DESIGN AND STATUS OF THE XFEL RF SYSTEM

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Abstract

The RF system of the European XFEL under construction at present at DESY in Hamburg, Germany, consists of 27 RF stations. At a later point of time the number might be increased to 31. The RF system provides RF power at 1.3GHz for the superconducting cavities of the main linear accelerator, the cavities of the injector and the RF gun. Each station consists of a 10MW multiple beam klystron, a HV pulse modulator, HV pulse cables, a pulse transformer, an interlock system, a low level RF system, a waveguide distribution system and a number of auxiliary power supplies. This paper describes the layout of the RF system and summarizes the design and status of the main high power components.

INTRODUCTION

In the beginning of the 1990s the TESLA collaboration started to develop superconducting cavity technology and other systems required to construct a future linear collider. The Tesla Test Facility (TTF) had been set up at DESY to develop, investigate and operate the required components. Today it is operated to provide beam for the VUV free electron laser FLASH. In the year 2001 the TESLA collaboration published the technical design report of a linear collider with an integrated free electron laser facility to be built at DESY [1]. One year later a supplement to the technical design report describing a dedicated accelerator for the XFEL was added [2]. Shortly after negotiations started to build a stand alone XFEL facility as a European project at DESY. In parallel further preparation and development continued and a technical design report was published in 2006 [3]. Construction of the European XFEL was launched officially on June 5, 2007. The European XFEL will produce X-rays of unprecedented brilliance, average brilliance, coherence, pulse duration and time structure. First beam is expected for 2013.

The accelerator of the XFEL is based on superconducting RF technology. 800 superconducting cavities operated at a maximum gradient of 23.6MV/m at 1.3GHz will be used to accelerate an electron beam of 5mA up to 17.5GeV. At a later point of time the number of cavities might be increased to 928 adequate for a beam energy of 20GeV. At the end of the accelerator the high energy electron beam is injected into different beam lines in which it will be used to produce X-ray beams with a wavelength down to 0.1nm. Details of the XFEL facility can be found in the technical design report of the year 2006.

Since the future International Linear Collider will be based on superconducting cavity technology too it might make use of many of the developments done for TESLA and the XFEL.

RF SYSTEM REQUIREMENTS

The XFEL RF system provides RF power for the superconducting cavities and the RF gun of the accelerator. In order to achieve the gradient of 23.6MV/m an input power of 122kW per cavity is required. 32 cavities will be connected to one high power RF source Taken into account losses of 10% in the waveguide distribution and a regulation reserve of 15% a klystron RF output power of 5.2MW is required. The total RF pulse length is 1.37ms, of which 720µs are required for filling the cavity with RF power and 650µs for electron beam acceleration.

During the initial phase of the XFEL construction 27 stations will be installed. Later the number might be increased to 31 stations in total. Although the nominal total power demand per RF station is 5.2MW peak and 72kW average, each RF station is designed to provide RF power up to 10 MW peak and 150 kW average at 1.5ms at 10Hz. This will help to guarantee operation with high reliability at nominal XFEL condition. It will also allow operation at conditions other than nominal. It is e.g. intended to operate the accelerator and thus the RF system at higher repetition rate up to 30Hz by reducing either the RF pulse width or the RF output power at the same time. The limiting factor will be the maximum average klystron beam power. The RF system requirements are summarized in table 1. Not all maximum numbers can be achieved simultaneously at the same time.

Table 1: RF system requirements (numbers for a potential extension in brackets).

		nom	max
Cavities in main linac		800 (928)	
Peak power per cavity	[kW]	122	230
Gradient	[MV/m]	23.6	28.5
Power per 32 cavities	[MW]	3.9	8.3
Power per RF station	[MW]	5.2	10
Installed linac RF stations		25 (29)	
Active linac RF stations		23 (26)	
Installed injector RF stations		2	
RF pulse duration	[ms]	1.37	1.7
Repetition rate	[Hz]	10	30
Average klystron beam power	[kW]	153	250
Av. RF power during operation	[kW]	71	150

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LAYOUT

Each RF station comprises a number of components, which will be installed in different locations of the XFEL facility. The klystron, pulse transformer, waveguide distribution system, low level RF system, which controls shape, amplitude and phase of the RF, auxiliary power supplies for the klystron and the pulse transformer, preamplifier and an interlock and control system, which protects the station and the linac will be installed in the accelerator tunnel. The HV pulse modulator, which transforms the AC line power to pulsed HV power will be installed above ground in a dedicated modulator hall. High voltage pulse cables and additional cables for the interlock system connect the components of each station in and outside the tunnel.

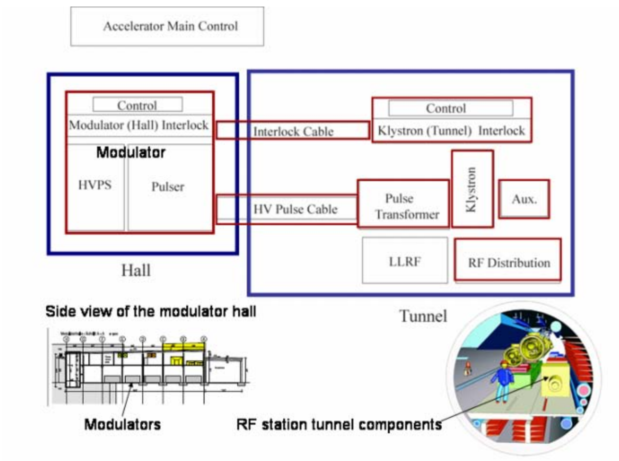

Figure 1: RF station layout.

MULTIPLE BEAM KLYSTRON

DESY awarded contracts to develop 10MW multiple beam klystron (MBK) as high power RF sources to three klystron vendors during the last years. The specification can bee seen in table 2. Multibeam klystrons have the advantage of lower klystron voltage than a conventional single beam klystron of same output power. Since the perveance of the individual beams in a multibeam klystron is low the efficiency of the klystron is high [4, 5].

Table 2: Klystron parameter.

Frequency	[GHz]	1.3
RF pulse duration	[ms]	1.5
Repetition rate	[Hz]	10
Cathode voltage	[kV]	120
Beam current	[A]	140
HV pulse duration	[ms]	1.7
Perveance	[$A/V^{3/2}$]	3.5×10^{-6}
RF peak power	[MW]	10
Efficiency	%	65

THALES Electron Devices developed the TH1801 10MW MBK and produced 6 klystrons till today [6, 7]. After initial difficulties with the first klystrons modifications were made. As a result the klystrons operate in a satisfying way. These klystrons are in use at different locations at DESY. Several thousands of operation hours exist, some of them at full power of 10MW, most at lower power, limited by the load power demands. Transfer curves are shown in figure 2. The maximum efficiency of the THALES klystron is 65% when operated on a matched load. (Mode A), it is 68% when operated on a load with VSWR of 1.2 and ideal phase (Mode B). Typically the efficiency of the different klystrons is 63%.

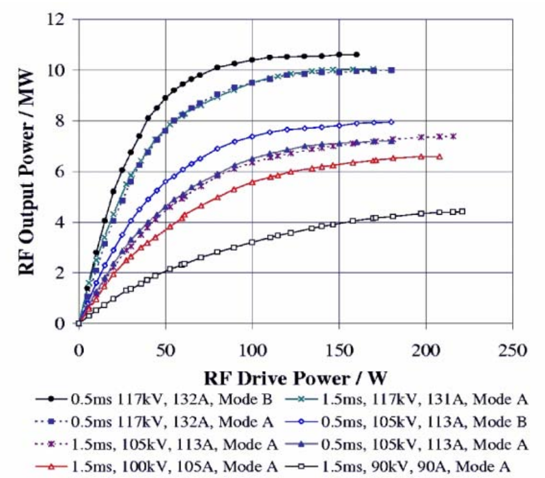

Figure 2: Transfer curves of the THALES TH1801 MBK.

CPI developed the VKL8301 MBK [8, 9]. The prototype has been tested at DESY and achieved 8.1MW at 1.3ms with an efficiency of 53.5%.

TOSHIBA Electron Tube Devices developed the E3736 [10, 11]. It was operated in the year 2006 for a longer period at DESY and achieved 10.4MW at 1.5ms and 10Hz with an efficiency of 66%.

Figure 3: THALES TH1801, CPI VKL8301 and TOSHIBA E3736 Multibeam Klystron.

Since the klystrons have to be installed under the cryogenic modules in the accelerator tunnel DESY awarded to all three vendors of the vertical MBKs contracts to construct horizontal versions of their

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klystrons. The first horizontal klystron is expected for the second half of 2007.

MODULATOR

Modulators and pulse transformers have to supply rectangular HV pulses up to 120kV at 140A to the klystron cathode. A bouncer modulator meeting these requirements has been developed by FNAL. The basic idea is to charge a capacitor bank to the 10kV level. By closing a semiconductor switch current starts to flow via the primary side of 1:12 pulse transformer. In order to compensate the droop during the discharge of the capacitor the bouncer circuit is triggered and starts to oscillate. The linear part of the oscillation is used to compensate the droop of the main capacitor. At the end of the pulse, when the main capacitor is discharged by 19%, the main switch opens and terminates the pulse [12, 13, 14].

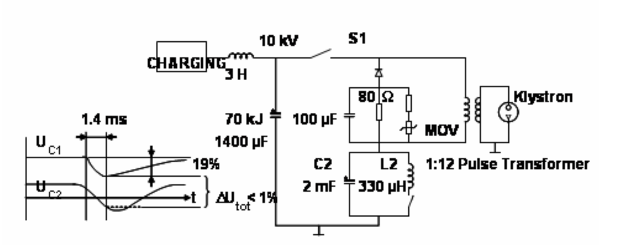

Figure 4: Schematic circuit diagram of the modulator.

Table 3: Modulator maximum parameter.

Modulator pulse voltage / Pulse transformer primary voltage	[kV]	11
Modulator pulse current voltage / Pulse transformer primary current	[kA]	1.8
Pulse transformer secondary voltage / Klystron gun voltage	[kV]	132
Pulse transformer secondary current / Klystron gun current	[A]	150
High voltage pulse duration (70% to 70%)	[ms]	1.7
High voltage rise and fall time (0 to 99%)	[ms]	0.2
High voltage flat top (99% to 99%)	[ms]	1.5
Pulse flatness during flat top	[%]	±0.5
Pulse-to-pulse voltage fluctuation	[%]	±0.5
Energy deposit in klystron in case of gun spark	[J]	20
Pulse repetition rate	[Hz]	10 (30)
Pulse transformer ratio		1:12

Three systems were supplied by FNAL to the Tesla Test Facility at DESY since 1994 and are still in operation at FLASH. Industrial companies (FUG, Poynting, ABB, PPT) constructed and produced subunits for additional bouncer modulators based on this design [15, 16]. These units have been assembled at DESY. At present 11 bouncer modulators are in operation, 3 made by FNAL and 8 in cooperation with industry. In order to qualify more vendors DESY awarded contracts to two additional companies to manufacture prototype modulators for the XFEL. One will be a bouncer type system manufactured by Imtech/Vonk, the other a pulse step modulator (PSM) by Thomson Broadcast and Multimedia. These systems will be tested in 2008 at the modulator test stand at DESY, location Zeuthen.

PULSE CABLE

Since the modulators and pulse transformers will be installed in different locations the high voltage pulses of the order of 10kV and 1.6kA must be transmitted by HV pulses cables, which are up to 1.5km long. Since the impedance of the klystron load at the primary side of the transformer is 6Ω four triaxial 25Ω cables will be used for each RF station. The conductor cross section of each cable is $75mm^2$, the diameter is 30mm. XLPE will be used as dielectric material. At the transformer the cables will be terminated by a matching network made of a capacitor of the order of 1µF and a resistor of about 10Ω [17].

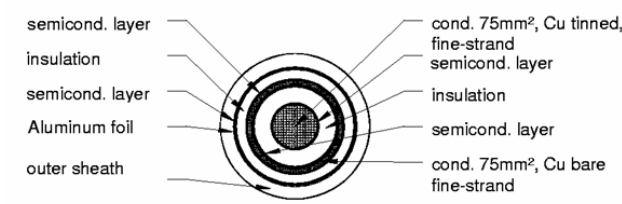

Figure 5: Cross section of the pulse cable.

Tests of a 1.5km long cable have been carried out connecting one modulator with one pulse transformer at FLASH. A THALES TH2104C 5MW klystron has been used as load.

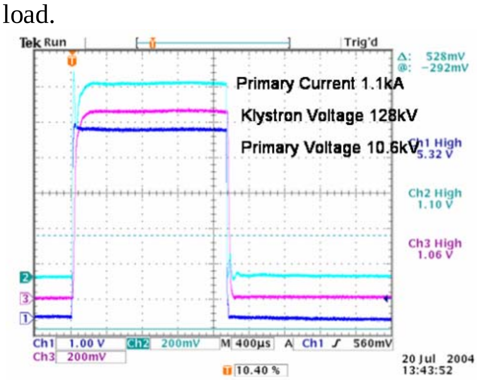

Figure 6: Waveforms measured with pulse cable between modulator and pulse transformer.

Although transmission of pulses was successful, it turned out that modifications of the modulator will be required to reduce EMI. A new modulator has been modified, installed in another hall on the DESY site and connected by 1.5km long pulse cables to the pulse transformer at FLASH. Tests are foreseen for the next FLASH run period starting in summer 2007.

WAVEGUIDE DISTRIBUTION

32 cavities in 4 cryomodules are connected to the 2 output waveguides of a 10MW multibeam klystron. Many new and sophisticated WR650 waveguide components e.g. circulators, loads, tuners, couplers have been developed within the last years. At FLASH linear distributions are installed and a similar scheme could also be used for the XFEL as shown in figure 7.

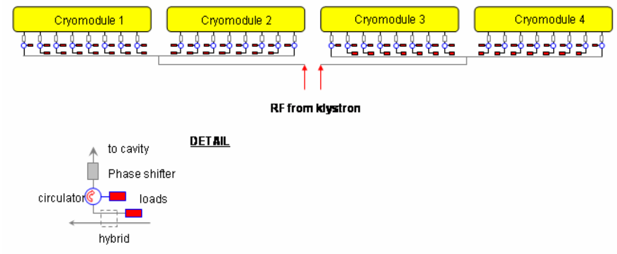

Figure 7: FLASH like waveguide distribution.

Directional hybrid couplers branch off equal amounts of power for each cavity. Since the superconducting cavity has a loaded quality factor of $Q_{load} \approx 4.6\times10^6$ almost all RF power is reflected back from the cavity during the filling time of 720 µs and also at the end of the RF pulse. Therefore circulators are in front of each cavity. Tuners allow adjustment of phase and loaded Q [18, 19].

Although this scheme is well established a new scheme will be used at the XFEL. Instead of a pure linear scheme for each cryomodule a combination of a linear and a tree like system will be installed.

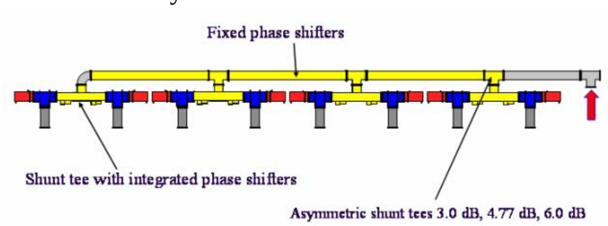

Figure 8: New combined waveguide distribution.

In the linear part asymmetric shunt tees branch off the power for a binary, tree like cell. The exact amount of power can be adjusted by changing the positions of tuning posts in the asymmetric shunt tees. Each binary cell consists of circulators with integrated loads for protection of the klystron from reflected power and a symmetric shunt tee with integrated phase shifters for power division and phase adjustment. The loaded Q of the cavity must be adjusted by the cavity input coupler. The advantage of the new scheme is that it consists of less components and that it can be setup in a two-dimensional way whereas the FLASH like system is three-dimensional system. Therefore the new scheme saves space, weight and costs. The new scheme is already tested on the waveguide test stand at DESY and is now being installed at FLASH for operation with beam.

INTERLOCK

The interlock system of each RF station consists of two parts which are located in the modulator or in an electronic rack in the accelerator tunnel near the klystron respectively. It protects accelerator and RF station in case of malfunction.

Since the modulator interlock is an integral part of the modulator it is supplied by the modulator manufacturer. It has an interface to the accelerator main control system and is connected via glass fibers to the RF interlock in the accelerator tunnel.

The RF interlock in the accelerator tunnel is based on programmable logic devices. Therefore its logic can easily be modified. Today FPGAs process signals within µs and therefore react fast enough to protect the accelerator or the RF station. Fast interlock signals are transmitted to the modulator interlock by the glass fibers connecting both parts. Communication of the RF interlock in the tunnel with the accelerator main control is accomplished by an ethernet connection. The interlock allows measuring and diagnosing different parameters of the RF station. All information is accessible for the accelerator main control. Trip levels can be adjusted remote controlled. The racks housing all electronic devices in the tunnel will be shielded by lead.

An RF interlock system meeting the XFEL requirements has been developed. It is in use at FLASH and at different test stands for the XFEL. It has been improved over the last years. Today the 3rd generation is in use.

More detailed information on the interlock can be found in [20, 21, 22].

ADDITIONAL COMPONENTS

Several other power supplies and a RF preamplifier will be installed in shielded electronic racks in the accelerator tunnel too.

The additional power supplies will be standard of the shelves supplies. They are required for the klystron solenoid, for the klystron filament, the klystron vacuum pumps and the pulse transformer core bias.

The preamplifier has to amplify the LLRF output signal of 1dBm to the required input power level of the klystron. A semiconductor amplifier with a 1dB compression point at 650W will be used. Although the gain of the klystron is 48dB and the required drive power is less than 200W at nominal operation conditions, more power is required if the klystron is operated at lower voltage, e.g. if it is operated at higher repetition rate than nominal but at the same average power.

LOW LEVEL RF SYSTEM

The low level RF system is a digital system which allows controlling the RF parameters. Detailed information on this system has been published on different occasions. See e.g. [23].

SUMMARY

All components for the XFEL RF system have been designed and constructed during the last years. Modifications of some components allowing the installation in the accelerator tunnel and qualification of additional vendors are being continued. Determined by the XFEL schedule first RF system components must be delivered early 2009 for the various component test facilities. The components for the XFEL injector must be received only shortly after. However delivery of the major amount of all components is planned for 2010 to 2012.

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