TESLA FEL Report 1996-06

A Proposal for the Cryogenic Supply
of a
VUV Free Electron Laser
at the
TESLA Test Facility at DESY

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Abstract

The operating of a 1 GeV linac consisting of superconducting 1.3 Ghz niobium cavities as an electron beam source of a Vacuum Ultraviolet Free Electron Laser (FEL) requires an essential upgrade of the TESLA Test Facility (TTF) cryogenic system, if the heat load budget is based on the FEL conceptual design report. At an operating temperature of 2 K for the cavities, the main components of the TTF helium distribution system could also be used for the FEL-linac without major changes. The TTF 900 W refrigerator has to be replaced either by a connection to the HERA cryogenic plant or by a new larger refrigerator. The use of the HERA cryogenic system will reduce the upgrade potential for the supply of the HERA accelerator. The TTF vacuum compressors will have to be upgraded or a second larger pumping assembly has to be installed. Alternatively, cold compressors could be used as part of a new refrigerator. About two years before the completion of the FEL-linac, the upgraded cryogenic capacity will already be useful for the parallel supply of the TTF-linac and the tests of cavities for the additional FEL cryo modules.

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1.Introduction

It is proposed to double the beam energy of the TESLA-Test-Facility (TTF) linac from 0.5 GeV to 1 GeV, for the operation of a Vacuum Ultraviolet Free Electron Laser (FEL) [1]. With a given design field gradient of 15 [MV/m] of the superconducting 1.3 Ghz TTF cavities, the active structure of the TTF-linac has to be doubled in length to achieve 1 GeV beam energy. From the cryogenic point of view the overall heat loads will also be doubled in comparison to the original TTF-layout.
The design of the existing cryogenic supply for the TTF-linac was based on the original TTF-concept [2,3] with some safety margin. After some changes in the TTF-concept, which resulted in a longer main transfer line, and the addition of a separate superconducting injector cavity and a cold bunch compressor bypass, the existing TTF-cryogenic plant is already at the limits of its capacity for the supply of the TTF-linac consisting of four cryo modules , if a maximum field gradient of 25 [MV/m] and a pulse repetition rate of 10 Hz is assumed [4] . At present, a new layout of the TTF-linac is being discussed, but has neither been published nor approved by the TTF community. The TTF-linac shall consist of three modules only and the pulse repetition rate shall be decreased to 5 Hz [5] . The heat load budget of the reduced TTF-linac depending on different operating conditions is discussed in appendix 1.
The FEL-linac heat load budget can be varied across a wide range if different accelerating fields and pulse repetition rates are assumed. Some of these scenarios are sketched out in appendix 2. In this paper it is supposed that the TTF/FEL community will not be satisfied if the performance of the FEL-linac will be limited by the capacity of the cryogenic supply and no future upgrade is covered by the layout of the cryogenic system !
Superconducting components of the FEL-linac will have to be tested at the TTF test plant in parallel to the operating of the TTF-linac. The capabilities of the TTF cryogenic system for the parallel supply are discussed in appendix 3. In any case, an upgrade of the cryogenic system will increase the efficiency of the operating of the TTF-linac as well as the tests of FEL components.
Also, it has to be taken into account that the supply of an experiment like the FEL is different from the supply of a test plant like the TTF in respect to reliability, operational costs and redundancy. Depending on the final operating conditions of the FEL, costs and philosophy different schemes of the cryogenic supply of the FEL can be sketched out, some of them will be discussed here.

2. FEL Operating Temperature & Helium Distribution System

The choice of the operating temperature for the FEL will affect the design of the helium distribution system , in particular the subatmospheric components (transferlines, feedbox, valves and heat exchangers). If the operating temperature is allowed to increase to an upper limit of 2 K, corresponding to a helium vapor pressure of 32 mbar, the relative pressure drops will be small enough to use the distribution system of the TTF linac for the FEL-linac. This is discussed in appendix 4. In this paper the assumption is made that 2 K will be the operating temperature of the FEL-linac and there will be no change in the helium distribution system. (Only a second bunch compressor bypass will be added between module 4 and module 5). The distribution system consists of a six-fold TTF main transferline, a TTF-feedbox (including a low temperature heat exchanger), a module transferline, a transferline to the injector cavity (CRYOCAP) and module feed- and endcaps[6] (see fig. 1).

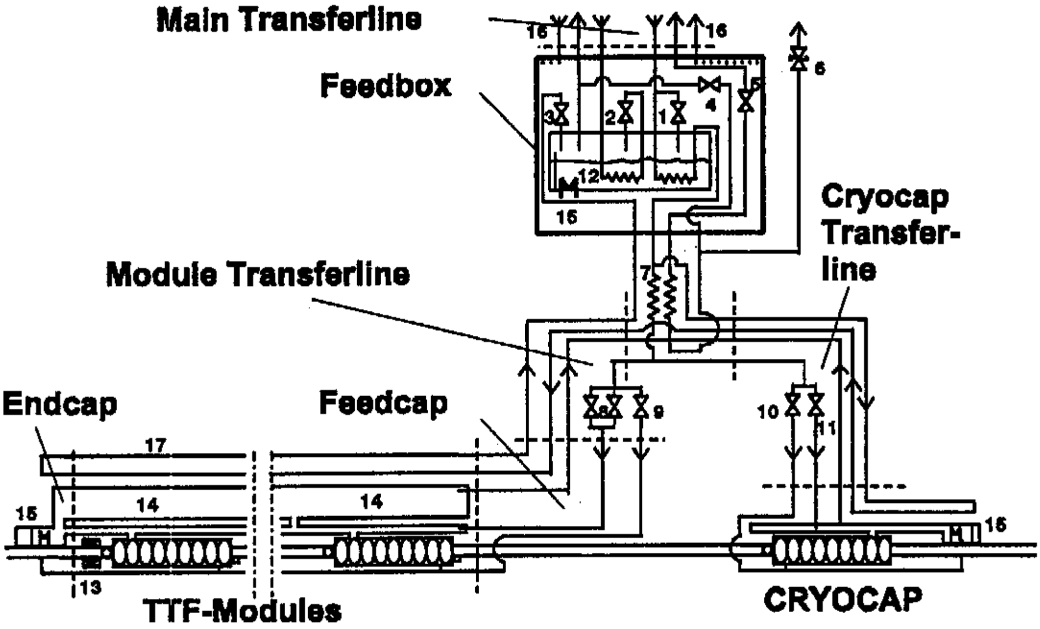


fig. 1 Simplified flow scheme of the cryogenic supply of the TTF-linac
(1) 5 K supply Joule Thomson (JT) valve, (2) 7.5 K supply JT-valve (from large heat exchanger), (3) 4.4 K return JT-valve, (4) cool down bypass valve, (5) 2 K return isolation valve, (6) relief valve system, (7) low temperature heat exchanger, (8) 2 K supply JT-valves, (9) cool down bypass valve, (10) cool down bypass valve, (11) 2 K supply JT-valve, (12) subcooler, (13) module quadrupole, (14) Ø 300 mm module return tube, (15) liquid level sensor and heater, (16) 40/80 K thermal shield supply (details not shown), (17) 4.4 K thermal shield.

3. Heat Loads of the FEL-linac

3.1. General Comment on the Estimation of Heat Loads

Heat loads are calculated according to the (published) heat load specifications of the components. The calculated heat loads are multiplied by a **'design factor'** of **1.5** to get the design heat loads. The design factor has to be applied to each single component. The design factor corresponds to additional heat loads which are needed for the controlled operating of the plant and to cover uncertainties in the realization of the specifications.
(A cryogenic plant, which is designed according to the calculated heat losses can never be operated !)
All heat load estimates are based on calculated values according to the TTF-CDR[7]. The heat load budgets have to be reviewed as soon as the first data from heat load measurements for the different components are available.

3.2. Heat Load Budget of the FEL-Linac

3.2.1. FEL-Linac Heat Load Budget Scenarios

Depending on the operating conditions of the FEL-linac, the dynamic heat loads can be varied across a wide range. Some different scenarios are discussed in appendix 2. If the accelerating field and the repetition rate are assumed low enough, one might even come to the conclusion that the FEL-linac could be supplied by the existing TTF cryo system - this paper was written, to cancel this idea.

3.2.2. FEL-Linac Heat Load Budget According to the Published FEL-CDR

Depending on the heat loads of the TTF components given in the TTF-CDR[7] the heat loads for the complete FEL-linac consisting of 8 cryo modules, two bunch compressor bypasses and the injector cryostat, are estimated in table 1. According to the FEL Conceptual Design Report [1] ' one big attraction of the SASE FEL scheme is the absence of no apparent limitation which would prevent operation at even smaller wavelength....so that there is a big common motivation of both FEL and high energy physics communities to exceed the TTF goal of 15 [MV/m].' To cover the future potential of the FEL-linac, heat loads are calculated here for a field gradient of 25 [MV/m] and 10 Hz pulse repetition rate.

Table 1
Estimated heat loads of the FEL-linac
2 K, 25 [MV/m] field gradient and 10 Hz assumed[6]

	units	70K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	[g/s] all
CRYOCAP			100	17.8	17.8	1.78	1.78				
TTF-modules	8	136	1088	17.8	142.4	21.4	171.2			0.1	0.8
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	2	30	60	3	6	3	6				
bunch c r	2	3	6	3	6			3	6		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
sum all losses			1702		241.2		179.0		39		0.8
design factor	1.5		2553		361.8		268.5		58.5		1.2
							327.0				
design sum			2600		370		330				2

The heat loss of Q=270 W in the 2 K cooling bath corresponds to an evaporated mass flow of (dm/dt) = Q / ΔH = 270 [J/s] / 23.4 [J/g] = 11.6 [g/s] . If an isenthalpic expansion from 3 bar to 31.3 mbar with an inlet temperature of 2.2 K at the JT-valve of the modules is assumed, the gas quality factor will be Quality = 0.14 (= 85 % liquid). To get 270 W bath cooling capacity the cryogenic plant has to deliver 11.6 [g/s] / .85 ≈ 14 [g/s] helium massflow at the inlet of the module JT-valve (= pumped mass flow). An additional heat load of 60 W will occur in the return of the 2 K mass flow.

For the 40/ 80 K shield an inlet temperature of about 40 K and a ΔT of 40 K is assumed resulting in a helium massflow of 12 [g/s].

With a 40 [g/s] mass flow at the 4.5 K level and a heat loss of 300 W in the 4.5 K shields a temperature rise to about 5.5 K is expected before the fluid is expanded into the return of the feedbox subcooler. Because the 2 K and 4.5 K flows are branched in the feedbox the 2 K flow has to be added to the 4.5 K shield flow to give the total 4.5 K flow in the main transferline supply and return flow.

The cryogenic design values for the supply of the complete FEL-linac are:

40/80 K shield : 2600 W (12 [g/s]) (refrigeration)
4.5 K shield: 370 W (40 [g/s]) (refrigeration)
2 K volume: 270 W / 14 [g/s] (liquefaction/refrigeration) (*)
60 W (refrigeration)
2 [g/s] liquefaction rate at 4.5 K (quadrupole current leads)

(*) A mass flow of 14 [g/s] has to be liquefied into the 2 K bath of the cryo modules; it depends on the configuration of the cryo plant, which amount of liquefaction load can be transferred into refrigeration load (this will be discussed in the next sections).

4. FEL-Cryogenic Plant Design Values

In practice, the 2 K heat losses should be converted from liquefaction to refrigeration load as much as possible, to use the enthalpy of the pumped evaporated gas. This can be accomplished by low pressure heat exchangers with or without cold compressors. In any case the conversion is not free and one has to pay either with additional liquefaction, or with an additional refrigeration heat load.

4.1. Optional Components of the FEL-Cryogenic Plant

4.1.1. Low Temperature Heat Exchangers

In a first stage the pumped gas is used to precool the supply of the JT-valves from 4.5 K to about 2.2 K (3 bar) to enhance the efficiency of the isenthalpic expansion (i.e. to get more liquid). The pumped gas is warmed up from 2 K to about 3.5 K in these counterflow heat exchangers. Because of the quite high density of the pumped helium gas at 3.5 K, these heat exchangers can be built small and cheap. The TTF-feedbox (see fig.1) is equipped with a low temperature heat exchanger, which can also be operated in the supply for the FEL-linac (at 2 K ,32 mbar).

4.1.2. TTF Large Low Pressure Heat Exchanger

For the supply of the TTF-linac a low pressure counterflow heat exchanger is under construction, which converts the enthalpy of the pumped gas flow of 10 [g/s] (3.5 K, 15 mbar) to a high pressure supply flow to the TTF-feedbox (7.5 K, 14 bar). The general analysis of low pressure heat exchangers of this kind have shown that a mismatch of mass flows in the high and low pressure flow exist. As a result the high pressure flow has to be adjusted to about 9 [g/s]. The balance shows that 1 [g/s] liquefaction rate has to be delivered from the TTF-refrigerator for the 1.8 K bath. In addition, 110 W of refrigeration load have been reserved in the TTF-design to precool the high pressure mass flow from 7.5 K to about 5.5 K to achieve effective isenthalpic expansion into the subcooler bath of the TTF-feedbox and to compensate transfer line heat losses which affect the performance of the heat exchanger.

Preliminary analysis of the TTF-Low-Pressure-Heat-Exchanger has shown that the pressure drop and heat transfer considerations as discussed in appendix 4, are also true for this component. The demands for the FEL-linac could be met if the subatmospheric operating pressure is increased to 32 mbar.

Table 2
Estimated Performance of the TTF-Low Pressure HEX at FEL-Operating Conditions (2 K / 32 mbar)

flow area	temperature [K]	pressure [bar]	mass flow [g/s]
low pressure inlet	3.5	0.030	14
low pressure outlet	285	≥0.024	14
high pressure inlet	295	18	12
high pressure outlet	7.5	18	12

Again the mass flow mismatch will result in about 2 [g/s] liquefaction rate into the 2 K bath and about 152 W subcooling refrigeration are needed in the feedbox.
The heat load of 60 W in the return of the 2 K mass flow will cause a temperature increase from 3.5 K to about 4.4 K at the inlet of the heat exchanger. It is assumed here that this load can be compensated by additional subcooling in the feedbox. The overall subcooling load is 212 W.
With a design factor of 1.5, 3 [g/s] liquefaction rate and 212W refrigeration load on 4.5 K level are needed. (Because liquefaction rate and subcooling load are coupled, the design factor acts only on the liquefaction rate here. In table A.2.5. of appendix 2 the subcooling load is affected by the design factor.)

4.1.3. Cold Compressors

Cold compressors are used to compress the subatmosheric gas at low temperature and high density, to avoid the disadvantages of large low pressure heat exchangers in the cryogenic plant. The gas is affected by the work of compression, which adds to the heat load of the cryogenic plant. Depending on the number of stages, the cold compressors can discharge the gas starting from about 20 mbar to atmospheric pressure, or to some intermediate pressure. The number of stages of cold compressors, the design of heat exchangers and the layout of warm pumping equipment has to be optimized for the given boundary conditions of the cryogenic plant. If the FEL-plant is compared to the TORE SUPRA cryogenic system[8], a configuration where cold compressors discharge the gas at 80 mbar and warm pumping equipment is used to compress to the suction pressure of screw compressors seems to be appropriate. Also, the operation of cold compressors is more relaxed if the flexibility of warm pumps is added to the system, in particular under transient state conditions.
If the process of compression is taken as an isentropic process (dS = 0) the work done to the gas equals the change of enthalpy of the gas. The factor of efficiency η compares the enthalpy change of the ideal process ΔH_{ideal} to the change of enthalpy of the real process ΔH_{real}:

$$\eta \approx \Delta H_{ideal} \,/\, \Delta H_{real}$$

Here $\eta = 0.7$ is assumed. In table 3 the enthalpy changes for different discharge pressures of the cold compressors and the corresponding heat losses at a mass flow of 14 [g/s] are shown.

Table 3
Heat Loss Estimates for Cold Compressors
Mass Flow 14 [g/s] , Efficiency η=0.7

	p [mbar]	T_{real} [K]	ΔH_{ideal} [J/g]	ΔH_{real} [J/g]	Q_{calc} [W]	Q_{design} [W]
low pressure inlet	**20**	**4.4**				
high pressure discharge	**80**	**9.1**	**16.9**	**24.1**	**337**	**506**
high pressure discharge	**100**	**10.1**	**20.6**	**29.3**	**410**	**615**
high pressure discharge	**120**	**11.0**	**23.8**	**34.1**	**477**	**716**

For the reasonable choice of a discharge pressure of 80 mbar for the cold compressors the estimate of heat load results in $Q_{CC\ design} \approx 506$ W (refrigeration load at about the 4.5 K level).

4.2. Optional Design Specifications for the FEL-Cryogenic Plant

4.2.1. Option No. 1 : No Subatmosheric Gas Enthalpy Recovery

40/80 K shield : 2600 W (12 [g/s]) (refrigeration)
4.5 K level: 370 W (40 [g/s]) (refrigeration)
16 [g/s] liquefaction rate at 4.5 K
warm vacuum compressors 14 [g/s] at 20 mbar(1.3 bar discharge)

4.2.2. Option No. 2 : Use of the external TTF-Large-Low-Pressure-Heat-Exchanger

40/80 K shield : 2600 W (12 [g/s]) (refrigeration)
4.5 K level: 870 W (69 [g/s]) (refrigeration)
5 [g/s] liquefaction rate at 4.5 K
warm vacuum compressors 14 [g/s] at 20 mbar(1.3 bar discharge)

4.2.3. Option No. 3 : Use of Cold Compressors

40/80 K shield : 2600 W (12 [g/s]) (refrigeration)
4.5 K level: 1210 W (75 [g/s]) (refrigeration)
2 [g/s] liquefaction rate at 4.5 K (quadrupole current leads)
cold compressors 14 [g/s] at 20 mbar (80 mbar discharge)
warm vacuum compressors 14 [g/s] at 80 mbar (1.3 bar discharge)

5. Realization of the FEL-Cryogenic Plant

5.1. Can a SSC Babcock & Wilcox plant be used ?

It is known in the cryogenic community that the LINDE KRYOTECHNIK AG was charged to built cold boxes for a magnet testing facility of the Superconducting Supercollider in the USA. One of these cold boxes (the so called B & W plant) was under construction when the SSC project was stopped and has not been finished yet .
The T-S-diagram of the B & W plant shows that the plant has a nominal capacity of 875 W at 4.5 K plus a liquefaction rate of 5.7 [g/s] at 4.5 K.
A 40/80 K shield supply is not foreseen in the B & W scheme. If a 12 [g/s] mass flow is extracted at 34 K and returned at the 80 K level it can be estimated from the T-S-diagram that for a liquefaction rate of 5 [g/s] (2 [g/s]) at 4.5 K a cooling capacity of 715 W (810 W) will be available at 4.5 K correspondingly.
Obviously the capacity of the B & W plant is too small to meet any of the specifications of the different options in section 4. In addition the subatmosheric paths in the heat exchangers of the B & W cold box are designed for a mass flow of 13 [g/s] and a nominal pressure of about 300 mbar. This design would not fit into the FEL-plant. Other questions of availability, conformance with the German pressure vessel code, changes in tubing and more, are not further discussed here.
It is not recommended to use the B & W cold box for the FEL-plant.

5.2. HERA Cryo Plant Connection

A connection of the FEL-linac to the HERA cryogenic plant will give enough cooling capacity to meet the demands of options 1 and 2 and - in addition - to replace the TTF-900 W cold box for the supply of the test of single cavities in parallel to the operating of the TTF / FEL-linacs. The replacement of the TTF 900 W cold box will add about 5 - 8 [g/s] liquefaction rate at 4.5 K to the capacities of section 4.2.2..
A minimal configuration would consist of a 400 m long four-fold transferline and high- & low pressure warm process tubes, a subcooler box at the connection to the TTF main transferline and a small additional distribution box at the HERA plant.
This helium distribution system will add heat loads of about 1 KW at the 40/80 K shield and 200 W at the 4.5 K level to the system.
The overall heat loads for the HERA-plant will result in:

40/80 K shield : 3500 W
4.5 K level: 1100 W
13 [g/s] liquefaction rate at 4.5 K

This loads could either be added to one of the HERA-north/south-ring cold boxes, or the third redundant HERA cold box could be used exclusively for the FEL-linac.
The use of cold compressors is not reasonable because there is no way of effective heat exchange from the 14 [g/s] mass flow at about 9 K and 80 mbar from the discharge site of the cold compressors to the 4.5 K return flow to the HERA refrigerator. But the TTF large low pressure heat exchanger could be used. A sketch of the HERA connection is shown in fig.2..

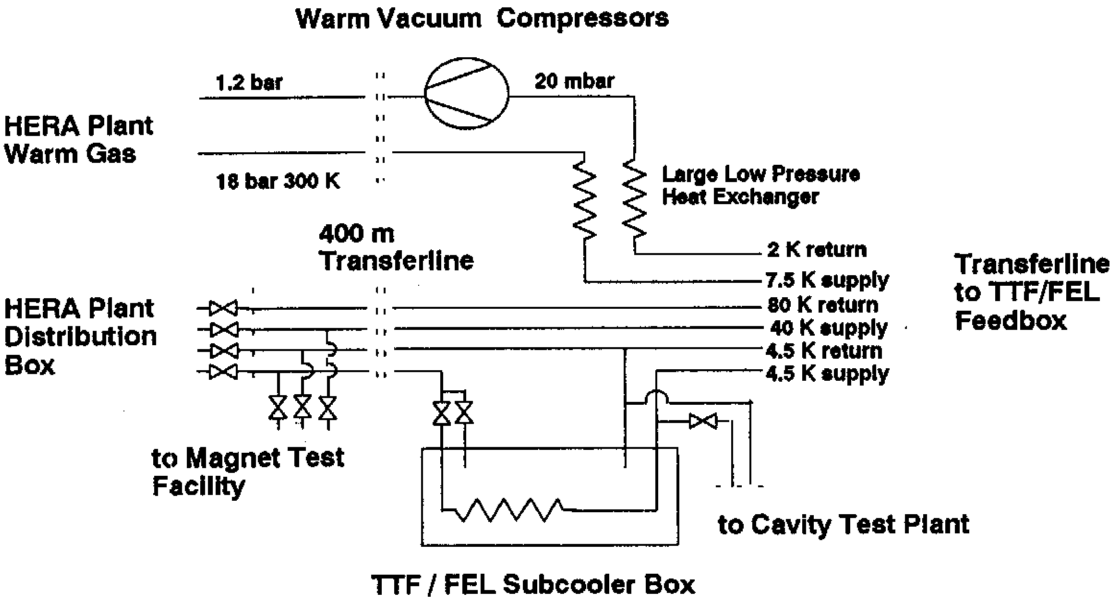


fig. 2. Flow Scheme of the Connection to the HERA plant (simplified)

5.3. New FEL Cryo Plant

A new FEL cryo plant should include a cold box, screw compressors, cold compressors, warm vacuum compressors and low temperature helium purifiers.

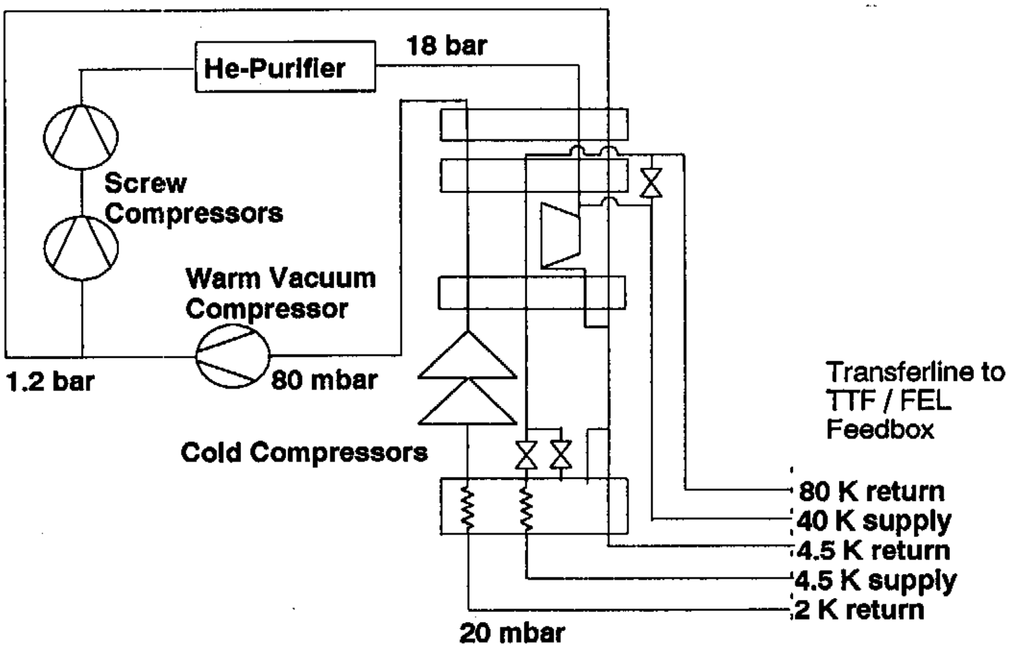


fig. 3 Principle Flow Scheme of a FEL-Cold Box (simplified)

The specifications for a new FEL-plant are:

40/80 K shield : 3 KW (12 [g/s]) (refrigeration)
4.5 K level: 1.3 KW (80 [g/s]) (refrigeration)
2 [g/s] liquefaction rate at 4.5 K
cold compressors 14 [g/s] at 20 mbar (80 mbar discharge)
warm vacuum compressors 14 [g/s] at 80 mbar (1.3 bar discharge)

These specifications are suited for the supply of the FEL-linac. It is supposed that the existing 900 W LINDE cold box is used in parallel for the cavity test plant.

5.4. New FEL Cryo Plant Including Cavity Test Plant Supply

If a new cryo plant shall also replace the 900 W LINDE cold box for the parallel supply of the test cryostats and the operation of the TTF/FEL-linac, the capacity of the existing cold box has to be added to the specifications of section 5.3.. The subatmospheric helium mass flow of the test plant could be pumped by the existing TTF vacuum compressor assembly and the large low pressure heat exchanger could be used for this circuit (see fig. 4).
The specifications are:

40/80 K shield : 3 KW (12 [g/s]) (refrigeration)
4.5 K level: 2.1 KW (80 [g/s]) (refrigeration)
3 [g/s] liquefaction rate at 4.5 K
cold compressors 14 [g/s] at 20 mbar (80 mbar discharge)
warm vacuum compressors 14 [g/s] at 80 mbar (1.3 bar discharge)
TTF-vacuum compressor assembly 10 [g/s] at 10 mbar
TTF large low pressure heat exchanger

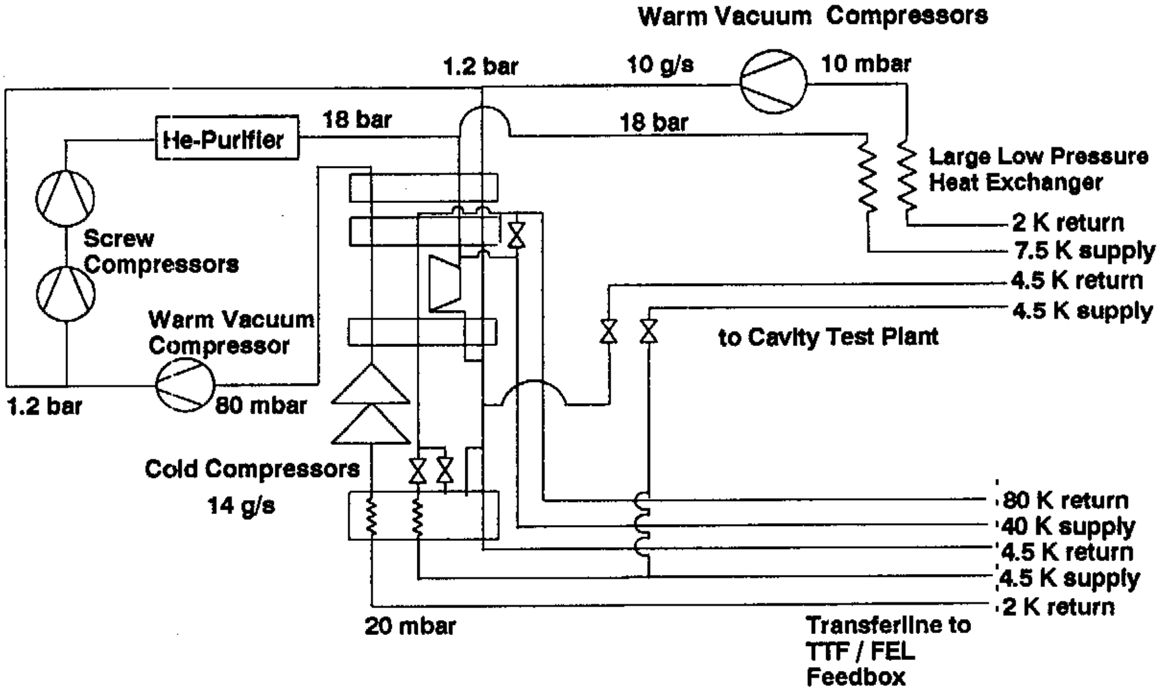


fig.4. New FEL cryo plant (simplified flow scheme) including the supply of the cavity test plant

5.5. Vacuum Compressors for the FEL-Cryogenic Plant

The TTF-vacuum compressors are designed for a mass flow of 10 [g/s] at a suction pressure of 10 mbar. An analysis of the suction capacity shows that this compressor assembly is to small for the FEL-plant and 14 [g/s] at 20 mbar. At least the roots blowers of stage 2 and 3 have to be replaced by larger machines.
The TTF-rotary vane pumps could be used in combination with cold compressors if the discharge pressure of the cold compressors is shifted to 100 mbar. As can be seen in table 3, this would add another 120 W refrigerator load to the cryogenic plant.
The TTF pumping capacity would be sufficient for the FEL-linac, if the pulse repetition rate is decreased to 5 Hz (see appendix 2).
For a parallel operation of the TTF/FEL-linac and the cavity test plant the use of parallel pumping systems is recommended as figured out in section 5.4. (fig.4.).

5.6. Use of the LINDE TTF 900 W Refrigerator and Auxiliary Equipment

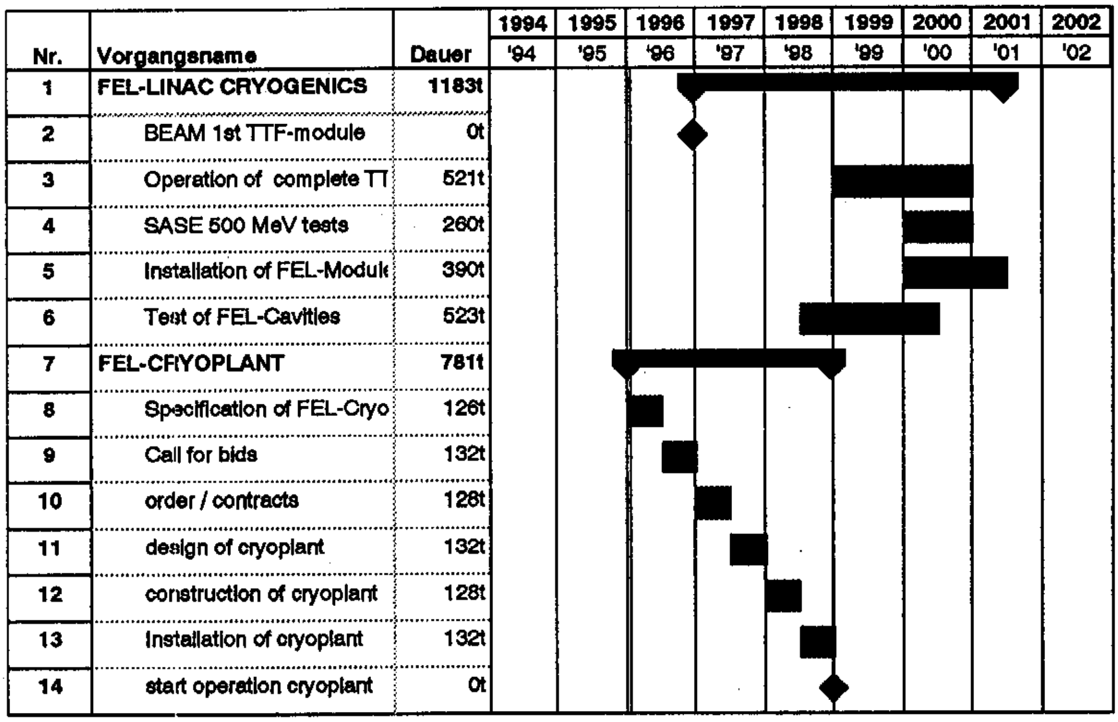
If the LINDE 900 W Refrigerator consisting of the cold box, three screw compressors and a low temperature high pressure helium purification system shall be operated beyond the supply of the TESLA test facility, at least the helium purification system has to be replaced.
In addition the cooling water infrastructure and the control system of the screw compressors have to be completely renewed.
When the operating of the FEL-linac will start, the age of the LINDE plant will be about 20 years. Problems with the reliability of several components are to be expected at that time.
It is not recommended to use the LINDE 900 W refrigerator beyond the operating of the TTF-linac.

6. Schedule for the Design, Construction and Installation of the FEL Cryo Plant

If the milestones of the TTF FEL, which are mentioned in the FEL CDR [1],are shifted for one year (which meets the present situation of the TTF-linac construction more or less), the overall schedule results in the bar diagram in fig. 5. About one and a half years before the start of the operating of the FEL-linac, there will be an overlap of the cryogenic supply of the TTF-linac and the test operations for the FEL cavities. Scenarios for the parallel operation of the TTF-linac and the TTF cavity test plant are sketched out in appendix 3. Depending on the operating conditions of the TTF-linac, the possibilities for cavity tests are more or less reduced.

As a consequence, the FEL cryo plant has to start operation about 18 months before the construction of the FEL-linac is finished if the cavity test plant shall run with full capacity.

After all specifications and boundary conditions have been fixed, a minimum time of three years is needed to build and commission a new FEL cryo plant .



Nr.	Vorgangsname	Dauer
1	FEL-LINAC CRYOGENICS	1183t
2	BEAM 1st TTF-module	0t
3	Operation of complete TT	521t
4	SASE 500 MeV tests	260t
5	Installation of FEL-Modul	390t
6	Test of FEL-Cavities	523t
7	FEL-CRYOPLANT	781t
8	Specification of FEL-Cryo	126t
9	Call for bids	132t
10	order / contracts	128t
11	design of cryoplant	132t
12	construction of cryoplant	128t
13	Installation of cryoplant	132t
14	start operation cryoplant	0t

fig. 5
Schedule for the Construction of the TTF / FEL Linac

7.Conclusions

If the users of the FEL-linac can agree on an operating temperature of the superconducting cavities of 2 K, the helium distribution system for the TTF-linac, consisting of a main transferline, a feedbox including a low temperature counterflow heat exchanger, a module transferline and a feedcap, can also be used for the FEL-linac. Depending on the configuration, the large low pressure heat exchanger can also be used for the FEL supply.

If the accelerating field and the pulse repetition rate are assumed low enough, one might come to the conclusion that the FEL-linac could be supplied by the existing TTF cryo system. But if the heat load budget is estimated according to the FEL-CDR, there is no way to avoid the installation of additional cryogenic equipment for the FEL-linac as soon as possible. In any case, the use of the LINDE 900 W cold box, including the screw compressors and the high pressure helium purifiers, is not recommended beyond the supply of the TTF-linac due to reliability considerations.

7.1. Minimum Cost Solution / HERA Connection

According to section 5.2 a connection to the HERA plant could supply the TTF / FEL-linacs as well as the TESLA test facility (test of single cavities and other components).
The TTF large low pressure heat exchanger should be used.
In a minimum cost scenario at least two roots blowers (stages 2 and 3) of the TTF-vacuum compressors have to be replaced by larger machines. Difficulties are to be expected, if only one set of vacuum compressors is used for the supply of the TTF-linac, as well as for the test facility.
From the FEL-cryogenic point of view the connection to the HERA plant is a reasonable technical solution. Investments of additional infrastructure (buildings, cooling water supply and main power supply) could be saved. The redundant capacities of the HERA plant could be shared with the FEL-linac.
A managerial question remains whether the operating of the HERA plant shall be coupled with the operating of an external facility and the redundancy of the HERA cryogenic supply and the potential for future upgrades of HERA shall be decreased.

7.2. New Designed FEL Cryo Plant

The design of a new cryo plant consisting of a cold box, helium purifiers and a screw compressor assembly, which is suited for the special demands of the FEL-linac is the most straightforward approach. If a new plant is aimed at, option 3 -including cold compressors- seems to be the most economical solution. With future cryo plants for the future TESLA 500 linac in mind, new concepts could be realized and some experience of the operating of cold compressors could be achieved.
Depending on the future use of the cavity test cryostats, a new plant including the capacities for the cavity test plant is recommended according to section 5.4..
As a disadvantage, additional costs of infrastructure will occur. A new FEL-plant will be a factor of 1.5 more expensive than the connection to the HERA plant.

7.3. Parallel Cryogenic Tests of FEL Components and Operation of the TTF-Linac

With the existing TTF cryo system tests of FEL cavities in parallel to the operating of the TTF-linac (consisting of 3 modules) can only be performed effectively, when the TTF-linac is in stand by. If the accelerating field of the linac is limited to 15 [MV/m] and the repetition rate is decreased to 5 Hz, parallel tests are possible but the operating is very restricted. (See appendix 3).

7.4. Review of Heat Load Budgets

Most of the heat load estimations, as well for the TTF-linac as for the FEL-linac, are based on **calculated** values. The heat load budgets have to be reviewed completely, as soon as the first heat loss measurements of the TTF helium distribution system and the first TTF module are available.

8. Acknowledgments

This paper is based on discussions with and suggestions from my colleagues of the DESY-MKS- group, in particular H.Herzog (LINDE company), R.Lange, H.Lierl, D.Sellmann, J.Weisend II and S.Wolff.

Appendix 1
Heat Load Budgets for Different Scenarios of the Three-ModulesTTF-Linac
Use of the external TTF-Low-Pressure-Heat-Exchanger is assumed.

How to understand the tables in the appendices 1 and 2:

The different devices are listed in the first column. Static and dynamic heat loads are separated in different lines, the heat loads of the transferlines are also separated in the loads of the supply and the return tubes ('r').
The second column represents the number of effective units. The next columns represent the load of a single unit and the sum of all units ('all') for the different temperature levels.
(Depending on the cold box the temperature of 70 K represents the 40/80 K shield level).
The 2 K temperature level is separated in the heat loads of the 2 K bath and the heat load of the gas return tubes. The last two columns show the liquefaction rate on the 4.5 K temperature level.
The design sum of all refrigeration losses on the 4.5 K level is the sum of the 4.5 K shield losses, the load for the precooling of the high pressure mass flow of the large low pressure heat exchanger, including the heat load of the 2 K return tube (as explained in section 4.1.2.) and the heat load of the 2 K bath. The last line is the pumped 2 K mass flow.

A.1.1. TTF-Linac 3 Modules in Stand By

	units	70 K[W]	70K[W] all	4,5 K[W]	4,5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90,7			0,35	0,35				
CCap dyn			0			0	0				
mod-static	3	76,8	230,4	13,700	41,1	2,8	8,4				
mod-dynamic	0	48,2	0	1,30	0	12,6	0				
current lead	3			1,80	5,4						0
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			26		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	1	30	30	3	3	3	3				
bunch c r	1	3	3	3	3			3	3		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
HOM test											0
sum all losses			602,1		121,5		11,75		36		0
design factor	1,5		1203,2		182,25		17,63		54		0
HEX precool					60,0						
design factor	1,5				90,0						
HEX mismatch											0,5
design sum			1203,2		272,3		17,63				0,5
design all			1203,2		289,9						0,5
m 2K [g/s]							0,89				

A.1.2. TTF-Linac 3 Modules 15 [MV/m] 5 Hz Repetition Rate

	units	70 K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			3			0.8	0.8				
mod-static	3	76.8	230.4	13.700	41.1	2.8	8.4				
mod-dynamic	1.5	48.2	72.3	1.30	1.95	12.6	18.9				
current lead	3			1.80	5.4					0.1	0.3
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	1	30	30	3	3	3	3				
bunch c r	1	3	3	3	3			3	3		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
HOM test											1
sum all losses			877.4		123.5		31.5		36		1.3
design factor	1.5		1316.1		185.18		47.2		54		2
HEX precool					70.8						
design factor	1.5				106.1						
HEX mismatch											0.5
design sum			1316.1		291.3		47.2				2.5
design all			1316.1		338.5						2.5
m 2K [g/s]							2.37				

A.1.3. TTF-Linac 3 Modules 15 [MV/m] 10 Hz Repetition Rate

	units	70 K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			6			1.58	1.58				
mod-static	3	76.8	230.4	13.700	41.1	2.8	8.4				
mod-dynamic	3	48.2	144.6	1.30	3.9	12.6	37.8				
current lead	3			1.80	5.4					0.1	0.3
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	1	30	30	3	3	3	3				
bunch c r	1	3	3	3	3			3	3		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
HOM test											1
sum all losses			952.7		125.4		51.13		36		1.3
design factor	1.5		1429.1		188.1		76.70		54		2
HEX precool					88.9						
design factor	1.5				133.3						
HEX mismatch											0.5
design sum			1429.1		321.4		76.70				2.5
design all			1429.1		398.1						2.5
m 2K [g/s]							3.86				

A.1.4. TTF-Linac 3 Modules 25 [MV/m] 5 Hz Repetition Rate

	units	70 K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			3.7			1.17	1.17				
mod-static	3	76.8	230.4	13.700	41.1	2.8	8.4				
mod-dynamic	1.5	59.2	88.8	2.10	3.15	18.6	27.9				
current lead	3			1.80	5.4					0.1	0.3
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	1	30	30	3	3	3	3				
bunch c r	1	3	3	3	3			3	3		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
HOM test											1
sum all losses			894.6		124.7		40.8		36		1.3
design factor	1.5		1341.9		187.0		61.2		54		2
HEX precool					79.4						
design factor	1.5				119.1						
HEX mismatch											0.5
design sum			1341.9		306.1		61.2				2.5
design all			1341.9		367.3						2.5
m 2K [g/s]							3.08				

A.1.5. TTF-Linac 3 Modules 25 [MV/m] 10 Hz Repetition Rate

	units	70 K [W]	70K [W] al	4.5 K [W]	4.5K [W] al	2 K [W] bath	2K [W] all	2K [W] ret	2K [W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			7.4			2.33	2.33				
mod-static	3	76.8	230.4	13.700	41.1	2.8	8.4				
mod-dynamic	3	59.2	177.6	2.10	6.3	18.6	55.8				
current lead	3			1.80	5.4					0.1	0.3
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	1	30	30	3	3	3	3				
bunch c r	1	3	3	3	3			3	3		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
HOM test											1
sum all losses			987.1		127.8		69.88		36		1.3
design factor	1.5		1480.7		191.7		104.82		54		2
HEX precool					106.2						
design factor	1.5				159.3						
HEX mismatch											0.5
design sum			1480.7		351.0		104.82				2.5
design all			1480.7		455.8						2.5
m 2K [g/s]							5.27				

Appendix 2
Heat Load Budgets for Different Scenarios of the FEL-Linac Operating
Use of the external TTF-Low-Pressure-Heat-Exchanger is assumed.

A.2.1. FEL-Linac 8 Modules Stand By

	units	70 K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			0			0	0				
mod-static	8	76.8	614.4	13.700	109.6	2.8	22.4				
mod-dynamic	0	48.2	0	1.30	0	12.6	0				
current lead	8			1.80	14.4						0
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	2	30	60	3	6	3	6				
bunch c r	2	3	6	3	6			3	6		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
sum all losses			1219.1		205		28.75		39		0
design factor	1.5		1828.7		307.5		43.13		58.5		0
HEX precool					72.8						
design factor	1.5				109.2						
HEX mismatch											0.5
design sum			1828.7		416.7		43.13				0.5
design all			1828.7		459.8						0.5
m 2K [g/s]							2.17				

A.2.2. FEL-Linac 8 Modules 15 [MV/m] 5 Hz Repetition Rate

	units	70 K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			3			0.8	0.8				
mod-static	8	76.8	614.4	13.700	109.6	2.8	22.4				
mod-dynamic	4	48.2	192.8	1.30	5.2	12.6	50.4				
current lead	8			1.80	14.4					0.1	0.8
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	2	30	60	3	6	3	6				
bunch c r	2	3	6	3	6			3	6		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
sum all losses			1414.9		210.2		79.95		39		0.8
design factor	1.5		2122.4		315.3		119.93		58.5		1.2
HEX precool					120.0						
design factor	1.5				179.9						
HEX mismatch											0.6
design sum			2122.4		495.2		119.93				1.8
design all			2122.4		615.2						2
m 2K [g/s]							6.03				

A.2.3. FEL-Linac 8 Modules 15 [MV/m] 10 Hz Repetition Rate

	units	70 K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			6.03			1.6	1.6				
mod-static	8	76.8	614.4	13.700	109.6	2.8	22.4				
mod-dynamic	8	48.2	385.6	1.30	10.4	12.6	100.8				
current lead	8			1.80	14.4					0.1	0.8
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	2	30	60	3	6	3	6				
bunch c r	2	3	6	3	6			3	6		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
sum all losses			1610.73		215.4		131.2		39		0.8
design factor	1.5		2416.1		323.1		196.7		58.5		1.2
HEX precool					167.1						
design factor	1.5				250.7						
HEX mismatch											1
design sum			2416.1		573.8		196.7				2.2
design all			2416.1		770.5						2.2
m 2K [g/s]							9.9				

A.2.4. FEL-Linac 8 Modules 25 [MV/m] 5 Hz Repetition Rate

	units	70 K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			3.7			1.17	1.17				
mod-static	8	76.8	614.4	13.700	109.6	2.8	22.4				
mod-dynamic	4	59.2	236.8	2.10	8.4	18.6	74.4				
current lead	8			1.80	14.4					0.1	0.8
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	2	30	60	3	6	3	6				
bunch c r	2	3	6	3	6			3	6		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
sum all losses			1459.6		213.4		104.32		39		0.8
design factor	1.5		2189.4		320.1		156.48		58.5		1.2
HEX precool					142.4						
design factor	1.5				213.6						
HEX mismatch											1
design sum			2189.4		533.7		156.48				2.2
design all			2189.4		690.2						2.2
m 2K [g/s]							7.87				

A.2.5. FEL-Linac 8 Modules 25 [MV/m] 10 Hz Repetition Rate

	units	70 K[W]	70K[W] all	4.5 K[W]	4.5K[W] all	2 K[W] bath	2K[W] all	2K[W] ret	2K[W] r all	[g/s]	4K [g/s] all
CCap static			90.7			0.35	0.35				
CCap dyn			7.4			2.33	2.33				
mod-static	8	76.8	614.4	13,700	109.6	2.8	22.4				
mod-dynamic	8	59.2	473.6	2,10	16.8	18.6	148.8				
current lead	8			1,80	14.4					0.1	0.8
large trans			20		20						
large trans r			250		20				20		
modul trans			2		2						
modul trans r			25		2				2		
CC trans			1		1						
CC trans r			10		1				1		
bunch comp	2	30	60	3	6	3	6				
bunch c r	2	3	6	3	6			3	6		
feedbox			100		3				10		
feedcan			20		10						
endcan			20		10						
sum all losses			1700.1		221.8		179.9		39		0.8
design factor	1.5		2550,2		332.7		269.8		58,5		1.2
HEX precool					212.1						
design factor	1.5				318,1						
HEX mismatch											2
design sum			2550.2		650.8		269.8				3,2
design all			2550.2		920.6						3.2
m 2K [g/s]							13.6				

Appendix 3
Operating of the TTF-Linac (3 Modules) and the TTF-Test Plant in parallel

A.3.1. General Remarks on Parallel Operations

The parallel operating of different cryogenic devices of the TTF cryogenic system is limited by the refrigeration capacity / the liquefaction capacity of the 900 W LINDE cold box, the amount of liquid helium which can be stored in the buffer dewar and the suction capacity of the vacuum compressors. When the pump down from atmospheric pressure to 16 mbar is started in one cryostat, disturbances will be caused in the other parallel operating cryostats. Heat load measurements with high resolution, like the cryogenic measurement of Q_{RF} in CHECHIA, can not be performed in parallel operation if only one set of vacuum compressors is used.

A.3.2. Performance of the 900 W LINDE Refrigerator & Heat Loads of the Distribution System

At 70 K shield loads between 1 KW to 2 KW the existing TTF-Refrigerator has a refrigeration capacity of 900 W at 4.5 K. Fig. A.3.2. shows the relation between refrigeration power and liquefaction rate of the plant. As a rule of thumb 100 W refrigeration power corresponds to about 1 [g/s] liquefaction rate of the 900 W cold box.

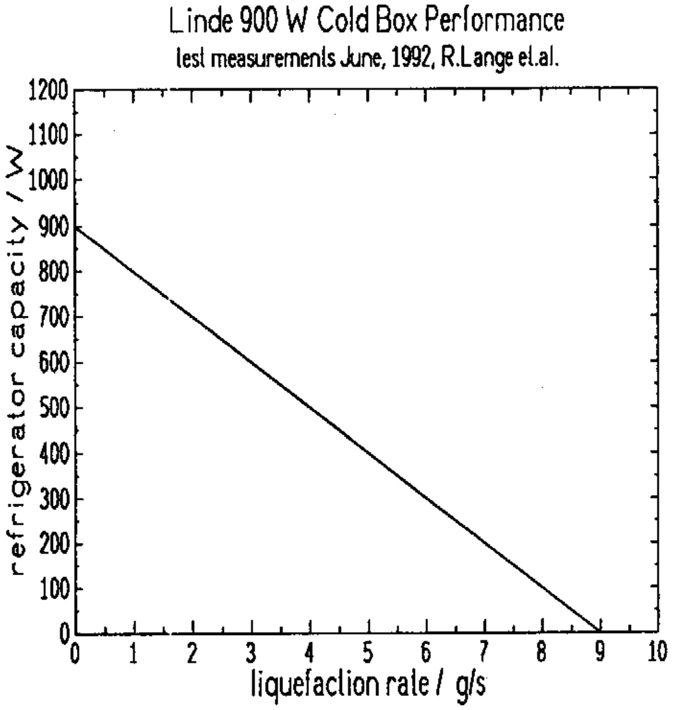


fig. A.3.2. Performance of the LINDE 900 W Cold Box (TTF-Refrigerator)

Under stationary conditions the heat load of the helium distribution system of the test facility, including transfer lines, subcooler box and distribution box amounts to about 150 W.

The heat load of a transfer line to a 2000 l liquid helium storage dewar, which is connected to the distribution system, is estimated to be about 60 W.

A.3.3. Operating of a TTF-Vertical Test Cryostat[10]

Single cavities are tested in one of the vertical test cryostats of the TTF-plant. The cold mass of one cryostat consists of about 20 kg niobium and 200 kg steel. The liquid volume amounts to about 650 l.

The cool down of a cryostat is done in three steps:

Step1) Cool down from 300 K to 4.5 K

For a cool down from 300 K to 4.5 K the change of enthalpy of the cold mass is $\Delta H_{mass}\sim 2.6*10^{7}$ J. This change of enthalpy corresponds to about 300 l liquid helium at 4.5 K.

Step 2) Filling of the cryostat with liquid helium

650 l liquid helium at 4.5 K are needed.

Step 3) Pumping down from 4.5 K to 1.8 K

About 400 l liquid have to be evaporated to cool down the liquid from 4.5 K to 1.8 K. In addition about 150 l helium have to be added to compensate the density change of liquid helium from 4.5 K to 1.8 K.

To get one vertical cryostat cooled down and filled for a cavity test at 1.8 K about 1500 l of liquid helium and about 9 h are needed. Under stationary operating about 1 [g/s] of liquid flow is needed to compensate the static heat losses of the dewar and to get stable conditions at the low temperature heat exchanger that is attached to the dewar. For useful cavity tests about 5 [g/s] of liquid (corresponding to a heat load of 100 W at 1.8 K) should be supplied to the test dewar.

A.3.4. Operating of CHECHIA[11]

Single equipped cavities are tested in the horizontal test cryostat (CHECHIA) of the TTF-plant. The cold mass of cavity and helium vessel consists of about 40 kg niobium and titanium. The liquid volume amounts to about 20 l.

The cool down of a cryostat is done in four steps:

Step 1) Cool down of the LN_2 and the 4.5 K shields (about 24 h)

The 4.5 K shield will cause a heat load of about 10 -20 W (refrigeration load).

Step2) Cool down from 300 K to 4.5 K

For a cool down from 300 K to 4.5 K the change of enthalpy of the cold mass is $\Delta H_{mass}\sim 2.5*10^{6}$ J. This change of enthalpy corresponds to about 30 l liquid helium at 4.5 K.

Step 3) Filling of the cryostat with liquid helium

20 l liquid helium at 4.5 K are needed.

Step 4) Pumping down from 4.5 K to 1.8 K

About 12 l liquid have to be evaporated to cool down the liquid from 4.5 K to 1.8 K. In addition about 5 l helium have to be added to compensate the density change of liquid helium from 4.5 K to 1.8 K.

To get CHECHIA cooled down and filled for a cavity test at 1.8 K about 70 l of liquid helium and about 24 h are needed. Under stationary operating about 0.15 [g/s] of liquid flow 1.8 K and 10 W at 4.5 K are needed to compensate the static heat losses of the dewar. For useful cavity tests about 0.5 to 1.5 [g/s] of liquid (corresponding to a heat load of 3 to 30 W at 1.8 K) should be supplied to the test dewar.

A.3.5. Cavity Test Scenarios for Different TTF-Linac Heat Loads

According to the heat load budgets for different operating conditions of the TTF-linac (see appendix 1) the operation of the test cryostats in parallel to the cryogenic supply of the TTF-linac can be discussed. It is supposed that the 2000 l liquid helium storage dewar is used as a buffer between the cold box and the distribution system and that the cool down of the vertical dewar is accomplished by means of this dewar.

Important parameters for the vertical tests are:
t_{2000l}= time to fill the 2000 l storage dewar
t_{refill}= time to refill the 2000 l storage dewar / vertical test dewar in stand by
t_{test}= cavity test time with 5 [g/s] supply including the liquid out of the 2000 l storage dewar
(100 W heat load in the vertical dewar)

With this parameters a **'test efficiency'** η_{test} can be defined :

$$\eta_{test} = \text{test time / recovery time} = t_{test} / t_{refill}$$

A.3.5.1. TTF-3-Linac in Stand By Mode (No RF)

According to table A.1.1. and diagram A.3.2. there is a reserve of 500 W refrigeration capacity of the cold box.
t_{2000l} = 16 h are needed to fill the 2000 l storage dewar (4.4 [g/s] liquefaction rate).
20 h to refill the storage dewar after cool down and vertical test dewar in stand by
30 h stationary operating (100 W heat load).

η_{test} **= 1.5**

Test scenario:
About a day to fill the 2000 l dewar and to cool down one vertical test dewar.
Cycles of 12 h measurement / 12 h recovery in vertical dewar.
The parallel operation of CHECHIA is possible.

A.3.5.2. TTF-3-Linac at E_{acc}= 15 [MV/m] and 5 Hz Repetition Rate

According to table A.1.2. and diagram A.3.2. there is a reserve of 350 W capacity of the cold box.
t_{2000l} = 24 h are needed to fill the 2000 l storage dewar (2.9 [g/s] liquefaction rate).
52 h to refill the storage dewar after cool down and test dewar in stand by.
18 h stationary operating (100 W heat load).

η_{test} **= 0.4**

Test scenario:
About a 1 ½ days to fill the 2000 l dewar and to cool down one vertical test dewar.
Cycles of 12 h measurement / 48 h recovery in vertical dewar.
No parallel operation of CHECHIA .
CHECHIA can be operated alone

A.3.5.3. TTF-3-Linac at E_{acc}= 15 [MV/m] and 10 Hz Repetition Rate

According to table A.1.3.and diagram A.3.2. there is a reserve of 300 W capacity of the cold box.
t_{2000l} = 29 h are needed to fill the 2000 l storage dewar (2.4 [g/s] liquefaction rate).
104 h to refill the storage dewar after cool down and test dewar in stand by
18 h stationary operating (100 W heat load)

η_{test} = 0.2

Test scenario:
About 1 1/2 days to fill the 2000 l dewar and to cool down one vertical test dewar.
Cycles of 12 h measurement / 60 h recovery in vertical dewar.
No parallel operation of CHECHIA.
CHECHIA can be operated alone.

A.3.3.4. TTF-3-Linac at E_{acc}= 25 [MV/m] and 5 Hz Repetition Rate

According to table A.1.5. and diagram A.3.2. there is a reserve of 330 W capacity of the cold box.
t_{2000l} = 26 h are needed to fill the 2000 l storage dewar (2.7 [g/s] liquefaction rate).
58 h to refill the storage dewar after cool down and test dewar in stand by.
18 h stationary operating (90 W heat load limited by the pumped mass flow).

η_{test} = 0.3

Test scenario:
About 1 1/2 days to fill the 2000 l dewar and to cool down one vertical test dewar.
Cycles of 12 h measurement / 40 h recovery in vertical dewar.
No parallel operation of CHECHIA.
CHECHIA can be operated alone.

A.3.3.5. TTF-3-Linac at E_{acc}= 25 [MV/m] and 10 Hz Repetition Rate

According to table A.1.5. and diagram A.3.1. there is a reserve of 240 W capacity of the cold box.
t_{2000l} = 40 h are needed to fill the 2000 l storage dewar (1.8 [g/s] liquefaction rate).
4 h stationary operating (90 W heat load limited by the pumped mass flow).
Test scenario:
About 2 days to fill the 2000 l dewar and to cool down one vertical test dewar.
Difficult cool down from 4.5 K to 1.8 K with a mass flow of 4.5 g /s.
4 h measurement, no recovery.
No parallel operation of CHECHIA.
CHECHIA can be operated alone.

Appendix 4
FEL-Linac Operating Temperature

The subatmosheric components of the helium supply for the TTF-linac are designed for a heat load of Q_{TTF}= 200 W at T_{TTF}=1.8 K corresponding to a massflow of $(dm/dt)_{TTF}$ = 10 [g/s] and a vapor pressure of P_{TTF}=16 mbar. If the heat load for the FEL-supply is doubled to Q_{FEL}=400 W (for the upper limit of this estimate) the mass flow rate will also be doubled $(dm/dt)_{FEL}$=20 [g/s]. (The more detailed analysis shows that the 2 K pumped mass flow will result in only 14 [g/s] , so the estimates here seem to be safe.)

With the given TTF helium distribution system[6] the factor 2 in mass flow at a pressure of 16 mbar would result in a factor 4 in absolute pressure drop which can be estimated from the simplified relation which can be taken as a rough rule of thumb for the different components:

$$\Delta \mathbf{p} \propto (\mathbf{dm/dt})^2 / \mathbf{P} \qquad (A.4.1)$$

At 16 mbar the pressure drop in the TTF-distribution system is much to high and a new distribution system for the FEL-linac has to be installed. The simplest solution would be a additional parallel supply of the five added FEL modules.

On the other hand it can be shown from relation (A.4.1) that the subatmosheric helium distribution system for the TTF-linac can be kept also for the complete FEL-linac, if the operating temperature for the FEL-linac is increased from 1.8 K (16 mbar) to 2 K (32 mbar). From relation (A.4.1.) the relative pressure drops **Δp / P** result in :

$$\Delta p_{TTF}/p_{TTF} = ((dm/dt)_{TTF} / (dm/dt)_{FEL})^2 * (P_{FEL} / P_{TTF})^2 * \Delta p_{FEL}/P_{FEL} \qquad (A.4.2)$$

The increase of mass flow can be compensated by the parallel increase of vapor pressure for the operating of the FEL-linac in terms of the relative pressure drops.

Apart from the pressure drop considerations, the heat transfer in the subatmosheric heat exchangers scales with the mass flow:

$$NU \propto RE^X \propto (dm/dt)^X ;\ x \sim 0.8 \ldots 0.9 \qquad (A.4.3.)$$

(NU = Nusselt number, RE = Reynold number)

The 40/80 K and 4.5 K helium circuits can tolerate higher mass flows corresponding to the increased heat loads of the FEL-linac.

If the effort for a additional helium distribution system for the FEL-linac is to be avoided it is recommended that 2 K as the operating temperature for the FEL-linac be allowed.

It is not discussed here how the overall performance of the linac is affected by the choice of 2 K instead of 1.8 K.

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