Chapter 9
Cryogenic Transfer Lines

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Abstract Transfer lines are common in cryogenic systems and are a form of cryostat. This chapter describes the requirements of transfer lines, surveys existing transfer lines and discusses issues such as modularization, routing, supports, thermal contraction, piping arrangement, materials, manufacturing and installation. The chapter concludes with a detailed case study of the design, manufacturing and performance of the XFEL/AMTF transfer line.

9.1 Introduction

Cryogenic transfer lines are typical components of almost all cryogenic systems. They are intended for transferring cryogenic fluids between two cryogenic devices [1]. Since the value of the cryogenic fluids is essentially in the thermodynamic states of their molecules, the transferring should not cause significant changes in the thermodynamic states of the transferred cryogens. It means that either the temperature increase or, in case of liquids, the vapor quality and also pressure changes should be negligibly small.

The simplest cryogenic transfer line is a vacuum jacketed pipe connecting two nitrogen dewars as shown in Fig. 9.1. In this example, the line is used for transferring liquid nitrogen (LIN). If the distance between the two dewars is short, the flowing nitrogen stays in the line for a short period of time. Then, the flowing nitrogen absorbs little heat and only a tiny portion of the nitrogen evaporates during the flow and the rest keeps its initial thermodynamic state. The relatively high value of the latent heat of nitrogen is obviously an advantage. However, if the line is very long the nitrogen stays in the line much longer. Then the flowing nitrogen absorbs much more heat. As a result, the vapor fraction of the nitrogen reaching dewar 2 is much larger. The inflowing nitrogen vapor obviously does not stay in the dewar but flows out; it counts as losses. The higher hydraulic resistance of the longer process line leads to a

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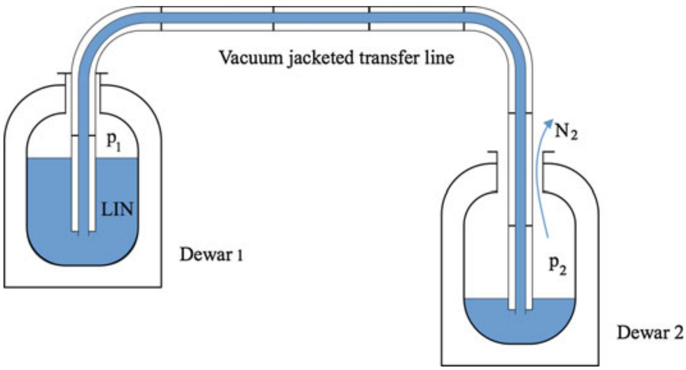

Fig. 9.1 A simple pipe-in-pipe cryogenic transfer line connecting two dewars

higher difference between pressure p_2 and p_1, which increases the difference between the initial and final thermodynamic states in the transferred nitrogen.

The pressure, temperature and density of the flowing cryogen have certain impacts on the mechanical design of the process line, vacuum jacket envelope and their supports. The higher the pressure and density, the thicker the pipe walls and the stronger the supports.

This simple example of a pipe-in-pipe cryogenic transfer line shows that designers of these lines have to take into consideration a number of parameters. The most important are:

- geometrical restrictions (total distance, possible routings and available space),
- required mass flow rate and its time characteristic,
- minimum and maximum temperature,
- minimum and maximum pressure,
- thermodynamic properties of chosen cryogenic fluid,
- mechanical properties of chosen pipe materials.

The design of pipe-in-pipe cryogenic transfer lines is extensively described in [2–4]. All the above considerations and a number of design guidelines provided in [4] are also valid in the process of designing much more complicated cryogenic transfer lines, in which the vacuum jacket houses several process lines transferring cryogenic fluids at different temperatures and pressures. Such multichannel lines are usually used for transferring cooling power between a cryogenic plant and cryogenic users in so-called large scientific facilities. Typical cryogenic users are cryomodules with superconducting cavities and cryostats with superconducting magnets, bus bars or cryogenic vacuum pumps. These facilities usually require complex cryogenic systems that are capable of providing very high cooling power at very low temperature levels and distribute this cooling power among the users. Figure 9.2 shows a simplified schematic flow scheme of such a complex cryogenic system. Here, a cryogenic device, let's say a chain of cryomodules housing superconducting cavities made of pure niobium, needs to be cooled down to a temperature of 2 K. The required cooling power is produced by a cryogenic plant

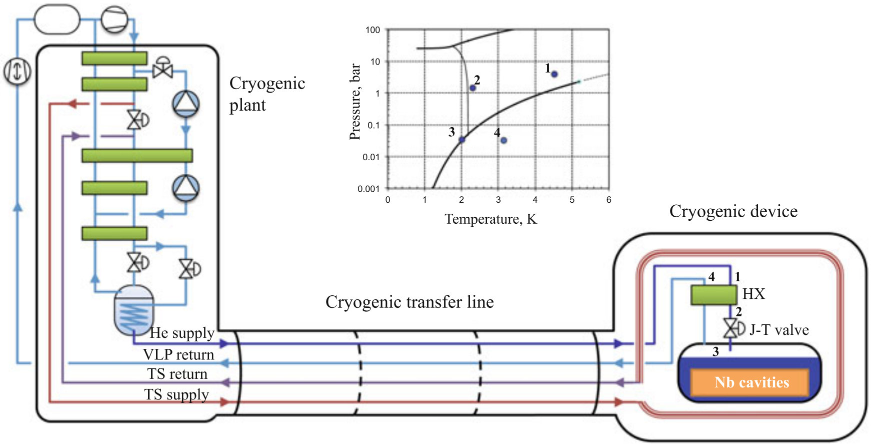

Fig. 9.2 Schematic of a complex cryogenic system

and transferred by means of a constant flow of cold helium to the device via the helium supply line. In this example, the cryogenic plant supplies supercritical helium at a temperature and pressure of 4.5 K and 3 bar absolute, respectively. Then the 2 K helium is produced at the cryogenic device, where the supercritical helium is first precooled to 2.2 K in a counterflow heat exchanger (HX) and then throttled in a Joule-Thomson valve down to a pressure of 31.3 mbar absolute.

This solution takes advantage of a significantly low value of the helium critical pressure (2.25 bar absolute). Transferring helium at higher pressure eliminates all the problems related to two-phase flow phenomena. Usually a pressure around 3 bar absolute is perfectly adequate. Then, the cryoplant compressors have to compress helium to a pressure not higher then 20 bar absolute, which is not too complicated from technical point of view.

Since helium is a very expensive cryogen it must be recovered and recirculated to the cryogenic system. Therefore in the above example the helium vapor is recovered from the cryogenic device and transferred back to the cryogenic plant via the vapor low-pressure line (VLP). The vapor flow is driven by a vacuum pump at the cryogenic plant, which generates the subatmospheric pressure required for reaching 2 K in the helium vessel inside the cryogenic device. In the case of very large systems, which require significantly high cold helium flows, vacuum pumps are replaced by sets of cold and warm compressors.

All the cold elements of the cryogenic device are surrounded by a thermal shield. The shield is actively cooled by an additional helium circuit at a temperature of 40–60 K. The thermal shield circuit is composed of the TS supply and return lines connected to the high pressure helium line in the cryoplant cold box, downstream the first set of its heat exchangers.

In the above example the cryogenic transfer line is one of the main components of the cryogenic system. Apart from all the four process lines (He supply line, VLP return line, TS supply line and TS return line) it includes also thermal shields, vacuum jackets, vacuum barriers, supporting structures, thermal contraction

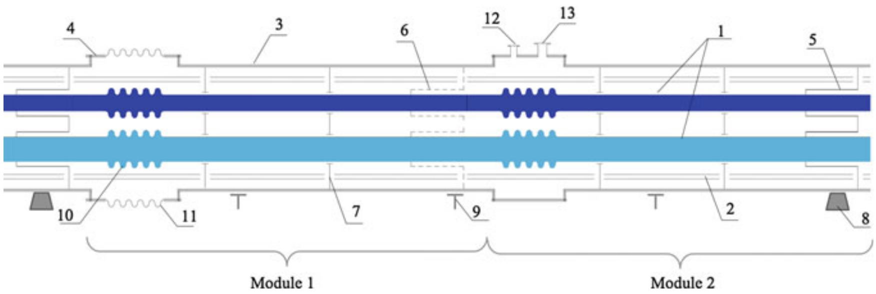

Fig. 9.3 Schematic illustration of a multichannel cryogenic line

compensation elements, pressure safety devices, vacuum pumping ports and some instrumentation (temperature sensors and pressure transducers).

The cryogenic transfer lines are almost always manufactured and preassembled at manufacturer sites that are located far away from their final locations. Therefore, the lines have a modular structure that facilitates production, transportation and installation, as well as some repair work, if needed. This strongly affects design choices such as a number and lengths of sections (modules) and interconnection arrangements. Figure 9.3 shows a schematic illustration of a straight section of a multichannel cryogenic transfer line.

This section is composed of two straight modules. Each of them consists of process pipes (1), thermal shields (2) and an external envelope (3). The two sections of the external envelope are connected by an interconnecting sleeve (4). The cryoline section ends with vacuum barriers (5) that separate the cryoline insulation vacuum from those of the adjacent vacuum sectors. All forces resulting from the dead weights, pressure loads and thermal contractions of the process lines are transferred to the vacuum jacket via a process line fixed support (6), sliding supports (7) and the vacuum barriers as well, which also act as fixed supports. The external envelope transfers these forces to conventional facility structures (anchors or foundations at the building floor and walls) via the fixed supports (8) and sliding supports (9) of the external envelope.

Both the process pipes and the external envelope are equipped with bellows. Internal bellows (10) compensate the thermal shrinkage of process pipes, whilst the external bellows (11) are to cope with all the thermal expansions and contractions of the vacuum jacket. The external envelope is also equipped with a vacuum pumping port (12) and pressure relief device (13).

The most well known large scientific facilities that use multichannel cryogenic lines are listed in Table 9.1. In almost all these facilities, the cryogenic transfer lines are part of cryogenic distribution systems, which in addition to cryogenic transfer lines include a number of distribution boxes. For example the LHC cryogenic distributions system, which is the largest system in the world, is composed of eight separated cryogenic distribution lines. Each distribution line is 3.1–3.3 km long and consists of a number of cryogenic transfer line sections that connect 38 service modules (distribution boxes) [5, 6]. Another example is the RHIC cryogenic distribution system that includes 12 valve boxes and 25 sections of multichannel cryogenic transfer lines [7].

Table 9.1 Examples of large scientific facilities using multichannel cryogenic transfer lines

No.	Scientific facility	Institution (location)	Machine type	Cryogenic devices (operating temperature)	Cryogenic transfer line		
					Total length	Cold line no.	Temperatures (cryogen)
1	ESS[a]	European Spallation Source ERIC (Lund, Sweden)	Proton linac and neutron source	RF cavities (2 K)	450 m	4	4–53 K (helium)
2	FAIR/SIS100[a]	GSI (Darmstadt, Germany)	Heavy-ion storage ring	Magnets (4.3 K)	900 m	4 or 5	4.3–100 K (helium)
3	FAIR/ SuperFRS[a]	GSI (Darmstadt, Germany)	Fragment separator	Magnets (4.3 K)	500 m	4	4.5–100 K (helium)
4	FLASH	DESY (Hamburg, Germany)	Electron linac with free electron laser	RF cavities (2 K)	200 m	4	4.5–80 K (helium)
5	FRIB[a]	MSU (Michigan, USA)	Proton linac and fragment separator	RF cavities (2 K)	500 m	5	4–55 K (helium)
6	HERA	DESY (Hamburg, Germany)	Hadron-electron storage ring and collider	Magnets and RF cavities (4 K)	6.3 km	4	3.7–80 K (helium and nitrogen)
7	ISR	CERN (Genewa, Switzerland)	Hadron storage ring and collider	Magnets (4.2 K)	400 m	2	4.2–100 K (helium)
8	ITER[a]	ITER Organization (Cadarache, France)	Tokamak	Tokamak magnets (4.3K), divertor cryopumps (4.5 K)	3.5 km	4–6	4.3–100 K (helium)
9	JT60SA[a]	JAEA (Naka, Japan)	Tokamak	Tokamak magnets (4.4K), divertor cryopumps (3.7 K)	100 m	5 or 6	4.4–100 K (helium)
10	KEKB	KEK (Tsukuba, Japan)	Electron-positron storage ring and collider	Crab cavities (2 K)	1.1 km	4	4.5–80 K (helium and nitrogen)

(continued)

Table 9.1 (continued)

No.	Scientific facility	Institution (location)	Machine type	Cryogenic devices (operating temperature)	Cryogenic transfer line		
					Total length	Cold line no.	Temperatures (cryogen)
11	KATRIN	TLK (Karlsruhe, Germany)	Tritium-neutrino experiment	Magnets (4.5 K)	40 m	6	4.5–117 K (helium and nitrogen)
12	LHC	CERN (Genewa, Switzerland)	Hadron storage ring and collider	Magnets (1.9 K)	26 km	4 and 5	1.8–80 K (helium)
13	RHIC	BNL (Brookhaven, USA)	Heavy-ion storage ring and collider	Magnets (4.6 K)	5.2 km	5	4.6–70 K (helium)
14	SNS	ORNL (Oak Ridge, USA)	Proton linac and neutron source	RF cavities (2.1 K)	600 m	2	2.1–50 K (helium)
15	Tevatron	FERMILAB (Batavia, USA)	Proton storage ring and collider	Magnets (5 K)	6.7 km	2	4.6–80 K (helium and nitrogen)
16	TORE SUPRA	CEA (Cadarache, France)	Tokamak	Tokamak magnets (1.8 K)	100 m	8	1.7 K–80 K (helium and nitrogen)
17	TRISTAN	KEK (Tsukuba, Japan)	Electron-positron storage ring and collider	RF cavities and magnets (4.2 K)	330 m	4	4.5–80 K (helium and nitrogen)
18	XFEL/AMTF	DESY (Hamburg, Germany)	Cryomodule test stand	RF cavities (2 K)	170 m	4	4.5–80 K (helium)
19	XFEL/LINAC[a]	DESY (Hamburg, Germany)	Electron linac with free electron laser	RF cavities (2 K)	340 m	6 and 7	2–80 K (helium)

[a]under design or construction in Feb. 2016

9.2 Cryoline Routing and Modularization

The routing of a cryogenic transfer line defines its detailed location in the scientific facility site. In order to minimize both capital and operational costs the routing should be simple and the total length of the line should be as short as possible. However, in a great extent it is the geometrical features of the site infrastructure that determines space available for the line. An example of the most complicated cryoline routings is the ITER cryogenic distribution system [8, 9], which 3 D model representation is shown in Fig. 1.25 (Chap. 1). This system is to be located around the machine in the tokamak building.

Figure 9.4 shows a 3D model of the ESS cryogenic distribution line which runs from the cold box of the ESS accelerator cryogenic plant to the ESS linac tunnel in an underground gallery [10]. Since the gallery has chicanes, which are required for limiting the propagation of radiation from the tunnel to the cold box building, the transfer line is significantly elongated and has additional elbows.

Due to a complex internal design requiring a lot of precise assembly works the cryogenic transfer lines are usually produced in manufacturer workshops, which are located far away from the scientific facilities. In order to facilitate production, transportation and installation of cryogenic transfer lines, the lines are designed to be composed of a defined number of modules [11]. Each module is a short section of the cryoline that is connected to its adjacent sections via special interconnections. Producing and assembling cryoline modules at manufacturer sites reduces production costs and helps to meet high standards of production works. The prefabricated modules are transported to the site and linked together with the interconnections. The lengths and shapes of modules depend mainly on cryoline routings, transportation method and fixed support locations. Usually the lengths of modules follow the single

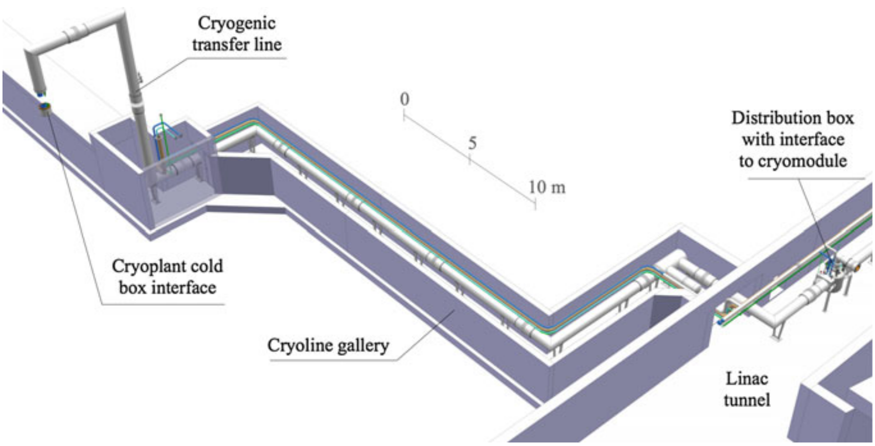

Fig. 9.4 Schematic view of the ESS linac cryogenic transfer line

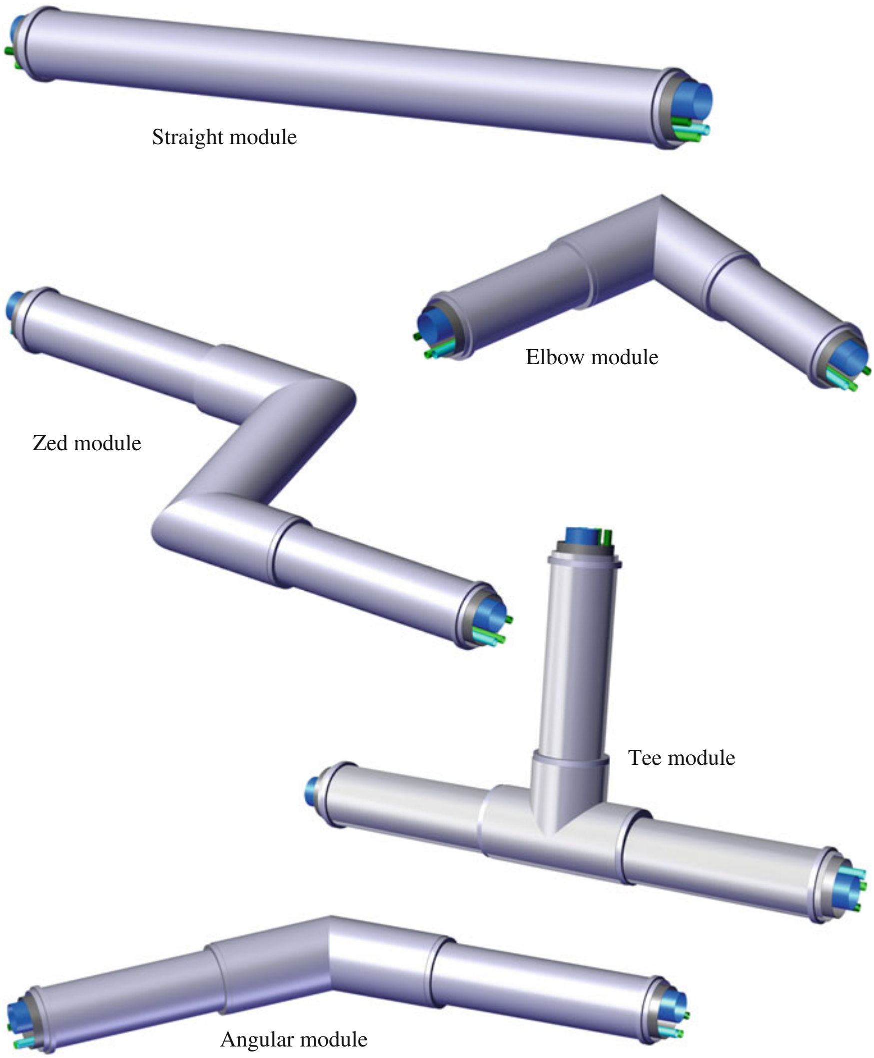

Fig. 9.5 Typical cryoline modules

or double random lengths of pipes (the most commonly stocked lengths) and are not longer than the length of a typical semi-trailer (ca. 13 m).

Figure 9.5 shows some typical cryoline modules. The most frequently used are straight and elbow modules. The Zed module is used where the cryoline routing has a significantly small step, while Tee module is dedicated for distributing cryogenic fluids to two cryogenic devices (or two groups of devices).

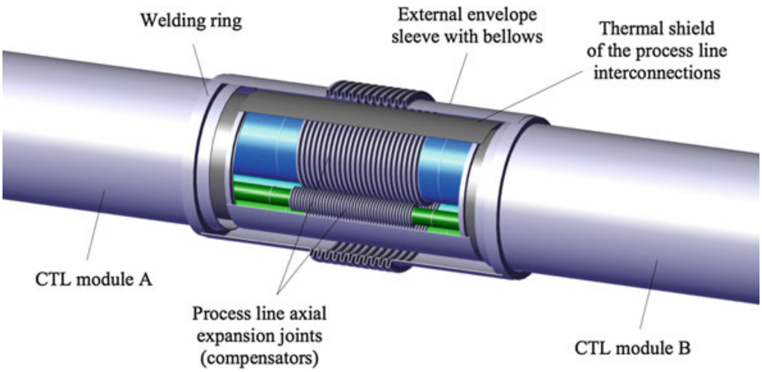

Fig. 9.6 Typical design of an interconnection between two cryoline modules

During the installation of a cryogenic transfer line at its final location the cryoline modules are connected to each other with so-called cryoline interconnections. Figure 9.6 shows an example design of a cryoline interconnection.

The external envelope sections of two adjacent cryoline modules are ended with a welding ring that the interconnection sleeve is welded to. The sleeve is made of a pipe section which is slightly higher in size than the cryoline module external envelope. Such a sleeve can be moved aside on one of the modules in order to get an access to the internal parts of the interconnection. Some of interconnection sleeves are equipped with bellows allowing for required axial or lateral displacements. In this case, the internal process lines should also be equipped with axial or lateral compensators.

9.3 Cryoline Cross-Section Arrangements

The arrangement of process lines in a cryoline cross section can impact the thermo-mechanical behavior and thermal feature of the cryogenic transfer line. Therefore the detailed locations of process lines and thermal shield inside the vacuum jacket (external envelope) should be defined at one of the earliest design stages [11]. Proper arrangement of the lines should help to:

- minimize the external envelope size,
- minimize heat fluxes among process lines,
- reduce insulation vacuum space,
- avoid any unwanted thermal bridges among internal components,
- link thermally the thermal shield components with their cooling line,
- provide space for the supporting and thermal shrinkage compensation system elements (supports, spacers, bellows, metal hoses, etc.),

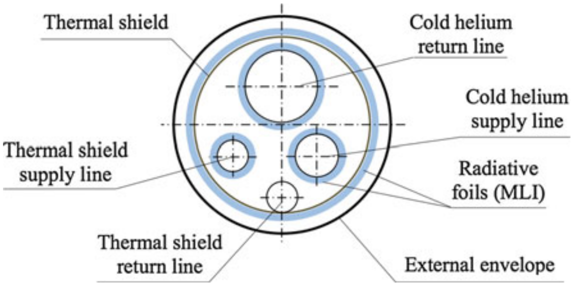

Fig. 9.7 Example cross section of a four channel cryogenic transfer line

- keep enough room required for assembly (welding process lines and wrapping radiation foils in interconnections, etc.),
- keep balance in the distribution of process pipe and radiation shield dead weight to avoid significant moments which can lead to unwanted torsions of process pipes along the line.

Figure 9.7 shows a schematic arrangement of the cross section of a four-channel cryogenic transfer line. Its all process lines are surrounded by a cylindrical thermal shield wrapped with radiative foils (MLI). The thermal shield is connected with the thermal shield return line, which works as a thermal sink for radiative heat loads absorbed by the shield. Since the cold helium supply line has larger diameter than that of the thermal shield supply line, there is a clear asymmetry in the locations of these process lines in respect to the vertical center plane. This geometrical asymmetry guarantees the symmetrical distribution of process line dead weights.

Figure 9.8 collects the cross-sections of cryogenic transfer lines of some well-known scientific facilities. The cryogenic transfer lines of HERA, KEKB, LHC, Tore Supra, TEVATRON, TRISTAN, RHIC and XFEL/AMTF were already built and operated, whereas the cryolines of ESS, FRIB, ITER and XFEL/Linac injector are currently being designed or constructed. The TEVATRON CTL is a single path cryoline, what means that it is designed to transfer cryogenic fluids into one direction only. In order to return helium back to the cryogenic plant the cryogenic system needs to use two such lines (feed and return lines) or return the helium via a warm process line. All the other cryogenic lines shown in Fig. 9.8 are dual path lines. They consist of supply and return lines. The number of lines depends on the related cryogenic device cooling process and varies from four (eg. TRISTAN and HERA CTLs) to ten (Tore Supra CTL). The sizes of the process lines differ very much from line to line, since they depend on cryogen mass flow rate, density and allowable pressure drop. Process lines used for transferring cold helium vapour at low pressure usually have the largest sizes. In case of the LHC/QRL CTL this line is DN250 in size and it transfers helium vapour at a subatmospheric pressure of 16 mbar absolute and temperature of 4 K in a distance of 3.4 km. The diameters of the cryoline external envelopes also vary from line to line. The largest is the LHC/QRT CTL which is equal to 640 mm, while the smallest is the CTL of KEKB (156 mm).

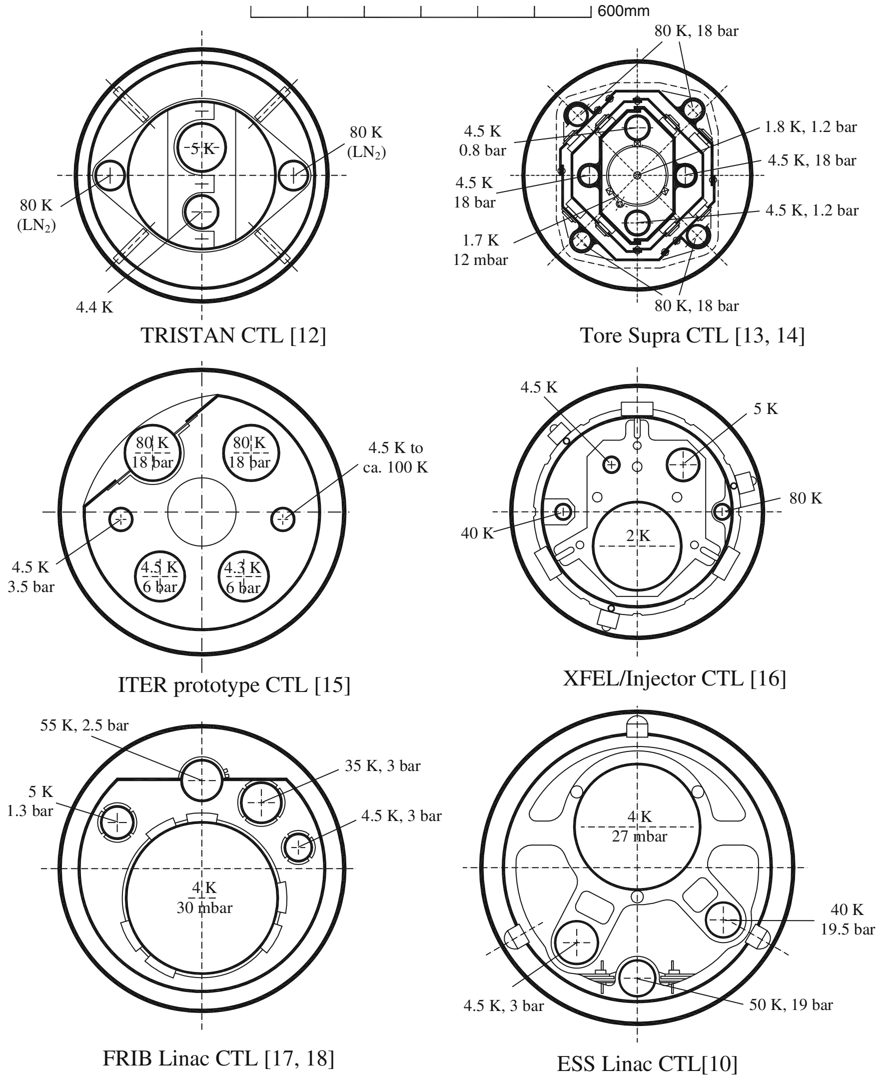

Fig. 9.8 Cross-section arrangements of cryogenic transfer lines existing or under construction

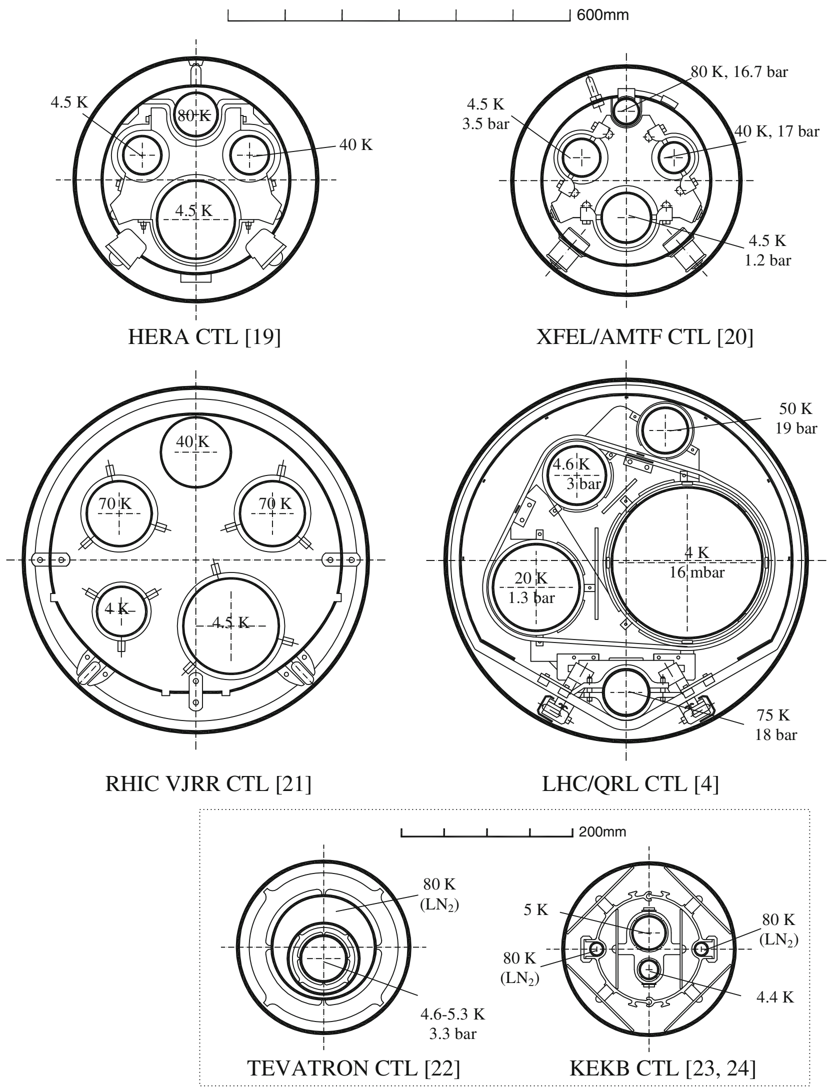

Fig. 9.8 (continued)

9.4 Supporting Structures

Due to high temperature and pressure differences, and significantly high dead weights of cryogenic transfer line components, cryogenic transfer lines require complex supporting elements to carry the weights, to direct and transfer static and dynamic loads, as well as to control the movements of cryoline components. Forces resulting from pressure, thermal and gravity loads acting on the process lines (and in some cases on the thermal shields) have to be transferred to the external envelope and further to the surrounding structures, such as building floors and walls, piping bridges, etc. These forces can be in an order of magnitude of 10 kN or even higher. For example a DN250 process line equipped with an axial expansion joint (of an effective cross section $A_{ef} = 690\ \text{cm}^2$), which maximum allowable pressure PS is 6 bar, at a test pressure of $\text{PT} = 1.43 \cdot \text{PS} = 8.58$ bar acts on its fixed support with an longitudinal force $F_x = A_{ef} \cdot \text{PT} = 59.2$ kN. For a cryogenic transfer line that in addition to the DN250 process line includes a DN65 cold helium line (PS = 6 bar) and two DN50 thermal shield lines (PS = 25 bar) the total force that has to be transferred by the fixed support can reach 90 kN.

The supporting system of any cryogenic transfer line is composed of internal and external supporting structures. The internal supporting structures include fixed and sliding supports and spacers of process pipes and thermal shield components. Since these supports connect mechanically the cryoline components at highly different temperatures they should be designed in a way that significantly minimizes all unwanted heat transfers. For given temperature differences, Fourier's law of thermal conduction gives only three general ways for reducing heat flows: (1) elongating the heat transfer distances, (2) decreasing the heat transfer cross sections and (3) choosing materials with low heat transfer coefficients (see Chap. 1). All of these methods are applied in designing process line supports, however, the mechanical strength requirement limits the elongations, cross section decreases and applicable materials.

Process line fixed supports are supporting elements that bind mechanically the process lines to the external envelope and remove all six degrees of freedom of the lines in respect to the vacuum jacket. These supports are usually made of stainless steel in order to allow for welding their elements both to the process lines and vacuum jacket. Figure 9.9 shows a typical design of a process line fixed support. This support is composed of several welding rings and sleeves and a plate. Ring 1 is for welding the fixed support to the inner surface of the vacuum jacket. At working conditions the heat from the external environment flows via the vacuum jacket wall, ring 1 and sleeve 1 to the fixed support plate. The TS return line is thermally connected to the plate and works as a thermal sink that stabilizes thermally the plate at a thermal shield temperature (usually between 50 and 80 K).

The cold process lines and the TS supply line are connected to the plate via a set of two sleeves and two rings which elongate the heat flow paths. In the case of the cold helium return line, heat flows from the plate via sleeve 2, ring 2, sleeve 3, ring 3 to the wall of the line. Process lines can be also connected to the plate with one

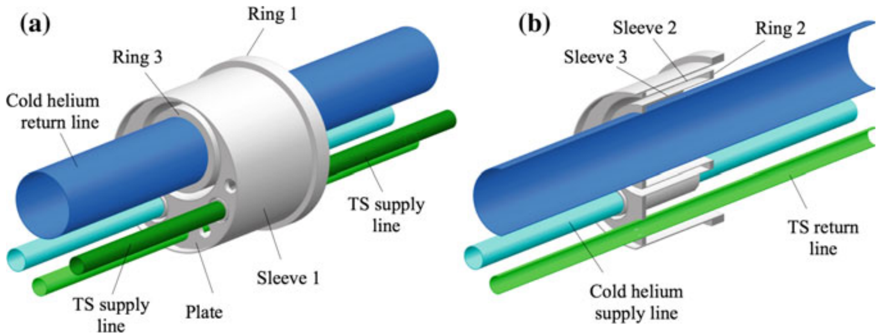

Fig. 9.9 Process line fixed support: isometric view (**a**) and its longitudinal cross section showing elongation sleeves of cold process lines (**b**)

sleeve and one ring. Then the heat transfer path is shorter and more heat flows to the transferred helium, but the fixed support has better mechanical properties, and since its design is less complicated, its manufacturing is easier and less expensive. In order to reduce heat leaks the cryoline designers can elongate the sleeves and make them from tubes of thinner walls as long as the fixed support has appropriate mechanical parameters. In case of long sleeves there is a risk of lateral deformations of the sleeves when exposed to radial forces. It can lead to unwanted thermal bridges which can significantly increase heat loads to the cold process lines. The lengths of sleeves usually varies from 0.3 to 0.8 m, whist their wall thicknesses are usually similar to the process line wall thicknesses (1.8–3.2 mm).

Process line sliding supports are supporting elements that direct pressure and thermal loads to the fixed supports. They also carry the weight of a section of process lines, equipment attached to the lines (thermal shield components, radiation foils, getters, absorbers, instrumentation) and cryogenic fluids in the lines as well. Since these support do not bear high mechanical loads they are typically made of composite materials characterized by low thermal conduction coefficient. Figure 9.10 shows an example design of a process line sliding support. This support is composed

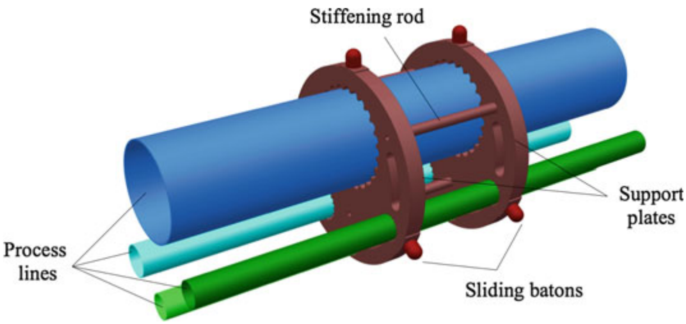

Fig. 9.10 Process line sliding support

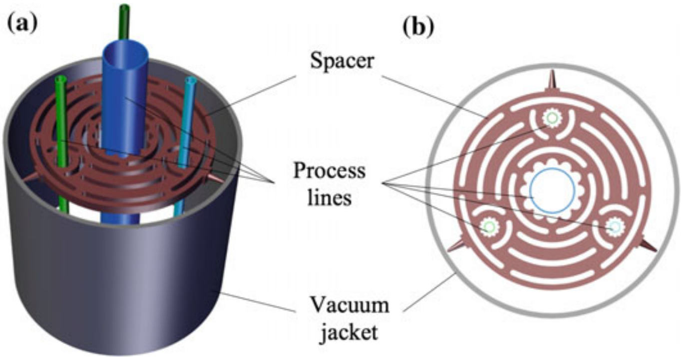

Fig. 9.11 Process line spacer: **a** isometric view, **b** top view

of two plates connected to each other with three stiffening rods. This solution protects the plates against tilting and blocking process line movements. The dead weight is transferred to the external envelope via a set of sliding batons. The batons have spherical ends to reduce the area of contact with the vacuum jacket internal surface. In order to minimize friction the batons can be replaced with wheels, rollers or balls.

Spacers are supporting structures of a special type. Their main function is to keep the lines in proper locations in cryoline cross sections in order to avoid unwanted thermal contacts. They do not bear significant loads from process lines but only limit the movements of the lines in their radial directions. Figure 9.11 shows an example spacer design. The sizes of the holes for process lines are distinctively larger then the line sizes. Since the spacer does not bear any significant mechanical load it can be made of a material of low thermal conductivity (that usually implies lower mechanical strength) and can have a form that elongates the heat transfer paths, which additionally lessens its mechanical properties but does not add any substantial heat loads to the cold lines.

The family of cryoline external envelope supports also includes fixed supports, sliding supports and spacers. These supports carry the entire cryoline weight and transfer all forces to the surrounding structures. The forces, apart of dynamic and static forces from process lines, can include also forces resulting from thermal and pressure loads acting on the external envelope itself. The vacuum jacket (external envelope) can be exposed to a significant variation of ambient temperature and it can also get cold locally due to a cryogen leak from a cold process line in case of a failure mode. Some additional pressure forces can appear if the set pressure of the external envelope safety devices significantly exceeds the atmospheric pressure. The total forces that the fixed supports of the external envelope have to bear can reach the value of 10 kN. Figure 9.12 depicts example designs of external envelope fixed and sliding supports. The fixed support has a hoop that increases the mechanical strength of the support. The hoop is made of steel plates and is welded to the external envelope through two steel patches and to the support base. The base of the support is to be screwed to a dedicated component of the surrounding structures.

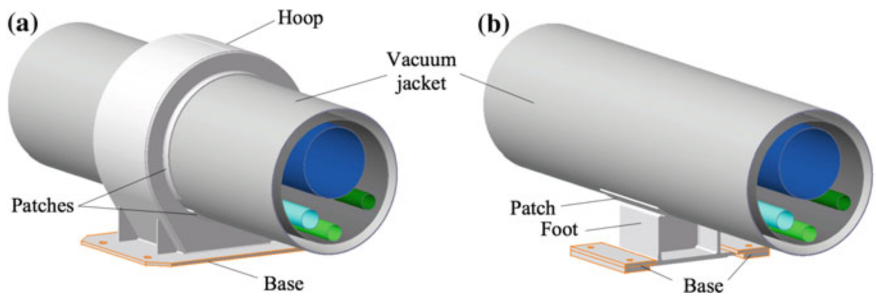

Fig. 9.12 External envelope supporting elements: **a** fixed support and **b** sliding support

The sliding support shown in Fig. 9.12b is designed for allowing some axial movements of the cryoline. The support foot is welded to the vacuum jacket via a steel patch. The support base is to be screwed to the surrounding structure but not fixed to the support feet at all. The base blocks the lateral movements and rotations of the support foot. Usually the expected movements of the sliding support feet are not higher then a couple of centimeters.

9.5 Thermal Contraction Compensation

All the components of cryogenic transfer lines tend to contract due to temperature variations. This pertains not only to components which are at cryogenic temperatures (cold process lines and thermal shields) but also their vacuum jackets, since they can be exposed to a variation of the ambient temperature as well as to a significant temperature drop during a failure mode of a cold process line break. Therefore, both the process lines and external envelope must be protected against excessive stresses and forces that can result from thermal contraction [11]. Cryoline thermal contraction compensation systems can employ axial expansion joints, metallic flexible hoses and natural compensation loops.

Natural compensation loops require a lot of space, so they are used only if the cryoline routing is adequately complex and have a number of elbow and angular modules located close to each other. Taking this solution requires detailed and complex thermo-mechanical analyses of cryoline behavior in the conditions of all possible operation and safety modes. Metallic flexible hoses are usually used in elbow or angular modules to compensate some rather small dislocations of process lines. There are usually two hoses installed in the bent section of a process line. Then the contractions of the line sections are absorbed by the lateral deformations of the hoses.

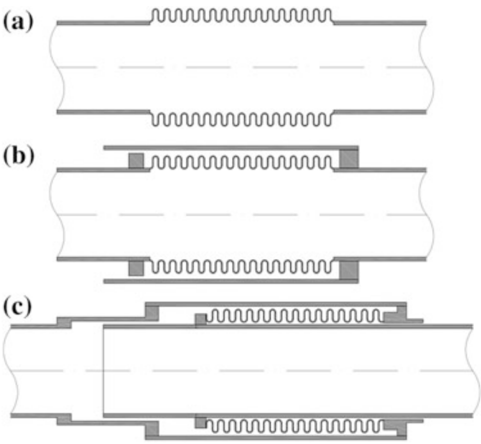

Fig. 9.13 Typical axial expansion joints used for cryoline process lines: **a** with bellows subjected to internal pressure, **b** with bellows subjected to internal pressure and equipped with a guiding sleeve **c** with bellows subjected to external pressure

Axial expansion joints seems to be the most often used thermal-contraction compensation components, even though they are considered as the main items that can significantly lower the reliability of transfer lines [7, 25, 26]. The joints consist of bellows made of one to a few plies whose thickness has to be as small as a fraction of millimeter (usually from 0.2 to 0.5 mm). Since these very thin elements are subjected to significantly high and cyclical thermo-mechanical loads, there is a risk not only of leaks but also of loosing the mechanical stability of process lines.

Figure 9.13 depicts three typical types of axial expansion joints installed in the process pipes of cryogenic transfer lines . The first one (Fig. 9.13a) is composed of two pipe sections and bellows. It is the simplest joint but also very sensitive to become unstable. If the pipe with such a joint is not properly guided and anchored or the expansion joint has very low stiffness the bellows or even whole pipe segment can buckle [27]. This can of course lead to unwanted thermal contacts increasing heat loads and what is more dangerous, to leaks in the cold process lines.

Axial expansion joints equipped with special guiding sleeves, as shown schematically in Fig. 9.13b, can mitigate the risk of buckling to a certain extend, if the risk of local instability comes from insufficient stiffness of the bellows. However, this configuration also requires a precise arrangement of anchors and guides.

Joints with bellows subjected to external pressure (see Fig. 9.13c) are the most stable from a mechanical point of view. When such joints are pressurized they actually become less sensitive to the sources of local instabilities. On the other hand their production is significantly much more expensive.

9.6 Materials

Materials used for manufacturing cryogenic transfer lines are almost always the same as for other type of cryostats. Process pipes and their strong fixed supports as well as vacuum barriers are made of austenitic stainless steels adequate for temperatures which lines are going to be cooled down to. External envelopes can be manufactured of some low carbon steels, as long as the lowest expected temperature of the vacuum jacket will not cause any brittle fractures. The ductile-brittle transition of low carbon steels ends in a temperature of −50 °C, so the application of low carbon steels is not recommended if the vacuum jacket temperature can drop below this value. Then external envelope should also be made of austenitic stainless steel.

Since cryogenic transfer lines are dedicated for transferring fluids at pressure usually higher than 0.5 bar gauge, their process lines are considered as pressure equipment and have to be designed and constructed in respect to dedicated regulations and standards applicable in the country where the lines are to be installed and operated. Example documents are the ASME B31 of the USA and the European metallic industrial piping code EN 13480, harmonized with the Pressure Equipment Directive 97/23/EC (PED) of the European Union. All these standards include a list of materials that are applicable for use at given cryogenic temperatures. Cold process lines are usually made of the standard Ni-Cr low-carbon stainless steel 1.4306 (304L), due to its significantly low price and applicability in a whole cryogenic temperature range. For external envelope usually the stainless steel 1.4301 (304) is used, which is cheaper than grade 1.4306 but applicable down to 77 K only.

Cryoline thermal shield components are usually made of some aluminum alloys of 6000 series. These alloys have good thermal conductivity, low outgassing rate and the surfaces of their commercial sheets, pipes and profiles have significantly low emissivity coefficient. They are also easily machined and highly weldable by using gas tungsten arc welding technique. AA6061, which is a good medium-strength all-purpose aluminum alloy, is used for thermal shields made of pipes of sheets, whilst AA6063 alloy is used for thermal shield made of extruded shapes.

Sliding supports and spacers of the process lines are usually made of fiber-epoxy composites, such as NEMA grades G-10, G-10-FR4 which is fire retardant, or G-10CR that is characterized by much smaller variability of their mechanical and thermal properties at cryogenic temperatures. In case of cryolines designed for long-time operation in radiation environment their sliding supports can be made ofG-11 or G-11CR composites, which are less sensitive to radiation and thus retain their properties longer.

9.7 Manufacturing and Installation

Cryoline modules are assembled from the inner to the outer parts. Their fabrication usually consists of the following works:

1. Welding of process line sections and external envelope sections (including all required examinations of welds, such as visual examination, radiographic or ultrasonic tests, etc.),
2. Cleaning the external and internal surfaces of the prepared sections,
3. Leak tightness tests of process line and external envelope sections,
4. Winding MLI on the process lines,
5. Installation of process line fixed and sliding supports,
6. Installation of thermal shield elements,
7. Winding MLI on the thermal shield,
8. Inserting the process line sections with their thermal shield into the external envelope section,
9. Connection of the process line fixed support to the external envelope section,
10. Preparation of the cryoline module for transportation.

Cryoline interconnections are also assembled from their inner parts to outer ones, and their assembling requires the following activities:

1. Sliding the interconnection sleeve over the end of one of the cryoline modules,
2. Welding the compensators or suitable pipe sections to the ends of the process line sections,
3. Testing the process line welds (visual examination, radiographic or ultrasonic tests, leak tightness tests, pressure test, if needed, etc.),
4. Winding MLI on the process lines,
5. Installation of thermal shield segments,
6. Winding MLI on the thermal shield,
7. Sliding the interconnection sleeve over the interconnection and welding it to the welding rings of the cryoline modules,
8. Testing the sleeve welds (visual examination, leak tightness test, etc.).

Typically the installation of a cryogenic transfer line requires assembling of a number of interconnections. In order to minimize the time and cost of the installation works the leak tightness test of the process pipe welds are performed in one turn for all the interconnections. The leak tightness test of the sleeve welds are also performed

9.8 Case Study: XFEL/AMTF Cryogenic Transfer Line

A good example of a multichannel cryogenic transfer line is the XFEL/AMTF cryoline. This line is used for transferring cryogenic cooling power from the HERA refrigerator to the Accelerator Module Test Facility (AMTF) in the national research center of the Deutsches Electronen-Synchrotron (DESY). Figure 9.14 shows schematically the run of the cryoline in the DESY site. The AMTF is intended for testing the superconducting cavities and cryomodules of the European X-ray Free Electron Laser (XFEL) [28]. The test facility requires for its continuous

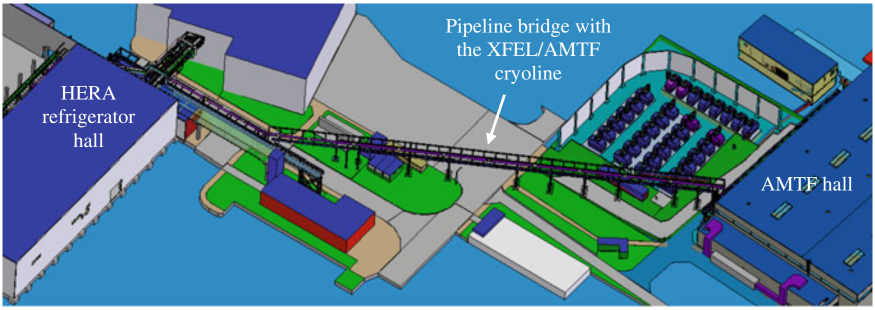

Fig. 9.14 Schematic run of the XFEL/AMTF cryogenic transfer line (*courtesy* DESY)

operation the cooling capacities of 0.8 kW at 2.0 K, 0.5 kW at 4.5 K and 3 kW at 40/80 K [20]. Since the 2 K helium is produced by isenthalpic expansion of the 4.5 K helium (previously subcooled to 2.2 K in counter flow heat exchangers) in the facility cryostats and test boxes, the XFEL/AMTF cryogenic line houses only 4.5 and 40/80 K circuits.

The XFEL/AMTF cryoline project was executed by Wrocław Technology Park AB under the Polish in-kind contribution to the XFEL project and coordinated by National Centre for Nuclear Research, Poland [29]. All the requirements for the cryoline were provided to the Polish partners in the comprehensive specification prepared by DESY [30]. Based on this specification, Wrocław University of Technology developed the detailed design of the line and supervised production and participated in the acceptance tests. The line was manufactured and installed in the DESY site by Kriosystem Ltd [20]. The execution of the cryoline project went through the following phases:

Phase 0. Specification of requirements,
Phase 1. Cryoline design,
Phase 2. Cryoline module productions,
Phase 3. Transportation of the cryoline modules to the DESY site,
Phase 4. Installation of the cryoline modules in the site,
Phase 5. Cryoline commissioning.

The first cool down of the cryoline to the nominal temperatures was successfully curried out in August 2012 and since December 2012 the line is in continuous operation.

9.8.1 Technical Requirements

All the essential requirements for the XFEL/AMTF cryogenic transfer line were prepared on the basis of DESY experience with cryogenic transfer lines for HERA and FLASH. The specification defined the run of the cryoline and its interfaces to

Fig. 9.15 Routing of the XFEL/AMTF cryogenic transfer line on the dedicated pipeline bridge (*courtesy* DESY)

the adjoining components [30]. The detailed routing of the line is shown in Fig. 9.15. The line runs from a valve box located between the HERA refrigerator hall and the HERA West building on a pipeline bridge in a height of 8 to 10 m above the ground level. At the AMTF hall the line goes 8.4 m down in two steps and ends at a subcooler box located inside the hall.

The line had to be designed, manufactured and installed in conformance with Pressure Equipment Directive 97/23/EC. In order to reach the conformity with the directive, the AD2000 Pressure Vessel Code [31] had to be applied. The specification also described all the essential requirements for mechanical design, tests to be carried out at manufacture workshop and DESY site and guarantee data. The defined sizes and operating conditions of the process lines, thermal shield and external envelope are given in Table 9.2.

The line had to be designed so as to ensure reliable and uninterruptible operation for at least 5 years and withstand 200 cool down/warm up cycles without damage and deterioration of quality. All pressure bearing components (process lines and their supports) had to be designed for the maximum pressure of 20 bar against vacuum and for the pressure of 0 bar against atmospheric pressure at all possible operating temperatures. Similarly, all the components of external envelope and their

Table 9.2 Sizes and operating conditions of the process lines, thermal shield and vacuum jacket

Pipe	Size	Diameter and thickness	Design pressure (bara)	Operating pressure (bara)	Operating temperature (K)
4.5 K supply	DN50	60.3 mm × 2 mm	20	3.5	4.5–6
4.5 K return	DN80	88.9 mm × 2.3 mm	20	1.2	4.5
40 K supply	DN40	48.3 mm × 2 mm	20	17	40
80 K return	DN40	48.3 mm × 2 mm	20	16.7	80
Thermal shield	NA	300 mm × 4 mm	NA	NA	80
Vacuum jacket	DN400	406.4 mm × 4.78 mm	1.5	−1	300

supports had to be designed for the internal pressure from 0 bar absolute to 1.5 bar absolute against the atmospheric pressure. In addition, the process lines had to be designed so as to withstand the maximal possible temperature difference between the inlet and outlet. It should also allow for independent cool-down/warm-up cycles of the different process circuits as well as for rapid cool-downs or warm-ups of any circuit.

Requirements on the tightness of the process lines and external envelope defined the values of allowable single and integral leak rates into the isolation vacuum. The single leak rate from any component of process pipes and external envelope such as welds, bellows and corrugated hoses should not be higher than 1×10^{-9} mbar dm^3/s at the design pressure and both room and operating temperatures, whilst the integral leak rate to the insulation vacuum should not exceed 1×10^{-8} mbar dm^3/s.

Maximum allowable heat loads to the thermal shield and 4.5 K process lines should not be higher than 1.5 and 0.15 W per meter, respectively. The cryoline should be aligned so as the connections to the valve and subcooler boxes are achieved within the limits of lateral forces for the process pipes and the vacuum shells of the connection ports of the boxes.

The design of the line also had to take into account the variations of ambient temperature in the range from 260 to 310 K and all possible thermal reactions resulting from the expansions and contractions of the bridge components.

9.8.2 *Design*

Due to a significantly high distance between a potential manufacturer workshop and the DESY site it was decided that the sizes of the cryoline modules should not exceed the dimensions of a standard European semitrailer (13.62 m × 2.75 m × 2.48 m). So the maximum length and width of the modules were taken as 13 and 2.5 m, respectively [32]. The modularization of the cryogenic transfer line is shown in Fig. 9.16. The line is composed of 11 straight modules, 3 elbow modules and 1 angular module with an angle of 150.5° [20]. The cross section of the line is shown in Fig. 9.8.

The interconnections between the modules were designed as typical sleeve-shaped interconnections holding the components of the process line thermal compensation systems. Figure 9.17 shows the schematic layout of the process line

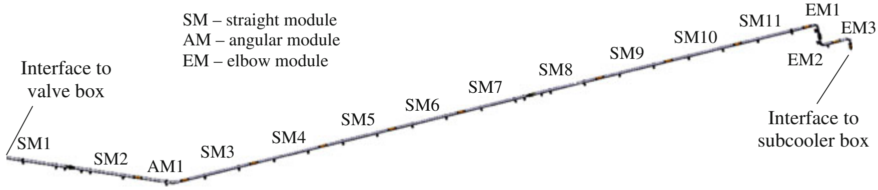

Fig. 9.16 Modularization of the XFEL/AMTF cryoline

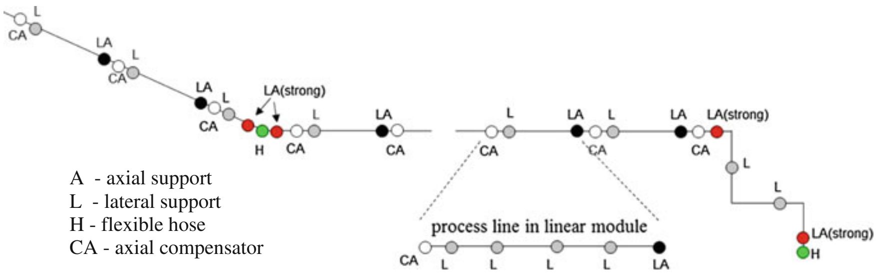

Fig. 9.17 Schematic layout of the process line support and compensation systems

supporting and thermal compensation systems [33]. These systems include axial compensators, flexible hoses, fixed supports and sliding supports. The sliding supports block lateral movements, whilst the fixed supports block both lateral and axial movements. Due to accumulation of the pressure forces at the extremities of the cryoline straight sections, each line requires only four strong fixed supports and 11 fixed supports of considerably smaller mechanical strength. The thermal contraction of each line is compensated by a set of 13 axial expansion joints and 2 flexible hoses. Since the three elbows of the process lines are very close to each other this section works as a natural compensation loop and there is no need for any expansion joints.

The external envelope acts on the bridge not only with its own pressure, thermal and dead weight loads but it also transfers the loads from internal process lines. The layout of its supporting and thermal compensation systems is schematically shown in Fig. 9.18. This supporting system consists of two fixed supports which block vertical, lateral and axial movements (VLA) in respect to the piping bridge. There are also 21 sliding supports allowing for axial movements only (VL) and 2 sliding supports blocking the line movements only in vertical directions (V). The thermal expansions or shrinkages of the envelope are compensated by three expansion joints. Each of the two long straight sections are equipped with axial compensators (CA). The thermal deformations in the section of the three elbow modules are compensated with a lateral expansion joint (CL), which is built in the interconnection between module E90-3 and the Subcooler Box.

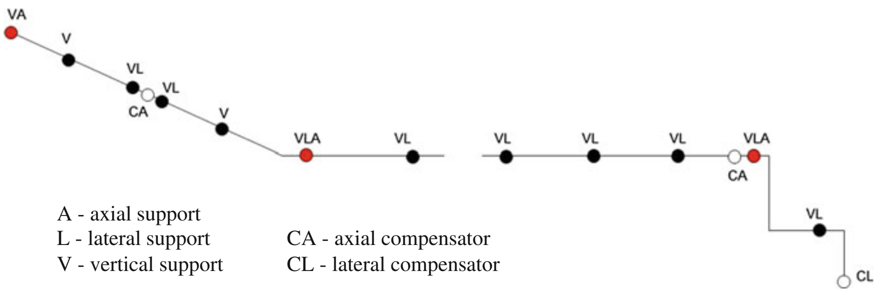

Fig. 9.18 Schematic layout of the external envelope support and compensation systems

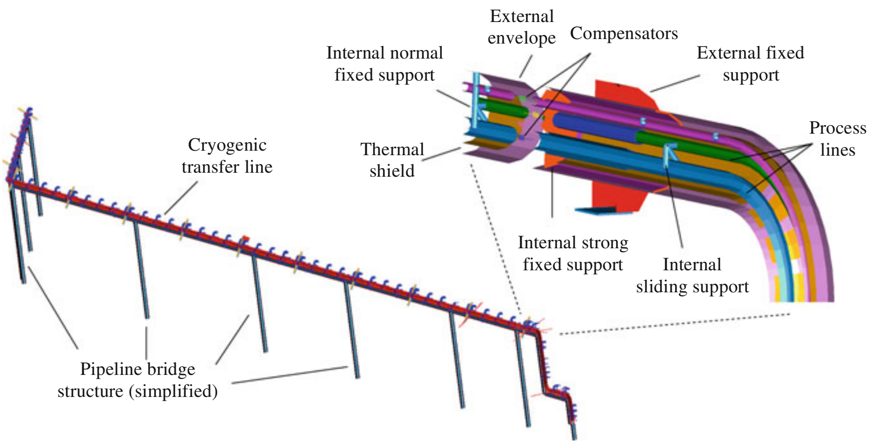

Fig. 9.19 FEM model of the XFEL/AMTF cryogenic transfer line (*courtesy* Wrocław University of Technology)

The thermal and mechanical behavior of the cryogenic transfer line with the proposed support and compensation systems was analyzed numerically. For this purpose a complex Finite Element Method model of the cryoline and its pipeline bridge was built as shown in Fig. 9.19 [34]. The model consisted of 107,000 elements and included all the kinematic joints of the external envelope, thermal shield and process line supports. It used shell elements for process lines, thermal shield and external envelope, beam elements for sliding supports and pipeline bridge structure, spring elements for all the compensators and finally membrane elements for elastic hoses. The model took into account the variation of the material properties in the specified temperature ranges. It was assumed that the process lines are made of stainless steel of grade 1.4306 or 1.4541 (A_5 = 40 %, $R_{p1,0}$ = 220 MPa and R_m = 520 MPa) and the external envelope is made of SS1.4301 (A_5 = 43 %, $R_{p1,0}$ = 235 MPa and R_m = 540 MPa).

The thermo-mechanical strength analyses of the entire cryoline were carried out for five cases [33]:

- Case 1: Design conditions (process lines and at their design pressure and operating temperatures, thermal shield at 80 K and external envelope under vacuum and at 285 K, which is an assumed assembling temperature),
- Case 2: Pressure test conditions (process lines at their test pressure (28.6 bara) and 260 K, which is the lowest possible temperature),
- Case 3: Failure mode I conditions (the external envelope of SM2 and AM1 at 160 K and the other cryoline components at the design conditions),
- Case 4: Failure mode II conditions (the external envelope of SM10 and SM11 at 160 K and the other cryoline components at the design conditions),
- Case 5: Failure mode III conditions (the external envelope of EM1, EM2 and EM3 at 160 K and the other cryoline components at the design conditions).

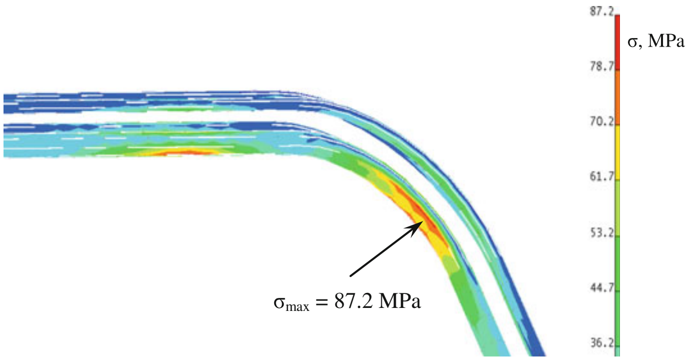

Fig. 9.20 Von Mises stress distribution on the EM1 process lines (*courtesy* Wrocław University of Technology)

The thermo-mechanical strength analyses resulted in the distributions of von Mises stresses and deformations as well as the forces acting on the supports. The obtained maximum stresses on the external envelope and process lines were equal to 80.4 and 87.2 MPa, respectively. Fig. 9.20 shows an example picture of the von Mises stress distribution on the process line sections. The maximum allowable stresses, which take into account a safety factor of 1.5, are equal to 156.7 MPa for the external envelope and 146.7 MPa for the process lines. So, the numerical modeling showed that the maximum stresses did not exceed 75 % of the allowable stress values and therefore, according to [35], both the vacuum jacket and process lines are in stress category II. It means that the lowest temperatures of the external envelope and process lines can reach −255 and −273 °C, respectively, what approves the selection of the materials.

The obtained values of deformations of process lines and forces acting on all the external and internal supports were used as input for designing these supports and selecting adequate expansion joints. The 3D models of the designed process lines supports are shown in Fig. 9.21. The process line strong fixed support is made of stainless steel of grade 1.4306 or 1.4541, whilst the normal fixed support and sliding supports are made mainly of G10 (marked in green). The double sliding support is made of two single supports fixed together with three metal rods and 3 G10 tubes. Such a support, apart of blocking lateral movements of the process lines in respect to the thermal shield, protects also the bunch of these lines against twisting. So each straight section is equipped at one end with a normal fixed support and at the other with a double sliding support.

The G-10 plate of the normal fixed supports is fixed to the radiation shield, which is made of ∅300 AA6060 pipe sections. The sliding supports are mechanically fixed only to the 4.5 K return line (DN 80). The other pipes are not connected to the support and are allowed to move axially, so all the process pipes can contract and expand independently. The sliding support plates are equipped with stainless steel rollers what allow them to move axially inside the radiation shield.

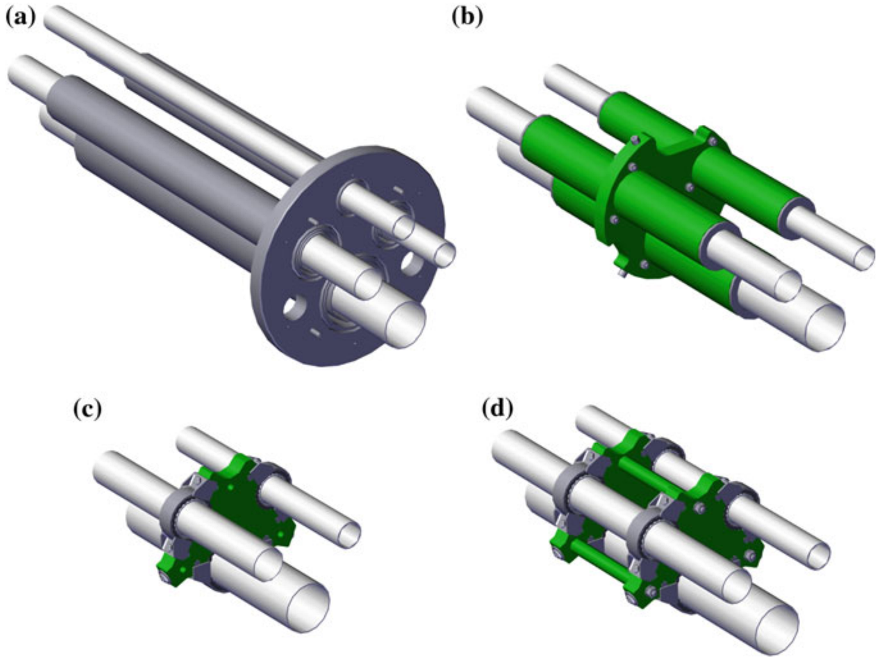

Fig. 9.21 3D models of the process line strong fixed support (**a**), normal fixed support (**b**), single sliding support (**c**) and doubled sliding support (**d**) (*courtesy* Wrocław University of Technology)

9.8.3 Manufacturing the Cryoline Modules

All the 11 straight, 3 elbow and 1 angular modules of the XFEL/AMTF cryogenic transfer line were manufactured by Kriosystem Ltd. in the period of 10 months. The assembly works of the straight modules contained the following set of technical operations:

1. Welding of process line sections and external envelope sections,
2. Test of the process line and external envelope sections,
3. Manufacturing components of the thermal shield,
4. Cleaning the surfaces of the process lines, external envelope and thermal shield,
5. Winding MLI on the 4.5 K and 40 K process lines,
6. Installation of the supports on the 4.5 K and 40 K process line sections,
7. Assembling the 80 K return line sections with the thermal shield components,
8. Inserting the 4.5 K and 40 K process lines into the thermal shield sections,
9. Fixation of thermal links to the thermal shield and the 80 K return line,
10. Winding MLI on the thermal shield sections,
11. Installation of the sliding supports to thermal shield sections,
12. Inserting the thermal shield sections in the external envelope sections,
13. Connection of the process line fixed supports to the external envelope sections.

Fig. 9.22 Sliding supports on the XATL1 straight module process lines (*courtesy* Kriosystem Ltd.)

As soon as each of the cryoline modules was assembled it was packed and prepared for its transportation to the DESY site. Figures 9.22, 9.23, 9.24 and 9.25 show the photos taken during the production of a straight module. Figure 9.22 shows process lines subassembly at technical operation 6 (double sliding support in the foreground). Figures 9.23 and 9.24 show one of the straight module subassemblies under technical operations 9 and 10, respectively. One of the fully assembled straight modules is shown in Fig. 9.25. Its process lines are ended with axial expansion joints enclosed in guiding sleeves (as schematically presented in Figure 9.13b).

9.8.4 Installation

The modules of the XFEL/AMTF cryogenic transfer line just after their manufacturing were packed and later transported to the DESY site. The installation work included the following steps:

Fig. 9.23 Aluminium thermal shield of the XATL1 straight module with its copper thermal links to the thermal shield return line (*courtesy* Kriosystem Ltd.)

Fig. 9.24 MLI radiation foils wrapped on the XATL1 straight module thermal shield (*courtesy* Kriosystem Ltd.)

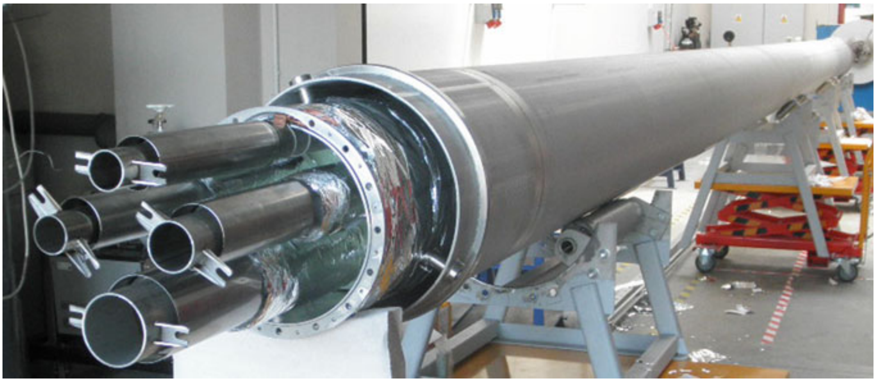

Fig. 9.25 Straight module assembled (*courtesy* Kriosystem Ltd.)

1. Lifting the cryoline modules on the pipeline bridge,
2. Positioning of the cryoline modules,
3. Fixing the external supports to the piping bridge,
4. Welding the process line sections of all the cryoline modules and connecting them to the process lines of the valve box and subcooler box,
5. Testing the welding seams of the process lines put during the installation,
6. Executing the pressure test of the entire process lines,
7. Wrapping MLI on the process line interconnection,
8. Installation of the thermal shield components in the cryoline interconnections,
9. Wrapping MLI on the thermal shield interconnections,
10. Closing the external envelope sleeves and welding them to the vacuum vessel rings,
11. Testing the welding seams of the vacuum vessel put during the installation,
12. Performing the leak tightness test of the entire cryogenic line.

During the installation some inner parts of the cryoline could be exposed to weather conditions. Therefore all the interconnections located on the bridge were protected with special tents that were conditioned in order to keep the inner parts dry and clean. Figure 9.26 shows a cryoline straight module being lifted on the pipeline bridge (step 1) and Fig. 9.27 shows the tents. The installation of the interconnection between the cryoline and subcooler box (step 4) is presented in Fig. 9.28. Here, the process lines are being connected with flexible hoses (protected with braids) and the lateral expansion joint is suspended above the interconnection. When all the internal parts of the interconnection were installed, the lateral compensator was moved down and welded to the dedicated welding rings on the vacuum jacket of the cryoline and the subcooler. Figure 9.29 presents the XFEL/AMTF cryogenic transfer line after its installation. In the foreground there is the

Fig. 9.26 Installation of one of the XFEL/AMTF cryoline straight modules on the pipeline bridge (*courtesy* Kriosystem Ltd.)

Fig. 9.27 The XFEL/AMTF cryoline interconnections on the pipeline bridge protected with tents (*courtesy* Kriosystem Ltd.)

angular module with its strong fixed support. The visible stubs on the straight section, which are covered with yellow lids, are the safety devices of the external envelope. In case of some failure modes of process line rupture these safety devices will discharge the helium from the isolation vacuum space to the surroundings and protect the external envelope against overpressurization.

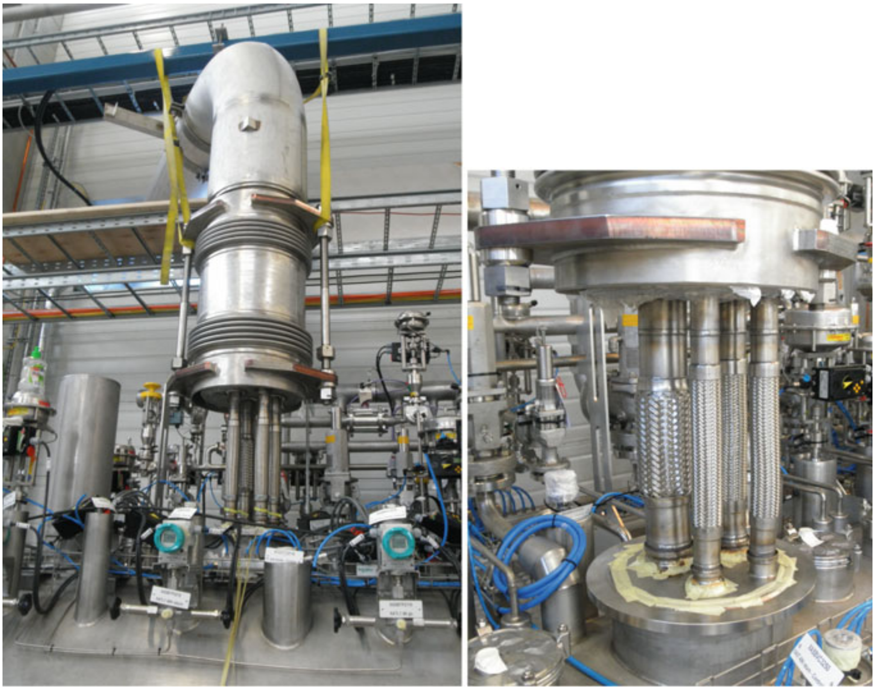

Fig. 9.28 Connecting the XFEL/AMTF cryoline to the cold terminal of the subcooler box (*courtesy* Kriosystem Ltd.)

Fig. 9.29 The XFEL/AMTF cryogenic transfer line installed on the pipe bridge (*courtesy* Kriosystem Ltd.)

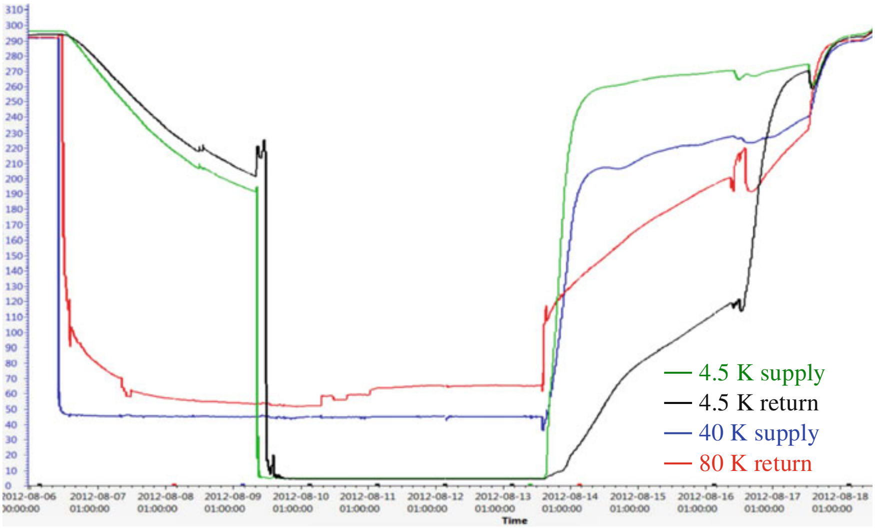

Fig. 9.30 The evolution of temperatures in the valve box process lines measured during the commissioning of the XFEL/AMTF cryogenic transfer line (*courtesy* DESY)

9.8.5 Commissioning and Performance

The preliminary acceptance test of the XFEL/AMTF cryogenic transfer line was carried out by DESY between 06.08.2012 and 18.08.2012 together with the cold performance tests of the subcooler box [28]. The measured temperatures in the valve box process lines are shown in Fig. 9.30. During the test the cryoline was rapidly cooled down close to the nominal operating conditions for a period of four days and then abruptly warmed up to ambient temperature. The data collected from the commissioning allowed for checking the thermodynamic efficiency of the cryoline by applying the Second Law analysis and Gouya-Stodola theorem. The performed entropy generation analysis showed that the thermodynamic efficiency of the cryoline was only 3 % different from the specified parameters [36]. In December 2012 the line was cooled down again and since then it is in continuous operation and serves the AMTF facility for the tests of the XFEL linac cryomodules and their cavities [28].

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