

The access halls and shafts are used for personal access and for material transport. They receive the cables, water pipes and the air ducts. The access via staircases or elevators is separated from the shaft. In case of smoke or a fire they are ventilated with overpressure to keep the escape routes smoke free. The shaft and the tunnel itself are separated by a partitioning wall.

The experimental hall XHEXP1 is equipped with nine air conditioner units and six smoke extractors. The heating, ventilation and air conditioning systems are located in a separate building near the hall. This minimizes body and ground vibration from the fans near the experimental areas. An underground channel connects this building with the experimental hall. The air channels inside the hall are located under the ceiling and above the crane. Air nozzles distribute the air inside the hall. The temperature requirements are moderate but the volume of the hall determines the large number of units and requires big channel cross sections. The experimental hatches have their own air conditioning or ventilation. They take the air from the ambient air of the hall.

In case of smoke or a fire alarm, the smoke extractors are activated. They remove the smoke accumulating at the ceiling and blow it outside, above the roof of the office building. Fans blow outside air into the hall in order to keep the floor and the escape routes smoke free.

Table 7.2.3 lists the specific location of the heating, ventilation and air conditioning (HVAC) systems for selected buildings of the XFEL facility.

### 7.2.5 Cryogenics

In general, the concepts for the cryogenic supply, which were developed for the superconducting TESLA linear collider [1], will be applied for the XFEL linear accelerator [2,3,4]. These concepts have been validated during long-term runs of the TTF1 and FLASH linacs.

The XFEL linear accelerator will consist of 944 superconducting-niobium 1.3 GHz 9 cell cavities, which will be cooled in a liquid-helium bath at a temperature of 2 K, to achieve a cavity quality factor  $Q_0=10^{10}$  at an accelerating gradient of 23.6 MV/m. A helium bath cooling at 2 K will make use of the helium II heat conduction properties and is a technically safe and economically reasonable choice [5]. Eight cavities and one superconducting magnet package will be assembled in cryomodules of about 12.2 m length. The 2-K cryostat will be protected against heat radiation by means of two thermal shields cooled to temperatures from 5 K to 8 K and from 40 K to 80 K, respectively (for details see section 4.2.2.4).

The cryogenic supply of the injector cryomodules is separated from the supply of the cryomodules in the main tunnel. From the cryogenic point of view the cryomodules, in the low-energy section (separated by bunch compressors), the third harmonic (3.9 GHz) system and the main linac cryomodules, are treated as one unit of about 1.7 km length. The 2-K cryogenic supply of the main linac will be separated in parallel cryogenic sections of 12 cryomodules each. These sections are called ‘strings.’ The string sections are connected by string connection boxes (SCB).

The cryogenic supply of the linac has to be maintained continuously 24h per day/ 7 days per week for run periods in the order of 2-3 years without scheduled breaks or shut-down of the cryogenic system at an availability in the order of 99% or better.

In addition to the linac cryogenics, a large cryomodule test facility (AMTF) for serial production tests of all XFEL superconducting RF-cavities and cryomodules has to be operated during the series production of the linac components (see section 7.2.6). Also the helium

supply for the TESLA test facility (TTF) and the FLASH linac has to be maintained in parallel to the operation of the XFEL facilities. As a consequence, the new XFEL cryogenic installations have to be integrated into the already existing cryogenic infrastructures at DESY, consisting of the HERA and the TTF cryogenic plants. These detailed requirements have been defined in [3].

### 7.2.5.1 Cryogenic Components of the Linac

Figure 7.2.3 summarizes the cryogenic components of the linac: 116 cryomodules of the main linac, two 3.9 GHz cryomodules, 11 valve-boxes of the SCB type, 2 bunch compressor sections and 3 end boxes (connection boxes without valves) will be installed in the main tunnel. The design of the XFEL cryomodules is based on the latest step in the development of the TTF cryomodules (see section 4.2.2.4) In addition to the cavities, a superconducting magnet package is cooled by the 2-K helium circuit (for details see section 4.2.2.5). Two injectors, consisting of one cryomodule each, have to be supplied separate from the main linac as well as from each other for the final installation of the XFEL-linac. For the start of the project, only one injector will be installed, but the helium distribution system will be already prepared for the integration of the second injector. In addition, the distribution system will allow the exchange of the cryomodule of one injector during the operation of the main linac and the second injector.

A new XFEL refrigerator, suited for the demands of the XFEL linac will be connected to a main distribution box. One HERA refrigerator will also be connected to the distribution box to serve as a limited capacity back-up. The distribution box manifolds the different cryogenic circuits to the main linac and to an injector valve-box. A set of multiple-staged cold-compressors will be attached to the distribution box. The injector valve-box branches to individual feed-boxes of the injector cryomodules.

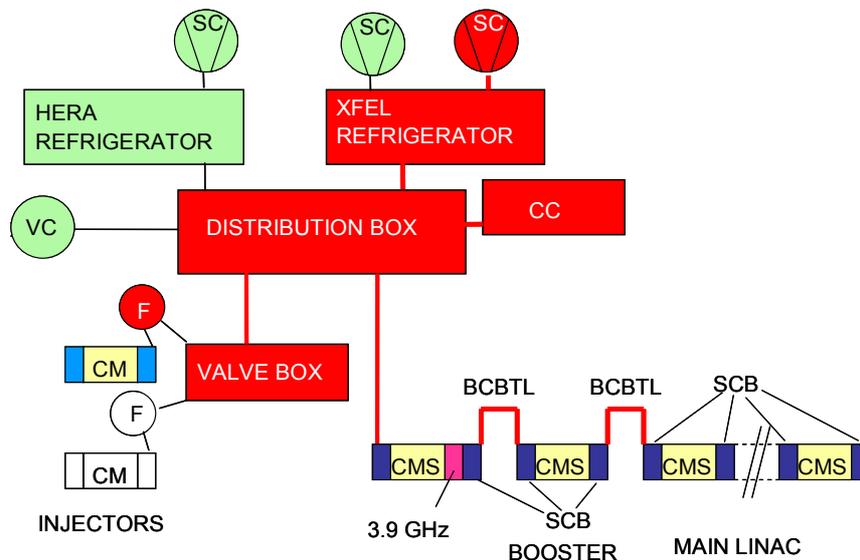


Figure 7.2.3: The cryogenic components of the XFEL linac. SC= screw compressor, CC=cold compressor, VC= warm vacuum compressor, F=feed box, CM= cryomodule, CMS= cryomodules in a string, BCBTL= bunch compressor bypass transfer-line, SCB= string connection box. Colour code: red = main installations, light green = redundant installations, general coloured = installations at the start of the XFEL-linac operation.

The ‘regular’ arrangement of cryogenic strings is disturbed at the booster- and bunch-compressor sections. At the bunch-compressor sections the warm linac components have to be by-passed by transfer lines of 68 m and 92 m length, respectively. The transfer lines will contain the 2.2 K forward, the 2 K gas return and the 5-8 K and 40-80 K supply and return tubes of the cryomodules.

In addition, the two-phase liquid-helium II supply of the cavities has to deal with the fact that the linac will be installed ‘laser-straight’ and not on a gravity equipotential surface. The minimum level is at about 900 m behind the start of the XTL tunnel and approximately 5 cm lower than the maximum level at the beginning of the linac. The string connection boxes, containing - among other things - the Joule-Thomson valves (JT-valves) for the 2-K liquid-helium supply and warm-up/cool-down bypass valves (BP-valves), will be installed in a way that only liquid-helium downhill flow will result. The arrangement also avoids two-phase liquid-helium flow in the bunch-compressor bypass transfer-line sections (BCBTL). As a result, the BCBTLs can be installed at the top or the bottom of the warm bunch compressor components.

### 7.2.5.2 Cryogenic Operation and Control

The superconducting cavities and magnet packages can be operated as long as the cavity vessels and magnet cryostats are filled sufficiently with liquid helium at a temperature of 2 K, corresponding to a helium vapour pressure of about 31 mbar. As a consequence, the control of the 2-K helium liquid level and the 2-K vapour pressure is mandatory for the safe operation of the linac.

Figure 7.2.4 shows the scheme of the cryogenic 2-K string supply. The helium vessels of the cryomodules (cavity vessels and magnet cryostats) are connected by a two phase supply tube. At the end of each string of 12 cryomodules the two-phase tube is connected to a helium reservoir, equipped with a liquid level probe and a pressure sensor. During steady state operation the two-phase tube is filled with liquid to about 1/3 of the diameter. This liquid level is monitored by means of the level probe in the reservoir. Helium from the 2.2-K forward tube of the cryomodules is expanded from 1.2 bar to 31 mbar through a JT-valve in each SCB. The helium supply through the JT-valve in the two-phase supply tube of the string is regulated by the level signal in a control loop.

Thus the JT-valve reacts on any changes of the 2-K cryogenic load within the string by keeping the liquid level constant. In addition, extra cryogenic load can be generated by means of electrical heaters in the liquid reservoirs, in order to compensate for fast changes of the dynamic load. The electrical heaters will buffer the fast load changes and will give the refrigerator (in particular the cold compressors) time to adapt. A redundant unit will be installed for each liquid helium level probe and for each heater in the reservoir.

The helium vapour pressure of 31 mbar will be regulated to a variation of smaller than  $\pm 1$  mbar by the operation of the cold compressors and by means of a control valve in the 2 K return to the refrigerator.

If the 2-K helium liquid level drops below a lower limit or if the level increases above an upper limit, which could indicate cavity quenches in the string, a hardware interlock is triggered, which switches off the RF for the affected string of cryomodules and inhibits the beam injection into the linac. A trigger signal is also generated, if an increase of the pressure

in the 2-K areas is detected. (In addition, cavity quenches will be detected by the low level RF-controls independently from the cryogenic controls.)

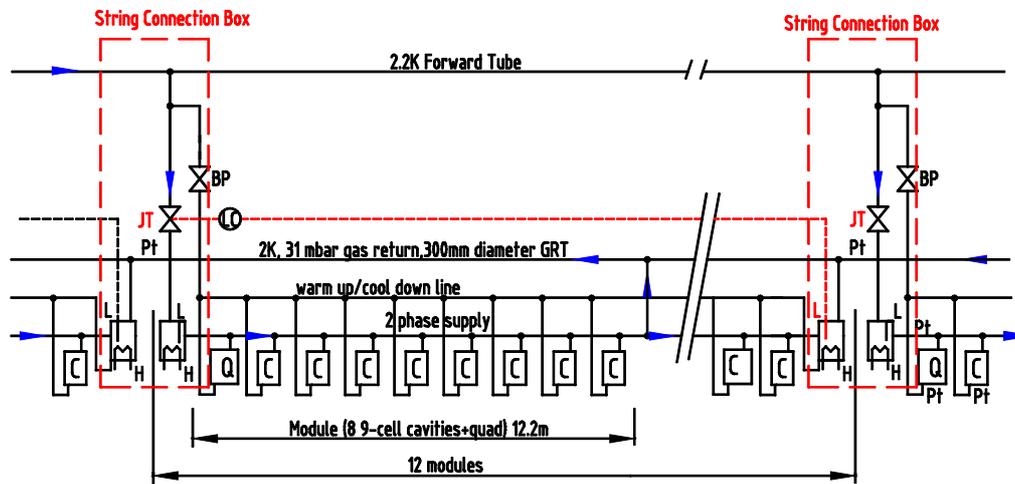


Figure 7.2.4: A simplified flow scheme of the 2 K cooling loop of a cryogenic string. JT = Joule-Thomson valve, BP = bypass valve for cool-down/warm-up, L = Level probe, H = electrical heater, C = cavity vessel, Q = quadrupole (magnet package).

### 7.2.5.3 Transient and Fault Condition Operations

The cool-down/warm-up procedures for the XFEL linac were reported in detail [6]. To avoid a misalignment of the cavities and the magnet packages the cool down/warm-up rates are limited. All cavities of the linac will be cooled-down/warmed-up in parallel in about four days. Another day will be required to fill the helium vessels with liquid. It is expected that the superconducting cavities will show no performance decrease due to hydrogen diffusion at the Niobium surface (so called ‘Q-disease’). Therefore, no fast-cooling procedures from about 150 K to 4 K are foreseen.

Precautions against loss of insulation or beam vacuum in the cryostats are derived from studies for cryo-units of the TESLA linear accelerator [7]. Some SCBs are equipped with vacuum barriers resulting in vacuum sections of about 300 m length, to limit the impact of insulation vacuum break-down. Fast acting vacuum valves at the beam tube in each SCB will prevent the venting of the cavities. The 2-K and 40-80-K cryogenic circuits will be equipped with safety relief valves at both ends of the linac. At the SCBs safety valves for the 5-8-K circuit and the 2.2-K forward tube will be installed. The safety valves in the tunnel will vent into a DN200 warm gas tube. The relief for this tube will be installed close to the cryo-hall (XHC) and the shaft XS1. Fault conditions in the cryogenic shield circuits can be tolerated to some extent, as long as the 2-K liquid helium level and the vapour pressure are kept constant. In general, we know from the FLASH linac operation that short interrupts of the cryogenic supply (e.g. trips of turbines in the cold box) will not necessarily cause an interruption of beam operation.

### 7.2.5.4 Heat Loads

Table 7.2.4 summarizes the static and dynamic heat loads of one XFEL-linac cryomodule at the nominal operating conditions of the XFEL-linac at the different temperature levels.

Table 7.2.5 summarizes the complete heat loads of the XFEL main linac, the injectors and the related helium distribution systems. The calculated values of the different heat loads have to be converted into values, which can serve as a safe basis for the design of the cryogenic plant by means of a ‘design factor’ of 1.5.

source	2K static	2K dynamic	5K-8K static	5K-8K dynamic	40K-80K static	40K-80K dynamic
RF load	0.00	6.47	0.00	0.00	0.00	0.00
radiation	0.00	0.00	1.39	0.00	32.09	0.00
supports	0.60	0.00	2.40	0.00	6.00	0.00
input coupler	0.24	0.19	2.56	0.86	18.00	15.16
HOM coupler	0.01	0.38	4.27	3.47	1.70	17.64
HOM absorber	0.15	0.06	1.50	0.25	0.00	2.50
beam tube bellows	0.00	0.32	0.00	0.00	0.00	0.00
current leads	0.20	0.10	1.80	1.44	7.80	7.56
HOM to structure cables	0.00	0.94	0.00	0.00	0.00	0.00
	0.13	0.00	1.39	0.00	5.38	0.00
sum	1.33	8.45	11.04	6.01	70.97	42.86
sum static + dynamic		9.78		17.05		113.83

Table 7.2.4: *The static and dynamic heat loads of one cryomodule consisting of eight 1.3 GHz superconducting cavities and a magnet package at an accelerating field gradient of 23.6 MV/m,  $Q_0 = 10^{10}$ , RF-repetition rate of 10 Hz and the nominal XFEL beam parameters.*

The use of the design factor is a general demand in the cryogenic community; it includes a margin for plant regulation, a buffer for transient operating conditions, a buffer for performance decreases during operation and a buffer for general design risks. As a result, the design factor adds to the general availability and reliability of the cryogenic operation of the facility.

### 7.2.5.5 Refrigerator

The XFEL-project heat loads shown in Table 7.2.5 result in the specification of the helium refrigerator plant presented in Table 7.2.6. The design of the refrigerator will follow the concepts, which were already outlined for the TESLA Model Refrigerator (TMR) [1,8]. The TMR had been designed with valuable advice from CERN and from industry. For the XFEL project the concept is adapted to the smaller loads of the XFEL linac, corresponding to a 4.4 K equivalent capacity of about 12 kW (about 22 kW for the TMR). The overall size as well as the technology of this refrigerator comes close to that of the existing refrigerators for the LHC project at CERN. As a consequence, all components of the XFEL refrigerator are already developed and available from industry.

Figure 7.2.5 shows a simplified flow scheme of the XFEL refrigerator. The refrigerator processes are almost identical to the TMR and have been reported in detail already [1,8]. Helium is compressed at ambient temperature by a two-stage screw compressor group (LP 1,2,3 and HP 1 in Figure 7.2.5) to a pressure in the 20 bar range. After re-cooling to ambient temperature and careful oil removal and drying from residual water vapour, the high pressure helium is cooled in a cascade of counter-flow heat exchangers and expansion turbines. At the 40-K and 5-K temperature levels helium flows are directed to the thermal shields of the linac cryomodules, respectively. The corresponding return flows are fed back to the refrigerator at suited temperature levels. Inside the refrigerator cold-box the helium is purified from residual air and neon and hydrogen by switchable adsorbers (AD1 and AD5) at the 80-K and 20-K temperature levels, respectively.

source	2 K static	2 K dynamic	5-8 K static	5-8 K dynamic	40-80 K static	40-80 K dynamic
main linac cryomodules	154	879	1281	625	8233	4457
3.9 GHz cryomodules	3	43	19	11	126	55
main linac distribution	322		472		2279	
injector cryomodules	3	17	22	12	142	86
injector distribution	212		208		1807	
sum	694	939	2002	648	12587	4598
design sum	1041	1409	3003	972	18880	6897
total design		2450		3975		25777

Table 7.2.5: *The heat loads of the main linac cryomodules (104 modules RF operated, 12 in cold stand by) under nominal operating conditions with reference to Table 7.2, the third harmonic cryomodules, the linac helium distribution system, two injector cryomodules and the related injector helium distribution system. The design sum results from the multiplication of the calculated loads by a factor of 1.5 ('design-factor'). The total design heat loads result from the addition of the static and dynamic design loads.*

A part of the 5-K flow is expanded from about 5 bar via a Joule-Thomson valve into a liquid reservoir (LRS in Figure 7.2.5) to about 1.2 bar, corresponding to a temperature of 4.4 K. This liquid is sub-cooled to about 2.2 K in the Joule-Thomson counter flow heat exchanger HXJT and enters the 2.2-K forward tube of the linac cryomodules. At each SCB the helium is expanded to 31 mbar via a JT-valve, resulting in a mass fraction of 91% helium II liquid at 2 K (see section 2.3.4). The heat dissipation of the linac cavities causes evaporation of the helium. The low pressure helium vapour returns to the refrigerator through the 300-mm gas return tube (GRT) in the cryomodules. After superheating to about 3.5 K in HXJT, the gas is compressed in a multiple-stage cold compression system to a pressure in the 0.5 to 0.9 bar range, depending on the operating conditions. This stream is separately warmed up to ambient in exchangers 4, 3, 2 and 1 and enters its own sub-atmospheric pressure screw compressor LP 3. The combination of cold compressors and an adjustable sub-atmospheric suction pressure of a screw compressor ('mixed compression cycle') can accommodate a large dynamic range

and is very useful during transient operation modes [9]. DESY has a long time operation experience with the screw compressors of the HERA plant running at sub-atmospheric conditions.

The design flow rates, pressures and power requirements of the refrigerator are summarized in Table 7.2.6. The coefficients of performance (COP, the inverse of the overall refrigerator efficiency) at the different temperature levels, correspond to measured values of the LHC plants [9], assuming lower efficiencies than specified for the TMR, because of the smaller plant size of the XFEL-refrigerator.

		mass flow	outlet	return
2K load	2450 W	117 g/s	1.1 bar 2.2 K	0.0275 bar 3.5 K
5-8K shield	4000 W	142 g/s	5.5 bar 5.16 K	5.4 bar 8.2 K
40-80K shield	30000 W	142 g/s	18 bar 40 K	17 bar 80 K
compressors				
LP 3		117 g/s	floating	0.5 – 0.9 bar 295 K
LP 1+2		1045 g/s	floating	1.2 bar 295 K
HP 1		1162 g/s	20 bar 295 K	floating
power consumption	refrigeration	COP	specific load	% of power
2K	2.45 KW	$\leq 870$ W/W	2.13 MW	59
5-8K	4.00 KW	$\leq 220$ W/W	0.88 MW	24
40-80K	30.00 KW	$\leq 20$ W/W	0.60 MW	17
total			$\leq 3.61$ MW	100

Table 7.2.6: *Process parameters of the XFEL-refrigerator. The requirements for the XFEL linac are marked in red. The other parameters depend on the final layout of the refrigerator, which will be left to industry, to achieve the most economical results. The COPs (the inverse of the overall refrigerator efficiency for the different temperature levels) correspond to the measured values of the existing LHC plants.*

The XFEL cryogenic system will contain about 4.5 t of helium. Suitable storage capacities for liquid and gaseous helium will be provided. The refrigerator infrastructure is described in reference [4].

### 7.2.5.6 Use of the HERA Cryogenic Plant

The HERA cryogenic plant consists of three parallel helium refrigerators, each of an equivalent cooling capacity of about 8 kW at 4.4 K. One of the refrigerators will be used for the supply of the FLASH-linac and the AMTF. The remaining two refrigerators are available for the XFEL after the end of the operation of the HERA accelerator in June 2007. Among other things, two cold-boxes of the HERA plant would have to be modified, to meet the capacity requirements of the XFEL-project (see Table 7.2.6) [10]. In addition, out-dated

equipment would have to be replaced to ensure the required availability for the operation of the XFEL-linac [2]. An industrial study has been launched, to investigate these aspects in detail.

In any case, an unmodified HERA refrigerator will be used as a low-capacity back-up, as already outlined (see Figure 7.2.3). Specific components, like the warm gas storage tanks, a 10-m<sup>3</sup> liquid storage dewar and the helium purifiers will be adapted to the XFEL cryogenic system with minor changes.

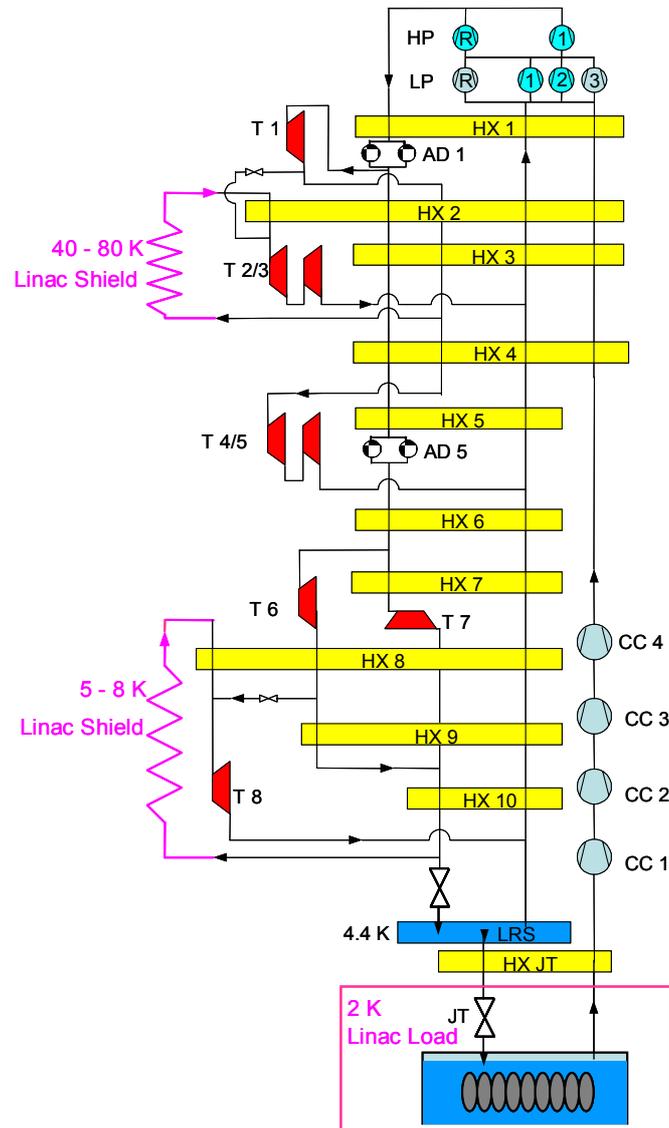


Figure 7.2.5: Flow diagram of the XFEL refrigerator. LP 1,2,3 = low pressure screw compressors, LP R = redundant low pressure screw compressor, HP 1 = high pressure screw compressor, HP R = redundant high pressure screw compressor, HX = heat exchangers, T = expansion turbines, AD = impurity adsorbers, LRS = liquid helium reservoir, JT = Joule-Thomson valve, CC 1,2 = cold compressor stage. Specifying the final number of turbines, heat exchangers and CC stages will be left over to industry, to achieve the most economical result. The flow scheme corresponds to the TMR [1,8].

### 7.2.5.7 Redundancy and Availability

The continuous operation of the linac depends on the availability of the cryogenic supply. Hence, highest availability at reasonable costs has priority in all design considerations, aiming at an availability in the order of 99% or better. For the TMR the sources of unavailability have been carefully investigated [1, 8]. As a result, the required availability can be achieved by means of a single refrigerator, if adequate built-in component redundancy is foreseen and a clear strategy to fight impurities exists. The availability of the process controls is mandatory for the overall availability (see section 7.2.5.8).

The design of the XFEL-refrigerator includes redundant screw compressors for the low and high pressure stages. Turbines as well as cold compressor cartridges can be exchanged easily. The cold box contains switchable gas adsorbers.

In the baseline concept, the existing HERA refrigerator will be used as a low-capacity back-up for the main XFEL refrigerator. The HERA refrigerator can operate as a 4-K helium liquefier with warm helium compressors (from the CMTF) connected to the 2 K return circuit to maintain the XFEL linac at 2 K with static heat-loads only. By this operation, maintenance periods for the main XFEL refrigerator can be bridged.

### 7.2.5.8 Cryogenic Process Controls

A highly available cryogenic process control system is required for widely distributed cryogenic components and the continuous cryogenic plant operation [11]. A high degree of automation of the cryogenic processes will contribute to the reliability.

Basic real-time process control functions like functional process control blocks and supervisory programs written in state notation language (SNL) are mandatory for controlling the cryogenic processes. Process control databases, device specific data, asset properties as well as maintenance data will be stored in a set of relational databases implemented in Oracle. The control system has to integrate local PLC controls of the screw compressors, the cold compressors and other sub-systems as well as state-of-the-art micro-processor controlled valve actuators and transmitters. In general, standard industrial components will be used as far as possible

The environmental conditions in the XFEL tunnel demand special precautions to protect the electronics against radiation damage. Redundant process controllers and a comprehensive redundancy scheme will provide high availability and a reliable failover of damaged components. Redundant I/O components in the XFEL tunnel will extend the mean time to repair for cryogenic operation.

Precise timing of control loops and diskless operation require real-time operating systems like vxWorks on the process controllers. The operator interface applications will have to run natively on multiple platforms. These applications will be implemented in a rich client platform (RCP), preferably written in Java. This approach will allow maximum flexibility and platform independence.

The EPICS toolkit will meet all the requirements within the XFEL project time frame. It provides reliability, stability, a rich functionality, extensibility, and has a powerful user base within the European partner states of the XFEL collaboration.

# Numerical Simulations of Possible Fault Conditions in the Cryogenic Operation of the TTF / FEL – and Tesla Linear Accelerators

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The cryogenic designs of the existing superconducting TTF / FEL linear accelerator and the future TESLA linear collider have to include fault scenarios like the sudden loss of insulation vacuum or the venting of the beam tube. As long as relevant cryogenic components are not available for specific tests, there is the need for numerical simulations of possible fault scenarios. An object oriented computer code has been developed in order to correspond to the real fault conditions as close as possible. Some results of the calculations for the TTF / FEL and TESLA linear accelerators are presented and discussed.

## INTRODUCTION

For the operation of the TESLA e+e- linear collider presently under development superconducting niobium 1.3 GHz cavities have to be cooled in a liquid helium bath at a temperature of 2 K. The 2 K helium circuit is protected against heat input from the environment by means of insulation vacuum and two thermal shields at temperature levels at 4.5 K and 40-80 K respectively. The linear collider of 33 km length is divided in 12 cryogenic units of about 2.5 km length. Each unit is divided in up to 18 strings consisting of 12 cryomodules of 12.2 m length. The design of the cryogenic system for TESLA [1] has to include severe fault scenarios like the accidental loss of the insulation vacuum or beam vacuum. On the other hand, in order to reduce costs, decrease heat loads and to gain space for the active accelerating structures, complicated and expensive mechanical structures like vacuum barriers or helium relief systems in the accelerator tunnel should be avoided in the cryogenic design as far as possible

In case of an accidental loss of the insulation vacuum the heat loads of all cryogenic circuits will increase drastically and will cause an increase of helium pressures and temperatures. The effect of an insulation vacuum break-down was investigated experimentally for other cryogenic systems [2,3] of smaller sizes. It turns out that the individual structure of the cryostats and design details will influence the reactions of the cryogenic system. For the TESLA cryogenic systems special investigations are needed. In addition, the venting of the beam vacuum of the cavities with air has to be investigated [3,4,5].

As long as no cryogenic TESLA components are available for tests of the mentioned fault scenarios, numerical simulations have to be used as an orientation for the design. The cryogenic system of the TTF / FEL linear accelerator presently under construction [6] has to be reviewed under similar considerations.

## THE PHYSICAL MODEL FOR THE SIMULATIONS

For realistic worst case scenarios for the loss of the insulation vacuum it is assumed that air from the environment is entering the vacuum vessel of a cryomodule through holes of 100 or 212 mm diameter size, corresponding to an insulation vacuum pumping flange diameter or to the hydraulical diameter of the insulation vacuum space, respectively. The upper limit of air-flow into the beam vacuum is estimated by the inner diameter  $d=78$  mm of the cavity beam tube flange. The air mass flow is given by the area of the hole, the density of the air and the assumption that the air is entering with the speed of sound [5]. It is assumed that the heat which is transferred to the cold surfaces of the cryostats results mainly from the

change of the specific enthalpy of the air from 300 K to the condensed state, times the mass flow of the entering air. No further heat conduction of the air is taken into account

For the calculations the TESLA cryogenic system is represented by a standard unit, divided in 18 mathematical sections. Each section is corresponding to one string length. (For the TTF / FEL linear accelerator, consisting of 8 cryomodules and of 36.6 m transfer lines, one section corresponds to the length of one cryomodule.) The helium parameters of one TESLA unit are shown in table 1.

Table 1 Helium and cryostat parameters of one TESLA cryogenic unit.

		2 K vapor	2 K liquid	4 K	40/80 K
Volume	[m <sup>3</sup> ]	172	36	14	13.7
Mass	[kg]	136	5245	1870	170
Temperature	[K]	2	2	4.5	40-80
Tube diameter	[mm]	300		60	60
Operation pressure	[bar]	0.031	0.031	4	16
Relief pressure	[bar]	2	2	5	20
Design pressure	[bar]	4 (below 80 K)	4 (below 80 K)	20	20
Safety valve flow area	[mm <sup>2</sup> ]	2 x 9500		1960	1960

It is assumed that air is entering at a section of arbitrary choice. In case of an insulation vacuum breakdown, the 40/80 K and the 4 K shields of a section length are saturated successively to some extent until the air starts to condense also onto the 2 K surfaces (see table 2) of the section under consideration. As soon as the 2 K surfaces are saturated, there will be air left for the shields of the adjacent sections – and so on. With reference to our model, saturation of a cold mass is achieved as soon as the cold mass is heated up to the condensation temperature of air (82 K) in case of the 40/80 K shield and to the triple point temperature (59.8 K) in case of the 4 K and 2 K areas. A cold mass consists of the masses of tubes and shields or of the masses of the 2 K cryostat, respectively.

Table 2 Surfaces of the cryogenic system of a TESLA unit exposed to air condensation

	2 K area	4 K shield	40/80 K shield	Cavities
Surface[m <sup>2</sup> ]	4911	5430	6646	1511

The resulting heat inputs into the 40/80 K, 4 K and the 2 K circuits are calculated simultaneously. (For the break-down of the beam vacuum only the inner surface of the cavities and the 2 K helium circuit is taken into account.) Perfect heat conduction between the thermal shields and the tubes is assumed for the 40/80 K and 4 K helium return tubes. The heat transfer from the tubes or the 2 K cold mass to the appropriate helium volumes is calculated from the helium flow conditions or – as long as the 2 K cryostats are filled with liquid – is set to 6 kW/m<sup>2</sup> for surfaces covered with multi layer insulation and to a maximum of 40 kW/m<sup>2</sup> for the inner surfaces of the cavities according to values reported in the references [2,3,4].

From the heat input into a section of a cryogenic circuit, the heat transfer into the corresponding cold masses and the isochoric state change of the appropriate helium volume are calculated, depending on the heat transfer from the cold masses to the helium (or vice versa). The resulting pressure rise may cause a helium mass flow from or into the adjacent sections, depending on the pressure differences. Only at the end of the unit (or TTF / FEL linac), a pressure relief for each individual helium circuit is introduced, representing full lift safety valves. According to the design [1], the 300 mm 2 K vapor return tube, which is connected to the helium vessels of the cavities at the end of each cryomodule, acts also as a relief tube for the 2 K volume of a complete unit. The relief pressures and safety valve sizes are shown in table 1. As soon as the relief pressure is reached, the mass flow across the valve is calculated. The resulting helium mass flow induces an isobaric state change of the helium in the connected section of the appropriate cryogenic circuit. In case of the TTF / FEL linac additional relief tubes between the cryostats and the safety valves are included in the calculations, which are at room temperature at the start of the helium discharge ( see fig.6). The calculations are conducted stepwise both in length and time. The time steps have to be matched to the section lengths in order not to exceed the speed of sound for the propagation of a helium density change.

## THE COMPUTER CODE

The structures of the cryogenic system, consisting of three cryogenic circuits, including helium volumes at different thermal states, different tubes and cold masses, made of different materials, relief valves and two thermal shields are projected into a C++ object oriented computer algorithm. From the definitions of the basis C++ classes 'cold masses', 'helium', 'tubes' and 'valves', specific sub classes are derived, resulting in the definitions of a 'string' class and a 'cryomodule' class. Transfer line sections in the TTF / FEL linac are treated as special installations of 'cryomodule' class objects. The member functions of the basis classes incorporate the FORTRAN subroutine files HEPROP and CRYOPROP [7] for the computation of the thermal properties of helium and other materials, and in addition, other already existing FORTRAN computer codes for process calculations.

## RESULTS OF THE SIMULATIONS

Figures 1 to 3 show the helium pressures of the 2 K volume of a TESLA unit versus time after the start of the break-down of the insulation vacuum. The unit is separated into 18 string sections. Each string consists of 12 cryomodules. Already an air leak of  $d=100$  mm size into the insulation vacuum of a string in the middle of a TESLA unit causes a pressure rise which exceeds the allowed maximum of 4 bar, if the

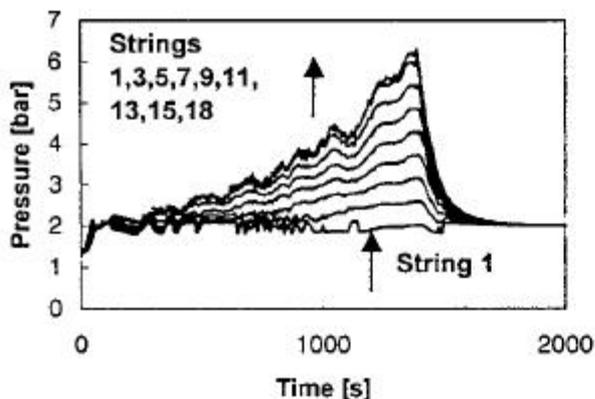


Figure 1 2 K helium pressures of indicated strings versus time, air leak of  $d=100$  mm into insulation vacuum at string 10 at the time  $t=0$ , no vacuum barriers in the unit, relief valves only at string 1.

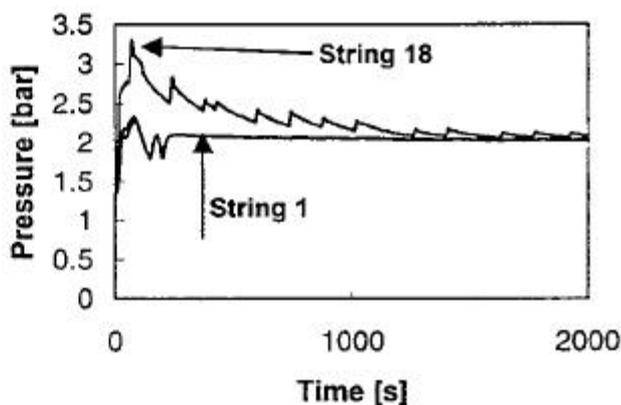


Figure 2 2 K helium pressures of strings 1 and 18 versus time, air leak of  $d=212$ mm into insulation vacuum at string 10 at the time  $t=0$ , vacuum barriers at the end of each 6<sup>th</sup> string, relief valves only at string 1.

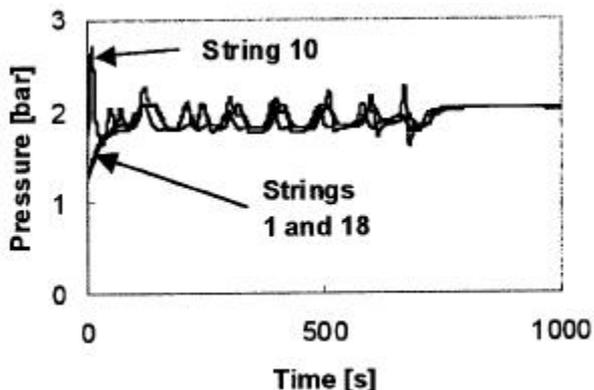


Figure 3 2 K helium pressures versus time, air leak of  $d=212$  mm into insulation vacuum at string 10, additional safety valves at string 18, no vacuum barriers.

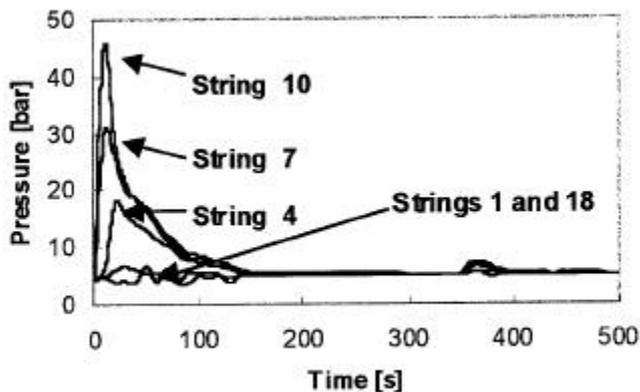


Figure 4 4 K helium pressures of indicated strings versus time, boundary conditions as for figure 3. (The 4K return tube is only considered here.)

insulation vacuum of a unit of 2.5 km length is not separated in smaller sections of the insulation vacuum (fig.1). By the introduction of only two vacuum barriers at the end of each 6<sup>th</sup> string, even an air leak of d=212 mm will cause no pressure rise above 4 bar (fig.2). A similar effect can be reached, if safety valves are installed at both ends of the unit (fig.3). Pressure peaks in the 4 K circuit, which exceed the allowed 20 bar will still remain according to our calculations (fig.4). (The 40/80 K circuit can be discharged properly even under conditions corresponding to fig. 1; the corresponding results are not shown here). From the cryogenic point of view, also a beam vacuum break-down can be discharged without exceeding 4 bar in the 2 K volume (fig.5). The helium pressure of the 2K volume in the TTF / FEL linac will not exceed 3 bar after an air leak of d=100 mm size into the insulation vacuum has occurred (fig.6).

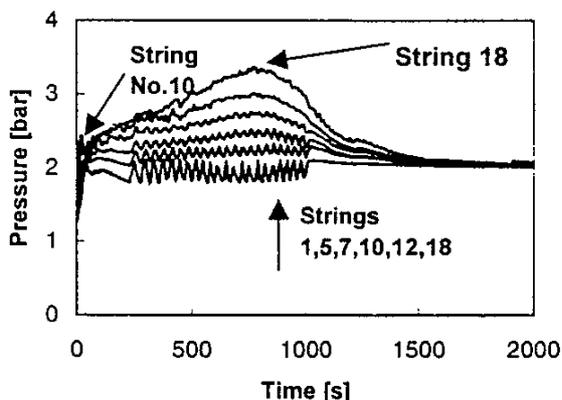


Figure 5 2 K helium pressures of indicated strings versus time, air leak into beam vacuum at string 10 at time t=0, relief valves only at string 1.

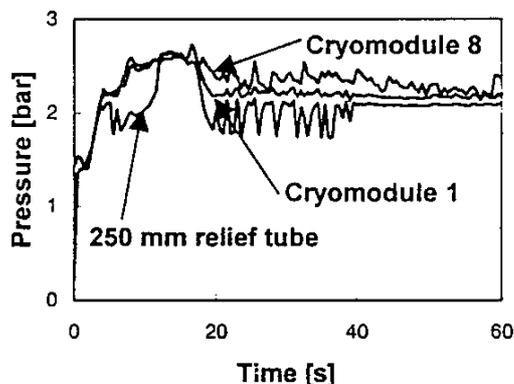


Figure 6 2 K helium pressures of the TTF/FEL linac versus time, air leak of d=100 mm into the insulation vacuum of cryomodule 2 at time t=0.

## CONCLUSIONS

According to the simulations of this study severe fault situations can be mastered for the operation of the 2 K circuit of the TESLA cryogenic system by means of minor extensions of the present design. The 4 K circuit needs further investigations. It is not at all assumed that the physical model used in this study can consider all aspects of air transport and heat transfer. The results of our study rather underline the necessity of experimental investigations for TESLA cryogenic components in line with experiments for similar helium systems [3,4]. At least on the scale of one TESLA cryomodule the effect of the break-down of the insulation vacuum and the beam vacuum has to be studied in a real experiment. Nevertheless at least qualitative hints for the design of the cryogenic system for TESLA can be derived from this study. Once defined, the object oriented C++ code can be effectively used to simulate parts of complicated cryogenic components like TESLA strings or cryomodules.

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