7 Infrastructure and auxiliary systems

7.1 Site layout and civil construction

7.1.1 Overall site layout

The overall layout of the X-Ray Free-Electron Lasers (XFEL) is shown in Figure 7.1.1. It will be realised in two steps.

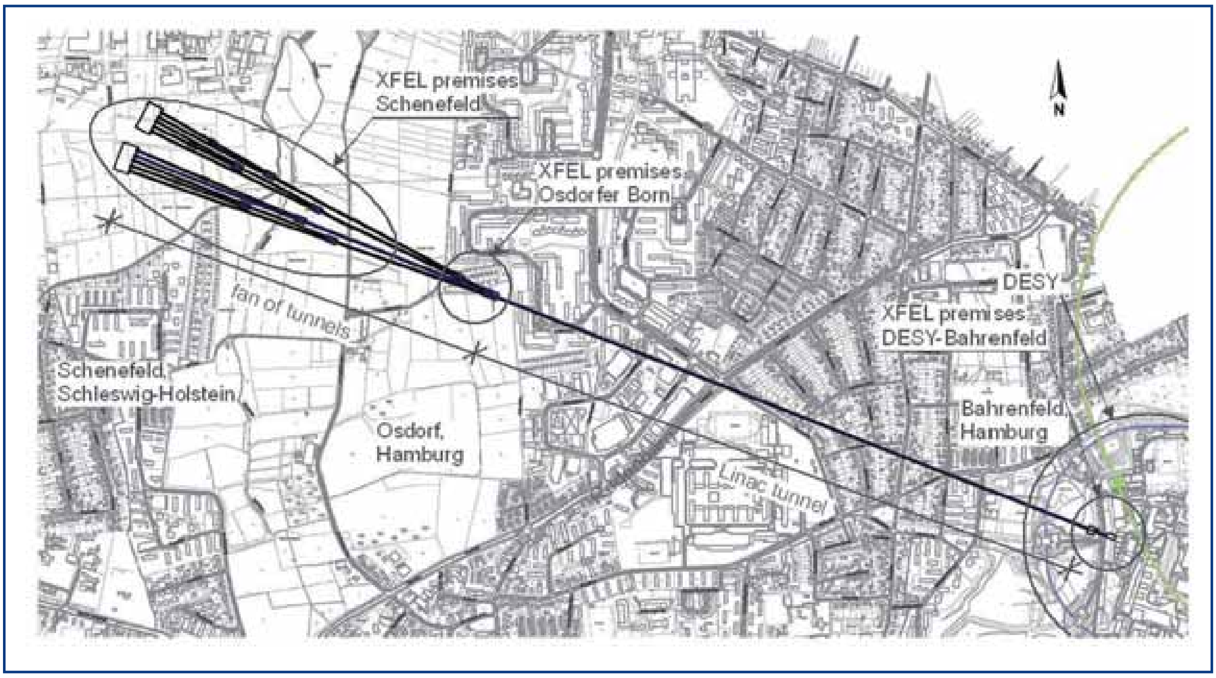

Figure 7.1.1 Topographical layout of the XFEL.

The facility stretches from the Deutsches Elektronen-Synchrotron (DESY) Laboratory site in Hamburg-Bahrenfeld in north-west direction to an area south of the city of Schenefeld (district Pinneberg). The facility predominantly consists of tunnels that run underground. The buildings at the surface are concentrated on three sites:

7.1.1.1 DESY-Bahrenfeld

This is where the injector is located and the tunnel for the linear accelerator (linac) starts. The cryogenic supply, power, water and climate are provided via access shafts that are also used for the insertion and removal of the tunnel drilling machine. On top of the shafts there exist halls that are provided with cranes for the transport of components into the injector building and the tunnel.

7.1.1.2 Osdorfer Born

After acceleration in the linac, the electron beam is at this position distributed into two undulator tunnels and into the first tunnel of the second building phase of the XFEL. The division of one incoming tunnel into three outgoing tunnels necessitates the construction of a large distribution shaft that is also used to accommodate the tunnel drilling machine and to transport the components of the machine and undulator beamlines into the tunnel buildings. In addition, the linac commissioning electron dump is positioned here. Only the underground part of phase two will be realised initially. This way the interference of the later phase two construction with the operation of the existing facility can be minimised.

7.1.1.3 Schenefeld

The undulator tunnels split up into photon tunnels and further undulator tunnels. Thus, a distribution fan of photon and undulator tunnels is generated, producing five photon beamlines that end in the experimental hall. Further shafts are located where the tunnels divide. They will also be used for the transport of the tunnel drilling machine and the beamline components. The experimental hall and the accompanying buildings (office and laboratory space, canteen, warehouses, etc.) form the centre of the experimental activities of the XFEL Facility.

Figure 7.1.2 shows a side view of the XFEL tunnels and shafts. The depth of the position of the tunnels underground is determined by several factors. For cryogenic reasons, the tunnel for the linear accelerator is positioned with its longitudinal centre (at a distance of 1,000 m from the start of the linac) tangential to an equipotential plane of the Earth's gravitational field. The distribution tunnels (undulator tunnels and photon tunnels) are positioned so that the experimental hall (at a distance of approximately 3,350 m from the start of the XFEL) is also tangential to the equipotential surface. Thus, the linac tunnel and the plane in which the distribution tunnels lie form an angle of approx. 0.02°. Their intersection lies approximately 200 m before the end of the linac tunnel.

To reach the radiation safety goals, the minimum depth of coverage of the tunnel with earth amounts to approximately 6 m. Thus, the shallowest surface area along the length of the tunnel determines the depth of the entire building complex. This occurs near the small river Düpenau at a distance of approximately 2,800 m from the start of the XFEL.

The tunnel and shaft buildings will be realised in a depth from 12 m up to 44 m below the surface. The foundation of the buildings will, thus, be situated below the groundwater table and the buildings will lie up to 20 m inside the groundwater.

The tunnels will most probably be constructed using a tunnel drilling machine using a supported-tunnel-shield method with segmented concrete lining. This will mean minimum interference with the groundwater level and flow.

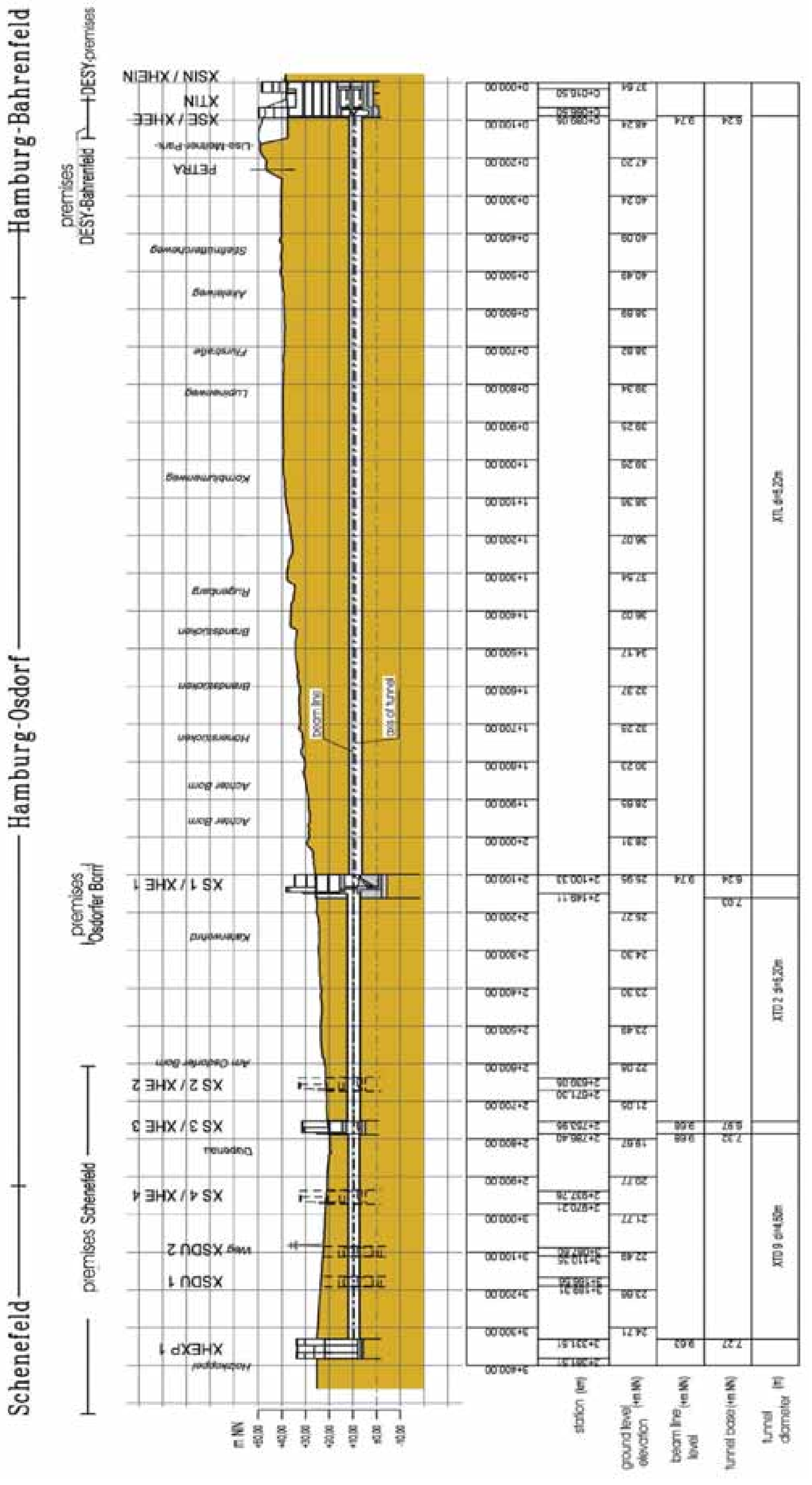

Figure 7.1.2 Side view of the XFEL tunnels and shafts.

The main parameters for the layout of the XFEL civil construction are listed in Table 7.1.1.

Length of injector building (XSIN+XTIN+XSE)	89.5 m
Length of the preaccelerating section 1 (130 - 500 MeV)	80.5 m
Length of bunch compressor 1	63 m
Length of the booster accelerating section (500 - 2000 MeV)	150 m
Length of bunch compressor 2	84 m
Length of main accelerating section (2 – 20 GeV)	1221 m
Length of collimation section	207 m
Length of distribution tunnel building	1230 m
Overall length of the facility	3400 m
Range of earth coverage of tunnels below surface	6 to 38 m

Table 7.1.1 *Main layout parameters for the XFEL civil construction.*

Figure 7.1.3 shows the nomenclature for the main buildings of the XFEL Facility for the two building phases, both above and below the surface. The individual buildings will be described in the following sections, organised according to their topographical position. In this report only the first building step will be described further.

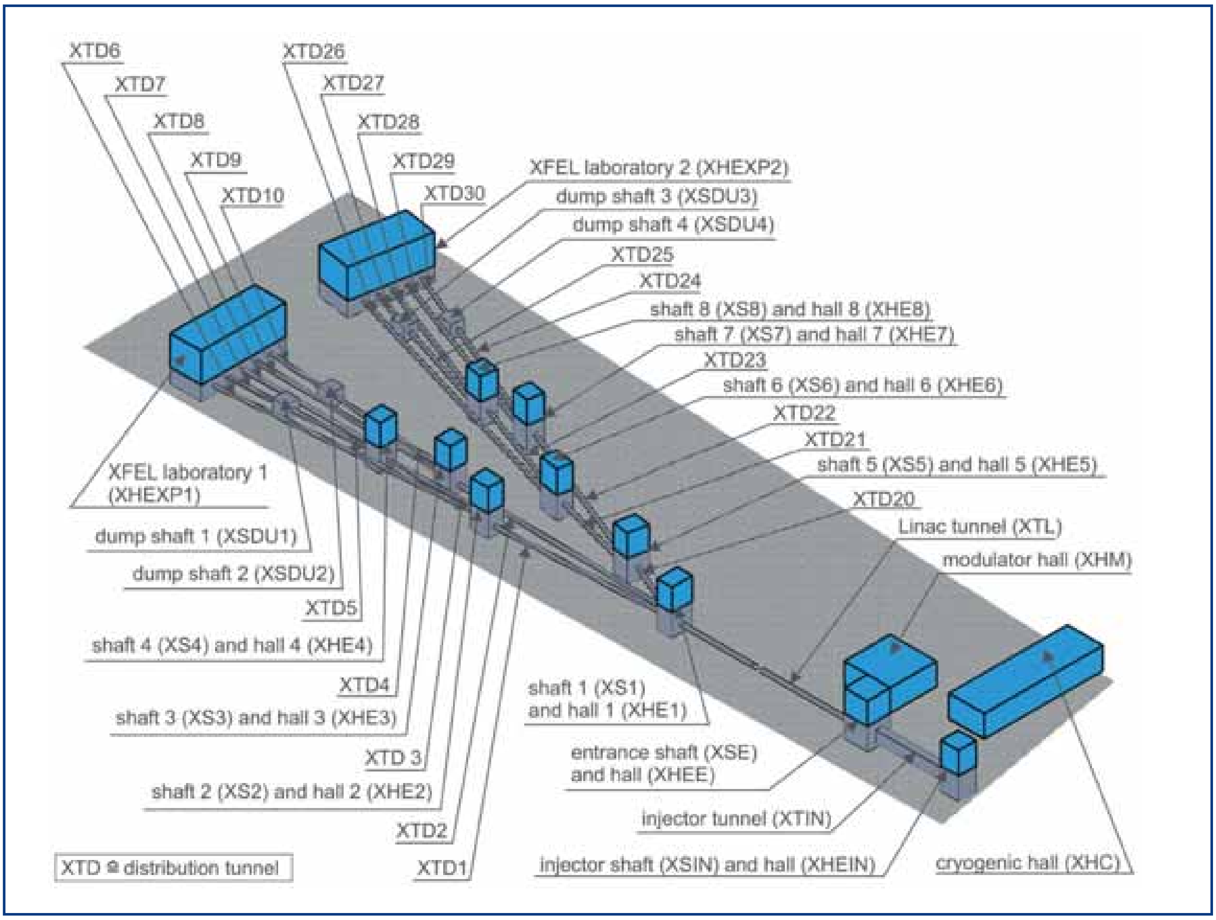

Figure 7.1.3 *Nomenclature for the main buildings of the XFEL Facility for the two building phases, both above and below the surface.*

7.1.2 Civil construction

7.1.2.1 XFEL site DESY-Bahrenfeld

Figure 7.1.4 shows an overview of the DESY site in Hamburg-Bahrenfeld. Figure 7.1.5 shows the new buildings that have to be constructed for the XFEL in the north-western area of the DESY site. This is where the tunnel XTL for the acceleration of the electron bunches starts with the injector complex.

The installation of components into the tunnel XTL is performed using the tunnel entrance building (XHEE). The pulsed radio frequency for the accelerating structures in the injector building and the tunnel XTL is produced in the modulator hall XHM and fed with pulse cables into the tunnels. The liquid Helium for the superconducting accelerating structures is provided by the cryogenic facility located mainly in the cryogenics hall XHC.

The technical infrastructure on the XFEL site DESY-Bahrenfeld is complemented by buildings for transformers and pumps, storage tanks for excess liquid Helium and heat exchangers.

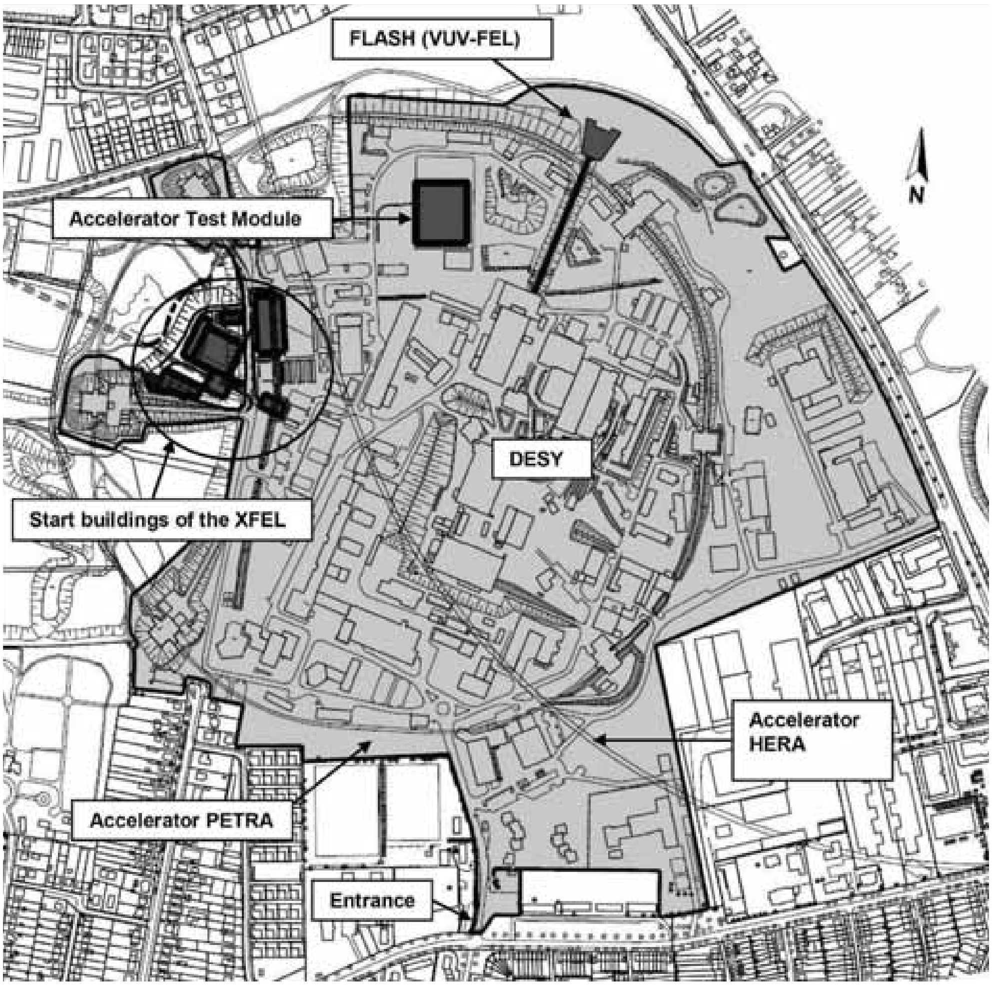

***Figure 7.1.4** Overview of the DESY site in Hamburg-Bahrenfeld.*

Figure 7.1.5 *Overview of the civil construction for the XFEL on the DESY site Hamburg-Bahrenfeld. The necessary enlargement of the existing DESY site is marked in red.*

The acceptance tests of the accelerating modules will take place in a newly erected building called Accelerator Module Test Facility (AMTF). Its position on the DESY site can be seen in Figure 7.1.4. For completeness its description is included in this report (Section 7.2.5).

Figure 7.1.6 shows a longitudinal cross-section of the injector building and the adjacent shaft XSE. The two injectors are located on the two lowest floors of the building XTIN. The remaining floors of the building XTIN are occupied by klystrons including electric power equipment and a cold box for the distribution of the liquid Helium to the superconducting accelerator modules of the two injectors and the main accelerator. In addition, they house the photo cathode laser system, cabinets for electronics and diagnostics hardware, and power supplies for the beamline magnets of the injector and the main accelerator.

During the construction phase, the shaft XSE serves as target shaft for the drilling of the tunnel XTL and as emergency exit. During the installation and operation phases, the shaft is used to gain access to the injector tunnel XTIN, the accelerator tunnel XTL and as emergency exit. In addition it is used as an installation shaft for all supply media for these buildings, including the liquid Helium.

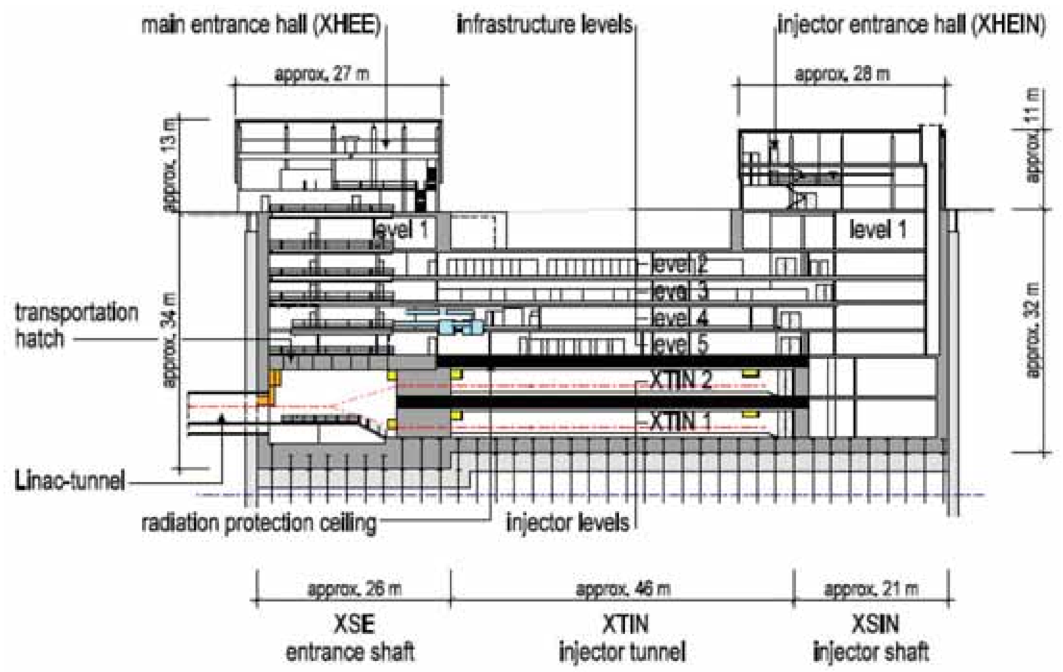

Figure 7.1.6 *Longitudinal cross-section of the injector buildings XTIN and XSIN and the adjacent shaft XSE. The dash-dotted red lines indicate the direction of the electron beam axes in the two injectors and the linac tunnel.*

Figure 7.1.7 shows a three-dimensional view of the injector complex including the underground facilities.

Figure 7.1.7 *Three-dimensional view of the injector complex at the XFEL site DESY-Bahrenfeld.*

The cryogenics hall will be built directly adjacent to the existing HERA cryogenics hall. To store the Helium the existing Helium gas tanks of the HERA cryogenics plus a storage tank for liquid Helium will be used. The HERA cryogenics hall and the new XFEL cryogenics hall XHC, to be built, will be connected using the cold box in the XFEL hall. Thus, the HERA cryogenics facility can be used to cool the injectors and/or linear accelerator when the XFEL cryogenics facility is down or being serviced.

Figure 7.1.8 shows the ground plan of the cryogenics hall for the XFEL Facility.

Figure 7.1.8 *Ground plan of the XFEL cryogenics hall. The dimensions of the hall are about 72 m × 32 m with a height of about 14 m.*

The modulator hall XHM is located next to the supply shaft XSE. It is designed to house up to 35 modulator stations (including the second injector and two reserves). Control and pulse cables are routed from the modulator hall via the shaft XSE to the tunnel sections of the injector building XTIN and the linear accelerator XTL where they will be connected to the pulse transformers of the corresponding radio frequency (RF) station. The size of the modulator hall is about 46 m × 41 m.

Figure 7.1.9 shows an aerial visualisation/simulation of the XFEL site DESY-Bahrenfeld.

Figure 7.1.9 *Aerial visualisation/simulation of the XFEL site DESY-Bahrenfeld.*

7.1.2.2 Accelerator tunnel XTL

The tunnel building XTL starts at the shaft XSE on the DESY-Bahrenfeld site and contains the booster linac, the bunch compressor sections, the superconducting linear accelerator structures and a collimation section. The tunnel XTL ends in the shaft XS1 on the XFEL site Osdorf. Here, the electron beam is distributed to the different undulator beamlines in the tunnel building XTD. The overall length of the tunnel XTL is 2,010 m.

The diameter of the tunnel XTL is 5.2 m. It is the result of an optimisation process with the space requirement and cost aspects as important boundary conditions.

Figure 7.1.10 shows a cross-sectional view of the tunnel XTL with basic dimensions.

A detailed analysis of the space requirements in the tunnel showed that the suspension of the accelerator modules from the top is advantageous, especially for servicing of the installed components.

Starting at the top right are located the return line for the warm Helium gas, followed in a clockwise direction by the cable trays for signal cables and cooling water pipes. The cable trays beneath the floor are used for the RF pulse cables to the klystrons, cooling water supply lines for the experimental hall and pipes for pumping back possible leakage water. The pipes above the floor to the left are used for compressed air and Nitrogen. The big pipe on the top left side is used as an air duct for rapidly removing smoke in case of a fire.

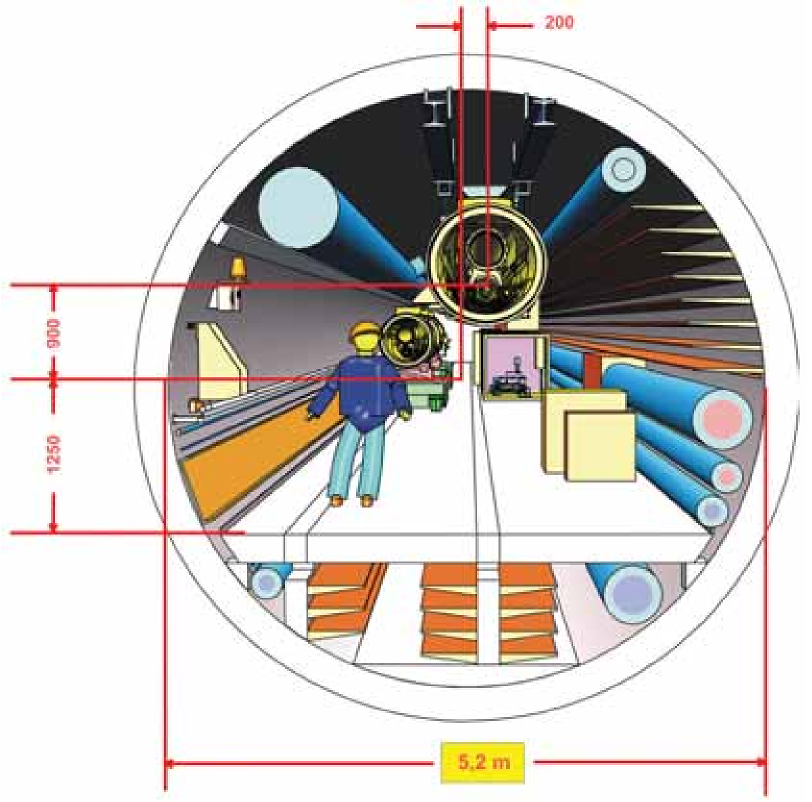

Figure 7.1.10 *Cross-sectional view of the tunnel XTL in the region of the accelerator modules including its basic dimensions. The beam axis of the accelerator is shifted from the tunnel centre by 200 mm to the right and 900 mm to the top (as viewed in the direction of beam acceleration). In the background the transport of another accelerator module is shown.*

Concerning the RF system, four superconducting accelerator modules of length 12.2 m each will be connected to become a unit of approximately 50 m length. Several other supply facilities will be grouped accordingly.

Figure 7.1.11 shows the same tunnel section as in Figure 7.1.10, but viewed from the other direction. Here one can see the infrastructure needed to supply the group of four accelerator modules: the klystron with pulse transformer and interface network and the electronics cabinets that contain the control systems and diagnostics hardware.

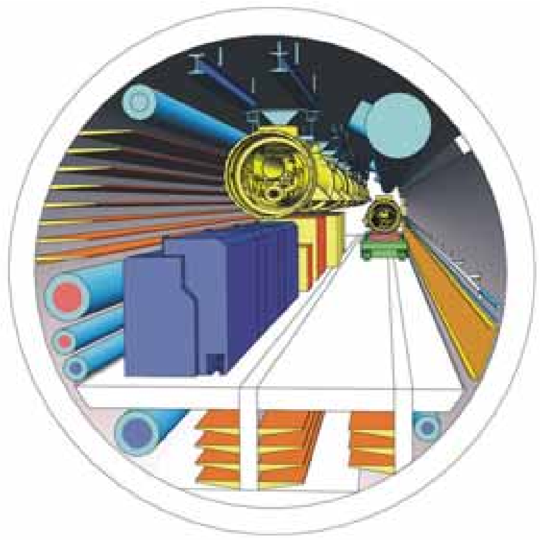

Figure 7.1.11 *Cross-sectional view of the tunnel XTL in the region of the accelerator modules (line of sight opposite to that of Figure 7.1.10).*

Figure 7.1.12 shows the same tunnel section in a longitudinal view. The free space of approximately 15 m in front of the supply section serves as a reserve space for the future installation of a second RF system to provide the possibility of a continuous wave (CW) mode for the operation of the accelerator.

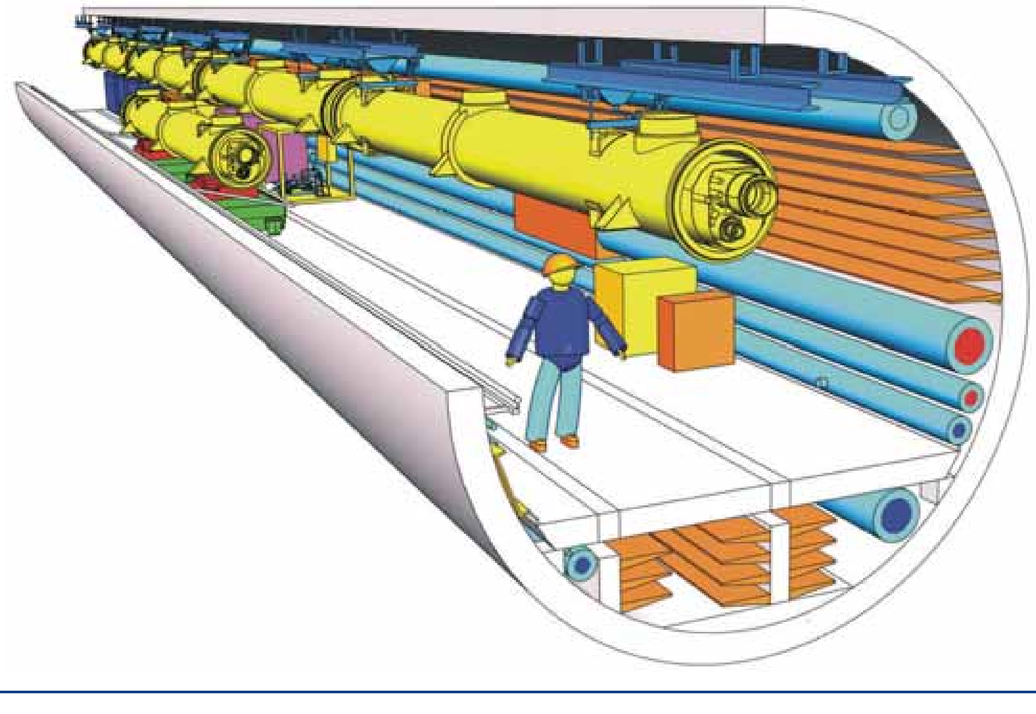

Figure 7.1.12 *Longitudinal view of the same tunnel section as shown in Figure 7.1.10. The entire section of approximately 50 m in length will be supplied with one RF system.*

Figure 7.1.13 shows the region of the electron beam distribution at the end of the linac tunnel XTL into the two undulator tunnels (and the tunnel XTD20, for a possible construction phase two of the XFEL Facility construction) at the shaft XS1. In addition, one can see a fourth beamline that is led downward through the shaft floor, where the beam dump for the commissioning of the linac is located.

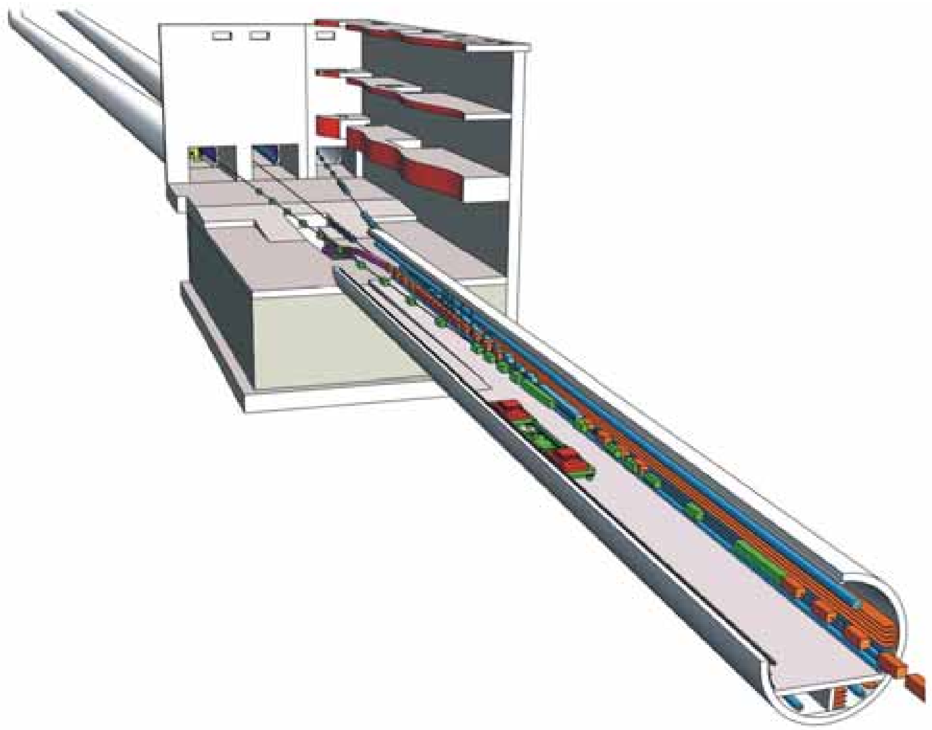

Figure 7.1.13 *Beam distribution at the end of the tunnel XTL. The three-dimensional drawing shows the distribution of the electron beam to the three distribution tunnels XTD1, XTD2 and XTD20 in the horizontal plane. In addition, the vertical deflection of the beam down to the emergency and commissioning beam dump is shown.*

7.1.2.2 Distribution tunnel system XTD

Figure 7.1.14 shows a schematic overview and Figure 7.1.15 shows the actual layout of the distribution tunnel building XTD for the first construction phase.

An electron bunch after acceleration in the linac, can go through the following states on its way towards the beam dump (see Figure 7.1.15):

- distribution by pulsed magnets alternatively to one or the other of two branches of undulator tunnels (I);
- passage through SASE 1 and SASE 2 undulator sections for the generation of intense photon beams with high energy (II);
- horizontal deflection to the next (Self-Amplified Sponteneous Emission (SASE) or spontaneous) undulator section by long magnet sections (III);
- generation of a photon beam of lower (SASE)/higher (spontaneous) energy in these undulator sections (IV);

- horizontal deflection to the next spontaneous undulator section by long magnet sections (III') (branch 1, only);
- generation of a photon beam of higher energy in this undulator section (branch 1, only);
- vertical deflection to the beam dump absorber (V).

The layout of the distribution tunnel building is determined by this sequence. For each separation of the beams, a new shaft building is needed into which the incoming beam enters and from which two new tunnels exit.

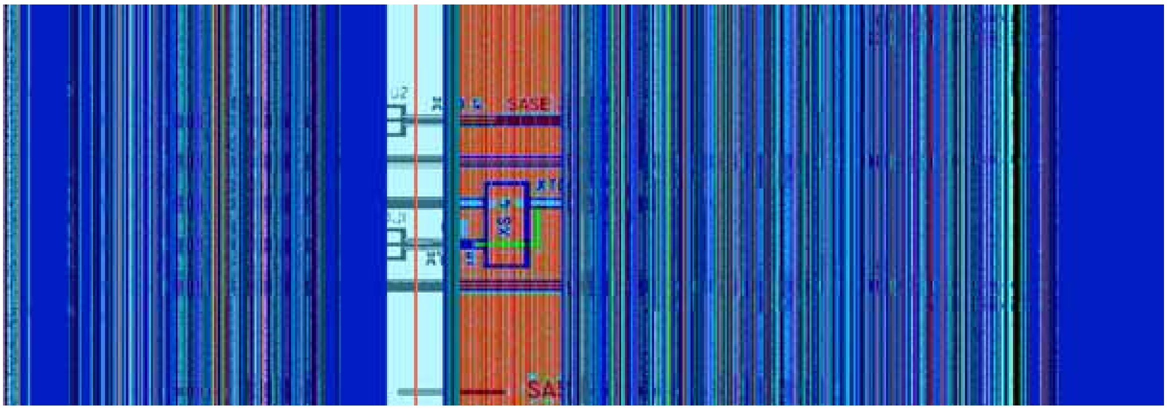

Figure 7.1.14 *Schematic view of the XFEL distribution tunnel system XTD (construction phase 1).*

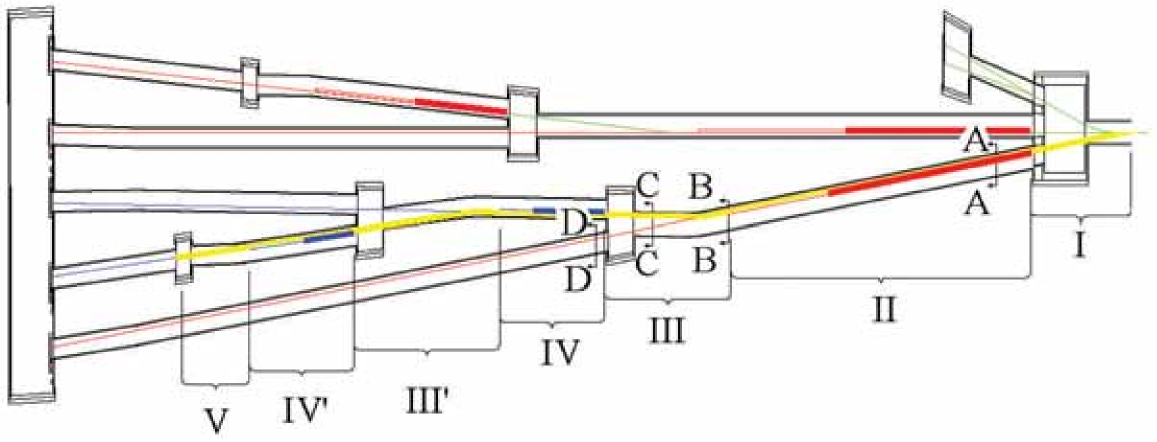

Figure 7.1.15 *Top view of the distribution tunnel building XTD (construction phase 1, distorted view in the ratio 5:1 for the horizontal to the vertical dimension). The sections labelled with Roman numerals indicate the various states that an electron bunch can be in while travelling through the structure. Letters indicate the position of the tunnel sections that are shown in cross sectional view in Figures 7.1.16 to 7.1.18. The electron trajectories are drawn in green, the trajectories of the photon beams generated in the SASE undulators are drawn in red and those generated in the spontaneous undulators are drawn in blue. Where electron and photon beam directions coincide, the colour of the photon beam is taken.*

The tunnel diameter in the two largest SASE undulator sections is determined by the high packing density of components and the optional placement of additional undulators in the future. The diameter of the photon tunnels that lead into the experimental hall is determined by the space requirements of the monochromator sections and the requirement that it must be possible, in the future, to accommodate additional photon beamlines. The tunnels XTD1-2 have an inner diameter of 5.2 m, identical to the tunnel for the linear accelerator, XTL. All other tunnels in the distribution building XTD have an inner diameter of 4.5 m. In this way only two different tunnel drilling machines are needed.

The basic dimensions of the tunnels of the tunnel distribution building XTD for construction phase 1 are listed in Table 7.1.2.

Name	Ø [m]	Length [m]	Function
XTD1	5.2	480	Undulator tunnel SASE 2
XTD2	5.2	594	Undulator tunnel SASE 1
XTD3	4.5	263	Undulator tunnel U1
XTD4	4.5	302	Undulator tunnel SASE 3
XTD5	4.5	205	Undulator tunnel U2
XTD6	4.5	660	Photon tunnel
XTD7	4.5	137	Photon tunnel
XTD8	4.5	365	Photon tunnel
XTD9	4.5	545	Photon tunnel
XTD10	4.5	221	Photon tunnel
XTD20	4.5 (w)× 4.3 (h)	61	e- Transfer tunnel to construction phase 2 (rectangular cross-section)

Table 7.1.2 *Basic dimensions of the tunnels of the tunnel distribution building XTD for construction phase 1.*

Figures 7.1.16 to 7.1.18 show cross-sectional views of representative tunnel sections in the tunnel distribution building XTD, including the technical infrastructure at those positions (undulator tunnel, beam distribution region, photon tunnel (gas filter section)). The relative positions of the selected sections in XTD have been indicated by letters in Figure 7.1.15.

The shaft buildings serve not only to accommodate the beam distribution but also as access points to the tunnels for personnel and material and for the routing of the supply lines for power, water, air conditioning, etc. to and from the tunnels. During the construction phase they serve as start and target shafts for the tunnel drilling machine.

The dimensions of the shafts are largely determined by the parameters for the beam deflection geometries:

- radius of deflection for the electron beam;
- geometrical size of the components for the beamline optics;
- minimum distance of the beamline components to the tunnel walls.

In addition, the length of the shafts is affected by the requirement to allow access to each tunnel while the neighbouring tunnel is in operation.

Figure 7.1.19 and Figure 7.1.20 show the layout of the lowest floor and a side view of the shaft XS2 which is analogous with XS3 to XS5.

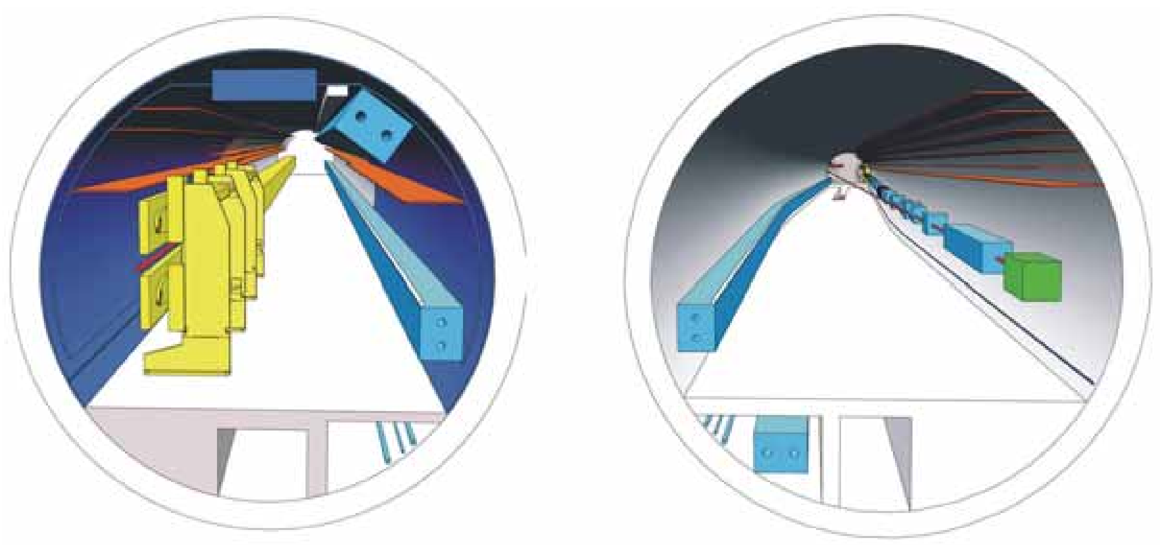

Figure 7.1.16 *Cross sectional view of the tunnel in the region of the SASE undulators as viewed in the beam direction. The diameter of the tunnel is determined by the transport path for a replacement undulator module and the necessary emergency pathway (see position A-A in Figure 7.1.15).*

Figure 7.1.17 *Cross-sectional view of the tunnel distribution region as viewed from the incoming tunnel. (see position B-B in Figure 7.1.15).*

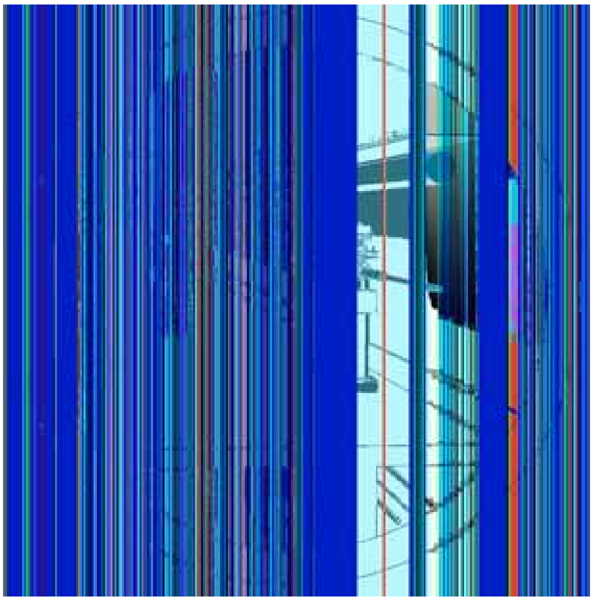

Figure 7.1.18 *Cross-sectional view in the region of the gas filter section (see position D-D in Figure 7.1.15 as viewed along the beam direction).*

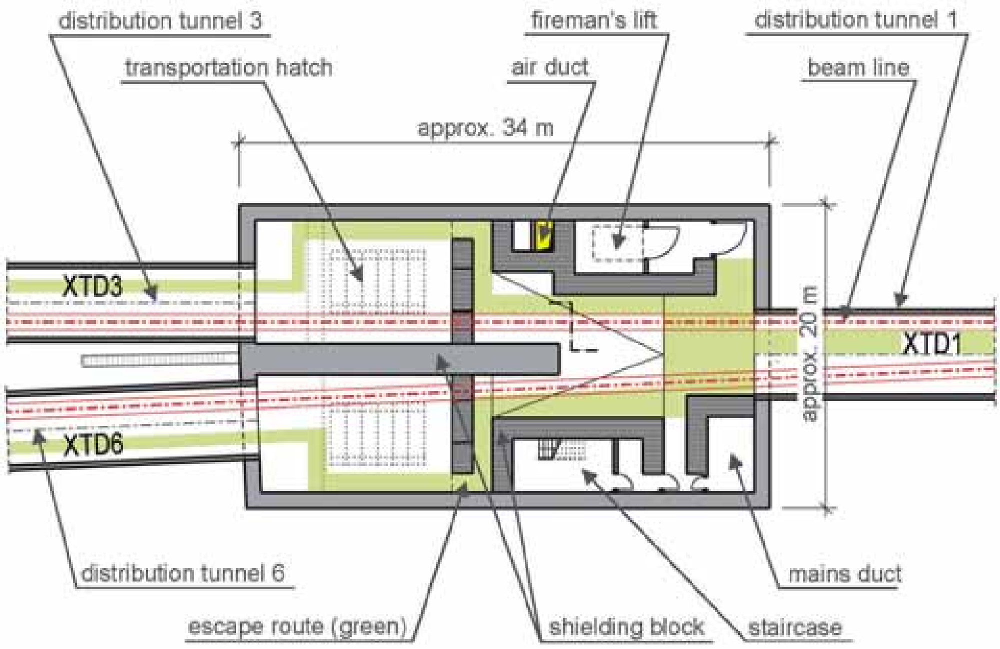

Figure 7.1.19 *Layout of the lowest floor of the shaft XS2.*

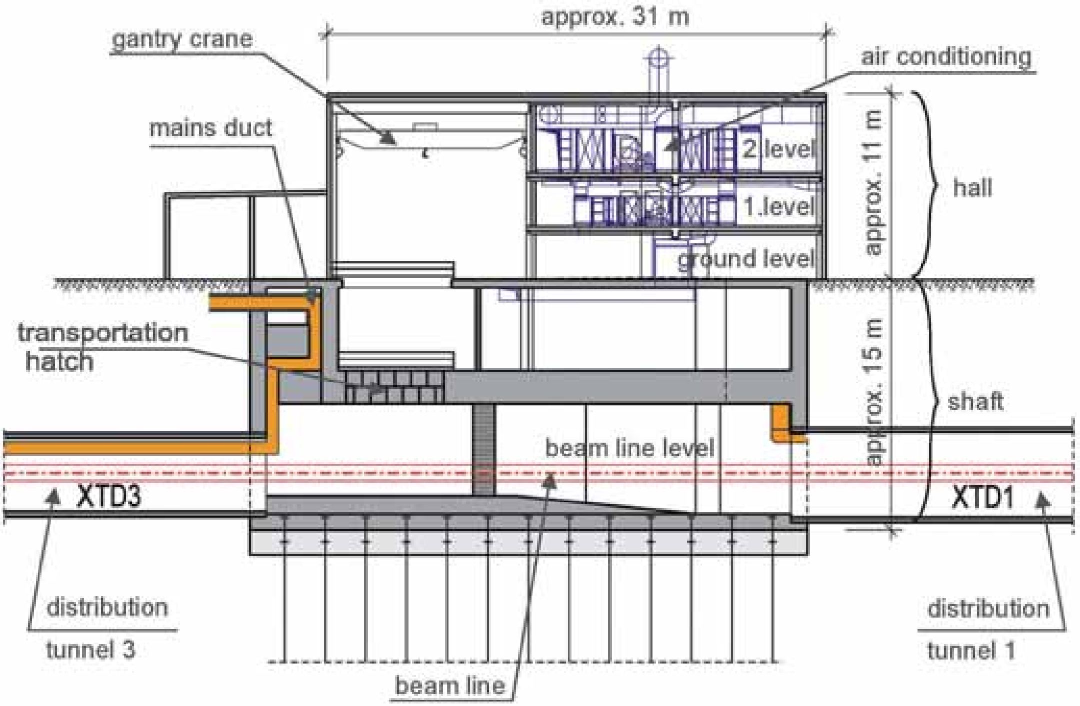

Figure 7.1.20 *Side view of the underground floors and the entrance hall of the shaft XS2.*

Figure 7.1.21 shows a side view of the absorber shaft building XSDU2.

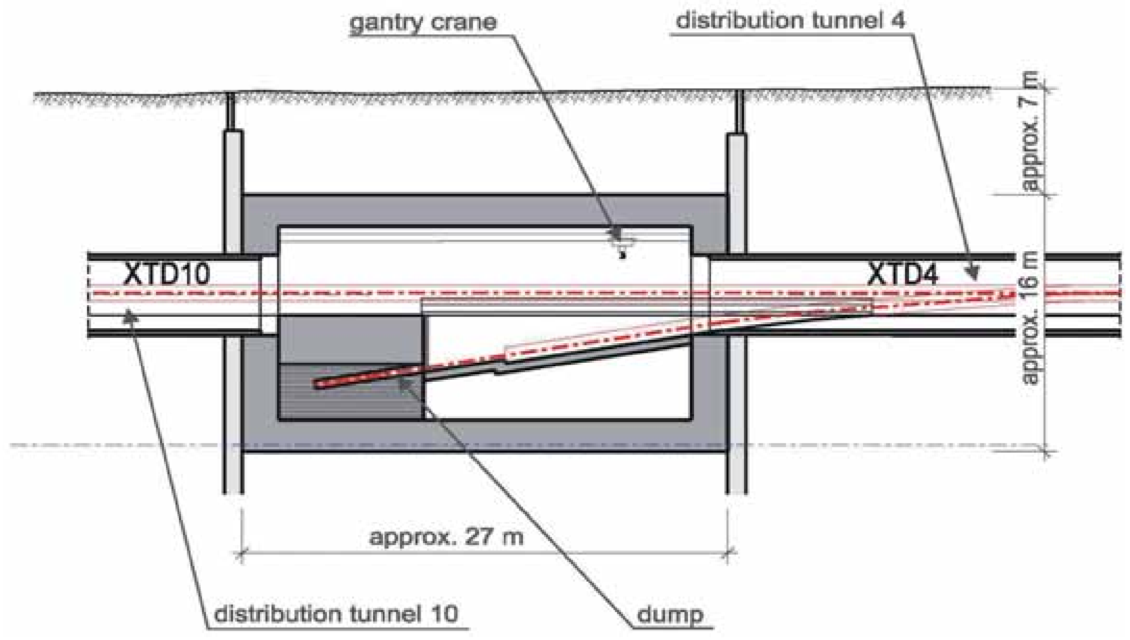

Figure 7.1.21 *Side view of the beam absorber shaft building XSDU2. The electron beam is deflected downwards, the photon beam is unaffected and travels towards the experimental hall. In addition, the crane facility and the local concrete shielding of the absorber are shown.*

7.1.2.4 XFEL site Osdorfer Born

Figure 7.1.22 shows an overview of the XFEL site Osdorfer Born.

The linac tunnel XTL ends here and the electron beam is distributed to the undulator sections in the tunnel system XTD and/or to the connection tunnel XTD20 that will feed the undulator tunnel fan for the second construction phase of the XFEL.

Figure 7.1.23 shows the layout for the ground floor of the distribution shaft building XS1. This shaft is considerably larger than the other shaft buildings as it is the only one that has to accommodate three outgoing tunnels.

The outer dimensions of the shaft XS1 are about 51 m × 23 m (length x width), at the beam level even 63 m × 23 m. The depth of the underground part is approximately 28 m because of the commissioning dump below the beam level. The entrance hall XHE1 has two stories with a height of about 8 m. The region of the installation crane is about 12 m high. The outer dimensions of the shaft XS5 for the distribution of the beam into the undulator tunnels for the second construction phase are about 38 m × 18 m (length x width). The depth of the underground part is approximately 18 m.

Figure 7.1.24 shows a three-dimensional view of the shaft complex XS1 and XS5 at the XFEL site Osdorfer Born.

Figure 7.1.25 shows an aerial visualisation/simulation of the XFEL site Osdorfer Born. The entrance hall XHE5 that covers the shaft XS5 will only be realised in the second construction phase of the XFEL Facility.

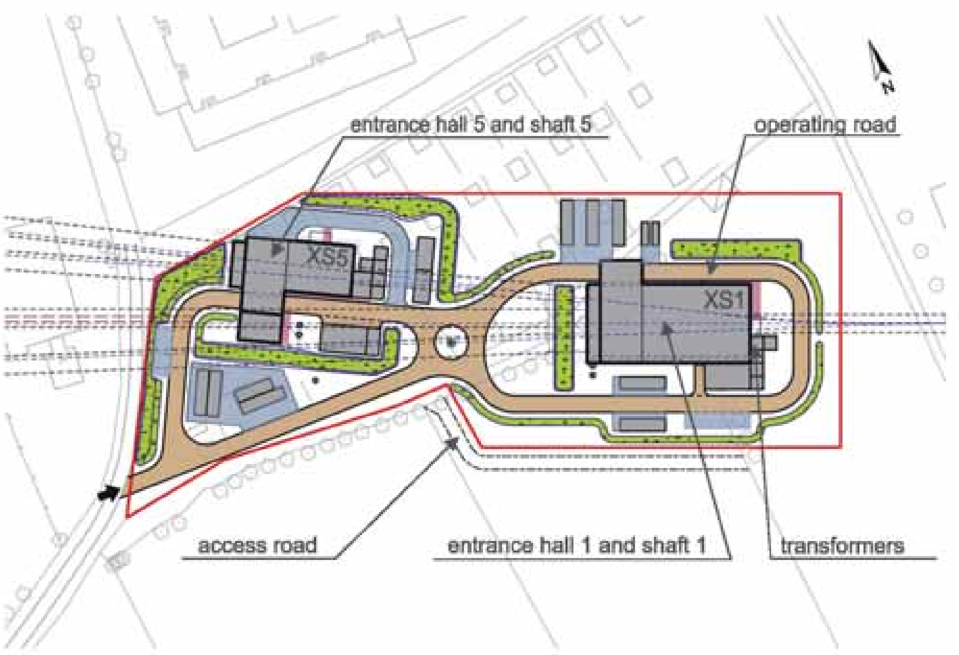

Figure 7.1.22 *The XFEL site Osdorfer Born. The accelerated electron beam is distributed to the undulator tunnels and to the connection tunnel XTD20 that will feed the undulator tunnel fan for the second construction phase of the XFEL Facility.*

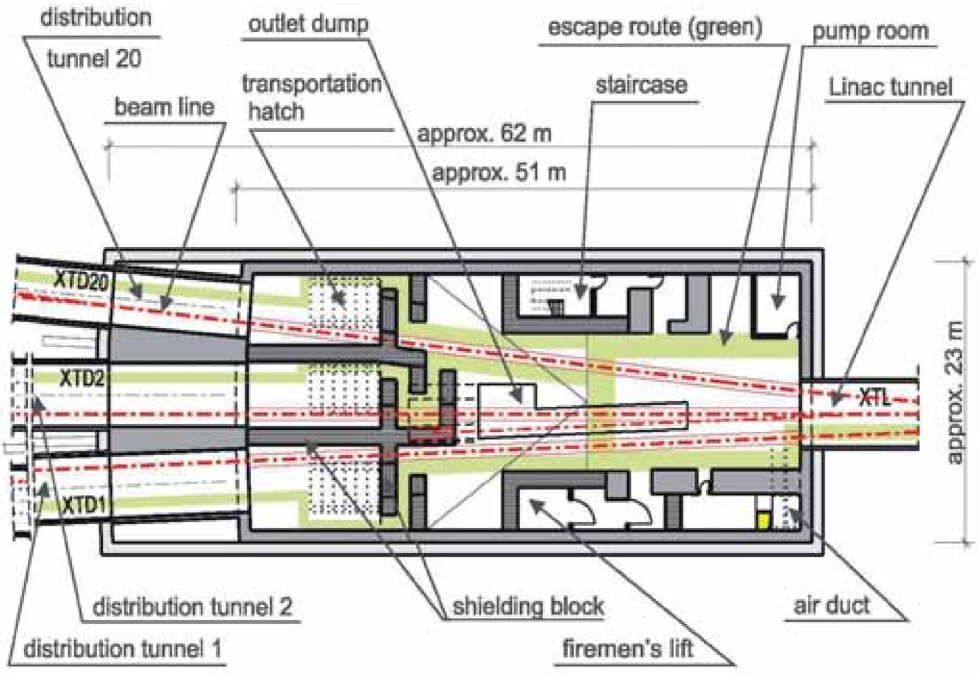

Figure 7.1.23 *Layout for the ground floor of the distribution shaft building XS1.*

Figure 7.1.24 *Three-dimensional view of the shaft complex XS1 and XS5 at the XFEL site Osdorfer Born.*

Fotomontage mit Architekturbeispiel für die Hallen, Planungsstand April 2005. © DESY

Figure 7.1.25 *Aerial visualisation/simulation of the XFEL site Osdorfer Born.*

7.1.2.5 XFEL site Schenefeld (Campus)

The XFEL site Schenefeld (also called “Campus”) ranges from the street “Am Osdorfer Born” in the north-west to an area south of the street “Holzkoppel” in Schenefeld. Figure 7.1.26 shows an overview of the position of the individual buildings on the Campus site for the first construction phase.

The Campus can be divided into two separate areas: The western part constitutes the heart of the facility. The underground experimental hall and the laboratory and office complex for the scientists and technical personnel are located here. In addition to the research in the experimental hall facilities to hold meetings, workshops, lectures and seminars are provided.

The civil construction in the eastern part of the Schenefeld site is concentrated largely on the access halls (XHE2 + XHE4) for the distribution and access shafts XS2-4 and the accompanying infrastructure and supply facilities. Both parts of the Campus are connected via a central road.

It is expected that there will be considerable interest from external institutes in building outstations on the Schenefeld site in order to get maximum benefit from the intensive scientific interplay on the campus. For this purpose a central area of approximately 4,500 m^2 has been planned in the southwest part next to the experimental hall XHEXP1.

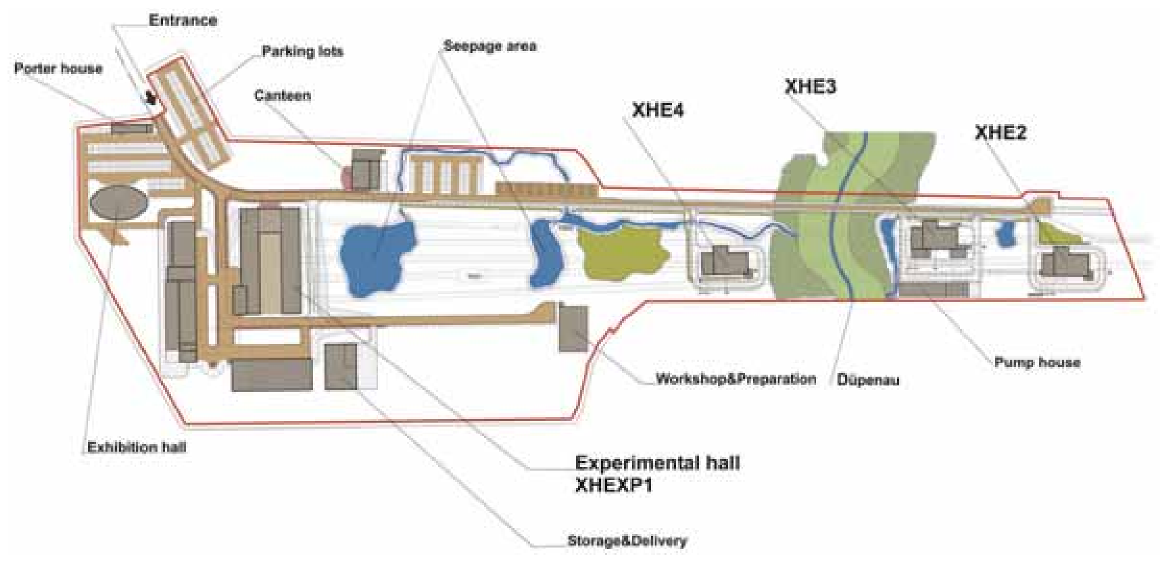

Figure 7.1.26 *Overview of the XFEL site Schenefeld for the first construction phase.*

Figure 7.1.27 shows the layout of the ground floor of the experimental hall XHEXP1 at the level of the five photon beamlines. It contains five separate areas for experiments that are positioned in line with the incoming photon tunnels. Also shown are the transport pathways and staircases. The experimental hall covers an area of 50 m × 90 m.

Two cranes are planned for the front and middle area of the hall to allow for the transport and installation of large components. The available height of the hall amounts to 14 m with considerable space above the cranes to accommodate ducts for supply media.

Figure 7.1.28 shows a three-dimensional view of the experimental hall and laboratory complex, as viewed from the incoming photon tunnels XTD6-XTD10.

The laboratory and office space for the technical and scientific staff includes seminar rooms and an auditorium for 200 people. It is located above the experimental hall. The office space is laid out for 350 staff. In addition, the building contains social rooms, transport pathways and rooms for the infrastructure needed for heating, power distribution and air conditioning. The laboratory and office building complex has an elevation of about 12 m above ground. Figure 7.1.29 shows the front view of the entrance region.

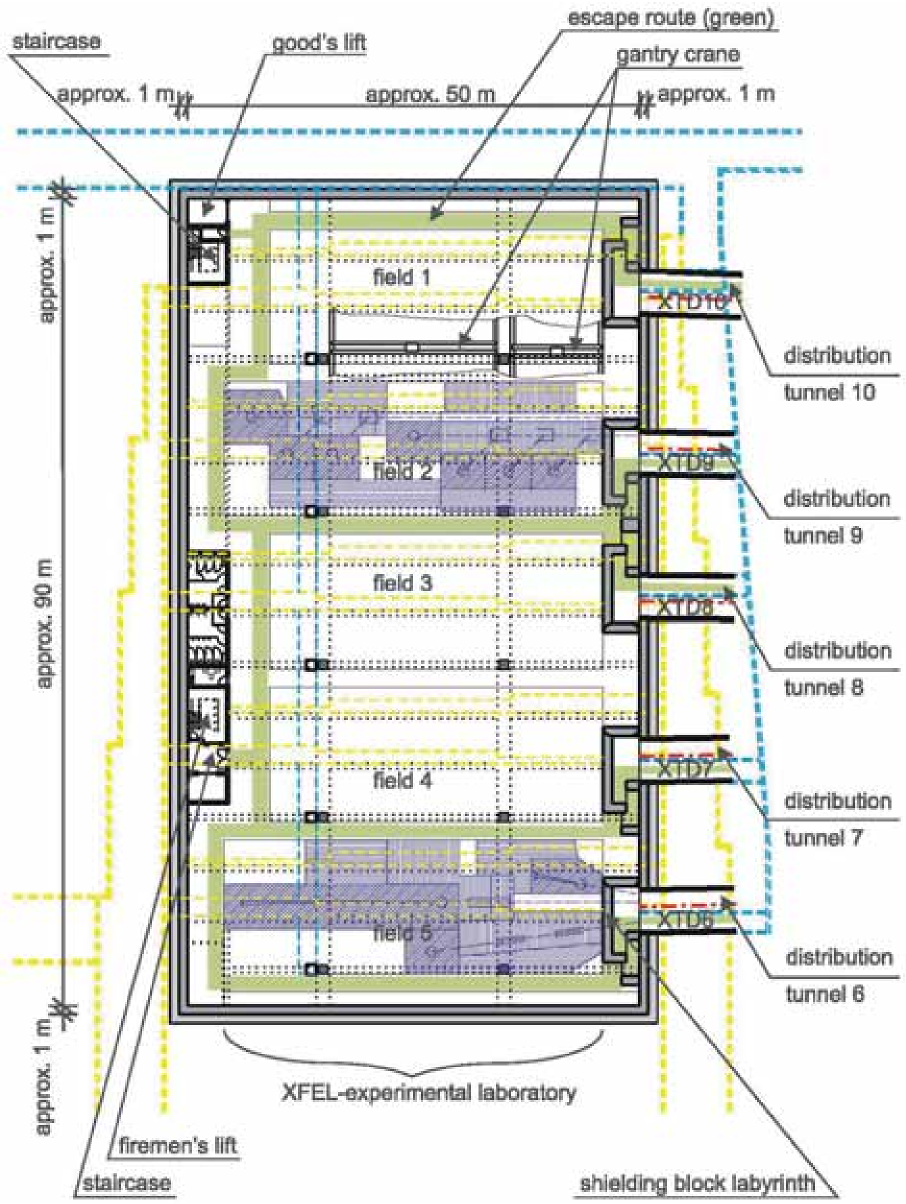

Figure 7.1.27 *Layout of the ground floor of the experimental hall XHEXP1. It contains five separate areas for experiments that are positioned in line with the incoming photon tunnels. Also shown are the transport pathways and staircases.*

Figure 7.1.28 *Three-dimensional view of the experimental hall and laboratory complex as viewed from the incoming photon tunnels XTD6-10.*

Figure 7.1.29 *Front view of the entrance region of the laboratory and office building that will be built on top of the underground experimental hall.*

In the vicinity of the laboratory and office complex a canteen, workshop, delivery area and exhibition hall for the general public are planned. For a capacity of 300 meals per day, a canteen of about 800 m^2 is needed.

In the workshop of approximately 1,000 m^2 small components can be produced or repaired, and experiments can be prepared. The long distance to the central DESY workshop makes such a facility mandatory. A small workshop for the technical services of 96 m^2 is also planned.

Besides the delivery of goods, a storage hall of 1,080 m^2 is foreseen for voluminous parts such as entire undulator modules.

The exhibition hall lies close to the entrance and is approximately 1,000 m^2 in size. It contains long-term future and current information about the ongoing experiments to visitors. This is important as many of these experiments are not directly accessible due to radiation protection or great sensitivity to vibrations induced by large visitor groups. In this area, the majority of the parking space for the XFEL campus is located.

The infrastructure for the supply of the experimental hall and the incoming photon tunnels (power supplies, transformers, emergency power, pump huts and heat exchangers, central heating and exhaust ventilation), is located next to the experiment complex. Air, water and electricity are routed to the experimental hall and the tunnels via underground channels.

Figure 7.1.30 shows an aerial visualisation/simulation of the XFEL site Schenefeld for the first construction phase.

Figure 7.1.30 *Aerial visualisation/simulation of the XFEL site Schenefeld for the first construction phase.*

7.2 Conventional technical infrastructure

7.2.1 Power distribution and power supplies

The electrical power for the XFEL Facility will be supplied from the DESY site. The power consumption will be approximately 9 MVA on the DESY site and 10 MVA on the Osdorfer Born and Schenefeld sites. This power requires a connection to the 110 kV network. The distribution on the DESY/XFEL sites will be done at the 10 kV-medium voltage level. The 110 kV-connection of the HERA storage ring provides 2 x 31.5 MVA at the 10 kV level. After the shut-down of HERA in July 2007, the existing 10 kV substation HST C can be used for the XFEL power supply.

The scheme of the 10 kV mains is shown in Figure 7.2.1. The switchboard of the substation HST C has to be expanded to feed the new transformers for the cryogenic plant XHC, the modulator hall XHM, the injector XTIN and the linac tunnel XTL. The transformers will be placed close to the consumers in order to lower the costs of the low-voltage AC cables (230 V/400 V/690 V). The input to the transformers will run directly from the 10 kV substation HST C via high-voltage cables.

The electrical supply for the Osdorfer Born and Schenefeld sites is planned to lay in the linac tunnel XTL. Therefore, four cable systems consisting each of 3 x 240 mm² Copper cables will be installed in cable trays beneath the tunnel floor. Every two cable systems will be connected together to a circuit, building a ring line. For service and maintenance purposes, a cable system or a substation can be disconnected and the power feed will still guaranteed.

Each 10 kV cable system will be twisted in order to reduce magnetic stray fields. This means sensitive monitors and electronic equipment will not be disturbed.

There are three central 10 kV substations foreseen near the halls XHE1, XHE3 and XHEXP1. The 10 kV substations will be installed above the surface in order to have direct access in case of a hazardous situation. The 10 kV power cables and the control cables run underground from the XFEL hall to the substations. A group of transformers is located adjacent to each service building.

7.2.1.1 Cables in service rooms, shafts and tunnels

All power cables are flame retardant and non-corrosive, so called “fire retardent and non-corrosive (FRNC)” cables. This applies for the 10 kV power cable and modulator pulse cables as well. The AC cables run on trays under the tunnel floor and in the shafts between the tunnel and the service rooms. The DC, control and signal cables are placed on separate cable trays and routes.

7.2.1.2 Distribution of the low voltage mains

The levels of the low voltage loads are:

- 690 V/400 V for the modulators and power supplies; and
- 400 V/230 V for heating, ventilation and air conditioning (HVAC), water pumps and lighting.

The 10 kV transformers provide the applied voltages. The low voltage energy will be distributed in switchboards located in separate service rooms.

The loads in the tunnel are: auxiliaries of the klystrons, electronics cupboards, magnet power supplies, diagnostics, magnet movers, etc. Here, 400 V/230 V are needed. Therefore, sub-distributions and mobile distribution panels will be placed at regular intervals in the tunnel.

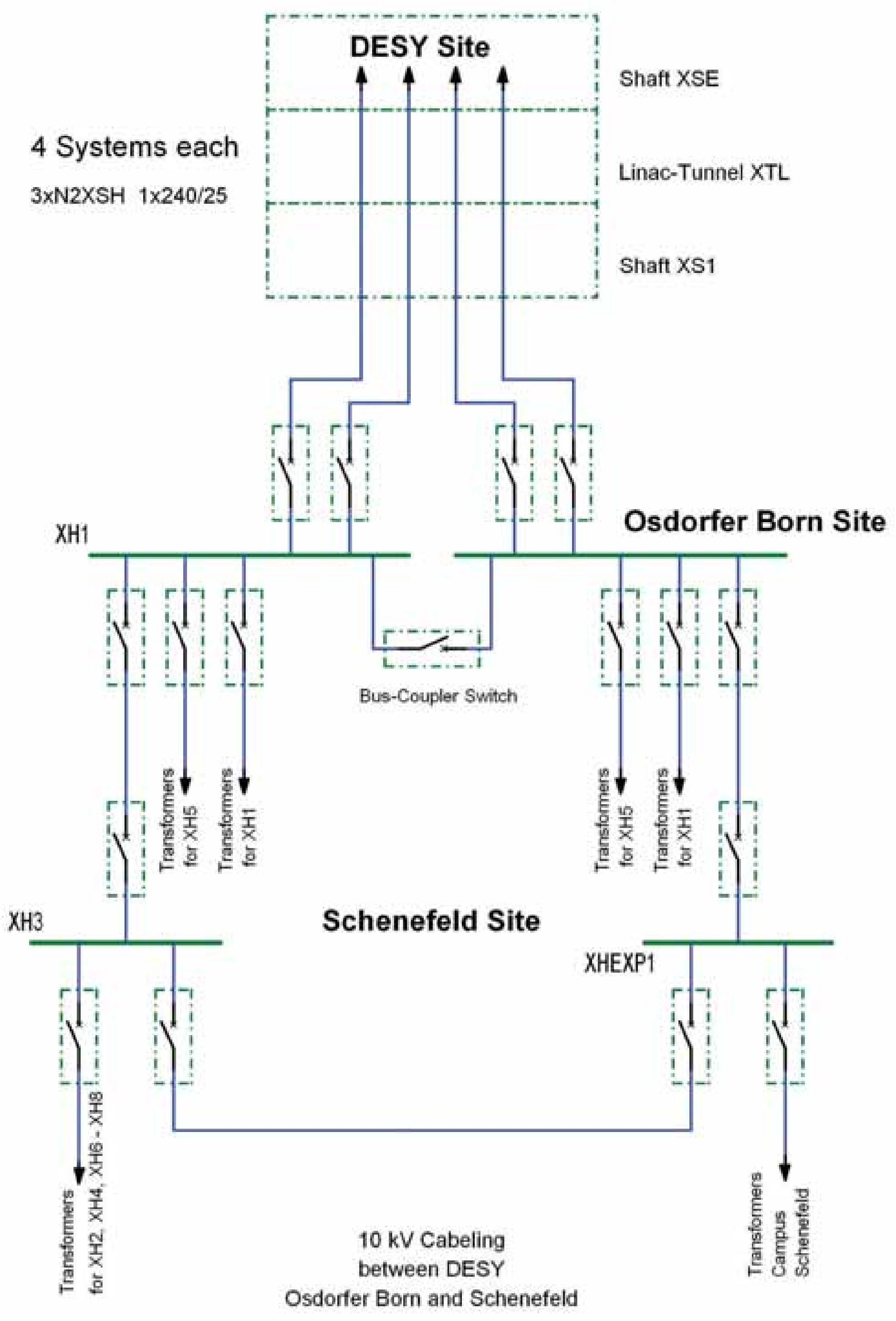

Figure 7.2.1 *10 kV mains of the XFEL.*

7.2.1.3 Tunnel lighting

The tunnels will be lit by fluorescent lamps installed under the tunnel ceiling above the walkway. The planned illumination is sufficient for a walkway but not for a workplace. For the illumination of a workplace for temporary work, portable lamps or spotlights have to be used.

7.2.1.4 Emergency and auxiliary power

The security relevant loads will have a back-up system such as an emergency power diesel generator, an uninterruptible power supply or DC batteries. The emergency generators will power the illumination of escape routes, stairways and the smoke extractors. They will be installed above the surface near the buildings XHE1, XHE3 and XHEXP1.

7.2.2 Magnet power supplies

Electromagnets are used to guide and focus the electron beams in the vacuum chambers. Their power supplies will be installed in different locations according to their purpose.

7.2.2.1 Power supplies in the linac tunnel XTL

In the cryomodules the magnets are superconducting. This means high current and low voltage. The cables between the magnets and the power supply have to be short, therefore, the power supplies in the linac tunnel XTL will be located close to the magnets.

Power supplies are also needed for the klystrons. The power supplies for the cryomodule magnets and for the klystrons are grouped into rack units every 48 m. In this way, cable losses and the number and length of cables are drastically reduced in the tunnel. Every rack unit has one redundant spare power supply which can be engaged by remote control.

The heat losses from the power supplies are transferred to the cooling water. The semiconductors and chokes are cooled using water with a temperature of 30°C. The cabinet air is cooled by an air/water cooler using 18°C water. The ventilation circuit of the cabinet works in a closed loop and is separated from the tunnel air. In this way the heating of the tunnel air by the power supplies is reduced.

7.2.2.2 Power supplies for the mormal conducting magnets in the beamlines

Due to their size, the power supplies for the normal conducting magnets are located outside the tunnel in service rooms that are ventilated and air conditioned to assure optimal efficiency. The DC cables between the power supplies and the magnets in the tunnel run on cable trays through the shafts and the tunnel. The cables will be installed in one piece to prevent overheating by bad connections. These cables are FRNC.

The steering and correction power supplies with power up to 10 kW are mostly cooled by air. The power supplies above 10 kW are cooled by 30°C cooling water. This reduces the heating of the ambient air. The semiconductors, chokes and transformers are directly water cooled. The electronic racks for regulation and controls are cooled by the ambient air. The power supplies will not be equipped with fans. This increases reliability and reduces the time and effort for maintenance.

The power supplies will have a grounding system. By this the magnets inside the tunnel are short-circuited and grounded during a maintenance phase. Due to this safety measure it is possible to perform work inside the tunnel by non-electrician staff.

The power supplies will have a redundancy system, which allows the switching-in of a spare power supply in case of a failure of the running power supply.

The location of the power supplies and the electrical power consumption under typical operating conditions at a beam energy of 17 GeV are listed in Table 7.2.1.

Location	**Name**	**Power consumption [kW]**
Cryogenics hall	XHC	2,300
Modulator hall	XHM	6,960
Access shaft "Osdorfer Born"	XS1	2,880
Access shafts "Schenefeld Campus"	XS2-4	2,210
Experimental hall and auxiliary buildings on "Schenefeld Campus"	XHEXP1	4,410
Total		**17,760**

Table 7.2.1 *The location of the power supplies and the electrical power consumption under typical operating conditions at a beam energy of 17 GeV. Locations and number of power supplies.*

7.2.3 Magnet water cooling and air conditioning

7.2.3.1 Water cooling

Extensive water cooling systems are needed for the XFEL Facility. The cooling water circulates in a closed loop. The recooling of the cooling water occurs by so-called hybrid dry coolers (see Figure 7.2.2). Three locations are foreseen: on the DESY site near the shaft XSE, on the Schenefeld site near the shaft XHE3 and near the experimental hall XHEXP1.

The hybrid dry cooler normally works dry by releasing the heat directly to the air. Only in the summer seasons are the coolers wetted with water to guarantee the supply temperature of 30°C. This way, a lot of auxiliary water and costs can be saved. An additional advantage is that the hybrid dry cooler does not create wafts of mist. It is a closed single loop circuit system without heat exchangers between hybrid dry coolers and water cooling circuits.

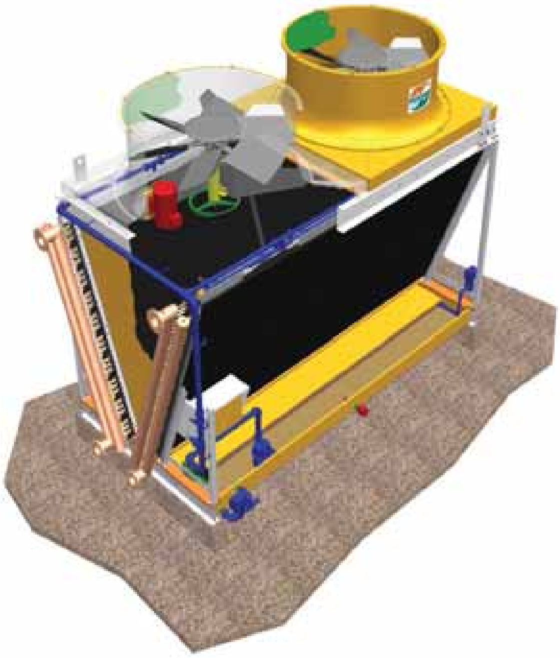

Figure 7.2.2 Hybrid dry cooler.

The auxiliary water is taken from the water of the wells. About 60,000 m³ per year are needed which can be supplied on the DESY site.

For the cooling of the air condition systems and the electronic racks, chilled water is foreseen. The chillers are located in the pump rooms and are, in turn, cooled by the hybrid dry coolers. The chilled water flows in a closed water circuit.

7.2.3.2 General requirements of the cooling water

The cooling water absorbs the heat of the loads in the tunnels and the modulator hall. It is in direct contact with electrical components. Therefore, the water is deionised. Due to the deionised water, only Copper, stainless steel and red brass are acceptable for materials which are in direct contact with the water. For flexible connections only, reinforced EPDM hoses and stainless steel corrugated pipes are allowed.

The supply temperature of the cooling water is 30°C. The return temperature should be higher than 50°C to reduce the amount of water that has to be circulated. This saves pumping power and reduces the number of coolers and the amount of outside installation area. The maximum pressure difference for all loads is 4 bar. The nominal pressure of the whole system is 10 bar. Each component must withstand a test pressure of 16 bar.

The water used to wet hybrid dry coolers must be deionised in order to prevent calcification. During frosty weather the coolers must be protected by Venetian blinds as the water in the coolers is not frost-protected. During hard frost and shutdown the coolants and the water pipes have to be drained. The deionised cooling water should be saved in a tank.

For cooling the electronic racks in the tunnel, chilled water is needed. The supply temperature is 18°C in order to prevent condensation in the electronic racks. The dew point of the tunnel air may not exceed 16°C. Again, the return temperature should be higher than 26°C to reduce the amount of water that has to be circulated. Electric parts in the cold water circuit should be only Copper or stainless steel for parts with direct water contact, to avoid corrosion and pitting. For flexible connections EPDM-tubes and/or stainless steel corrugated pipes are allowed.

Also for the air conditioning, chilled water is required. The water temperature is 6°C in the supply pipe and 12°C in the return pipe. The requirements for the pressures are the same as for the other water systems.

7.2.3.3 Pump rooms

Each pump room contains the main water pumps, the chillers, the deionised water treatment, the compressed air machines and their associated control panels. For maintenance, a 5 t crane is foreseen. There are also buffer tanks for the pressure maintenance and the sprinkler water for the hybrid dry coolers. The water pipes between the pump room and the outside hybrid coolers run underground.

7.2.3.4 Water cooling pipes

The water cooling pipes are designed according to the heat load that has to be transported. The height difference between the tunnel floor and the pump rooms is up to 30 m. In order to keep the return pressure in the tunnel pipe above 0.5 bar, booster pumps are foreseen to push the water to the pump room level. One booster pump is on standby. The booster pumps need a space of 4 m x 3 m. A crane of 1 t is necessary to exchange a pump.

For the leakage water in the tunnel, a pipe is installed. The leakage water pipe will have access every 50 m.

The return pipe will be thermally insulated to reduce the heating of the tunnel air. All pipes need sliding supports and axial expansion joints. All expansion joints and outlets will be accessible for maintenance. The components are connected directly or via sub-distribution to the pipes.

The dimensions of the main pipes, the space needed and the forces for fixed and intermediate fixed points are listed in Table 7.2.2.

Tunnel	Pipes cooling water	Space needed [mm] x [mm]	FP force [kN]	SP force [kN]	Pipes chilled water	Space needed [mm] x [mm]	FP force [kN]	SP force [kN]
XTL	DN 300	1 050 x 700	250	110	DN 100	610 x 460	90	72
XTD1 XTD2	DN 80	530 x 420	73	63	DN 50	480 x 390	47	43
XTD3	DN 100	610 x 460	80	65	DN 65	530 x 405	56	46
XTD4 XTD5	DN 80	530 x 420	73	63	DN 50	480 x 390	47	43
XTD6		530 x 420	73	63	DN 50	480 x 390	47	43
XTD7	DN 150	730 x 530	125	90	DN 50	480 x 390	47	43
XTD8 XTD9	DN 80	530 x 420	73	63	DN 40	480 x 380	47	43
XTD10	DN 150	730 x 530	125	90	DN 50	480 x 390	47	43

Table 7.2.2 *The dimensions of the main pipes, the space needed and the forces for fixed and intermediate fixed points. Cooling water: 30°C supply temperature, 50°C return temperature; chilled water: 18°C supply temperature, 26°C return temperature, FP: fixed point, SP: intermediate fixed point.*

7.2.4 Heating, ventilation and air conditioning

For each of the buildings (shafts, halls and tunnels), heating, ventilation and exhaust systems are foreseen. The total number of systems is approximately 100. The air-handling systems are equipped with air filter, heater, ventilation and extractor fans as well as silencers. They are steered by digital data controllers which control the operating state, the interlocks, and the temperature and communicate with a global control system.

During operation of the XFEL, the tunnels are ventilated continuously to remove the humidity generated by water diffusion through the tunnel walls, leakages through cracks and cooling water losses. The air injected into the tunnel is dried prior to injection so that it can absorb the additional humidity.

The air conditioning appliances for the tunnels are located close to the shafts to keep the air ducts short. For the air drying chilled water of 6/12°C is required. In winter the outside air must be heated. The temperatures of the hot water for the heaters are 30/50°C. Hot water is produced by a natural gas-powered central-heating boiler. On the DESY site, the heating, ventilation and air conditioning units are connected to the DESY long-distance heating.

Special air conditioning is required for the tunnel sections accommodating the SASE undulators where the ambient temperature has to be kept constant to within ±0.1°C. These sections will be equipped with local air conditioning systems that are installed in the tunnels. Detailed simulations are presently being carried out to establish an optimal solution for the layout.

In case of a fire in the linac tunnel XTL, the smoke is removed by two smoke extractors which operate independently from each other. The smoke is extracted by a dedicated smoke extraction duct which is installed above the walkway under the tunnel ceiling. About 25,000 m³ of air have to be transported per hour. The smoke extraction occurs close to the origin of the fire and is organised in sections using flaps in the smoke extraction duct. The flaps are controlled by smoke detectors. The supply air unit supplies the tunnel with fresh air in the case of fire. The smoke extraction system is backed up by an emergency power generator.

The air conditioning and the smoke extraction are performed by separate units. The outside air is treated before entering the tunnel at the shaft XSE. The air flows from the shaft XSE to the shaft XS1. At XS1 the tunnel air is released. The air exhaust ducts conduct beyond the roof of the building to keep the access roads to the halls smoke free.

In the tunnels that contain the photon beamlines (XTD6-10), the smoke is extracted through longitudinal ventilation. After detecting smoke or fire in the tunnel by smoke detectors, the ventilation is activated. The air moves from the experimental hall XHEXP1 to the access shafts located in the upstream direction (XS2-4). A ventilation fan presses the outside air into the tunnel and an extractor fan sucks the air and smoke out of the tunnel at the upstream shaft.

	Equipment	**Location of HVAC systems**
XHC	Cryo plant	Roof of the cryo plant
XTIN	Floors of the injector building	HVAC units on each floor
XTIN	Injector tunnel	First upper floor XHEIN
XHM	Modulator hall	First upper floor XHM
XSE	Entrance shaft under the radiation shielding ceiling	First upper floor XHM
XTL	Linac tunnel	Supply unit in First upper floor of XHM Extraction ventilator in shaft of XS1
XTL	Smoke extractor 1	First upper floor of XHM
XTL	Smoke extractor 2	Supply unit and smoke extractor in second basement
XS1 to XS4	Power supplies	Several locations at the shafts XS1-4 and entrance to the tunnels at XHEXP1
XS1 to XS4	Staircase overpressure unit	Shafts XS1 to XS4 under the radiation shielding ceiling to the tunnels XTD1 to XTD10
XHEP1	Experimental hall	HVAC building near XHEXP1 with nine air-conditioning systems and six smoke extraction units
XHEP1	Laboratories in office building	HVAC rooms in office building
	Canteen and kitchen	HVAC room near canteen

Table 7.2.3 *The specific location of the HVAC systems for selected buildings of the XFEL Facility.*

The access halls and shafts are used for personal access and for material transport. They receive the cables, water pipes and air ducts. 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 minimises 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 hutches 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 to keep the floor and the escape routes smoke-free.

Table 7.2.3 lists the specific location of the 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 Tera-Electronvolt Superconducting Linear Accelerator (TESLA) linear collider **[7-1]**, will be applied for the XFEL linear accelerator **[7-2 – 7-4]**. 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 **[7-5]**. 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 (SCBs).

The cryogenic supply of the linac has to be maintained continuously 24 hours a day/ seven days a week for run periods in the order of two to three 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, in a large accelerator module 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). The Helium supply for the TESLA Test Facility (TTF) and the Free-electron LASer in Hamburg (FLASH) linac also 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 **[7-3]**.

7.2.5.1 Cryogenic components of the linac

Figure 7.2.3 summarises the cryogenic components of the linac: 116 cryomodules of the main linac, two 3.9 GHz cryomodules, 11 valve-boxes of the SCB type, two bunch compressor sections and three 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 separately 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 already be 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.

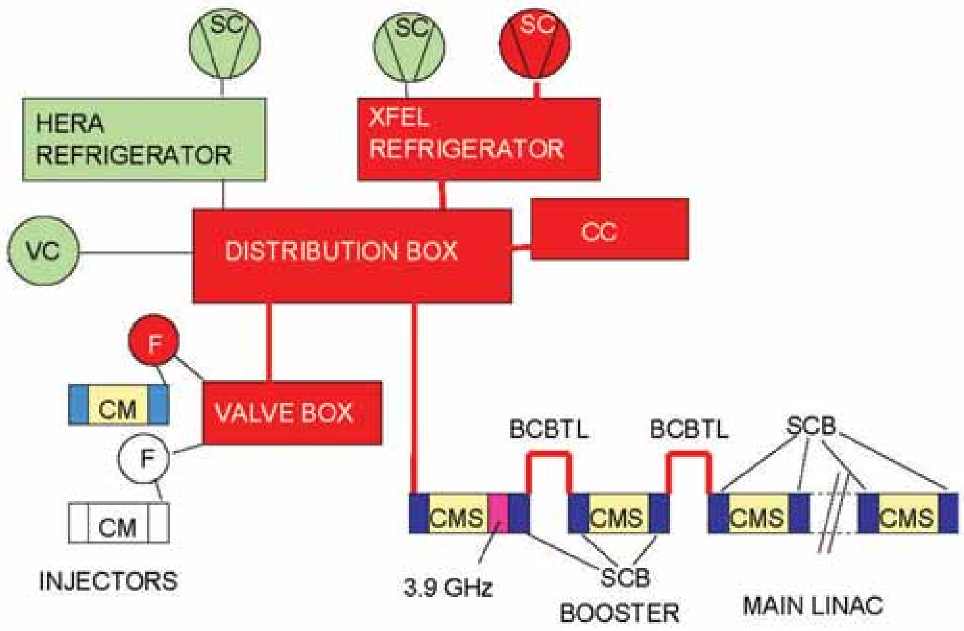

Figure 7.2.3 *The cryogenic components of the XFEL linac. SC= screw compressor, CC=cold compressor, VC= warm vacuum compressor, F=feed box, CM= cryomodule, CMS= cryomodules in a string, BCBTL= bunch compressor bypass transfer-line, SCB= string connection box. Colour code: red = main installations, light 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 bypassed 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 sufficiently filled 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 +/-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.)

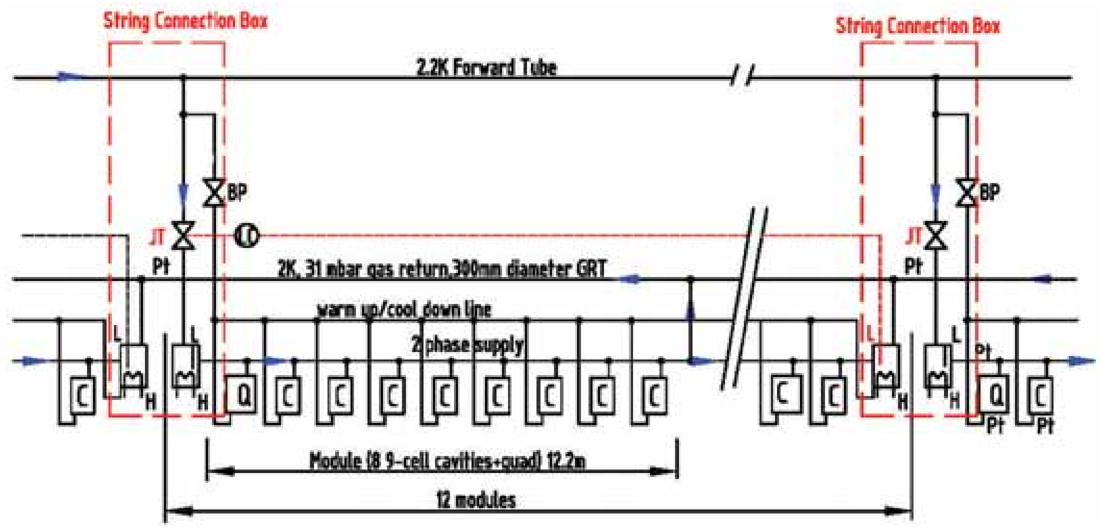

Figure 7.2.4 *A simplified flow scheme of the 2 K cooling loop of a cryogenic string. JT = Joule-Thomson valve, BP = bypass valve for cool-down/warm-up, L = Level probe, H = electrical heater, C = cavity vessel, Q = quadrupole (magnet package).*

7.2.5.3 Transient and fault condition operations

The cool-down/warm-up procedures for the XFEL linac were reported in detail **[7-6]**. 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 linac **[7-7]**. Some SCBs are equipped with vacuum barriers resulting in vacuum sections of about 300 m in length, to limit the impact of insulation vacuum breakdown. 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 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 interruptions in 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 summarises 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 summarises 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.

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.

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	0.00	0.94	0.00	0.00	0.00	0.00
Cables	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 (in W) 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.*

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) **[7-1, 7-8]**. The TMR had been designed with valuable advice from Conseil Européen pour la Recherche Nucléaire (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 **[7-1, 7-8]**. 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 recooling 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	2K static	2K dynamic	5-8K static	5-8K dynamic	40-80K static	40-80K 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 (in W) of the main linac cryomodules (104 modules RF operated, 12 in cold standby) under nominal operating conditions with reference to Table 7.2.4, 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 JT-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 JT 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 the ambient temperature 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 **[7-9]**. DESY has a long time operational 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 summarised in Table 7.2.6. The coefficients of performance (COPs) (the inverse of the overall refrigerator efficiency) at the different temperature levels, correspond to measured values of the LHC plants **[7-9]**, 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	≤ 870 W/W	2.13 MW	59
5-8K	4.00 KW	≤ 220 W/W	0.88 MW	24
40-80K	30.00 KW	≤ 20 W/W	0.60 MW	17
total			≤ 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 **[7-4]**.

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 will be 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) **[7-10]**. In addition, out-dated equipment would have to be replaced to ensure the required availability for the operation of the XFEL linac **[7-2]**. 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-m3 liquid storage dewar and the Helium purifiers will be adapted to the XFEL cryogenic system with minor changes.

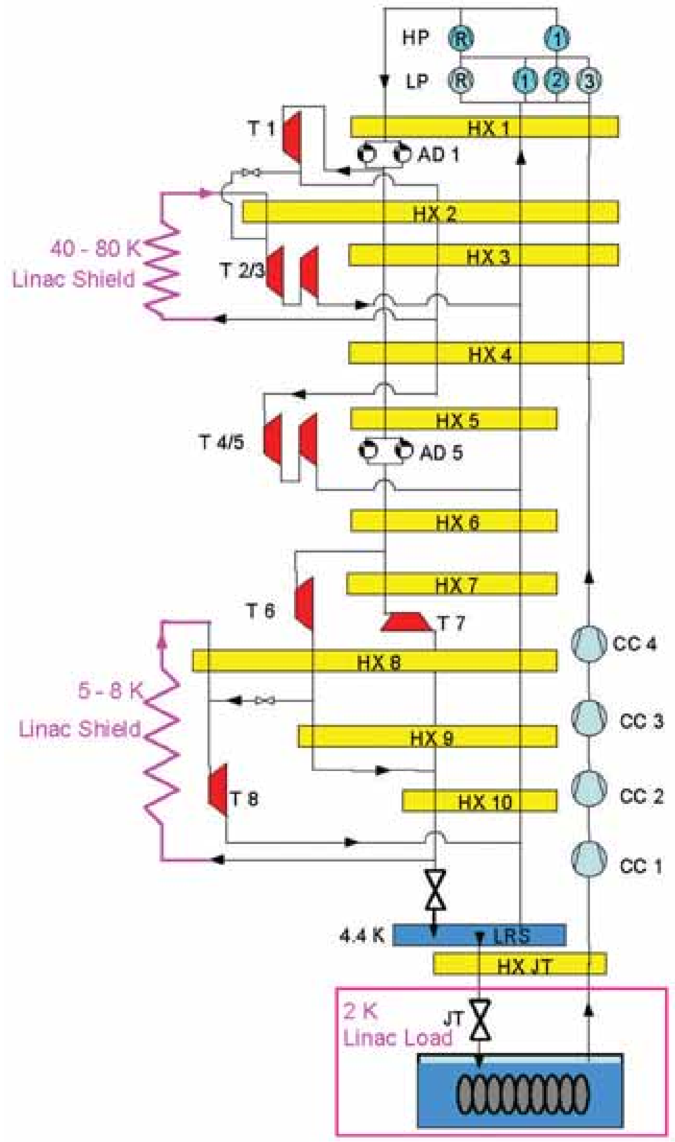

Figure 7.2.5 *Flow diagram of the XFEL refrigerator. LP 1,2,3 = low pressure screw compressors, LP R = redundant low pressure screw compressor, HP 1 = high pressure screw compressor, HP R = redundant high pressure screw compressor, HX = heat exchangers, T = expansion turbines, AD = impurity adsorbers, 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 to industry, to achieve the most economical result. The flow scheme corresponds to the TMR* **[7-1, 7-8]**.

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 [**7-1, 7-8]**. 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 **[7-11]**. 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 programmes 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 Programmable Logic Controllers (PLC) controls of the screw compressors, the cold compressors and other sub-systems as well as state-of-the-art microprocessor-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 timeframe. It provides reliability, stability, a rich functionality, extensibility, and has a powerful user base within the European partner states of the XFEL collaboration.

7.2.6 Accelerator Module Test Facility

7.2.6.1 Objectives of the Accelerator Module Test Facility

All main components constituting the accelerator modules, e.g. cavity, magnets and RF coupler, will have to be tested before the module assembly. Nevertheless, the completed accelerator modules also have to be qualified after the assembly and before their installation in the XFEL tunnel. The qualification includes a check of the general mechanical dimensions, the determination of the RF properties, and the measurement of the cryogenic performance of all systems, in particular, the gradient performance of the cavities. All the test results from the test facility will be used as a fast feedback into the series production, in order to avoid failures and guarantee the performance.

In addition to the cavities, magnets and accelerator modules, some RF components will also have to be tested. This includes testing the waveguide systems and the klystrons.

7.2.6.2 Test programme for single accelerating cavities

The maximum accelerating field and the corresponding unloaded quality factor Q_0 of each single cavity will be measured at a temperature of 2 K in a vertical bath cryostat. To increase the throughput of the vertical test stands, four cavities are assembled in one cryostat insert. The design of the cryostats can be scaled from the vertical test dewars of the TTF **[7-12, 7-13]**. Each cavity will be equipped with a fixed coupler antenna ($Q_{ext}=1\times10^{10}$) and a pick up probe ($Q_{ext}=1\times10^{13}$). The cavities will be operated in the accelerating π-mode. The accelerator field will be increased to its maximum value in steps. At each step the cavities will be powered for 20 s in CW-operation mode. In total about 40 hours are needed for one complete test run with four cavities, including the assembly and disassembly of the insert to the cryostat, and the cool-down and warm-up procedures.

The inserts will be assembled at the cavity manufacturer’s site and delivered to the test facility. Qualified cavities will be sent to the accelerator module manufacturer. Close to 1,000 single cavities have to be tested at a rate of about 12 cavities per week. Spot tests of the cavities already welded into their Helium-tanks will also have to be carried out in order to reveal systematic manufacturing errors caused by the assembly procedure. The tests will be carried out at 2 K in a CHECHIA **[7-14]** like cryostat. The tests include coupler processing and tests of the tuning system. About two weeks are needed for one complete test.

7.2.6.3 Test programme for the magnets

The performance of the superconducting magnets will be tested at 4.5 K in a horizontal bath cryostat. A so-called “anti-cryostat” allows accessing the bore of the magnet at room temperature with harmonic coils and a stretched wire system. Thus, the test programme includes measuring the magnetic field quality, saturation effects due to the Iron, and magnetic axis as well as roll angle measurements. In the cryostat one magnet will be tested at a time. In total, about 120 packages of superconducting magnets have to be tested within the total module series production of about two years.

7.2.6.4 Test programme for the accelerator modules

The performance of the accelerator modules will be tested at module test benches. The tests include cryogenic performance tests, and performance tests of the cavities. Preliminary tests will be done outside the test stands and comprise a reception control. The cryogenic tests include the integral leak check of all vacuum systems, cryogenic process tubes and the current leads, the test of the instrumentation and measurements of the static heat load at different temperatures. The final check of the magnet package together with the current leads will also be carried out.

During the performance tests of the cavities, the maximum accelerating field of the cavities and the corresponding unloaded quality factor Q_0 as well as the X-ray radiation and the related dark currents, will be measured. The quality factor will be monitored by means of cryogenic measurements of the dynamic heat load.

The pre-conditioned RF couplers will be further conditioned. The RF phase will be adjusted within +/- 20 degrees. There will also be a possibility to process the cavities.

Twelve days are needed for the complete test of one accelerator module, including the mechanical assembly and disassembly on the test bench. In total, approximately 120 modules have to be tested within two years.

7.2.6.5 Test programme for the klystrons

The performance of the XFEL klystrons will be checked at a klystron test stand. Each klystron will be checked together with its auxiliaries and pulse transformer. The assembled unit will then be lowered into the XFEL tunnel. In total, 31 klystrons have to be tested at a rate of two klystrons per month.

7.2.6.6 Test programme for the waveguides

The waveguide system for the individual accelerator modules will be completely mounted, checked, tuned and conditioned at full power. About 120 waveguide systems have to be tested within two years.

7.2.6.7 Layout of the Accelerator Module Test Facility

The given test rates and the estimates for the test schedules mean the following test stands need to be installed in the test hall:

- three test benches for complete accelerator modules;
- two vertical cryostats for cavities;
- one CHECHIA-like horizontal cryostat for cavities embedded in the Helium-tank;
- one horizontal bath cryostat for testing the magnets;

- one test stand for testing the klystrons;
- one test stand for testing the wave guides.

The number of test benches and vertical cryostats includes an overcapacity to compensate for shutdown periods, maintenance, repairs and repetition of tests. The Test Facility will be located on the DESY site and will comprise an experimental hall, a pump house, a Helium compressor station, and an office building.

The test facility hall houses all test stands, transport areas, accelerator modules' baking-out areas, and areas for intermediate storage of modules, cavity test inserts, magnets, etc. The hall will have an overall size of 70 m × 60 m ground area and a height of about 11 m. Two parallel hall cranes, each with a capacity of 20 t, a span of 30 m and a hook height of 8 m will be installed (see Figure 7.2.6).

Each individual module test bench including the CHECHIA-like cryostat has to be surrounded by a concrete shielding of 0.8 m thickness and covered by a roof shielding of 0.8 m thickness in order to establish radiation safety in all parts of the test hall. The front door of each shielding can be moved horizontally on rails in order to allow access to the cavity in the CHECHIA-like cryostat, or to shift the module, together with its support structure, into the mounting area.

For the installation of an accelerator module on a test bench, the module will be moved by the hall crane from the storage area to the front of one test bench and installed on a support structure. After installation, the support structure will be moved back into the shielding of the test bench. During the installations inside the shielding, the front door can be shifted relative to the support and will stay open.

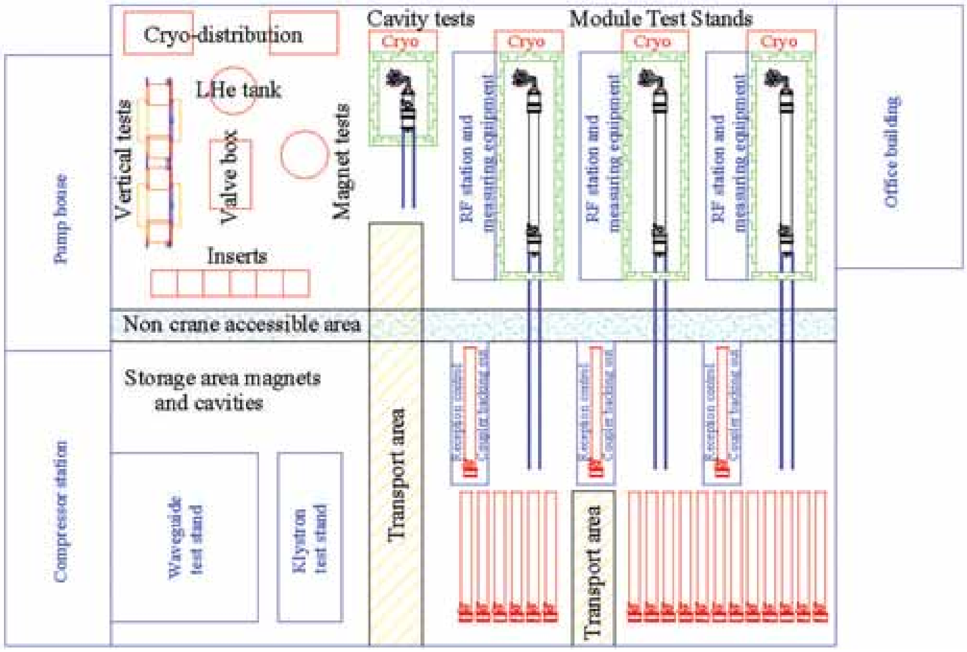

Figure 7.2.6 *Ground plan of the Accelerator Module Test Facility.*

The vertical cryostats will be inserted into the ground and covered with movable concrete shielding blocks of 1.2 m thickness. The cryostat inserts will be moved from the storage area into the cryostats using the hall crane.

The pump house is placed in the immediate proximity of the HERA water towers and contains water cooling and air compressing equipment.

The Helium compressors' station houses a set of compressors needed to lower the vapour pressure of the Helium baths to 30 mbar **[7-13]**. The walls of the compressors' station and the pump house will be sound protected.

The office building will comprise a workshop, control rooms, offices and social rooms.

7.2.6.8 Cryogenic system

The cryogenic system of the test facility will be supplied with cold Helium from the HERA refrigerator. For the continuous operation of the test hall, cooling capacities of about 10 kW at 40/80 K, 1.0 kW at 4.5 K and 0.6 kW at 2.0 K are needed. In order to reduce the strain on the Helium distribution system, only the 40/80 K and 4.5 K circuits will be branched to the cryogenic stands via a ~200 m long transfer line connecting the HERA refrigerator with the test facility. The 2 K liquid Helium will be supplied there by isenthalpic expansion of the 4.5 K Helium, which will be sub-cooled to 2.2 K before the expansion by means of counter-flow heat exchangers. A distributed warm compressor system will, therefore, be used to lower the Helium vapour pressure to 30 mbar. This will result in a required Helium liquefaction rate of about 50 g/s to be supplied on average from the Helium plant. Peak liquefaction rates will be levelled by means of a 10 m^3 liquid Helium tank.

The cryogenic system of the test facility will be designed as a modular structure (see Figure 7.2.7) and will basically consist of two sub-systems. The first one will be in charge of the cryogenic supply for the three module test benches and the CHECHIA-like cryostat, whereas all bath cryostats will be supplied from the second sub-system. Inside each sub-system the cryogenic supply is in turn subdivided into two "layers" in order to operate the test stands independently from each other, to avoid air condensation on cryogenic valves during exchange and installation of modules, or cavities or magnets, and to reduce the consequences of leaky valves. For each sub-system the corresponding valve box represents the first layer while the feed boxes of the accelerator module test benches and the CHECHIA like cryostat, together with the valves of the vertical and horizontal bath cryostats, form the second layer. As a result, all cryogenic supply and return tubes are separated by two cryogenic valves in series from each test stand.

The valve box in each sub-system will be supplied from the test hall distribution box. In order to compensate for heat loss in the connecting transfer lines, sub-coolers will be provided in the feed and valve boxes and the liquid Helium tank.

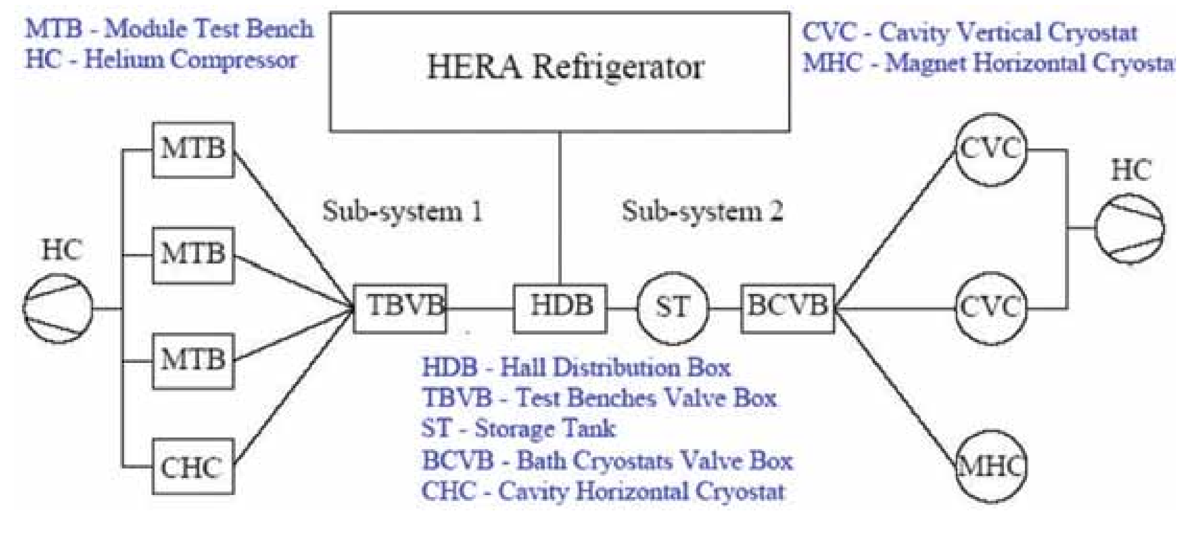

Figure 7.2.7 Block diagram of the cryogenic system.

Each test stand will be equipped with a 2 K vapour return tube. The return tubes in each sub-system will be connected to one 300 K Helium compressor unit. One additional Helium compressor unit will provide backup for both sub-systems. Before being processed by the compressor, the cold Helium will be warmed to ambient temperature in a heat exchanger. In the exhaust of the compressor unit, the pumped mass flow can be measured by warm gas flow meters for accurate measurement of the heat load in the 2 K circuit.

7.2.6.9 RF systems

Since one accelerator module test bench is mainly intended to compensate for maintenance, repairs, etc., and only spot checking of the cavities embedded into the Helium-tank will be carried out on the CHECHIA-like test stand only, three RF stations, each equipped with a 10 MW klystron and a modulator set, will be installed. The two RF stations will be permanently connected to the test bench. The third RF station can be switched between one test bench and the CHECHIA-like test stand. It is supposed that RF power can simultaneously be supplied to the test stands in parallel and independently from each other for conditioning the couplers.

Two additional RF stations will be installed for testing waveguides and klystrons. The RF station for testing the klystrons will be designed so as to allow a trouble-free installation of each klystron to be tested.

7.2.6.10 Vacuum system

For the insulation vacuum of the cryogenic system, standard turbo-molecular pump units will be provided. Each accelerator module test bench will get two such units allocated to the insulation vacuum of the modules.

The main RF couplers of one accelerator module will be equipped with one pumping tube to which one getter pump and one Ti-sublimation pump will be connected without individual valves. There will be only one manual valve at the pumping tube. The pumps and pumping tube will stay at each individual accelerator module from the assembly during the tests, until installation in the XFEL tunnel.

The cavity vacuum will mainly be created by means of oil-free turbo-molecular pump units. Each unit contains an integrated Helium leak detector. The accelerator module test benches and the CHECHIA-like stand will also get getter pumps to reach ultra high vacuum (UHV) conditions for the cavity vacuum. There will be also oil-free pumps, clean rooms, leak detectors and turbo-molecular pumps which can be moved according to requirements.

7.2.6.11 Controls

There will be different sub-control systems for the RF, vacuum and cryogenic systems, which have to be integrated by an industrial visualisation and data management system. In general, standard industrial components will be used as far as possible. The transfer of data between the different systems and data management will be mandatory for the operation of the test facility.

7.2.6.12 Infrastructure

Operation of the test facility will require 5 MVA of electrical primary power, 2.5 MW equivalent of water-cooling capacity, and about 330 m^3/h of instrument air (operation of the HERA refrigerator is not included in these numbers).

7.2.7 Survey and alignment of XFEL

Planning and assembly of the whole facility will be assisted by the DESY survey group from the first peg-out of buildings via control survey during construction of buildings and the tunnel, installation of components, alignment of the accelerator components up to maintenance work and inspection survey. In order to realise the high accuracy demands on the alignment of the accelerator and the experiments, special survey methods are being applied which may have an impact on buildings or operating procedures at certain places.

Geodetic reference networks serve as fundamentals for all survey methods. The technical design of the respective reference systems depends on the accuracy required.

7.2.7.1 Basic networks

In order to mark any installation of the facility, a basic network has to be established. Coordinates of aboveground reference points along the accelerator axis have to be determined in relation to the existing coordinate system at the respective site. In case of the XFEL, this will be the DESY site coordinate system with respect to HERA/PETRA.

Primary reference network

The primary reference network ensures the correct location and orientation of the various buildings, the tunnel, the accelerator and accelerator subsystems to each other. It is essential to install stable reference monuments (see Figure 7.2.8) at every site and at selected stations along the trace of the accelerator. These monuments are suitable to serve as a reference for position (GPS) measurements, height and gravity.

Figure 7.2.8 Survey reference monument.

At the Schenefeld site, approximately 10 survey reference monuments will be installed. At the other premises four of these pillars will be installed, which can be removed after construction work is done. Their role in the primary reference network will then be taken over by the survey pillars on the roofs of the buildings.

In order to enable the connection between the XFEL and the existing accelerators at the DESY site, the new reference monuments will be surveyed, together with existing survey monuments at the DESY site. The coordinates aboveground will be determined by using geodetic receivers of the GPS satellites. The required global precision of every reference point in the XFEL area has to be in the range of 5 mm (one standard deviation). The precise vertical network has to be established by precision levelling. The coordinates of the primary reference network have to be transferred to the subterranean reference network via sounding.

Secondary reference network

The (subterranean) secondary reference network ensures the global positioning of the components of the accelerator. The network has to be established with wall-mounted target marks (see Figure 7.2.9) at intervals of approximately 10 m. The complete survey system consists of these target marks and a wall-mounted rail on which the measuring instrument can be mounted and transported to every designated position. The target marks have to be installed at variable heights from floor level to top. Wherever possible, additional target marks have to be installed at the wall opposite the measuring instrument. The existing plumbing points in the shafts have to be included in this reference grid. With this setup, an accuracy of 0.2 mm over a section of 150 m length can be achieved.

Figure 7.2.9 *An example of wall mounted target marks (reference points) for the secondary reference network.*

7.2.7.2 Survey and alignment methods

With an initial survey, the coordinates of the target marks will be determined with regard to the primary reference network. After this, the target marks can serve as a reference used to peg out every machine component such as pillars, pedestals, mounts, magnets, modules, undulators and so on. For this, the survey instrument is placed on a carriage mounted to a transport rail (see Figure 7.2.10) and fixed to the concrete wall for the time of the measurement. By surveying a given number of reference points the position of the instrument is calculated (free stationing) and then any user-defined points, can be pegged out (see Figure 7.2.11). The lines of sight from the instrument to the reference points and to the target marks on the machine components have to be kept free at all times.

Figure 7.2.10 *Carriages for laser tracker and tachymeter.*

The survey methods for the reference system and machine components vary depending on the demands on the alignment accuracy of the machine.

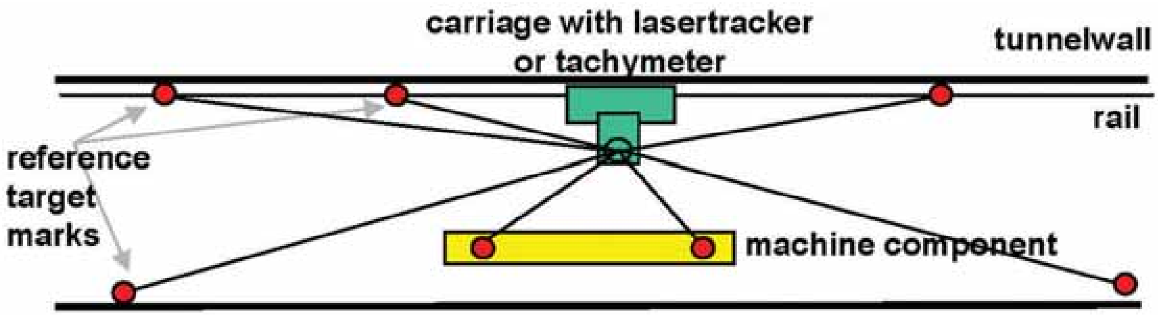

Figure 7.2.11 *The principle of the "free stationing" peg-out (see text).*

Injector and linac sections

The injector and linac sections can both be surveyed with classical optical methods. Thus, the demanded accuracy for this part of the XFEL – which is 0.3 mm over any 150 m range – can be reached.

There has to be a line of sight equipped with removable radiation shielding.

Start and distribution shafts

At the start shaft and at the distribution shafts, the coordinates are transferred from the aboveground primary reference grid down to the subterranean secondary reference grid. At the roof of the respective buildings there have to be survey pillars securely connected to the support structure of the building. These pillars are part of the primary reference network and their coordinates can be determined by geodetic GPS survey. During the construction phase there will be four of these pillars at every building, one at each corner of the shaft. For the plumbing measurements, four tubes (300 mm bore each) will be installed from the survey pillars down to the tunnel level. Underneath these ducts, a survey bracket at tunnel level will be mounted to ensure the transfer measurements. After completion of the construction phase three of the four survey monuments can be removed.

Since there are significant temperature gradients between the tunnel sections and the shafts it is impossible to continue the reference system through the shafts with classical optical survey methods. Therefore, the connection of the tunnel sections on both sides of a shaft is accomplished by means of a laser alignment system (LAS). This setup is implemented into a vacuum pipe (300 mm bore) which overlaps each tunnel section by the length of the crossed shaft (see Figure 7.2.12).

The diverging distribution tunnels are connected to the reference system via cross cuts and precise distance measurements (see Figure 7.2.12).

Photon beamlines and experiments

Since there are components at the end of the photon beamlines (e.g. Beryllium lenses and monochromators) which have to be aligned to 0.5 mm accuracy for the undulator section and since some photon beamlines are up to 1 km long, the demands for the initial installation can only be met by an LAS. The LAS will provide an accuracy of 25 µm over a 300 m range and ~100 µm over the range of 1 km. This will be installed in addition to the classical optical survey system and will be routed through the radiation shielding into the experimental area to ensure the correct geometrical connection of the experiments to the beamline. For the survey and alignment of the experiments, wall- and floor-mounted reference points as well as brackets for instruments at the pillars of the experimental hall, will be installed.

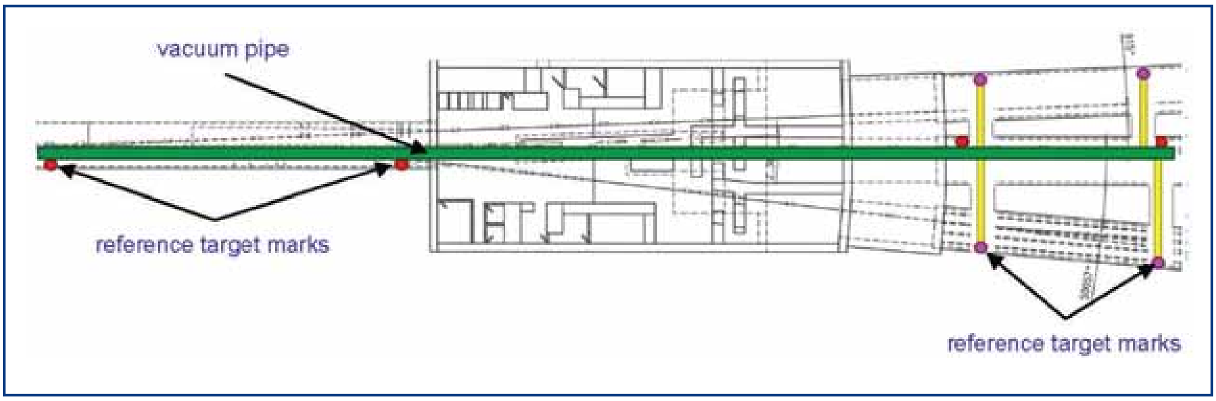

Figure 7.2.12 *Crossing the shafts with an LAS.*

7.2.7.3 Accuracy demands and performance

The demanded accuracy for the reference points of the primary reference network has been specified as 5 mm. This demand can easily be reached by a combination of GPS measurements with geodetic receivers for the 2-D-position and precise levelling methods for the height.

The accuracy of the secondary reference network is determined by the demands of the initial alignment of the accelerator parts. The demands of the injector and linac section are 0.3 mm over a 150 m range. An accuracy of 0.2 mm over 150 m can be reached by using laser trackers and a dedicated layout of the reference grid. The machine components can then be aligned to the desired accuracy.

Any higher accuracy demands can't be reached with classical optical methods. For the above mentioned photon beamlines and experiments, the demands stay in a range of 0.5 mm over 1 km length. The chosen laser alignment system will be capable of delivering a resolution of 25 µm over 300 m length or ~100 µm over 1 km which qualifies the system both for the crossing of the shafts and for the (survey of the) photon beamlines.

7.2.8 Installation of components

7.2.8.1 Installation procedures and vehicles

All transports in the tunnel have to pass through a shaft or the experimental hall. All shafts and the experimental hall are equipped with a freight elevator, staircase and, except for the injector shaft, with a crane and crane shaft. The big injector components will be installed via the shaft XSE. This shaft is the only one where the 12 m long accelerating modules can be let down. The other shafts XS1-4 are designed to allow the 5 m long undulators to pass through.

A large part of the shaft and tunnel walls will be equipped with in-profile rails that allow a fast and proper mounting of most of the installations.

In the linac tunnel (XTL), where all accelerator components are suspended from the tunnel ceiling, the top tubbing segments will have two in-cast channels to take the load and the longitudinal vacuum forces. A mock-up of the XTL tunnel will be constructed to allow tests of the module suspension, alignment, installation and connection, to verify the space requirements, test vehicles, train the installation crews and so on.

Most of the installation and underground transportation work will be done with standard vehicles (forklifts, scissor lifts, electric carts, trailers, etc.). A special vehicle is needed to transport, lift and install the modules and other heavy components in the XTL tunnel. Figure 7.2.13 shows the conceptual design of the accelerator module transportation and installation vehicle.

Another special vehicle will be developed to transport and install the undulator modules in the undulator tunnels. It will be based on standard air cushions supplied from compressed air outlets at the tunnel wall.

For the transport of the electron beam dumps from the installation shaft to their final position in the dump shafts XSDU1-2, a special trailer will be designed. The installation will be done with the underground crane and a special tool will slide it into the bore of the shielding.

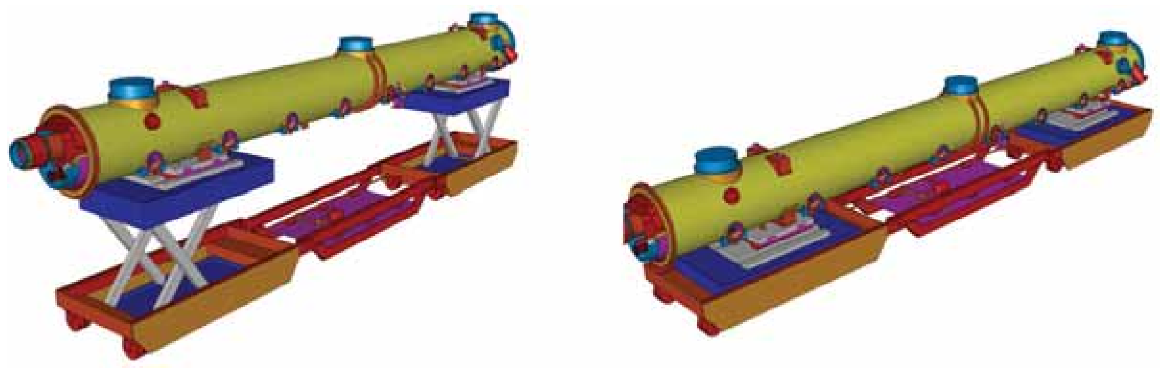

Figure 7.2.13 *The conceptual design of the accelerator module transportation and installation vehicle.*

Installation sequence

It is assumed that the work on the injector, the linac tunnel, the beam distribution and the undulator tunnels and in the experimental hall will run in parallel. The injector installation has a high priority, because it can, and should be, commissioned before the linac.

After the construction of a tunnel section is finished, the survey group will immediately measure the tunnel shape and place a rough longitudinal (and vertical) scale (10 m ticks) to allow an easy orientation for the workers.

In all buildings, except the linac tunnel (XTL), the installation of the basic infrastructure like light, power, phone and safety installation will start after the survey. This will be followed by the installation of cable trays and cables, water and gas pipes and other services. Because of the underfloor installation in the linac tunnel (XTL) the installation of the basic infrastructure has to wait for these parts and the floor plates to have been put into place.

7.2.8.2 Linac tunnel (XTL)

The installation of the pulse cables from the modulator locations to the klystron positions in the tunnel is very time consuming and has to start immediately after the civil construction of the linac tunnel (XTL), the first access shaft (XSE) and the modulator hall (XHM) has been finished. The cable trays will be mounted and then each cable will be pulled. The longest cable has to be installed first.

In parallel, the installation of the other underfloor services (pipes, power cables, etc.) in the XTL tunnel can start from both ends (shafts XSE and XS1). The transport of tools and material will be done by installation vehicles that run on the centre wall and the console at one side of the tunnel.

It is assumed that the far (XS1) end will be ready earlier, so one can start to place the floor plates from this side. They will be sized so that they can be handled with standard forklifts. In the range of the superconducting linac, the pulse cables have to be carefully guided through the gaps foreseen in the plates.

This task will be followed by the installation of the basic infrastructure: the smoke exhaust pipe, the fire protection walls, emergency guidance rail, communication services and the support rail for the survey equipment.

Next, the installation of the I-beams to suspend the linac components from the tunnel ceiling will start. The 4-5 m long beams will be lifted and mounted with scissor lifts (see Figure 7.2.13). The I-beam will be bolted to two in-cast channels in the top tubbing segments. The alignment will be assured by adjusted laser beams and targets attached to the I-beams. The position of the beams will then be checked by the survey group and the positions of the suspensions will be marked. After this preparation, the installation of the accelerator components can start.

The installation of the linac will start from the shaft XSE. The first element will be a 2 m long cryo-box followed by the first accelerator module. The waveguide distribution has to be placed before the module can be installed. After alignment the module will be connected to the next module or cryo-box in a clean room that will be set up locally. After several checks, the pulse forming network, pulse transformer, klystron, and several racks with shielding, water distribution, and power outlet box will be installed.

When the module installation has passed the region of the bunch compressors, the cryo bypass line will be installed, followed by the bunch compressor sections that are pre-assembled in ~12 m units. This is followed by the racks with shielding.

The components of collimation/beam distribution section will also be suspended from the tunnel ceiling. Their installation will start from the end of the linac in the direction of the shaft XS1.

7.2.8.3 Injector, undulator and photon tunnels

All magnets, undulators, photon optics, gun, module and cryo-boxes in the injector and the undulator/photon section, will rest on aligned and tamped bases bolted to the floor.

In the undulator sections, special supports for the vacuum chamber are needed and the vacuum chamber has to be installed before the undulator. All vacuum connections will be done using temporary local clean rooms. At the same time the installation of electronic racks can start.

7.3 Controls and operation

7.3.1 Control systems

The XFEL requires a complex control system with many I/O devices, computers and software modules. The design of the control system incorporates strategies to keep the system modular, simple and well structured with loose coupling and adequate and robust interfaces between its components. On a smaller scale, the required technologies for the XFEL were successfully demonstrated in the TTF vacuum ultraviolet (VUV)-FEL with the DOOCS control system. Since the framework for TTF is the basis of the development for the XFEL, further improvements will be tested in FLASH before the commissioning of the XFEL.

The XFEL will be built as a collaborative effort and therefore, the control system has to be able to integrate contributions from partners. In TTF a lot of experience has been gained to smoothly integrate various different systems into the common DOOCS environment. A homogeneous system is, of course, easier to setup and maintain and therefore, a discussion of how to implement individual systems with a balance of effort on all partners and benefits for the final system, is required.

From the experience of FLASH it has been learnt that a single electron bunch resolution of all monitoring devices, including the storage of the data, is required. This data can be used for offline analysis to improve the machine, correlate accelerator and user experiments and for slow feedback systems. The current implementation of such a high performance data acquisition system (DAQ) is described in **[7-15]**, further developments are foreseen.

7.3.1.1 Architecture

As shown in Figure 7.3.1, the overall architecture consists of three layers: A top level with display or client programmes as a presentation layer; a front-end level with device servers and I/O as a connection to the hardware and a middle layer with powerful data servers. The upper layer is the interface to the operators. These upper services, with the application programmes, are available to the consoles in the control room, the experts working at the machine or in their offices. For remote operations, all these applications are provided via secure links to the remote shifts or experts.

Examples of applications in the presentation layer are: archive viewer, synoptic displays with a graphic representation of the subsystems, alarm panel, save and restore tool, plotting and measurement and simulation tools.

Client programmes often require information from a group of devices or need to operate on such a group. Middle-layer servers can provide such collective reports and controls. An example of an implementation is a Finite State Machine (FSM) server. This server keeps track of several devices and is able to initiate state dependent control actions. A hierarchical grouping of servers is a better way of structuring the system. These kinds of servers are usually implemented in the middle layer. Databases, file servers, machine physics simulation servers, name servers, the DAQ system, slow feedbacks and other automation as well as Web services, and in general services without a direct device connection, are placed in the middle layer.

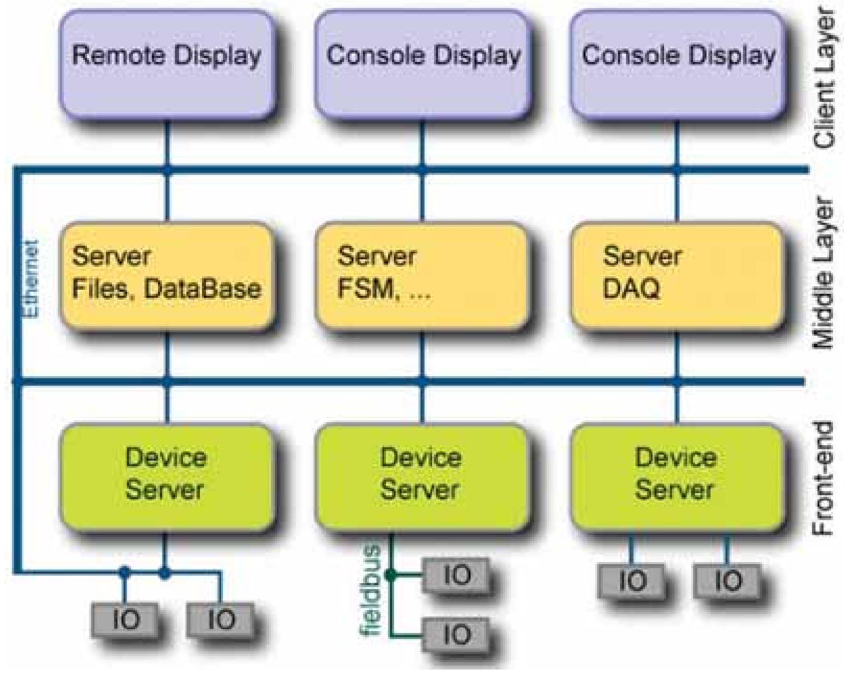

Figure 7.3.1 *Control system architecture.*

The front-ends are distributed and placed close to the hardware (accelerator components, undulators, beamline components and experiments), most of them inside the tunnel in cooled and radiation-shielded racks. Industry standards are used whenever possible so that most of the required electronic modules can be bought.

7.3.1.2 Hardware

Robust hardware for the front-ends with a high reliability is foreseen. VME and Advanced Telecom Computing Architecture (ATCA or µTCA) are the two options for crate systems. The VME standard has been successfully used in many accelerators, including TTF. The market share is expected to be constant over the next few years. With the optional VXS on the VME, bus, modern Gigabit serial communications are useable. ATCA and µTCA are new standards from the telecom industry for future crate systems and should be considered as an alternative to the VME bus. ATCA is a pure Gigabit serial communication system that allows redundant connections. Redundant power supplies are also used as well as the standard supports, full hot-swap support as well as crate monitoring and software interfaces to manage failures.

The crate systems are used for fast acquisitions and feedbacks. Slow and reliable tasks are better implemented in PLCs. The control system is preferably connected to the PLC by an Ethernet link, but a fieldbus link like CAN or ProfiBus is possible too. A further category of I/O devices are stepper motor controllers, temperature sensors, digital I/O and slow analogue to digital converters (ADCs). These devices are housed in DIN-Rail-Modules with an Ethernet bus coupler for a group of I/O devices.

7.3.1.3 Network

The front-ends are connected mainly by Ethernet, or if Ethernet is not available, by a fieldbus (CAN or ProfiBus) and digital cameras are attached by FireWire. All the other communication runs on Ethernet via switches and routers. The Ethernet speeds used in the field are 100 and 1,000Mbit/second or higher which results in a maximum data rate of about 10 or 100MB per second, respectively. The backbones of the switches are being connected with higher speeds and by fibre optical links. The control system is decoupled from the outside intranet and internet by a firewall to secure the control system network from attacks or viruses. Remote operations or maintenance will be foreseen. This includes access from a remote expert at home to reduce the downtime in case of failures.

The tunnels and halls are equipped with wireless networks. Maintenance work on the electronics and front-end devices usually requires access to the control system data. Wireless Local Area Network (WLAN) infrastructure will be used for maintenance tasks with mobile devices.

7.3.1.4 Software

The control system software covers the whole range from server programmes, communication protocols, applications and some Web services. The whole control system will run several thousand processes on distributed computers. Self-healing technologies will be applied to keep services running. Automated procedures are required to manage software upgrades and to keep the system consistent.

Operating systems on the servers and front-ends will be UNIX flavours (LINUX or Solaris). Object-orientation is the main paradigm of the control system to get a well structured and modular architecture that is easier to maintain and improve. The main part of the control system will be based on modular libraries to allow easy upgrades.

Programming languages will be mainly based on the languages C++ and Java.

The growing complexity of the software requires adequate tools: Integrated Development Environments (IDEs) for the complete design cycle from editors, Graphical User Interface (GUI) designers, compilers, debuggers, performance analysers, documentation generation and code repositories. A centralised repository like Concurrent Versions System (CVS) is mandatory for developers working in a team or in collaboration with members in different institutes. Access to this system will be provided from the Web.

The commercial software MATLAB for mathematical processing, will be fully integrated. Whenever possible, mature “open source” products will be integrated too.

It is planned to provide controlled access for remote operations or maintenance. Single sign-on for the users of Web services and controls applications is foreseen.

7.3.1.5 Operation

The demands on the control system from XFEL operation are:

- automated procedures to hardware setup (e.g. the RF systems);
- procedures to switch to a spare module section in case of a failure (e.g. to keep the linac energy constant);
- various slow feedback systems;
- handling of different electron bunch patterns;
- full access to all parameters of the diagnostic devices with a single bunch resolution.

Beside the “traditional” control system applications, some further tools are required for the operation of the XFEL. It is planned to continue the development of the TTF electronic logbook and similar technologies for this.

A control system demands manpower during the whole lifetime of the accelerator. It needs bug-fixes, improvements, extensions, security patches and also hardware repairs. The operability and availability of the entire facility is, to a great extent, influenced by the control system. Automated operation, fast detection of problems and reasons for faults and good error recovery are important for reliable operation.

In order to reduce downtimes caused by the control system and central hardware, the “Mean Time Between Failures (MTBF)” has to be increased and single points of failure avoided. Some examples of MTBF in hours are: PC motherboard 5×10^4, VME central processing un it (CPU) 18×104, Fan 5×10^4, SCSI disk 10^6, IDE disk 3×10^5, power supply 4×10^4... 10^5, integrated circuit 3×10^7. These values vary considerably with temperature, radiation dose, power dissipation or operation close to, for example, voltage ratings. The conclusions from these numbers are:

- the electronics will be installed in cooled racks;
- the racks need radiation protection;
- central systems like timing and network are connected in a star-shaped topology;
- the central network is operated by two redundant switches;
- systems should depend on a minimum of other systems;
- fans and power supplies should be redundant when possible;
- self-healing by automated processes and error reporting should be implemented.

7.3.1.6 Timing

The purpose of the timing system is to trigger devices like the gun, kickers, klystrons and data acquisition modules with configurable delays on certain events of the machine operation, to provide synchronised clocks for ADC sampling and to distribute further reliable information. For the trigger, a jitter in the order of a nanosecond is sufficient while ADC clocks might require a much better stability (well below 100 ps). The timing signals have to be stable and therefore, are programmed into the hardware, with all parameters controllable and readable by the control system. The system is planned on the basis of serial optical links with a transmission frequency of about 2.6 GHz which is synchronised with the RF master oscillator as a stable frequency reference. A timing resolution up to about 400 ps has been achieved.

A star topology of the optical links is aimed at, to have a system with a maximum redundancy. All optical fibres of the links will have the same lengths (about 3 – 4 km). Sender and receiver modules will be based on the same design with a Field Programmable Gate Array (FPGA) as the CPU. To reduce the number of sender modules it is planned to equip the modules with up to four transceivers. The optical links will be bidirectional to implement a temperature compensation of the link timing as well as to provide the possibility of a feedback from the subsystems to the CPU.

From the coded events transmitted over the links, variable gates and trigger signals with programmable delays are derived in the receiver modules to allow the subsystems to adjust the timing events most flexibly to their required needs. In addition, information about, for example, bunch patterns can be transferred by the system.

7.3.1.7 Machine protection system

The complete accelerator has to be equipped with a machine protection system (MPS) to prevent beam operation, e.g. in case of technical failures. The MPS is an independent, fast alarm system that allows the beam and subsystems, e.g. Laser and RF, to be switched off within microseconds. The system will be based on fast distributed interlock logic. Decentralised boxes with interlock inputs and some inhibit outputs are linked by fibre optic cables in the upstream and downstream directions. Each box gets an interface to the control system for the readout of the status and interrupt sources. The control system is not involved in the fast protection process, but in the configuration of the whole system.

7.3.2 Radiation safety

7.3.2.1 Radiation protection considerations

This section describes the radiation safety requirements for the XFEL. The main emphasis has been placed on the impact of the XFEL operation on the public (local population) and the environment. Most important here is the limitation of the radiation level (doses) to the public, coming directly from stray radiation or indirectly through a potential activation of soil and groundwater or air and coolants released from the facility.

Following the German regulation **[7-16]** and the As Low As Reasonably Achievable (ALARA) principle, planning goals in terms of dose limits for the public have been set. According to the German regulation, the maximum allowed personal dose due to direct radiation and radiation from radioactive release (activated air, water, etc.) is 1 mSv/a, and for radiation from radioactive release alone 0.3 mSv/a. Considering the ALARA principle, our planning goals for the XFEL are 1/10 of the above given limits. This results in 0.1 mSv/ per person for the public from direct radiation and radiation from radioactive release and

0.03 mSv/a from radiation from radioactive release alone. The corresponding limits for staff members are higher according to their surveillance status. The limit for the public is, therefore, the more demanding requirement. For comparison, the natural doses in the northern part of Germany are about 1-2 mSv/a. Most of the single dose contributions given below occur at different locations along the facility. One, therefore, has to keep in mind that these single dose contributions do not have to be added. To be conservative, however, this has been done to estimate the maximum dose.

The studies of the radiological impact on the public and the environment carried out by the DESY radiation protection group (summarised in **[7-17]** and **[7-18]**) have been evaluated by an independent German institute, the Öko-Institut e.V. Darmstadt **[7-19]**. The Öko-Institut e.V. Darmstadt agreed with our basic assumptions and calculations and found no missing items or problems for an implementation of the XFEL in the foreseen way.

The basic parameters and main assumptions for beam losses in the cold and warm machine can be found in Table 7.3.1. The earth coverage of the tunnels will be on average about 12 m and at minimum 6 m.

Maximum beam energy	20	GeV
Maximum beam power	1.2	MW
Maximum beam power/dump	0.3	MW
Maximum rate (0.3 MW)	9.4×10^{13}	e/s
Operation time/year	5000	hours
Cold machine:		
Maximum local beam loss (0.4 W/m’”8 m=3.2 W)	1.0×10^{9}	e/s
Maximum time of loss/year	5000	hours
Maximum lost particles/year	1.8×10^{16}	e
Warm machine:		
Maximum beam loss (0.3 MW)	9.4×10^{13}	e/s
Maximum time of loss/year	1	hour
Maximum lost particles/year (0.3 MW)	3.4×10^{17}	E

Table 7.3.1 *The basic parameters and main assumptions for beam losses in the cold and warm machine.*

7.3.2.2 Stray radiation due to neutrons and muons

There are two different kinds of secondary radiation capable of penetrating thick material layers: high energetic neutrons and muons. At three locations, high energetic neutrons have to be investigated: The cold part of the machine with permanent losses, the warm part of the machine with exceptional losses and the beam dumps with permanent losses (**[7-20]** and **[7-21]**).

The annual dose for the public living above the cold part of the linac is based on the inherent safety mechanism which means that more than ¾ of the lost power is absorbed by the cold mass. This results in a dramatic pressure rise in the 2 K cooling circuit and therefore, superconductivity is lost and the acceleration is stopped immediately. At the cryogenic limit, with an average power loss of 0.4 W/m for the cold part of the main linac, an annual dose of 0.002 mSv will be created for the public, assuming a minimum earth coverage of 6 m and 5,000 h of operation per year. Concerning the above given beam losses for the warm part of the machine, the annual dose will be 0.041 mSv assuming again a minimum earth coverage of 6 m. Local loss points such as emergency dumps and collimator sections can be additionally shielded inside the tunnel according to their power loss and the thickness of the soil layer above.

For the shielding of the dumps, two options have been worked out **[7-18]**. The baseline design consists of 4 m ordinary concrete and 5.5 m sand, leading to a maximum annual dose of 0.038 mSv on the earth surface directly above the dump shafts, which is located on the XFEL site.

Muons with maximum energies of 20 GeV are capable of penetrating 60 m of soil but have a strong forward characteristic. Those muons can hardly be shielded artificially (**[7-22]** and **[7-23]**). The most intense muon sources are the beam dumps with maximum doses of about 0.0001 mSv per year on the surface **[7-18]**.

7.3.2.3 Activation of soil and groundwater

Around the beam dumps, the activation of soil and groundwater has been estimated by Monte Carlo simulations with FLUKA (**[7-24]** and **[7-25]**). For soil and groundwater activation behind the 4 m thick concrete shielding of the dump shafts, a realistic model of transformation of soil and groundwater activation in the first 1 m around the dump shielding into activation concentration of drinking water and doses for the public, were used (details can be found in **[7-26]** and **[7-27]**). It has been shown that the production of radionuclides in the soil leads, in the first 1 m near the dump shielding, to a maximum annual dose of 0.012 mSv **[7-18]**. The content of ^{3}H (Hydrogen) and ^{22}Na (Sodium) in groundwater after 20 years of operation was found to be 0.024 Bq/g and 0.0025 Bq/g, respectively. This leads, under the assumption that a person is taking all of their drinking water (700 litres per year) from the above described location, to a maximum annual dose of 0.008 mSv **[7-18]**.

7.3.2.4 Activation of air

For the XFEL, one expects a higher activation of the tunnel air at three different locations:

1 tunnel air close to areas with collimation systems;

2 tunnel air which passes the beam dump area;

3 enclosed air near the beam dump system which will escape if access is needed to this area.

Taking into account the above ventilation concept described, one can calculate the air activation concentration at the nearest air outlets for the activation area. Calculations **[7-18]** lead to a relative release factor (in comparison to the release numbers from the

German Strahlenschutzverordnung **[7-16]**) of 0.32 which results in an annual dose of 0.096 mSv directly at the air outlet due to air from group 1. One has to keep in mind that this air will be released on the existing DESY site so this dose cannot directly be transformed to a dose for the public. For groups 2 and 3, the corresponding numbers are 0.0035 as the relative release factor which results in an annual dose of 0.001 mSv directly at the air outlet due to air from groups 2 and 3. This air will be released at the corresponding access shafts and can, therefore, easily be used as the maximum dose for the public due to activated air from groups 2 and 3 **[7-18]**. The average dose due to activation of released air was calculated to be 0.010 mSv per year at maximum **[7-18]**. More details about the method of calculating the air activation can be found in the studies **[7-28]** and **[7-29]**.

7.3.2.5 Activation of coolants

The highest activity concentration of cooling water is expected in the dump cooling water **[7-27]**. It circulates in a closed loop (see Section 4.7.4). Two long-living radioactive isotopes have to be considered: Tritium and Beryllium-7. Their activities in the primary cooling circuit after one year of operation are 20 MBq and 2 MBq, respectively, which results in activity concentrations of 1.0×10^7 Bq/m^3 and 1.1×10^6 Bq/m^3, respectively **[7-18]**. These numbers are well below the corresponding release numbers for “uneingeschränkte Freigabe” of the German Strahlenschutzverordnung **[7-16]** and, therefore, the activation of cooling water implies no special risk at the XFEL.

The superconductive cavities are cooled with liquid Helium. The coolant is continuously transported within a loop consisting of accelerator structures in the tunnel and a cooling plant outside. In shutdown periods, storage outside the tunnel must also be possible and therefore, the activation of Helium may be of radiological interest. The only activation product is Tritium. Similar to the calculations in **[7-30]**, under the assumption of operation at the cryogenic limit of 0.4 W/m over the whole accelerator and an operation of 5,000 hours per year, one gets a total activity of 2.2 GBq and an activity concentration of 250 Bq/g after a total operation time of 20 years. This is well below the release number for “uneingeschränkte Freigabe” of the German Strahlenschutzverordnung **[7-16]** and, therefore, implies no special risk at the XFEL.

7.3.2.6 Summary and other studies

In Table 7.3.2 , a summary of all maximum exposures and the sum of all these sources can be found, keeping in mind that these doses arise at different locations. The planning goal of 0.1 mSv/a personal dose for the public from direct radiation and radiation from radioactive release, and 0.03 mSv/a from radiation from radioactive release alone, has been met and realistic doses to the public are safely more than two orders of magnitude lower because of the very conservative assumptions used in the calculations of the above numbers.

Exposure path	Maximum exposure
Stray radiation, warm part	0.041 mSv/year
Stray radiation, beam dumps	0.038 mSv/year
Stray radiation, muons	0.0001 mSv/year
Activation of soil	0.012 mSv/year
Activation of groundwater	0.008 mSv/year
Mean activation of air	0.010 mSv/year
Sum	**0.11 mSv/year**

Table 7.3.2 *A summary of all maximum exposures and the sum of these sources.*

As is the case for the HERA accelerator, the XFEL will have a radiation monitoring system installed to survey online dose rates at several locations along the beamline. Therefore, studies have been started to design new radiation monitoring detectors to handle the special timing conditions. In addition, a lot of detailed studies were done to optimise the shielding of the XFEL shaft buildings (similar to **[7-31]**) to ensure a minimum of controlled areas.

The interlock system used at DESY including all the maintenance and testing procedures is described elsewhere (**[7-32]** and **[7-33]** and also in Section 7.3.4). A similar system, with state of the art components, will be installed at the XFEL to ensure a safe operation and a variety of combinations of access and machine operation. Details of the expected activation of materials can be found in **[7-34]**, **[7-35]** and **[7-36]**, procedures for beam dump handling, environmental and personal monitoring, potential failure scenarios and dismantling issues, are described in **[7-18]**.

7.3.3 General safety

7.3.3.1 Fire safety and emergency response

General

The following rules underline the general safety requirements.

Fire safety measures in the tunnels and the buildings have to be provided during construction, shutdown, maintenance and operation of the XFEL. During all of these phases, access to the tunnels is restricted to trained and instructed personnel. Tunnels and buildings are designed so that people can safely manage to escape to a safe area in case of a fire. For this purpose, the XTL tunnel is divided into segments with an individual length of approximately 600 m. Segments are separated by fire-resistant walls in combination with water curtains. The length of each of the other tunnels does not exceed 700 m. All tunnels are separated from the shafts by fire-resistant walls with a fire-resistance time of 30 minutes.

The underground experimental hall is equipped with automatic fire detection and smoke extraction systems. Supporting structures are built with fire-resistant construction materials with a fire-resistance time of 90 minutes. The maximum escape route from this area is 40 m.

Fire loads in all underground areas are kept as low as possible. Specifically, only flame retardant cables are used in the underground areas. The storage of flammable materials in underground areas is prohibited.

In addition to these primary measures, fire detection and extinguishing systems as well as organisational and technical measures for emergency response will be installed, as detailed below.

Fire detection, alarm and extinguishing systems

All tunnels and underground buildings are equipped with a fire detection and localisation system. The XTL tunnel and two of the XTDs with a comparatively high fire load have a smoke extraction system. The other buildings are equipped with a fire detection and localisation system with an automatic evacuation alarm (siren).

The tunnels are connected to a fire water supply comprising a fire water pipe with connections at least every 50 m. The experimental hall and the buildings are also connected to a fire water supply.

During the installation phase, mobile water curtains are installed in the linac tunnel (XTL). Electronic racks are equipped with local inert gas extinguishing systems integrated into the racks which are triggered automatically in case smoke is detected. Transformers in the tunnels have water mist extinguishing systems.

Communication system for tunnel and buildings

Communication booths are installed in all tunnels with a maximum distance of 50 m. The installed communication systems will allow communication by radio, mobile phone and fire brigade radio.

Emergency power supply and emergency lighting

All tunnels and buildings will be equipped with emergency lighting. In addition, all tunnels will be equipped with an emergency power supply to maintain the operability of installations relevant for safety in case of failures of the main power supply. The emergency supply will cover the smoke extraction system, the communication system, the emergency lighting and the signposting of escape routes.

Access monitoring system

The tunnels and shafts are equipped with an access monitoring system with personal separation.

Organisational requirements for fire safety and emergency preparedness

The following organisational fire safety precautions will be implemented:

- emergency escape plans and fire safety regulations (Brandschutzordnung Teile A,B,C) as well as emergency plans for the fire brigade will be established and employees will be regularly instructed in fire safety regulations;
- a welding permit defining specific fire safety precautions will be required for hot works in all buildings;
- smoking will be prohibited in the tunnels and shafts during all phases (construction, installation, commissioning, maintenance and operation);
- emergency preparedness measures will include:
  - an emergency response system which ensures that first aid by a qualified paramedic can be provided to all areas within the XFEL installations within a response period of 15 minutes;
  - specific response measures for the evacuation of employees with restricted mobility including the use of stretchers and rescue chairs in areas where such employees are present;
  - a specific wheeled stretcher carrier for the evacuation of injured persons to be provided in the tunnels.

7.3.3.2 Safety of equipment and accident prevention

Design considerations

The design of the equipment will incorporate various safety measures including:

- the use of non-halogenated cable and insulation materials in line with the DESY cable specification. Flame-retardant cable materials will be used in the tunnels and underground areas;
- the design of pressure vessels and pressure lines will be in accordance with the requirements of the European Pressure Vessel Directive, or implementation of a similar safety standard;
- the design of machines, mobile equipment, transport vehicles and lifting equipment will be in accordance with the requirements of the European Machine Directive and the harmonised European norms;
- the design of electrical equipment and installations will be in line with the requirements of the European Low Voltage Directive and the applicable standards (EN, VDE, IEC, etc.);
- transport vehicles used within the tunnels will have safety features such as headlights illuminating narrowed areas of emergency escape routes and safety railings for guidance in case of narrowed escape routes;

- installations containing substances hazardous to water will be designed in accordance with the regulations for such installations. This includes the use of double-walled equipment or appropriate secondary containment as well as technical or organisational leak detection measures for equipment holding significant amounts of substances hazardous to water, such as pulse transformers.

Requirements for the safe operation of equipment

The following measures will be implemented to ensure safe operation of the equipment:

- prior to commissioning, initial inspections will be performed of all fixed electrical equipment as well as of installations requiring supervision under German and/or EU law. This specifically includes pressure vessels, cranes, elevators and transport vehicles. All equipment will be included in the existing inspection database and regular follow-up inspections will also be performed;
- for other types of equipment (including mobile electrical equipment, gates, safety cabinets, emergency lighting, fire alarm systems) regular inspections will be performed based on the German Ordinance on the Safe Operation of Equipment;
- for all workplaces, hazard analyses will be performed in accordance with the German and European legal requirements.

Organisational Health & Safety requirements for the construction phase

The specific safety precautions during the construction phase will be established in the form of a Health & Safety Coordination Plans (SiGe-Plan) for each construction site. Health & Safety Coordinators will also be appointed to supervise the implementation of the safety requirements during the construction phase.

7.3.4 Personnel interlock

7.3.4.1 General

The personnel interlock system is an active part of the accelerator radiation safety system to secure radiation restricted areas which are established due to beam operation. The main task of the system is to switch off all relevant radiation producing devices in case of danger and so prevent accidental exposure of people to radiation.

For this purpose, installations such as emergency off-switches, access doors, safety key boxes or beam shutters are equipped with electrical contacts and switches. Their signals are processed in a central interlock logic unit where a beam operation permission is generated after a warning procedure. This permission of the interlock system is necessary to operate accelerator components like klystrons, kickers, septa or magnets, or to open beam shutters and absorbers. If one of the safety input signals disappears, these components must be switched off in a safe way or beam shutters must be closed.

At DESY, there exists more than 40 years of experience with the conceptual and technical design and building of reliable complex personnel interlock systems. For XFEL, a technology will be used, which has been developed at DESY in the past five years and is working successfully at the complete interlock system for the FLASH facility and at subsystems of other DESY accelerator interlocks. Also for PETRA3 and its experiments and pre-accelerators this technology will be used. The general concept of the new technology has been approved by experts of the German TÜV (Technischer Überwachungs-Verein).

7.3.4.2 Design features

All functions of high safety relevance are based on two independent redundant systems: The contacts and switches at local installations are doubled, each with its own cabling. Their signals are parallel-processed in logic units and the approval of both systems is required to start a warning procedure. For switching off beam generating devices, two different redundant methods are always chosen, each triggered by a separate system of the beam operation permission interlock.

Another important design feature is the fail-safety of the system. In case of failures or damages, a safe state must be achieved. For example, beam shutters are installed in a way that they close at lack of pressure; or power failures or broken cables and contacts interrupt a signal chain.

A tree structure of modular subsystems is chosen to achieve a transparent signal flow within the system and to allow flexibility for upgrades and changes. In the signal paths, interrupt buttons are installed to allow easy testing procedures. According to the law, official interlock test procedures have to be performed at least once a year.

For the system to operate successfully a stable operation of all components is necessary and in case of a failure, easy repair or replacement must be possible. Uninterruptable power supplies are also used to keep the interlock system working in case of main power failures.

For a large accelerator like XFEL with many remote interlock subsystems, information about the status must be available in the main accelerator control room. The new interlock technology provides a computer connection which is used by the accelerator control system to enable surveillance, event logging and the operation of some functions at an interlock console.

7.3.4.3 Basic technology

All high safety level systems are working with hard-wired 60 V powered relay technology using modern special relays with forcible guided contacts.

The logic units are housed in modules. Only a few standard modules are required to fulfil many purposes. Additionally, the modules themselves are constructed in a modular way; circuits for certain functions are located on plugged boards for easy replacement or redesign in case some industrial hardware is no longer available. Figure 7.3.2 shows an electronic module which is used for an interlock door.

To enable a continuous remote supervision during operation, the logic status of each relay in a module is read out by an opto coupler and the information is processed by a local interface board.

Each module is equipped with a standard interface board which connects the interlock electronics on the main board with a commercial CANopen bus controller. The interfaces of all modules of a system are connected by a CANopen bus line with an embedded Linux computer module. This local interlock server has a protected separate local area network (LAN) connection to the control system's computers.

Figure 7.3.2 *Door interlock module with plugged interface board.*

For some tasks of lower safety relevance, a computer-controlled operation is foreseen. For example, warning panels and blinking lamps are operated with local bus driven switches at the accelerator doors.

7.3.4.4 Subsystems

Door interlock

Before beam operation is possible, all interlock areas concerned have to be searched. Everyone must leave the area and all interlock doors have to be shut. The area search is supported by the door interlock system using a start/interrupt function, an acoustic announcement, set buttons at the doors and search buttons in the area. The order in which doors and search buttons must be set is computer-controlled. When the search is completed, a sum signal for the interlock area is generated in an additional third relay safety path. If a door to a searched area is opened, the 60 V signal lines are interrupted in both systems by the two door contacts and the sum signal "area searched" disappears.

For large accelerator tunnels, a controlled access procedure to searched areas is supported by the door interlock system. For this purpose it is possible to override the “searched” signal in the third safety path during the opening of the door whilst the door contacts remain active. This procedure, under the control of the operators in the accelerator control room, is allowed under several safety conditions: a video and audio communication system between door and control room is necessary, the names of the persons entering the area must be registered, each person has to take a safety key and the override procedure is only active as long as a button is pressed by the operator.

The XFEL tunnels have a total length of about 6 km. If long tunnels like XTL, XTD1 and XTD2 are split into two interlock areas, there will be 15 accelerator interlock areas. The main interlock doors of each area will be equipped for controlled access procedures. An area search has to be performed by at least two people.

For each of the five photon beamlines three experimental interlock areas are foreseen. The door interlock system is different to enable an area search by a single person. Controlled access to searched areas is not possible.

Safety keys

Interlock safety keys are housed in modules. All modules are equipped with switches to detect the presence of a key in two systems. All keys have to be in their modules for a beam operation permission. The keys are used to inhibit beam operation, they are needed for a controlled access to searched areas.

Emergency-off system

Each emergency off-button in an interlock area is part of the personnel interlock system and inhibits any beam operation when pressed. The buttons are installed in such numbers and distances, that it is always possible to reach one of them within the beam warning time.

An emergency off-button has two internal switches, one for each system. The buttons are connected with the CANopen bus system to give information about their location and status.

In case other sources of danger in the area must also be switched off, interfaces are provided which allow shutdown across the system or by single buttons.

Beam operation permissions

At the presence of all safety relevant input signals, a beam warning procedure can be started at a central logic interlock unit. Afterwards, a beam operation permission can be given. Typical input signals originate from the door interlocks of all areas involved, the key modules and the emergency-off system. Signals from all other essential safety installations can also be processed as required.

Accelerator

Before generating an electron beam in XFEL, it must be ensured that the beam will be dumped in one of the absorbers. The dump safety system will be a combination of active and passive elements. The function of active components such as bending magnets has to be checked by the personnel interlock system.

Depending on the operation mode (Injector test, Commissioning, FEL beam 1-3, FEL beam 4-5) the electrons must go to the appropriate dump. This is essential to permit access to some tunnel areas during beam operation in other tunnels. To enable access in one of the photon tunnels XTD6-XT10 whilst the neighbouring photon beamlines are in operation, beam shutters are required in the photon beam sections of XTD1-XTD5. Their contacts indicating the “closed” position must be checked by the interlock system.

Experiments

For an experimental area, the personnel interlock system must provide permission to open a beam shutter in the photon beamline. Therefore, all safety input signals of the experimental area must be present. If this operation permission disappears whilst the beam shutter is open, the electron beam operation has to be interrupted. Only closing the beam shutter is not sufficient because this process is too slow to guarantee personnel safety.

7.3.4.5 Klystron interlocks

The 35 klystrons for operating the accelerator modules are located in the tunnels XTIN and XTL. Connected to the cavities, these are the main beam generating devices and must be switched off in two independent ways if required by the personnel interlock system as it is realised at FLASH.

7.4 Summary of costs and manpower requirements

The capital investment and cost of the personnel needed for the technical and conventional infrastructure and the civil constructions of all buildings of the XFEL facility as described in the previous sections of this chapter are summarised in this section. The basis for the cost estimate is the site layout and the buildings specified here. For an overview about the total project cost, a description of the methodology of the performed estimate for capital investment, the determination of the costs for personnel and the expected uncertainties, see Chapter 10.

Table 7.4.1 gives a summary of the project cost in terms of capital investment and the cost of personnel for the technical and conventional infrastructure and the civil constructions of the XFEL Facility. The civil construction cost is shown separately for the different sites of the facility. The relative distribution of the full costs for the civil construction is shown in Figure 7.4.1. The civil construction and the infrastructure contribute about 20% each to the to the overall project cost. In terms of personnel cost, the contribution is about 35%. The personnel cost for the civil construction amount to only about 1% of the total personnel cost since manpower is only needed to supervise the construction. Integrated over the entire construction phase, 996.7 full-time equivalents (FTE) are required for the technical and conventional infrastructure and the civil construction.

	Capital investment [M€]	Personnel cost [M€]	Full cost [M€]
Linac building	21.12		21.12
Desy site buildings	35.34		35.34
Osdorfer Born site buildings	18.40		18.40
Schenefeld site buildings	86.52		86.52
Global Infrastructure	5.07	2.18	7.25
Utilities	75.93	13.93	89.85
Cryogenic system	34.35	4.39	38.74
Module test facility	23.83	14.34	38.17
Installation and alignment	8.56	13.99	22.55
Control system and operability	5.23	20.16	25.39
Safety and interlock	8.96	5.03	13.99
Total	**323.30**	**74.02**	**397.32**

Table 7.4.1 *Project cost distribution civil construction and the infrastructure of the XFEL Facility. Values are given for capital investment, personnel costs and full costs in Million-Euro.*

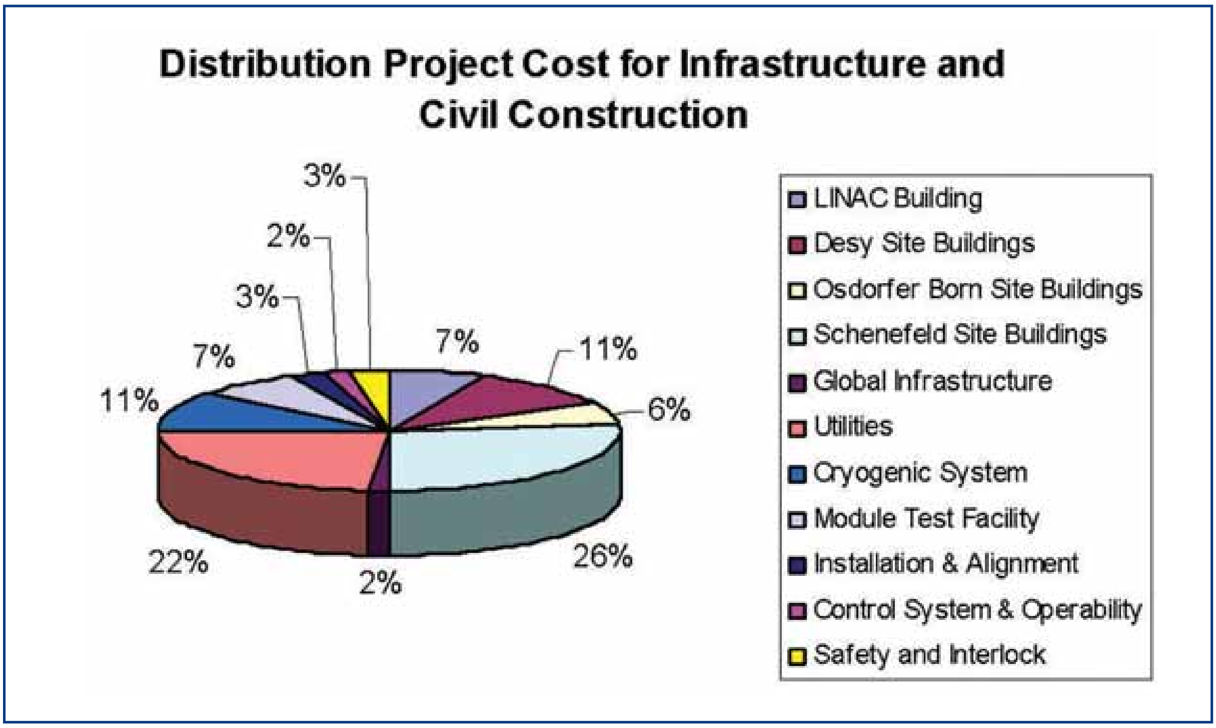

Figure 7.4.1 *Relative distribution of full project costs for civil construction and infrastructure.*

Infrastructure and auxiliary systems

The costs summarised in Table 7.4.1 and Figure 7.4.1 include the costs and manpower of the following:

Civil construction (first five entries in Table 7.4.1): site preparation, tunnels, underground halls and shafts, technical surface buildings, office buildings and auxiliary buildings of the site at DESY, Osdorfer Born and Schenefeld; a list and locations of all buildings can seen in Figure 7.1.3.

Utilities: power distribution from the DESY site with cables, transformers and sub-stations, magnet power supplies, cooling and fresh water, air conditioning, heating and ventilation, undulator section temperature stabilisation, smoke extraction system, emergency power and water lines for fire extinguishing system.

Cryogenic system: refrigerator for the liquid Helium, Helium distribution box, multiple-stage cold compressors, valve boxes and feed boxes to the accelerator modules, Helium transfer lines to bypass warm sections in the linac and costs for modification of the HERA Helium plant as limited back-up.

Module test facility: test benches for complete accelerator modules, horizontal and vertical cryostats for cavity test, horizontal cryostats for magnet test and infrastructure (power supplies, RF system, cryogenic systems, etc.) to operate the test stands.

Installation and alignment: mock-up tunnel for test and training of the installation crews, regular and specialised (modules, undulators, dumps) transport vehicles, installation of all auxiliary systems and support structures, installation of the components of the superconducting linac, undulators, photon beamlines and the experimental hall, set-up of a surface and a sub-terrain reference system with reference monuments and points, laser-based tracking system, survey assistance during the entire construction phase for sites, buildings, accelerator components, beamlines, undulators and experiments.

Control system and operability: device, middle-layer and application server, DAQ system, archive system, electronic racks and front-end electronics, networks based on Ethernet, optical fibres and bus systems, machine protection system, definition of start-up and operation modes, failure handling and recovery procedures.

Safety and interlock: radiation protection monitoring system, radiation surveillance, simulations and preparation of legal permissions, legal permission fees, fire detection, alarm and extinguishing systems, smoke detection and alarm system, communication systems, access monitoring system, on-site emergency response staff, emergency equipment, door interlock, safety key system, emergency switches, electronic racks and electronics boards for two independent redundant systems.

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