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THE HIGH POWER RF SYSTEM FOR THE EUROPEAN XFEL

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Abstract

The RF system for the European XFEL consists of 26 high power RF stations each capable of 10MW RF pulse power. This paper will report on the overall system layout, cover RF system components e.g. klystrons, modulators and high power RF waveguide distribution. It will also cover system modifications during construction phase and report on commissioning results.

DESCENT OF THE EUROPEAN XFEL

The European XFEL descends from the TESLA project, a linear collider with a center-of-mass-energy of 500GeV. In the early 1990s the TESLA collaboration was established and the TESLA Test Facility has been set up at DESY by the TESLA collaboration to develop all components required to construct a linear collider based on superconducting RF technology. A technical design report on the linear collider with integrated free electron laser was published in 2001 [1]. In 2006 it was decided to build the free electron laser as stand-alone facility at DESY. Construction started in 2007 and first X-rays were produced in 2017. The high power RF system components for the European XFEL have been developed to meet the requirements for the TESLA linear collider and have later been modified to meet the European XFEL demands.

The TELSA linear collider proposal served as the basis for the International Linear Collider, ILC, too. Since both, the ILC and the XFEL, descends from the TESLA linear collider, many of the high power RF systems components now in operation for the E-XFEL, might be used for ILC too.

EUROPEAN XFEL

The European XFEL produces X-rays of unprecedented properties in terms of brilliance, average brilliance, coherence, pulse duration and time structure.

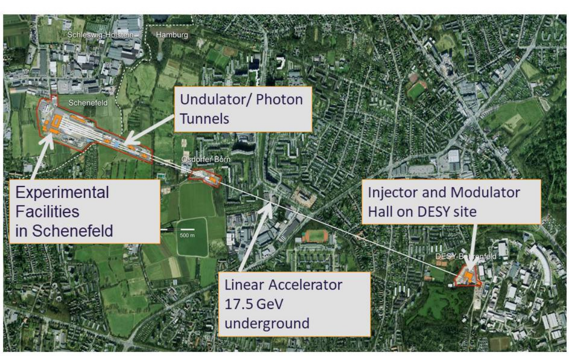

Figure 1: XFEL site.

The E-XFEL is located in Hamburg, with the injector on the DESY site, the experimental facilities in Schenefeld and the main linear accelerator in an underground tunnel in between. The E-XFEL site layout is shown in Figure 1. Electrons generated by a RF gun are accelerated in the superconducting cavities of the linac and are distributed to up to five beam lines for experiments. The total length of the facility is 3.4km. Details can be found in [2].

RF SYSTEM REQUIREMNTS

The linear accelerator of the E-XFEL is based on superconducting RF technology. Electrons are generated in a normal conducting RF gun and are accelerated in the superconducting cavities of the 1.9km long linac. The 2700 electron bunches are accelerated in 600µs long macro-pulses with a repetition rate of 10Hz up to 17.5GeV. The electron beam current is 5mA. The main linac consists of 96 cryogenic modules with 8 superconducting 9-cell Niobium-cavities each. The high power RF system (HPRF) provides RF power at 1.3GHz, at a RF pulse duration of 1.38ms with a repetition rate of 10Hz. The average accelerating gradient is 23.6MV/m.

In order to achieve this gradient 122kW per cavity are required. 32 cavities in 4 cryogenic modules are connected to one RF station. Taking into account losses and a regulation reserve 5.2MW of RF power per station are required in the main linac. The RF station for the RF gun in the injector provides 8MW up to 650µs pulse duration, the station for one single module in the injector up 1.3MW at 1.38ms. Table 1 summarizes the requirements.

Table 1: HPRF Requirements

Number of sc cavities	776
Power per cavity	122kW
Gradient at 17.5GeV	23.6MV/m
Power per 32 cavities (4 cryogenic modules)	3.9MW
Power per RF station main linac/RF gun/injector	5.2MW/8MW/1.3MW
Number of RF stations total/main linac/injector	26/24/2
RF pulse duration main linac/RF gun/injector	1.38ms/0.65ms/1.38ms
Repetition rate	10Hz

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RF SYSTEM LAYOUT

Figure 2 shows the layout of one RF station. The high power klystron produces the RF power which is distributed by a RF waveguide distribution system to the superconducting cavities. The HV voltage pulses required by the klystron are generated by a HV pulse modulator which is connected to a pulse transformer by pulse cables. Several racks house additional auxiliary power supplies, interlocks, controls and water cooling. With exception of the modulator, which is installed in a separate hall on the DESY site near the injector, all other components are installed under the cryogenic modules of the main linac which is shown in Figure 3.

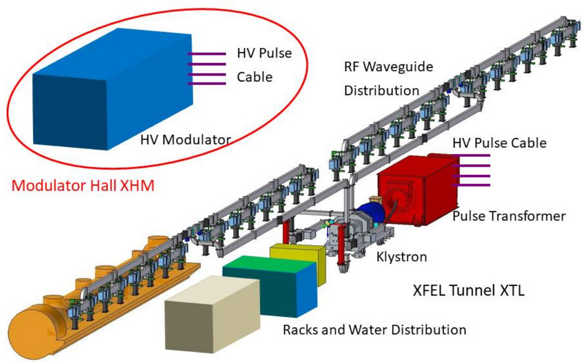

Figure 2: RF station layout.

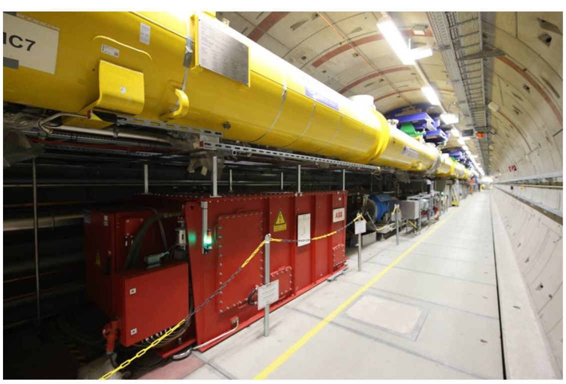

Figure 3: RF station in the E-XFEL tunnel.

The RF stations for the injector are an exception. These are located on the 3rd underground floor in the injector building. Figure 4 shows the RF stations in the injector. The RF power for the RF gun and a one single cryogenic module is transferred by long waveguides in the shafts between the floors to the RF gun and one single module.

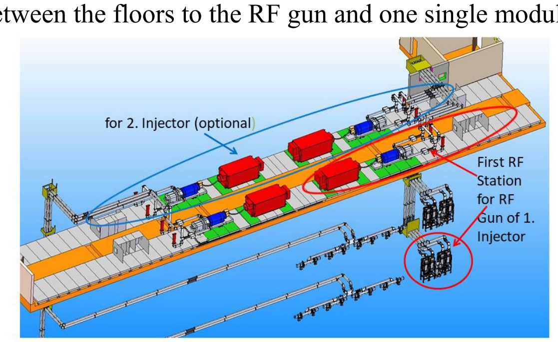

Figure 4: RF stations for injector.

RF SYSTEM COMPONENTS

The main components for the HPRF are klystrons, modulators and RF waveguide distributions, which will be covered in the next subsections. Auxiliary power supplies are standard of the shelves components which are installed under the cryogenic modules in electronic racks which are water-cooled and are covered by concrete blocks for radiation protection. In addition an interlock system based on FPGAs allows for protection of the RF system components, control and monitoring of signals.

Klystrons

Multi beam klystrons (MBK) have been selected as RF power sources. Table 2 shows the requirements of the klystron. The original requirement was for the TESLA linear collider. Therefore 10MW of pulsed RF power was specified. A single beam 10 MW klystron with an efficiency of about 65% would require a cathode high voltage of about 250kV. Reliable operation at this voltage level at long pulse duration of 1.5ms would be difficult to achieve. In addition the high voltage modulators would be expensive.

Table 2: Multi Beam Klystron Requirements

RF Frequency:	1.3GHz
Cathode Voltage:	<120kV
Beam Current:	<140A
µperveance:	<3.5
Max. RF Peak Power:	10MW
RF Pulse Duration:	1.5ms
Repetition Rate:	10Hz
RF Average Power:	150kW
Efficiency	65%
Gain	48dB
Length	ca. 2.5m
Lifetime goal	>40000h

Figure 5: Multi beam klystrons for the E-XFEL.

The use of 6 or 7 beams in one klystron envelope lowers the voltage level to about 120kV. Three vendors developed multi beam klystrons meeting the requirements. Finally two were selected for the European XFEL. Figure 5 shows the multi beam klystrons for the E-XFEL made by THALES and TOSHIBA. Both klystrons are mounted horizontally on girders, which allow easy installation in the accelerator tunnel, have common interface for easy change between klystrons of different vendors and are connected by a connection module with filament transformer, voltage and current measurement

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and for quick HV connection to the pulse transformer. 26 klystrons are installed, 6 klystrons made by TOSHIBA and 20 by THALES. Figure 6 shows the output power generated by the klystrons in the different RF stations. Besides the klystrons for the RF gun and the first injector module, some klystrons produce more power than the expected 5.2MW to achieve the average gradient in the cavities. This is due to the fact that some cryogenic modules are equipped with modules which can be operated at higher gradient. After installation at first operation some klystron showed some klystron gun or cavity arcs. However, the number decreased during operation and is much below specified number. More details can be found in [3].

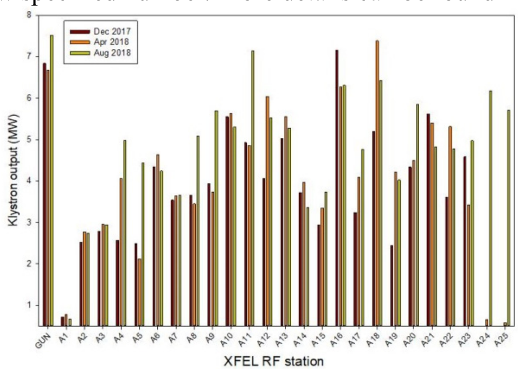


Figure 6: Klystron RF output power for different RF stations at different dates.

Modulators

Pulse step modulators located in a separate hall produce HV pulses at the 10kV level at 1.6kA. The rectangular pulses are transmitted by tri-axial pulse cables to the 1:12 pulse transformers near the klystrons in the tunnel. Each modulator is connected to a pulse transformer by 4 cables of maximum 1.6km length. The modulator is a commercial product made by Ampegon and is shown in Figure 7. It consists of 24 HV modules, which are stacked and which together provide the 10kV HV pulses. The modulator requirements are summarized in table 3. More details can be found in [4].

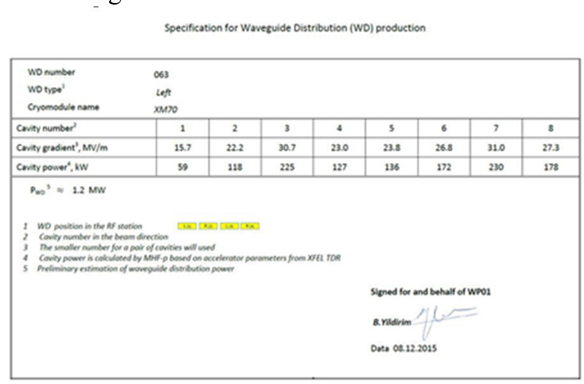
Figure 7: HV modulator.

Table 3: HV Modulator Requirements

	typical	max.
Modulator Pulse Voltage	9.6kV	12kV
Modulator Pulse Current	1.62kA	1.8kA
Klystron Gun Voltage	115kV	132kV
Klystron Gun Current	135A	150A
High Voltage Pulse Duration (70% to 70%)	1.57ms	1.7ms
High Voltage Rise and Fall Time (0 to 99%)	0.15ms	0.2ms
High Voltage Flat Top (99% to 99%)	1.37ms	1.5ms
Pulse Flatness during Flat Top	±0.2%	±0.3%
Pulse-to-Pulse Voltage fluctuation	±0.1%	±0.1%
Energy Deposit in Klystron in Case of Gun Spark	<20J	20J
Pulse Repetition Rate	10Hz	10Hz
Pulse Transformer Ratio	1 :12	1 :12

RF Waveguide Distribution

The RF distribution is made by WR650 waveguide. It distributes the power to the cavities and protects the klystron from reflected power by means of circulators with integrated loads. The first layout was designed to provide equal RF power to the cavities. During production of the cryogenic modules it turned out that cavities had different performance in maximum gradient, some below the average gradient of 23.6MV/m. An example of a test result is shown in Figure 8.


Specification for Waveguide Distribution (WD) production

WD number 063
WD type[1] Left
Cryomodule name XM70

Cavity number[2]	1	2	3	4	5	6	7	8
Cavity gradient[3], MV/m	15.7	22.2	30.7	23.0	23.8	26.8	31.0	27.3
Cavity power[4], kW	59	118	225	127	136	172	230	178

P_{WD}[5] ≈ 1.2 MW

1 WD position in the RF station
2 Cavity number in the beam direction
3 The smaller number for a pair of cavities will used
4 Cavity power is calculated by MHF-p based on accelerator parameters from XFEL TDR
5 Preliminary estimation of waveguide distribution power

Signed for and behalf of WP01

B.Yildirim

Data 08.12.2015

Figure 8: Test result of one cryogenic module.

In case of an equal power distribution, the RF station would be limited by the weakest cavity. In order to overcome this problem, the distribution was modified to adjust the power for each cavity. Figure 9 shows the distribution for one module. The adjustment is done by asymmetric

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shunt tees, between cavities, a pair of cavities and between modules. All modules have been tested and performance determined before installation. Once the results were available a specific distribution has been tailored and connected to each module. The installation and an installed module distribution can be seen in Figure 10.

After installation in the tunnel waveguide components between modules and to the klystron have been installed. Afterwards modification of power distribution is only possible between modules by change of asymmetric shunt tee between them.

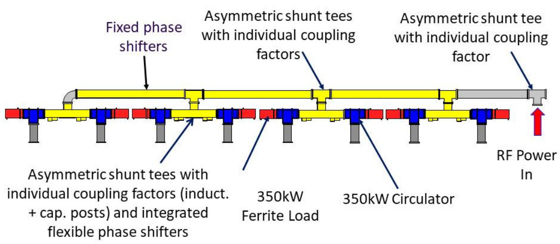

Figure 9: Module waveguide distribution.

Figure 10: Waveguide installation to module.

By this method the potentially achievable energy of the accelerator could be increased beyond 17.5GeV to 19.5GeV, whereas only 15.7GeV would be achieved when limited by the weakest cavity per module. Details can be found in [5].

During commissioning of the accelerator it was difficult to achieve the maximum energy. Some RF stations were limited by different types of commissioning problems, e.g. by waveguide arcs between modules or multipacting in couplers. These problems could be solved by change of waveguide components and RF conditioning. Another reason was that some cavities have changed performance, which caused, that not all distributions fit the new power demand. Since the module waveguide distributions are fixed only the waveguide distribution between modules and to the klystron can be adjusted. The last two RF station were commissioned in spring 2018. The accelerator finally achieved the maximum design energy of 17.5GeV in July 2018. At present it continues user operation at 14GeV.

COMMISSIONING SUMMARY

The high power RF system for the E-XFEL was developed starting in the 1990s for the TESLA linear collider. XFEL construction started in 2007 and was finished in 2016. High power RF systems components have been developed, constructed, tested and installed during this time. Commissioning and first operation of the XFEL showed minor, but up to now no severe problems with the high power RF system. This might be partly due to the fact that an extensive development and test phase has preceded and that several key components have been designed for higher performance at the linear collider. Nevertheless spare components. e. g. klystrons, subsystems for the modulators, electronics, and waveguides have been already ordered. An important modification in the future might be an adjustment of power distribution between modules connected to one RF station.

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