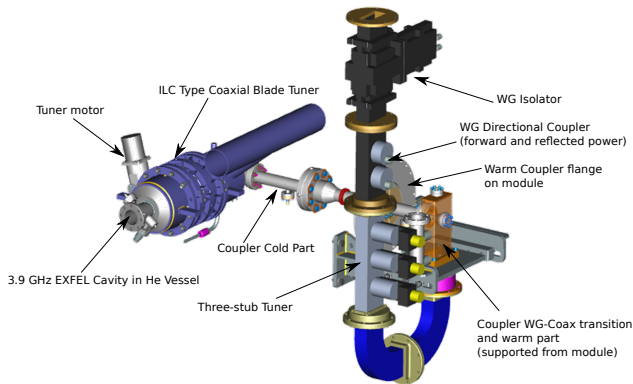


Figure 1: A cavity with all its main ancillary components.

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

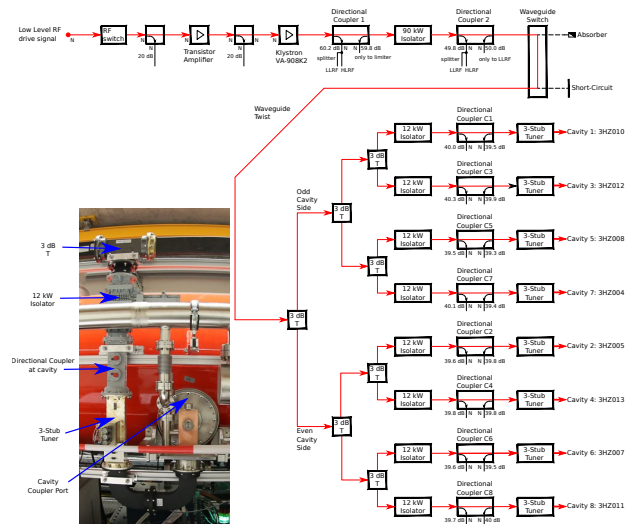


Figure 2: Power RF generation and distribution in AH1.

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 Rupprtronik

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