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The Cryogenic System of TESLA 500 - An Update

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The cryogenic system for the 20000 superconducting 1 m long 1.3 GHz 9-cell niobium cavities of the 33 km long TESLA 500 collider presently under development by an international collaboration is described. A redesign of the cryostats for the cavities for cost reasons also results in an improvement for the 2 K cooling, especially in the first part which starts with a slope of -8 mrad near the DESY site. Calculated and design loads and details of the layout for the 14 refrigerators housed in 7 above-ground cryogenic halls are given.

1 INTRODUCTION

TESLA 500 is an e+e- linear collider of 500 GeV centre of mass energy presently under development by an international collaboration [1]. For acceleration of the particles with a beam pulse length of 0.8 ms and 5 Hz repetition rate about 20000 approximately 1 m long superconducting 1.3 GHz 9-cell niobium cavities of 25 MV/m accelerating gradient and $Q_0 > 5*10^9$ resonance quality are used. The cavities are cooled in a liquid helium bath to a temperature of 2 K (Helium II). Eight such cavities, welded into their titanium helium vessels and equipped with power couplers, higher order mode (HOM) couplers, antennas and tuners are housed in a common standard cryostat of 11.37 m length - the "cryomodule". In addition, about every third cryomodule contains a 1 m long superconducting magnet package (quadrupole, correction dipoles and beam position monitor) which is cooled at 4.5 K. The magnet current is supplied by high T_c leads cooled to ~50 K. The "cold mass" is covered with 2 thermal shields, at 4.5 K and 40 - 80 K, respectively, and is supported inside the vacuum vessel at 3 positions by fibre glass support posts. The approximately 33 km long chain of cryomodules placed into a 5.2 m diameter tunnel extending to the north-west of DESY in Hamburg (one possible site) is divided into 12 cryogenic units. Each unit is about 2.5 km long containing 210 - 214 cryomodules (depending on the number of required quadrupoles, 53 - 105) and is cooled by one refrigerator. Each unit is divided into 18 "strings" (17 strings with 12 cryomodules each and string no. 18 with 6 - 10 cryomodules). Generally 2 neighbouring refrigerators are housed in a common refrigeration hall above ground.

Special situations occur within the first two units. Due to the fact that DESY is situated in the suburbs of the city there is no space for a cryogenic hall along the first 5 km. The first 2 units are also used for a Free Electron Laser (FEL) of 50 GeV e^- beam energy with 5 Hz beam pulse repetition rate in addition to the 5 Hz of the high energy beam of the collider. Finally, there is a pre-accelerator for 3 GeV in front of unit 1 consisting of 18 cryomodules. All this results in a higher heat load in these units. The tunnel starts with a slope of -8 mrad and a curvature of about 1000 km radius until the horizontal orientation is reached in the middle of the third unit. The cryogenic scheme is illustrated in Figure 1.

2 CRYOMODULE

Experience with the fabrication of first cryomodules for the TESLA Test Facility (TTF) has led to a design change for TESLA. Instead of the previously published design [1,2] in which a 300 mm diameter helium two-phase pipe was used for filling the cavity helium vessels with liquid and simultaneously for returning the pumped gas to the refrigerator, a separate 76 mm diameter helium two-phase pipe as in the TTF cryomodules [3] has been added for filling the cavity helium vessels. While the previous design was thought to be a simplification it turned out that the direct connection of each cavity helium vessel to the 300 mm diameter tube together with the required precision would have resulted in much higher fabrication costs. The 300 mm diameter tube now serves as a gas return pipe alone which also removes possible problems in the cooling scheme (see below). In addition, an attempt was made to further decrease the outer diameter of the cryomodule which was achieved by shifting the 76 mm 2 K two-phase tube aside (Figure 2) [4]. In this context the necessity of the 4.5 K thermal shield was questioned, but it was retained as insurance against higher thermal losses.

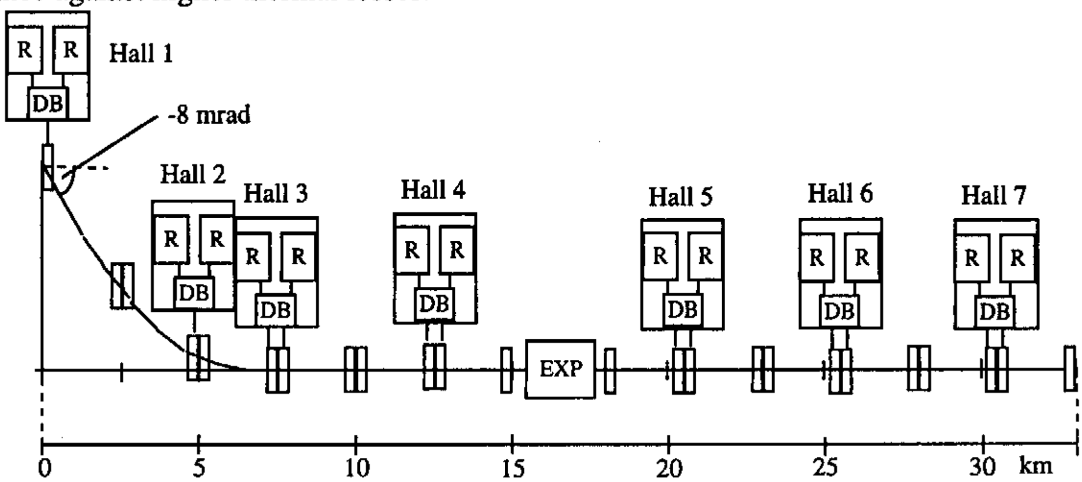

Figure 1 Cryogenic scheme of TESLA (R = refrigerator, DB = distribution box)

3 HEAT LOADS

Static and static plus dynamic (total, with RF and magnet current on) heat loads have been estimated for all cryogenic components such as standard cryomodules, cryomodules with quadrupole packages, special cryomodules at string interconnections, feed- and end-boxes, transfer lines and distribution boxes. A summary is given in Table 1. In addition to the estimated heat loads the table contains design loads which are a factor 1.5 higher in order to compensate for uncertainties in the design, fabrication and long term performance. This designed over-capacity can also be used for maintaining operation of the collider at reduced beam pulse repetition rate when a refrigerator fails. Heat loads for cryo-units 3-12 are assumed to be identical (neglecting minor differences coming from different numbers of quadrupole packages). As can be seen, the static load is only about 12 % of the total load at 2 K for the standard units. Dynamic heat loads for units 1 and 2 take into account a 10 Hz beam pulse repetition rate with every second pulse used for the FEL (15 MV/m instead of 25 MV/m, $Q_0 > 1*10^{10}$) which are therefore about 18 % higher. The heat load budget for unit 1 also takes into account a superconducting pre-accelerator for 3 GeV containing 18 cryomodules.

The planned reserve of refrigeration capacities together with a perhaps reduced beam pulse repetition rate allows also for an upgrade to 800 GeV centre of mass energy making use of the proposed superstructure concept [5]which leads to a higher filling factor of cavities along the linac.

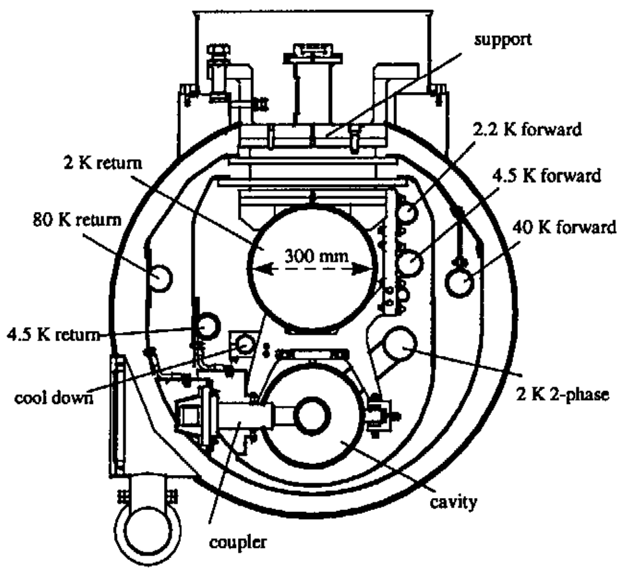

Figure 2 Revised cross section of cryomodule [4]

	2 K		4.5 K		40-80 K		electric power
	static[W]	stat. + dyn. [W]	static[W]	stat. + dyn. [W]	static[W]	stat. + dyn. [W]	[MW]
unit 1 nominal	324	3063	2573	3298	15385	25600	3.91
unit 1 design	486	4595	3860	4946	23077	38399	5.87
unit 2 nominal	281	2737	2338	2986	13385	22068	3.49
unit 2 design	421	4106	3507	4479	20078	33103	5.23
unit 3-12 nominal	281	2373	2354	2904	13659	21579	3.16
unit 3-12 design	422	3559	3531	4356	20488	32369	4.75

Table 1 Heat loads of cryo-units

4 COOLING

The basic cooling segment is a string (see Figure 3). Subcooled single phase helium at 2.2 K and 1.2 bar is supplied from the refrigerator in a pipe through all cryomodules. At the end of each string (usually the far end seen from the refrigerator, except for unit 1) the helium is expanded in a JT-valve into a phase separator at the entrance of the 76 mm diameter 2-phase tube. After expansion, the quality of the helium is 0.0944 and the total mass flow per string is 9.4 g/s (design value for unit 3-12, 11.4 g/s for unit 1). The liquid level in the 2-phase tube will be controlled to fill the tube to about half. The liquid then flows to the 96 cavity helium vessels filling them completely. The gas evaporated by the heat load returns through the 2-phase tube and the 300 mm diameter gas return pipe (connected at each cryomodule interconnection) to the refrigerator. The gas return pipe collects the gas from all 18 strings (from $\approx$ 0 g/s at 31.3 mbar to 168.1 g/s at 30.0 mbar in unit 3-12, to 216.9 g/s at 29.1 mbar in unit 1). At the end of the string the surplus liquid is collected in a box containing a heater. The level can be used to control either the heater or the JT-valve. Cool down and warm up for each half string is achieved by an additional tube inside the cryomodules connected to the bottom of each helium vessel. The JT-valve, the 2 cool down/warm up regulating valves, the phase separator and the liquid collector are housed in the end of a special type of cryomodule.

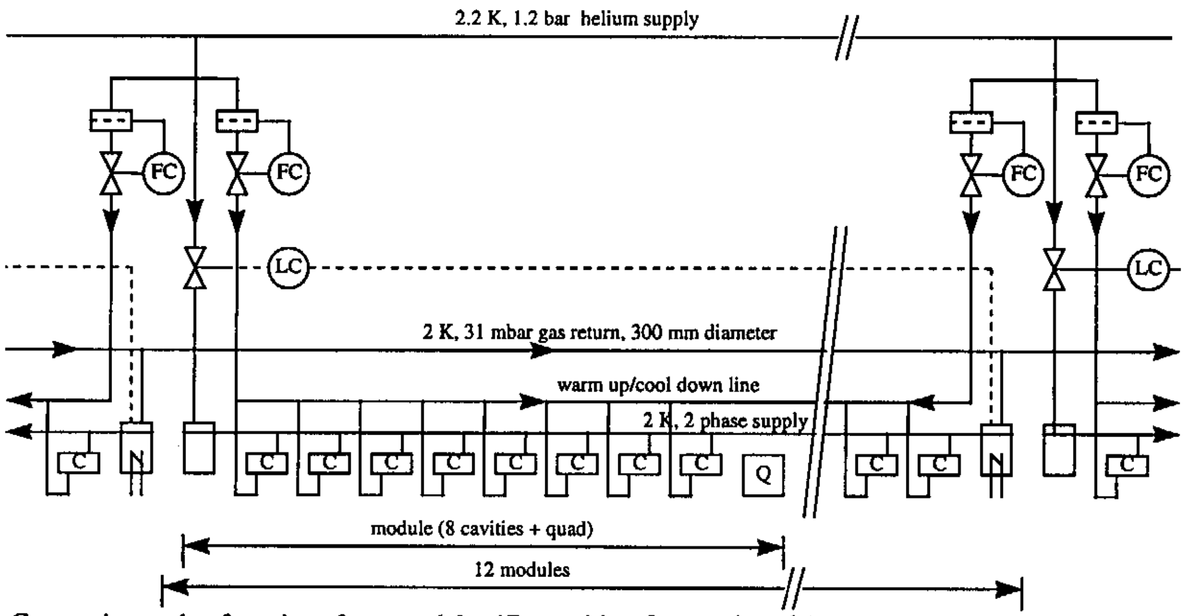

Figure 3 Cryogenic supply of a string of cryomodules (C = cavities, Q = quadrupole)

A special situation occurs in cryo-unit 1 because of the slope. Here the JT-valve must expand into the near end (seen from the refrigerator) of each string. The liquid flow is maintained by gravity. In the previous cryomodule design liquid and gas were flowing in the same 300 mm diameter tube and in counter-current direction. In this unit there was some risk of blockage of the liquid flow by high vapour flow velocities [6]. This problem is significantly reduced with the new design.

5 CRYOGENIC PLANTS

Each cryo-unit will be supplied from a refrigerator sitting in a refrigeration hall above ground. Two neighboured refrigerators will be placed in a common hall of about 85 m by 32 m. The advantage of this is that in case of a break down of one refrigerator the neighbouring one can take over the static load and due to its built-in over-capacity is even able to cope with the dynamic load of both units at a reduced beam pulse repetition rate.

Studies of the refrigeration plants were made by well known cryogenic suppliers [7,8] showing that the concept is reasonable. Proposals for achieving a high availability of the complete cryo-system were also submitted. The coldboxes containing 6 or 7 turbines will be split into warm-end and cold-end coldboxes. The 2 K helium will be achieved by pumping with 4 - 5 cold compressors depending on whether sub-atmospheric pressure can be handled at the entrance of the warm compressors or not. In the refrigeration halls of the standard cryo-units (no. 3 - 12) a few single warm compressors, purifiers and adsorbers will be installed for redundancy. The heat loads of cryo-units no. 1 and 2 require somewhat higher cooling capacity. To overcome severe problems when one refrigerator fails, the heat load of these units will be removed by two half size refrigerators in each refrigerator hall. However, it may well be that installing 14 identical refrigerators is more economical.

To use the available space effectively and because of static pressures the cold compressors will be installed in the 15 m diameter shaft connecting the refrigeration hall with the accelerator tunnel. The cold boxes will either be installed in the shaft too, or will be placed horizontally in the hall. The total installed electric power will be about 10 MW in each cryogenic hall.

6 SUMMARY

Following the experience of fabrication of the first cryomodules for the TESLA Test Facility (TTF) a redesign of the cryomodule for TESLA was made leading to a smaller outer diameter of the cryomodule and simultaneously greatly reducing the problem of possible blockage in the cooling of the first -8 mrad inclined cryo-unit of TESLA. The collider is cryogenically divided into 12 cryo-units, each containing 18 strings of up to 12 cryomodules. The heat load budget including 50 % safety margin requires a cooling power of 4595 kW, 4.946 kW and 38399 kW at 2 K, 4.5 K and 40/80 K, respectively, for cryo-unit 1 and 3.559 kW, 4.356 kW and 32369 kW at 2 K, 4.5 K and 40/80 K, respectively, for the standard cryo-units (3 - 12). The cooling is performed from 14 refrigerators in 7 cryogenic halls where each hall requires about 10 MW electrical power. The cryogenic scheme allows for an energy upgrade to 800 GeV centre of mass.

7 REFERENCES

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The Cryogenic Supply of a VUV Free Electron Laser at the TESLA Test Facility at DESY

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The 390 MeV linear accelerator of the TESLA Test Facility at DESY will be extended to 1 GeV and used as an electron beam source for a Vacuum Ultraviolet Free Electron Laser (VUV FEL). Consequently the existing TTF cryogenic system requires an essential upgrade to supply the 1 GeV linac: The helium distribution system of the TTF linac will be connected to the HERA helium plant by a valve box, a 250 m long transfer line and a subcooler box. The cooling capacity at 2 K will be doubled by an additional warm vacuum compressor assembly.

1 INTRODUCTION

The concept of the TESLA 500 linear accelerator consisting of 1.3 GHz superconducting niobium cavities includes the use of the electron beam as a source for a Free Electron Laser (FEL), which will open up new horizons in the scientific and technical application of synchrotron radiation [1]. As the other concepts for TESLA 500 also the operation of a Free Electron Laser will be demonstrated already at the TESLA Test Facility (TTF) at DESY. Beyond this test, the 390 MeV TTF-linac will be extended to 1 GeV to operate as a source for a vacuum ultraviolet FEL user facility [2]. In the final state the TTF/FEL – linac will consist – among other things – of 8 - 10 TESLA cryomodules, each containing 8 superconducting 1.3 GHz 9-cell niobium cavities cooled in a 2 K helium bath, a superconducting quadrupole package at 4.5 K and thermal shields at 4.5 K and 40/80 K temperature levels. A sketch of the TTF/FEL-linac is shown in figure 1.

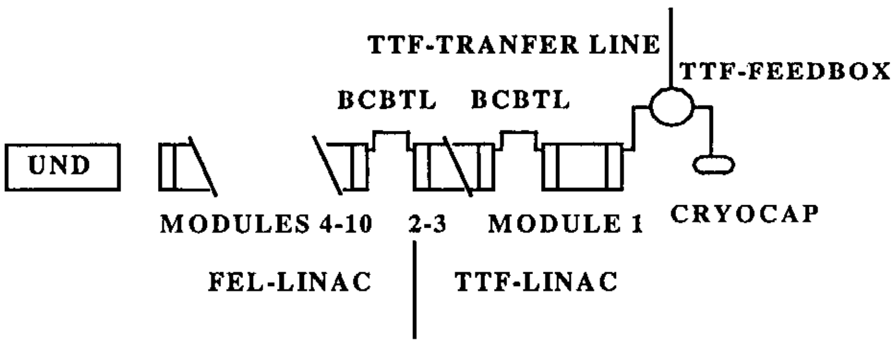

Figure 1: Simplified Sketch of the TTF/FEL - LINAC
BCBTL = bunch compressor bypass transfer line; UND = undulator;
CRYOCAP = superconducting injector cavity

The parallel cryogenic supply of the 1 GeV linac, a Superconducting Magnetic Energy Storage (SMES) cryostat and the TTF-test plant, requires an essential upgrade of the existing TTF cryogenic system [3]. With reference to the operation experience with the first TTF module cryostat the concept of the extended cryogenic system and the main components are described

2 THE CONCEPT OF THE EXTENDED CRYOGENIC SYSTEM

The concept of the extended cryogenic system for the supply of the TTF/FEL-linac is shown in the block diagram in figure 2. The heat loads of the TTF/FEL-linac are listed in table 1.

The helium distribution system of the TTF-linac, consisting of the TTF-transfer line and the TTF-feedbox, will be connected to the HERA helium plant by a HERA-FEL valve box , a 250 m long HERA-FEL transfer line and a FEL subcooler box as shown in fig.1. The cryogenic supply for the extended linac, by means of the TTF-transfer line, the TTF-feedbox and a low pressure counter flow heat exchanger, will be maintained as designed for the operation of the original TTF-linac, consisting of three cryomodules, a bypass transfer line between the first two modules and an injector cryostat (CRYOCAP) [4,5].

The FEL subcooler box will be installed close to the TTF/FEL-linac. By means of the FEL subcooler box the 4.5 K supply of supercritical helium from the HERA plant is sub cooled and the helium circuits are branched to the TTF-linac distribution system, to the SMES, to a test stand for single cryomodules (SMT) and – as an option – to the TTF plant for the test of single superconducting cavities. (During normal operation, the existing 900 W (4.5 K) TTF cold box and the first set of vacuum compressors will still be used for the supply of the TTF test plant.)

A second set of warm vacuum compressors will be added to the system in order to increase the redundancy and to decouple the operation of the TTF/FEL-linac from the TTF test plant. The low pressure counter flow heat exchanger will be incorporated in the supply from the HERA plant.

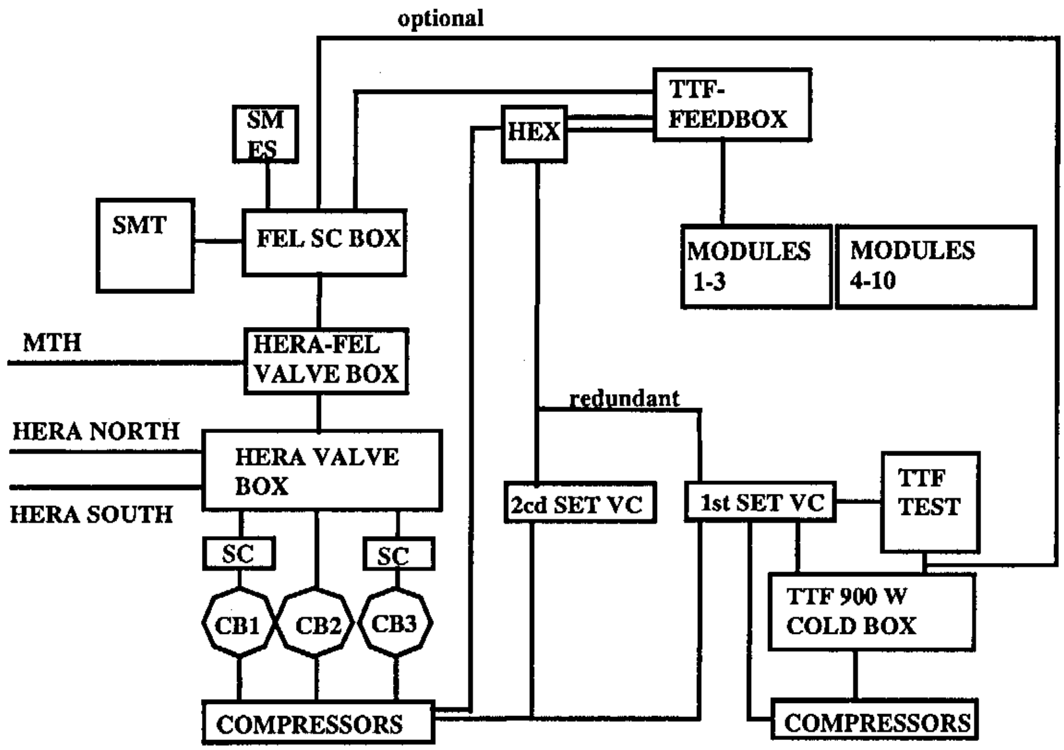

Figure 2: Block Diagram of the Extended Cryogenic System for the TTF/FEL-Linac
VC = vacuum compressors; HEX = low pressure counter flow heat exchanger; SC = internal HERA subcooler; CB = HERA cold box; SMT = single module test; SMES = superconducting magnetic energy storage cryostat; MTH = Magnet Test Facility (HERA)

Table 1: Dynamic Heat Loads of the TTF/FEL-linac

circuit	40/80 K shield [W]	4.5 K [W]	2.0 K bath cooling [W]	2.0 K pumped mass flow [g/s]	4.5 K liquefaction [g/s]
FEL nominal	1887	580	120	6.1	2.3
FEL design	2831	870	180	9.2	3.5
resulting heat load (design)	2831	1050			3.5

The HERA plant consists of three helium refrigerators. The cryogenic capacities of the HERA refrigerators and the heat loads of HERA and of the HERA experiments are shown in table 2. During the normal operation of the HERA storage ring only two of these refrigerators are in use for the cryogenic supply of the superconducting HERA magnets and the HERA high energy physics experiments. The comparison of tables 1 and 2 shows that as well the excess capacity of the active refrigerators as the redundant refrigerator can be used for the supply of the TTF/FEL-linac on the 4.5 K and 40/80 K temperature levels.

Table 2: Excess Cryogenic Capacities of the HERA Helium Plant

circuit	4.5 K [W]	4.5 K [W]	4.5 K liquefaction [g/s]	4.5 K liquefaction [g/s]	40/80 K shield [W]	40/80 K shield [W]
	CB NORD	CB SOUTH	CB NORD	CB SOUTH	CB NORD	CB SOUTH
HERA	2605	2886	7.30	6.20	12000	12000
HERMES			0.34		287	
H1	174		1.00		1253	
ZEUS		113		0.84		200
SL cavities		1164		1.60		1769
magnet-test hall	880		0.30		1200	
sum	3659	4163	8.94	8.64	14740	13969
cold-box capacity (nominal)	6500	6500	20.50	20.50	20000	20000
excessive capacity	2841	2337	11.56	11.86	5260	6031

3 THE MAIN COMPONENTS OF THE EXTENDED CRYOGENIC SYSTEM

3.1. The HERA-FEL-Valve-Box

The HERA-FEL valve box was designed and constructed by the LINDE company and was attached to the HERA valve box in the 1997/1998 shut-down of the HERA storage ring. By means of the valve boxes each of the three HERA cold boxes can be used for the supply of the HERA magnet test facility and the TTF/FEL-linac in parallel to the operation of the HERA storage ring. Also the magnet test facility and the TTF/FEL-linac can be operated independently, including warm up and cool down cycles. The HERA-FEL valve box is equipped with 11 cold valves.

3.2. The HERA-FEL-Transfer Line

The HERA-FEL transfer line connects the 4.5 K and 40/80 K cryogenic circuits between the HERA-FEL valve box and the FEL subcooler box from the HERA cryogenic building to the TTF/FEL-linac experimental hall across the DESY site. The transfer line has a length of 250 m. The transfer line will be designed and built by a co-operation of the LINDE and BABCOCK companies. The transfer line will be commissioned in summer 1999.

3.3. The FEL-Subcooler Box

Depending on the operating conditions of the HERA plant, the temperature of the 4.5 K supply can vary from 4.5 K to 5.8 K. In the FEL subcooler box the supply mass flow is subcooled to 4.4 K and branched to the TTF/FEL-linac (via the TTF-transfer line), to the SMES cryostat, to a single cryomodule test and – as an option – to the TTF-test plant. Also the 40/80 K circuits are branched to the different users and the return flows are collected. The FEL subcooler box consists of 25 cold valves and a helium bath subcooler of about 1 m^3 volume.

3.4. The Second Vacuum Compressor Assembly

The second set of vacuum compressors will be specified very close to the first set [5]. It will be an arrangement of roots blowers and rotary vane pumps. The helium mass flow will be specified to 10 g/s at a suction pressure of 10 mbar and 20 g/s at 20 mbar.

3.5. The Second Bunch Compressor Bypass Transfer Line

The electron bunches in the TTF/FEL-linac have to be compressed by sections of warm magnets between the first two cryomodules and modules three and four. These sections of warm magnets have to be bridged by bypass transfer lines (BCBTL), as sketched in figure 1. For the extended linac a second 8-fold bypass transfer line will be placed between modules three and four. The second bypass transfer line has also to allow different designs of modules 1- 3 and modules 4 - 10.

4 SUMMARY

By means of the connection of the cryogenic supply of the TTF/FEL-linac to the HERA helium plant, the operation of the TTF/FEL-linac will profit from the redundancy of the HERA refrigerators, and, in addition, the excessive cryogenic capacities of the HERA cold boxes can be used economically. Also, the second set of vacuum compressors will increase the reliability of the cryogenic system.
The extended cryogenic system will be commissioned at the end of the year 1999.

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Operating Experience with the First TESLA Test Facility (TTF) Cryomodule

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The cryomodule is the fundamental building block of the proposed TESLA 500 linear collider. It contains the superconducting RF cavities and magnets needed for accelerating and focusing the beam along with the associated cryogenic pipes and thermal insulation. The first of these cryomodules has been operated in the TESLA Test Facility linac. This paper reports on the operating experience of the cryomodule including heat leak, cavity alignment and helium regulation. This cryomodule required disassembly and repair of the cavity tuning system. The experience gained during this work and the impact of the repair on cryomodule performance is also covered.

1 INTRODUCTION

The TESLA cryomodule contains the superconducting RF cavities and magnet packages necessary for the proper functioning of the proposed TESLA 500 linac [1]. The development of a reliable, affordable cryomodule that meets all operating requirements is a key goal of the TESLA program. The design and construction of the first of these cryomodules has been described previously [2]. This cryomodule has been in operation since June 1997. It has undergone 3 thermal cycles between 300 K and 1.8 K and has amassed approximately 8 months of operating time at cryogenic temperatures. The purpose of this paper is to sum up the operating experience to date. Problems with the cavity tuning system required that the cryomodule be partially disassembled to effect repairs. These repairs and their impact on the performance of the module are also discussed. Figure 1 shows a cross sectional view of the cryomodule.

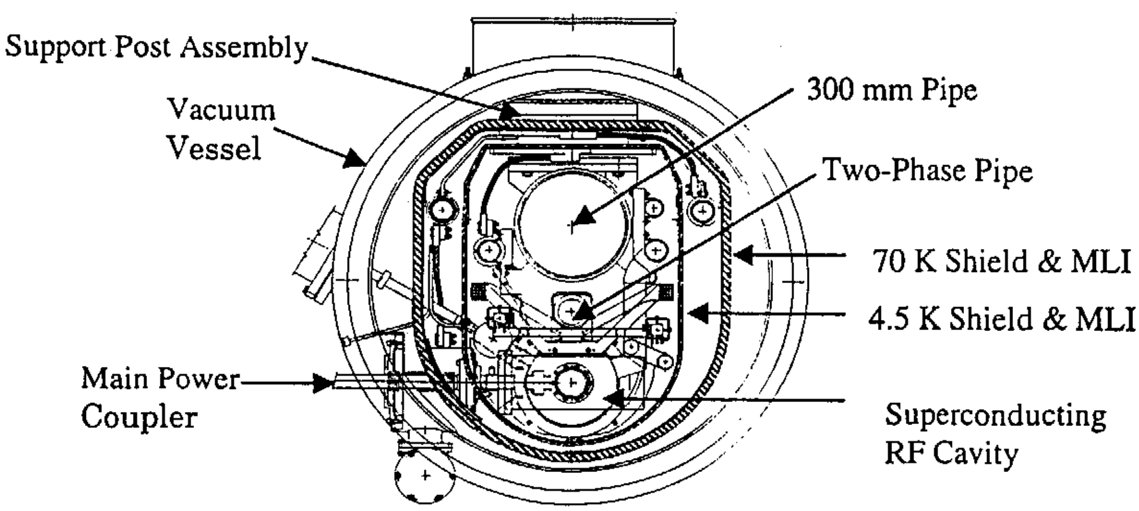

Figure 1 Cross Section of Cryomodule

2 TUNER REPAIR

A tuner is attached to each cavity to allow adjustment of the resonant frequency within a range of 880 kHz. The tuner consists of a stepper motor, harmonic drive (gear assembly) and linkage arms. After the first thermal cycle, 1 of the 8 tuners had stopped working. After the second thermal cycle, a total of 2 tuners had stopped working rendering these cavities inoperative. Suspicion centered on the harmonic drive. There had been subtle, though potentially important, changes in the tuner design between the testing of the first prototype and use of the tuners in the cryomodule. Additionally, not all the tuners had been cold tested before installation into the cryomodule. These factors made it probable that future failures would occur and it was decided to disassemble the cryomodule, diagnosis and fix the tuner problem.

The cryomodule was removed from the linac in mid November 1997 and disassembled to the point at which the tuner motor and harmonic drive were accessible. This step took 2 weeks. The tuner motors and harmonic drives were then subjected to a series of inspections and tests at both room and cryogenic temperatures. As a result, the following changes were made:

- The bearing between the motor shaft and harmonic drive was changed to one that provides a more reliable connection.
- The harmonic drive was replaced with one that had tighter mechanical tolerances and was made from non-magnetic stainless steel.
- A lubricant coating (titanium nitride) was added to both the bearing and the harmonic drive.

After this work was completed, all motor / harmonic drive assemblies were extensively tested at liquid helium temperatures. No further failures were seen.

While the cryomodule was open, 2 broken temperature sensors were replaced and some missing multilayer insulation blankets surrounding the main coupler ports were installed. No changes were made to the alignment of the cavities.

Once the tuner motor and gears had been repaired, tested and installed on the cavities, the cryomodule was reassembled and installed back on the linac. This step took approximately 5 weeks. At this point, it was discovered that a leak had opened up between the beam tube vacuum and the isolation vacuum. The leak was 10^{-6}mbar l/s in size and located near cavity # 7. There was no explanation for this leak and since to find and repair it meant another disassembly of the cryomodule, with the real possibility of creating more leaks, it was decided not to fix the leak. To date, the presence of this leak has not caused any degradation of the cryomodule performance.

While doing this work we developed techniques to disassemble and repair the cryomodule. However, even when done very carefully such repairs can cause additional damage. Since the repair, the tuning system has operated without difficulty at cryogenic temperatures for 4.5 months. In the future, all tuner motor assemblies are to be cryogenically tested before installation into the cryomodule.

3 HEAT LEAK

The static heat leak to the 70 K and 4.5 K levels was found by measuring inlet and outlet temperatures and pressures, calculating the change in enthalpy and multiplying by the measured mass flow rate. Measurements with test heaters wrapped around the 70 K and 4.5 K cooling lines indicate that the error in these measurements is less than a few percent. The 1.8 K / 2K result was calculated by multiplying the latent heat of helium at 1.8 K or 2 K times the measured vapor mass flow rate at the vacuum pumps; after subtracting out the amount of vapor generated during the J-T expansion at the inlet to the two-phase line. Note that after the tuner repair, the cavities were operated at 2 K as that is the temperature level planned for the TESLA 500 machine

Table 1 shows the predicted and measured static heat leaks for the 70 K, 4.5 K and 1.8 K / 2K levels. There was essentially no difference in the measured static heat leak before and after the tuner repair. Recall that to repair the tuners, the module was partially disassembled which included cutting the MLI blankets and removal of most of the thermal radiation shields. A great deal of effort was made to restore the thermal insulation system of the cryomodule back to its original state. This work appears to have been successful. Additionally, it had been hoped that by installing some missing 70 K MLI pieces around the main coupler ports that the 70 K heat leak could be reduced. Unfortunately, any advantage gained by doing this appears to have has been negated by the cutting and patching work done on the main 70 K MLI blanket.

The measured static heat leaks are significantly above the predicted values. However, this discrepancy is believed to be due to all the additional diagnostic lines installed in the first cryomodule [2]. Later tests are planned with more typical cryomodules.

Temperature Level	Predicted Static Heat Leak (W)	Measured Static Heat Leak (W) (before repair)	Measured Static Heat Leak (W) (after repair)
70 K	76.8	90	90
4.5 K	13.9	23	23
1.8 K / 2 K	2.8	6	6

Table 1 Predicted & measured static heat leaks

4 ALIGNMENT

In order for the TESLA 500 linac to achieve its desired beam conditions, the cavities and quadrupole in the cryomodule must be aligned to a certain tolerance and keep this alignment when cold and under vacuum. The cavities must be aligned to within + / - 0.5 mm of the ideal beam axis in both the horizontal and vertical planes. The quadrupole must be aligned to within + / - 0.1 mm of the ideal beam axis horizontally and vertically. In addition, the vertical midplane of the quadrupole must not be rotated more than 0.1 mrad from the vertical plane. The 300 mm gas return pipe acts as the structural backbone of the cryomodule. During the cryomodule assembly, the cavities and quadrupole are attached to this pipe and aligned to the ideal beam axis. The pipe is somewhat flexible and adjusting the positions of the 3 support posts, which connect the pipe to the cryomodule vacuum vessel, can change the alignment of the pipe. This design only works properly if the cavities don't move relative to the 300 mm tube once aligned and the 300 mm tube doesn't move in an unexpected manner once aligned relative to the beam axis. Upon cooling, thermal contraction will cause the 300 mm tube, cavities and quadrupole to move vertically upwards by 1.8 mm relative to their warm position. This effect is allowed for in the alignment process. The alignment of the cavities and quadrupole are monitored in real time by a wire position monitoring system developed by INFN – Milano [3]. Horizontal offset data from this system from both before and after the tuner repair is shown in figure 2.

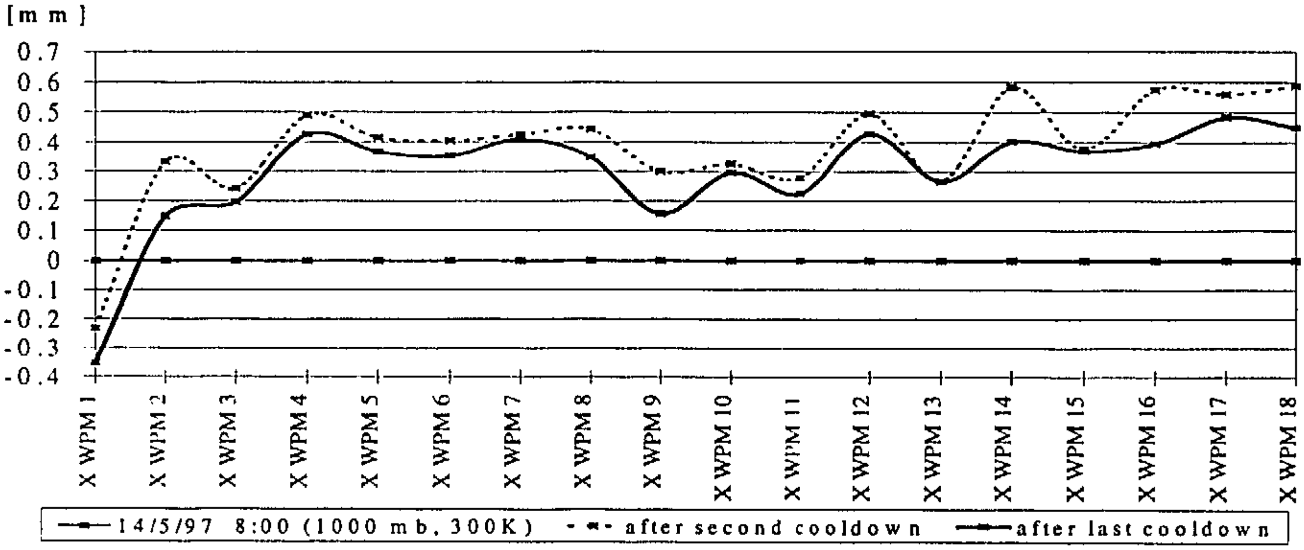

Figure 2 Horizontal Offsets of Cavities and Quadrupole as Measured by the WPM System

WPM numbers 17 and 18 represent the quadrupole while numbers 1 - 16 represent the 8 cavities. Looking at the deflection, notice that most of the cavities fall within the 0.5 mm tolerance and that all of the cavities have an offset of no more than 0.6 mm. However, in the case of the quadrupole the offset is up to three times larger than the tolerance. The results in the vertical plane are similar. Note that in all cases the greatest deflections occur at the ends of the cryomodule. The cause of these deflections is believed to be movement of the 300 mm pipe due to unbalanced forces at the ends of the pipe caused by vacuum pumping and cooldown. As it is not possible to guarantee that all forces on the pipe are always balanced, the pipe and its supports need to be changed to meet the alignment tolerances. Thus, in the 3rd generation of cryomodules currently under design, one of the support posts will be moved much closer to the quadrupole. This will have the effect of stiffening the pipe in the vicinity of the quadrupole so that the deflection of the quadrupole remains within the alignment tolerance. This change will increase the deflection of some of the cavities but a finite element analysis of the design predicts that the cavities will remain within the tolerance limits.

Figure 2 also shows that there is a difference in the offset before and after the tuner repair. The installation of the cryomodule into the linac is not completely reproducible and thus the forces generated on the 300 mm pipe during vacuum pumping and cool down differ. While the deflection of the quadrupole in this cryomodule is too large for the TESLA 500 linac the misalignment will not affect the performance of the TESLA Test Facility linac.

5 HELIUM REGULATION

Proper operation of the linac requires that the pressure and level of the He II covering the cavities be well controlled. Changes in the saturated pressure of the helium may cause detuning of the cavities or may cause the helium to exceed the desired 2 K operating temperature. Improper control of the helium level may result in poor cooling of the cavities and quench. Both the level and pressure must be able to promptly respond to changes in the 2 K heat load due to the presence or absence of the RF power.

A commercial process control system (D3) regulates the cryogenic system. The pressure is set by warm vacuum pumps and is controlled to + /- 0.1 mbar. The helium level in the two-phase line is set by the position of the JT valve at the inlet of the two-phase line supplying the cavities. The level in the two-phase line is kept 50% full and regulated to +/-0.5 %. So far, the regulation of the helium pressure and level has had no impact on the cavity performance.

Due to the better than expected cavity performance ($Q > 10^{10}$ rather than 5×10^9) and larger static heat leak in this first cryomodule, the difference in heat load due to the RF power is less than expected. The time response of the cryogenic system can easily handle the change. The helium regulation issues become more problematic as the length of the linac increases. Thus, these questions will continue to be examined as the TTF linac is extended. Once the TTF linac reaches its planned length of 10 cryomodules it will approximate the size of a cooling string in the TESLA 500 linac [1]. Full-scale tests of the helium regulation system will then be possible.

6 CONCLUSIONS

The first TTF cryomodule has logged 8 months of cryogenic operation and 3 complete thermal cycles. The experience gained from the operation of the cryomodule and from the tuner repair has provided valuable information that is being applied to the design & assembly of future cryomodules. In addition, the first cryomodule has provided reliable service as part of the TTF linac experiment.

7 REFERENCES

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