CONCEPTUAL LAYOUT OF THE EUROPEAN X-FEL LINEAR ACCELERATOR CRYOGENIC SUPPLY

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Abstract

As a source for the European X-ray Free Electron Laser (European X-FEL project) at DESY a superconducting linear accelerator will deliver a pulsed electron beam of about 20-GeV. A conceptual layout for the cryogenic supply of the linac is presented. The linac will consist of about 1000 superconducting niobium 1.3-GHz 9-cell cavities, which will be cooled in a liquid-helium bath at a temperature of 2-K. In addition to the main linac of about 1.6-km length, two injector sections have to be supplied separately by means of helium refrigerators and the related helium distribution system.

THE EUROPEAN X-FEL PROJECT

In order to reach the X-ray region (0.1 nm) by means of a Free Electron Laser the European X-FEL-Project is presently under development at DESY [1].

A new superconducting linear accelerator will supply a pulsed electron beam of 20-GeV for the operation of the FEL. The TESLA technology will be applied for the linear accelerator:

The X-FEL linear accelerator will consist of about 1000 superconducting niobium 1.3-GHz 9-cell cavities, which will be cooled in a liquid-helium bath at a temperature of 2-K. Eight cavities and one superconducting magnet package will be assembled in cryomodules of 12.2-m length. The 2-K cryostat will be protected against heat radiation by means of two thermal shields cooled to temperatures of 5-K to 8-K and 40-K to 80-K respectively. A cross-section of a cryomodule is shown in Fig. 1.

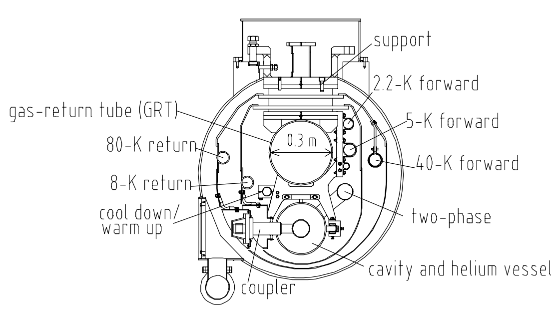

Figure 1: A cross-section of a XFEL-cryomodule.

CRYOGENICS

The XFEL-linac consists of two parallel injector cryomodules, a booster section, a bunch compressor section and the main linac cryomodules. The cryogenic supply of the two parallel injector cyromodules is separated from the supply of the booster and the cryomodules in the main tunnel. From the cryogenic point of view the four booster cryomodules including 3rd harmonic cavities and the main linac cryomodules are treated as one unit of about 1.6-km length. The 2-K cryogenic supplies of the main linac unit will be separated in 10 parallel cryogenic sections each of 12 cryomodules. These sections are called ‘strings.’ Including the booster cryomodules, 108 cryomodules of the main linac unit will be normally used for beam acceleration. Twelve spare cryomodules are kept in stand-by.

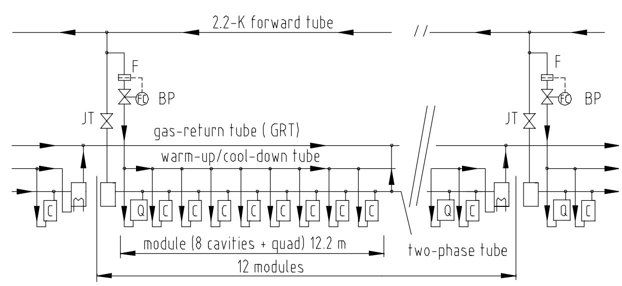

Figure 2 : A simplified scheme of the equipment and instrumentation of a XFEL-linac cryogenic string, which consists of 12 cryomodules, is shown. ‘Q’ corresponds to a superconducting magnet package.

The strings are separated by string connection boxes. Each box contains a Joule-Thomson valve (JT) for the steady-state operation and a bypass valve (BP) for the cool-down/warm-up. The JT-valves are supplied with helium at a temperature of 2.2-K and a pressure of 0.12 MPa by means of the 2.2-K forward tube (see Fig.1 and Fig.2). Here the helium is expanded to 0.0031-MPa into the two-phase tube and the individual helium vessels of the cavities are filled with liquid helium at 2-K. The helium vapour is directed back to the refrigerator by means of the gas return tube (GRT, see Fig.1). The string connection boxes are equipped with a vacuum barrier, which separates the insulation vacuum of the strings. The GRT as well as the supply and return tubes of the thermal shields will not be separated in string sections. At the end of each cryomodule the two-phase tube is connected to the GRT. The first string of the main linac unit is sub-divided by a bunch compressor section of 120 m length. This warm section separates the first four booster cryomodules from the main linac cyromodules. The bunch compressor section is bridged by a bypass transfer line (BCBTL), which contains all cryogenic process tubes. Inside the BCBTL the process tube diameters can not be reduced to smaller sizes, if unacceptable large helium flow pressure drops shall be avoided. The large GRT diameter and the corresponding large diameter of the vacuum tube of the BCBTL will occupy a significant amount of space in the tunnel and at the connections to the adjacent cryomodules in particular.

Cryogenic Loads

Table 1 shows the static and dynamic losses of one cryomodule. In addition to the initial design operation of the linac at 20-GeV beam energy, the cryogenic supply has to be prepared for a wide range of operation parameters, which might exceed the loads given in table 1. The cryogenic capacities of one TESLA-Model-Refrigerator (TMR) [2] are assumed here as a reasonable limit for the design of the X-FEL-linac facilities (see table 2). The overall loads for the 20 GeV design as well as the loads for a fictive set of parameters, which correspond to the 2-K cooling capacities of a TMR are also summarized in table 2. In order to compare the different requirements and capacities at different temperature levels, the corresponding 4.5-K cooling capacity equivalents have been added to table 2. Also estimates for the primary power consumption are shown.

Table 1: The cryogenic loads of one XFEL-cryomodule containing 8 cavities and one quadrupole package at 2-K. The dynamic loads are calculated for an accelerating field of E_{acc} = 23.5 MV/m, a macro pulse of 1.35 ms and a pulse repetition rate of 10 Hz at an unloaded RF-quality factor of $Q_0 = 1*10^{10}$ corresponding to a beam energy of 20 GeV for the linac

cooling circuit	static load [W]	dynamic load [W]	sum of loads [W]
2 K	1.44	8.75	10.19
5-8 K	8.64	5.70	14.34
40-80 K	70	117	187

Table 2 : The overall cryogenic loads for the XFEL linear accelerator. The loads include a design factor of 1.5 . The loads in the 27 GeV column correspond to a fictive set of parameters for the linac, which come close to the 2 K capacities of the TMR (Eacc= 31.2 MV/m, 10Hz, $Q_0 = 0.5*10^{10}$). The cryogenic loads of the cryogenic distribution system are also included. A conversion factor of 3.5 is applied to the 2 K loads in order to estimate the 4.5 K equivalent capacities with reference to the TMR coefficients of performance (COP) [2]

cooling circuit	static loads linac	20 GeV linac	27 GeV linac	TMR	one HERA refrig.
2 K load [W]	500	1893	4253	4253	
2 K mass flow [kg/s]	0.025	0.089	0.199	0.199	
5-8 K load [W]	2042	2964	3320	7465	
5-8 K mass flow [kg/s]	0.073	0.105	0.118	0.250	
40-80 K load [W]	17637	36534	55230	80788	20420
40-80 K mass flow [kg/s]	0.084	0.173	0.262	0.383	
4.5 K equivalent [W]	3800	9590	18206	22350	8400
electrical power [MW]	0.94	2.23	4.00	5.13	2.68

Overall Structure of the Cryogenic Supply

The overall structure of the cryogenic supply is shown in fig. 3. The refrigeration is separated in two sections: one (or more) helium refrigerators supply the cooling capacities from room temperature to 40-K and 5-K respectively. The 2-K helium circuit is supplied by a separate set of cold compressors and low temperature heat exchangers, which are connected to a distribution box. The distribution box branches the different helium circuits coming from one (or more) refrigerators to the injectors and the main linac. For the independent supply of the injectors an additional valve box is required, which splits the helium flows to the individual feed-boxes of the injectors. The different cryogenic components are connected by multiple tubes helium transfer lines. The cryogenic equipment of the main linac consists of a feed-cap, an end-cap, the string connection boxes and BCBTL. The BCBTL is connected to the adjacent cryomodules by means of feed-caps. One of these feed-caps acts also as an additional string connection box.

Refrigerator Options

With reference to the experience with other large superconducting accelerator facilities like HERA or the VUV-FEL-linac at the TESLA test facility, it is expected that the cryogenic supply of the XFEL-linac has to be maintained across a period in the order of several years without any major shut-down of the cryogenic plant. The availability should exceed 99.7 % (utilities excluded). A new designed and constructed ‘state-of-the-art’ cryogenic plant could deliver the cooling capacities at the different temperature levels for the XFEL-linac (see table 2) in a most effective and straightforward way, following the concepts of the TMR [2]. A new cryogenic refrigerator will consist of a cold box, a multi-stage screw compressor system and the utilities. Compared to the HERA refrigerators about 17 – 41 % of primary power could be saved by means of a ‘state-of-the-art’ facility with reference to the LHC-refrigerators at CERN or the TESLA concepts [2] respectively. According to an internal study [3] two modificated HERA refrigerators could also deliver the requested final cooling capacities for the X-FEL linac, which are shown in Table 2. The HERA cryogenic plant consists of three independent refrigerators. The capacities on one HERA refrigerator are given in table 2. Two of these refrigerators will supply the HERA accelerator until the end of the operation in the year 2007. One of the refrigerators will be used for the supply of the VUV-FEL linac at the TESLA test facility and the X-FEL-accelerator module test facility beyond the year 2007. Already for the initial supply of the 20 GeV linac significant up-grades would be required for the HERA-refrigerators: one cold box could supply the main part of the 40/80-K cooling capacity, the complete 5-K shield cooling circuit and the cool down of the 2-K helium mass flow from 16-K to 5-K. The second cold box could cool down the 2-K helium flow from 300-K to 16-K and support the 40/80-K circuit.

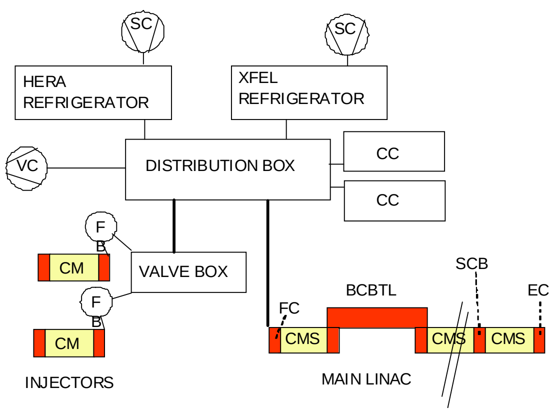

Figure 3: Block diagram of the XFEL-cryogenic supply. SC = screw compressors, VC = vacuum compressors, CC = cold compressors, F = feed box, FC = feed cap, SCB = string connection box, EC = end cap, BCBTL = bunch compressor bypass transfer line, CM = cryomodule, CMS = cryomodules.

This operation of the HERA cold boxes would require modifications of the internal tubing of the cold boxes and the installation of an additional turbine in each of the cold boxes. Other turbines have to be replaced by machines of more capacities. If the analysis is restricted only to the modifications in the cold boxes, a significant amount of investment cost could be saved compared to the procurement of a new refrigerator. On the other hand, the core of the HERA plant will have an age of about 26 years when the operation of the XFEL-linac will be started in 2012 and the highest possible availability will be requested for at least another 15 years of operation. Therefore several components will have to be replaced in addition to the cold box modifications. Some of these components are listed in table 3. As a consequence, the use of the HERA cryogenic plant will imply the risks of ‘hidden’ investments in addition to the obvious modifications, including the risks of a critical supply of spare parts for expired equipment. The overall efficiency will be lower than for a new ‘state-of-the-art’ plant.

Table 3: A comparison of advantages and disadvantages in the use of the HERA cryogenic facilities for the XFEL-linac

pro	contra
lower initial investment costs	risk of ‘hidden’ investment costs
technical possible	critical supply of spare parts
	replacement of screw compressor oil cooling systems
	replacement of control I/O
	replacement of valve actuators
	modifications of warm gas distribution systems
	complicated operation of 2 parallel cold boxes, mixing of helium across the CBs
	lower efficiency
	risk of lower availability
	interferences with the operation of the VUV-FEL linac and the accelerator module test facility

CONCLUSIONS

For the time being, a new ‘state-of-the-art’ refrigerator is considered for the cryogenic supply of the XFEL-linac, according to the concepts of the TMR. In a first step, only about half of the compressor capacity of the TMR will be installed in order to serve the requests for the 20-GeV X-FEL-linac (see table 2). All the other cryogenic equipment will be sized for the final maximum cryogenic capacities and helium mass flows of a TMR.

The HERA cryogenic plant can be used as a back-up system and can be linked to the X-FEL- distribution box as shown in Fig. 3 with only minor modifications. As soon as the tests of the XFEL-cryomodules in the accelerator module test facity will be finished, warm vacuum compressors from the test facility could also be connected to the distribution box. By means of one HERA refrigerator and the vacuum compressors parts the XFEL-linac and the injectors can be commissioned independently from the commissioning of the new XFEL-refrigerator. In addition, one HERA refrigerator could supply the cooling capacities for the static cryogenic loads of the XFEL-linac during shut-down periods of the new XFEL-refrigerator.

REFERENCES

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