THE CRYOGENIC SYSTEM OF TESLA

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for the TESLA collaboration

Abstract

TESLA, a 33 km long 500 GeV centre-of-mass energy superconducting linear collider (upgradeable to 800 GeV) with an integrated X-ray FEL facility of 0.1 nm wave length, has been proposed by an international collaboration to be built at DESY. The backbone of this collider are more than 21000 superconducting 9-cell RF cavities, operated at 1.3 GHz with 5 Hz beam repetition rate, and about 800 superconducting magnet packages with quadrupoles and steering dipoles. The paper gives an overview of the cryogenic system necessary to cool these elements to 2 K. The system mainly consists of about 1800 cryomodules assembled in twelve 2.5 km long cryogenic units, supplied from 7 refrigerators.

1 INTRODUCTION

The 33 km long e^+e^- linear collider TESLA (Tera eV Energy Superconducting Linear Accelerator) with 500 GeV centre-of-mass energy and an incorporated X-ray FEL facility has been proposed by the international TESLA Colaboration [1]. The collider consists of 2 about 15 km long linear accelerators pointing to each other, one for electrons, the other for positrons. Other major components are 500 MeV e^- injectors for the standard high energy beam, for a polarized beam and for the FEL beam, a 250 MeV e^+ injector and 5 GeV pre-accelerators and 17 km long damping rings for electrons and positrons. There is a high energy physics experimental area at the centre and close to it the X-ray FEL laboratory. The special feature of TESLA are superconducting accelerating structures. The energy can be upgraded to 800 GeV centre-of-mass. A Technical Design Report (TDR) including costs has been worked out under the assumption that TESLA will be built north-northwest of DESY. The TDR has been submitted to the German Scientific Council at the German federal government.

2 CRYOMODULES

2.1 Cavities

The elementary acceleration structure is a 9-cell 1.038 m long (effective length, Fig. 1) superconducting cavity of 1.3 GHz made of pure 2.8 mm thick niobium to be cooled to 2 K. The nominal acceleration gradient at 500 GeV centre-of-mass energy is 23.4 MV/m reached at a quality factor $Q_0 = 10^{10}$. The cavities are housed in helium vessels made from titanium.

The availability of this technology has been demonstrated at the TESLA Test Facility at DESY [2].

There will be more than 21000 cavities of this kind in TESLA.

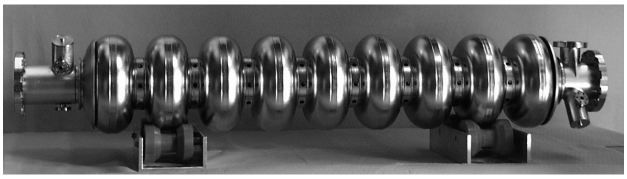

Fig. 1: Superconducting 9-cell cavity

2.2 Magnet Packages

Beam focussing is achieved by cos2Θ superconducting quadrupoles of 0.52 m field length and 60 T/m gradient at 100 A (Fig. 2). The quadrupoles are housed in helium vessels which also contain vertical and horizontal (in every second package) superconducting steering dipoles of 0.074 T field at 40 A. These magnet packages are cooled to 2 K, same as the cavities. The coils are powered through high temperature superconducting (HTS) current leads without gas cooling. Attached to the magnet package is a cavity type beam position monitor (BPM).

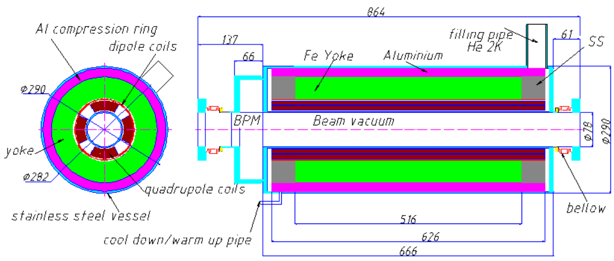

Fig. 2: Superconducting magnet package

There will be about 800 magnet packages in the collider.

2.3 Cryostat

The active superconducting elements are assembled in 16-17 m long cryostats (Fig. 3) mostly all of which house 12 cavities in the so called compressed 9-cell structure (space between end cells of neighboured cavities: 283 mm) [3]. Up to 150 GeV every second cryomodule and between 150 and 250 GeV every third cryomodule also houses a superconducting magnet package. Attached to the cavities are input couplers, higher order mode (HOM) couplers, tuners, bellows and flanges. The active elements (cavities and magnets) are supported by a 300 mm diameter girder tube acting as gas return pipe (GRP) which itself is supported at the outer vacuum vessel through 3 fibre glass support posts. The "cold

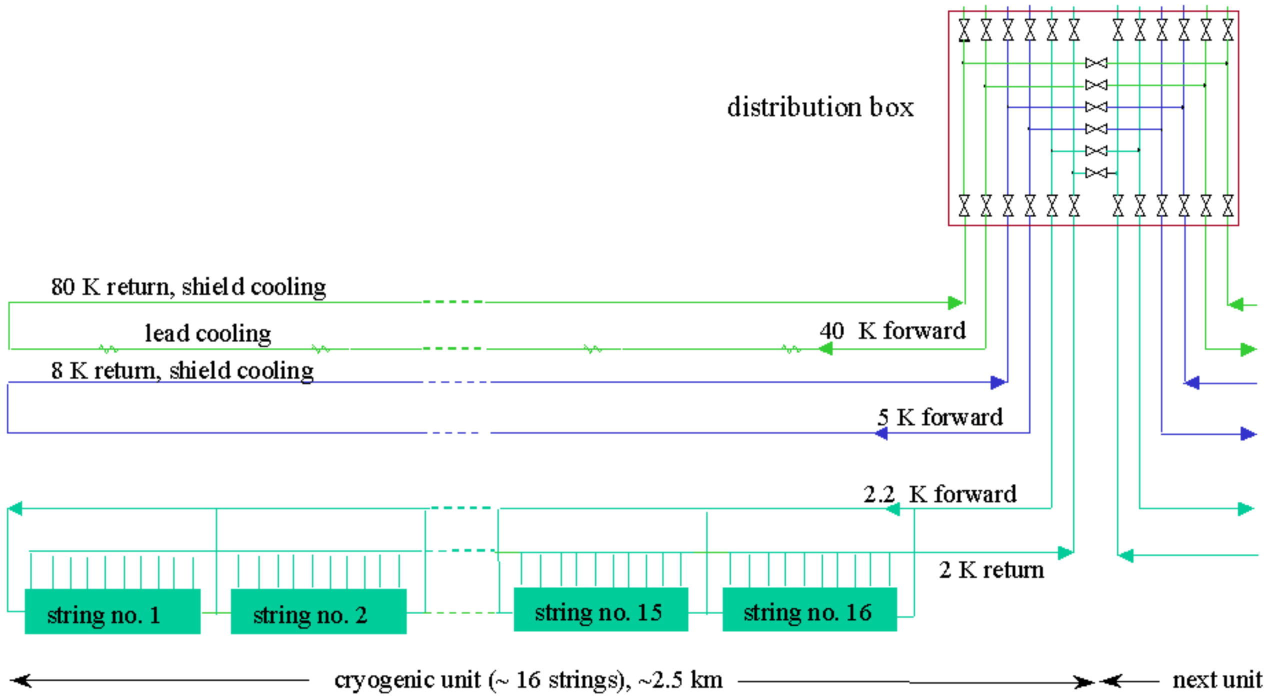

Fig. 4: Cryogenic unit (consisting of 16 cryogenic strings)

mass" is surrounded by two thermal radiation shields (one at 5-8 K, the other at 40-80 K) covered with multi-layer insulation (MLI). The cryomodule also contains the necessary helium process tubes for cavity cooling (2 K), shield cooling and cool-down/warm-up.

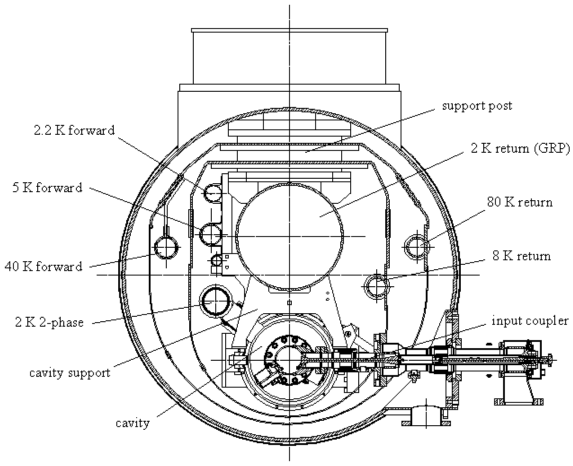

Fig. 3: Cryomodule cross section

Table 1: Heat loads [W] of a 17 m long cryomodule with quadrupole

Temp.	**static**	**dynamic, high energy beam**	**additional dynamic, FEL beam**
2 K	1.74	7.31	5.47
5-8 K	11.32	4.62	4.18
40-80 K	90.13	92.89	70.18

2.4 Cryomodule Heat Loads

Heat loads have been calculated for static operation (without RF and magnet current), 5 Hz dynamic operation at 23.4 MV/m with quality factor $Q_0=10^{10}$, and for additional 5 Hz FEL operation at 21.1 MV/m (only in the first part of the electron linac) with the same Q_0. The results are shown in Table 1. As can be seen the losses are dominated by the RF losses (81 % at 2 K).

3 CRYOGENIC DISTRIBUTION

3.1 Cryogenic Units

About every 150 cryomodules are assembled to a 2.5 km long cryogenic section called cryogenic unit (Fig. 4), supplied cryogenically from a refrigerator from one side through a feed box [4]. Vacuum barriers are installed every 500 m in order to limit the pressure increase in the cryogenic lines in case of an accidental break of the insulation vacuum [5] and for better leak checking. There are 12 units in total, 6 for each linac. Except for the first 3 km (mainly unit no. 1) which are declined by - 8 mrad the units are levelled with respect to gravity.

3.2 Cryogenic Strings

Inside each cryogenic unit cryogenic strings of 10 cryo-modules form the smallest cooling circuit (Fig. 5). They are about 170 m long. A special cryomodule containing 3

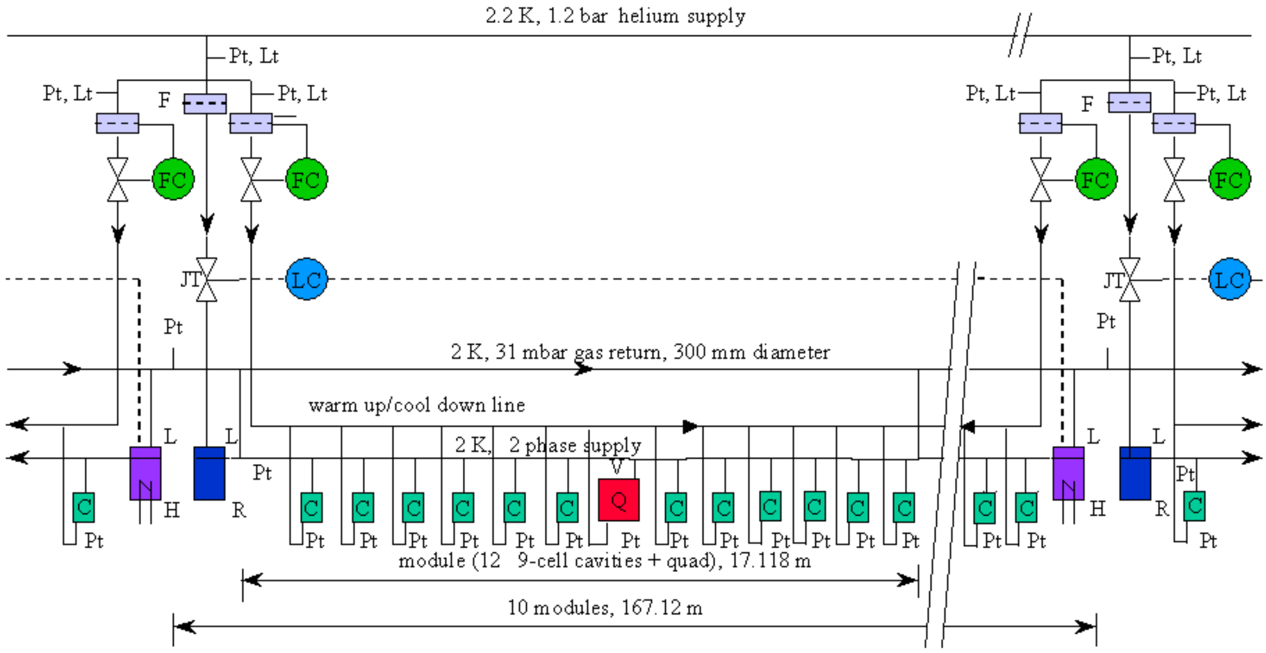

Fig. 5: Cryogenic string (consisting of 10 cryomodules)

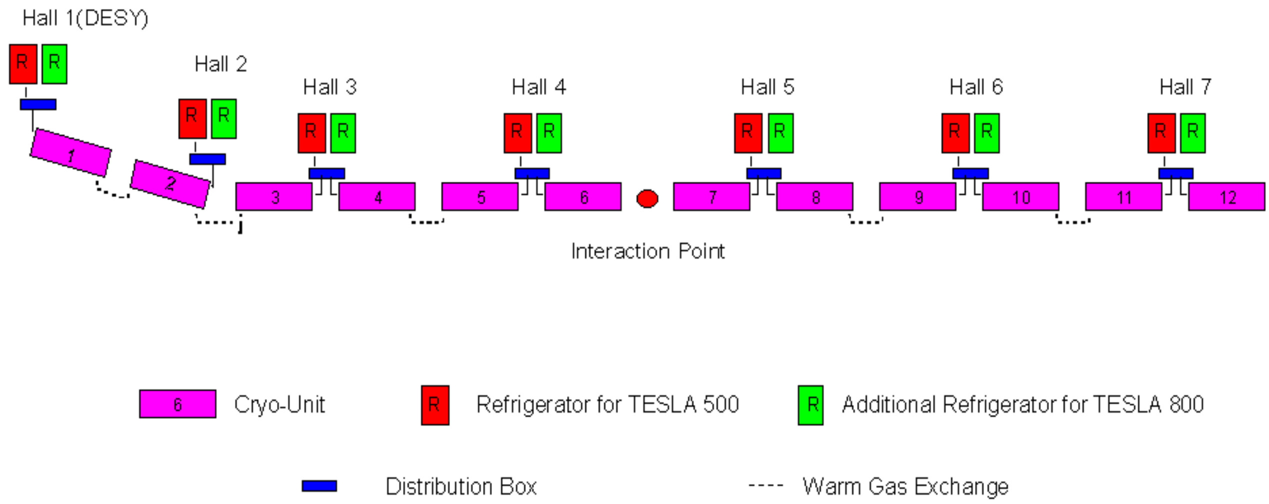

Fig. 6: Cryogenic system (consisting of 12 cryogenic units supplied from 7 refrigeration halls)

control valves (one of them a Joule-Thomson (JT) valve) is necessary at the end of each cryogenic string.

During steady state operation, 2.2 K one phase helium of 1.2 bar coming from the feed-box is expanded in the JT valve into a small liquid helium separator. From here the liquid is flowing through the 76 mm diameter 2 phase tube into the cavity and magnet helium vessels. Evaporating helium is returned through tube connections at each cryomodule interconnection to the GRP and further to the refrigerator.

Cool-down and warm-up is performed by helium gas of suitable temperature directed from the supply line (same as the 2.2 K one phase line) though a control valve and a gas header supplying all helium vessels from the bottom.

3.3 Unit Heat Loads

Heat loads have been calculated for all cryogenic units from all components like modules, feed- and end-boxes, vacuum barriers, distribution boxes and transfer lines.

Table 2: Design heat loads [kW] at refrigeration halls

T	hall1	hall2	hall3	hall4	hall5	hall6	hall7
2 K	3.70	3.07	4.23	4.21	3.87	5.13	4.22
5 K	4.73	4.60	7.42	7.39	6.88	8.25	7.36
40 K	44.6	53.5	80.7	79.6	74.4	78.6	80.5

Also the heat loads of 3 e^- injectors on the DESY site, of the superconducting RF for the 2 damping rings and for the bunch compressors, and of the additional 5 Hz operation for the FEL in the first part of electron linac have been taken into account. The design refrigeration capacity at the position of the 7 cryogenic halls (see next chapter and Fig. 6) has been derived by multiplying these loads with the factor 1.5 for uncertainties in the calculation and cryomodule performance as well as for control reserve (Table 2).

4 REFRIGERATION PLANTS

4.1 General Concept

Except for the first 2 cryogenic units which have their own refrigeration plant, one refrigeration plant will serve 2 cryogenic units (Fig. 6). As the size of these plants will be only 20 % larger than the ones of the Large Hadron Collider (LHC) at CERN, they will be based on a well established technology. They will have a high thermodynamic efficiency (compressors 55 %, cycle 49 %, total Carnot 27 %, which is equivalent to 245 $W_{el}/W(4.5\ K)$), a good part load efficiency, high reliability and will be completely remote controlled. There are no turbines above 80 K [6].

4.2 Refrigerators

The main components of each refrigerator are 10 screw compressors in two stages (one redundant compressor in each stage) with 24 bar maximum pressure, a horizontal cold-box with 9 turbines, and two 3-4 stage cold compressor trains (one redundant) in order to reach 2 K. Apart from the compressors there are also redundant oil pumps, oil coolers and helium after-coolers. Inside the cold-box there are double 80 K and 20 K adsorbers which are switchable. A distribution box in the 15 m diameter tunnel shaft allows to distribute the refrigeration power to the different consumers (cryogenic units, injectors etc.).

Table 3: Main cryogenic components

type	number
cryomodules (several types)	1781
vacuum barriers	48
feed- and end-boxes	38
cryo-units (2.5 km long)	12
injector feed-boxes	3
distribution boxes	7
injector distribution box	1
transfer lines	824 m
cryo-plants (cold-boxes)	7
warm screw compressors	68
cold compressor	56
liquid helium dewars	7
warm gas storage vessels	31

For helium storage there are a dewar for 120 m^3 liquid and generally 5 gas tanks of 250 m^3 (20 bar) at each cryo-hall. A 200 mm diameter helium warm gas tube connects the helium plants of each linac to allow helium exchange and recovery in case of a complete refrigerator break down. This tube is also used to collect helium from safety valves at the 5-8 K shield cooling line in case of an accidental break of the insulation vacuum. For more details on safety aspects see reference [5]. The main cryogenic components of the whole system are listed in Table 3.

The refrigerator requirements and performances are being studied theoretically in a model refrigerator (Fig. 7) [6].

4.3 Plant Operation

The refrigeration plants will be operated fully remote controlled and unattended. Personnel will be available only on call (like for LHC at CERN). Special care must be taken for impurity handling. Cool-down and warm-up of ~ 700 tons (2 cryogenic units) can be done within 10 days without liquid N_2 assistance. The filling with liquid helium will then require 2 ½ more days. No heaters are required for warm-up of the returning gas.

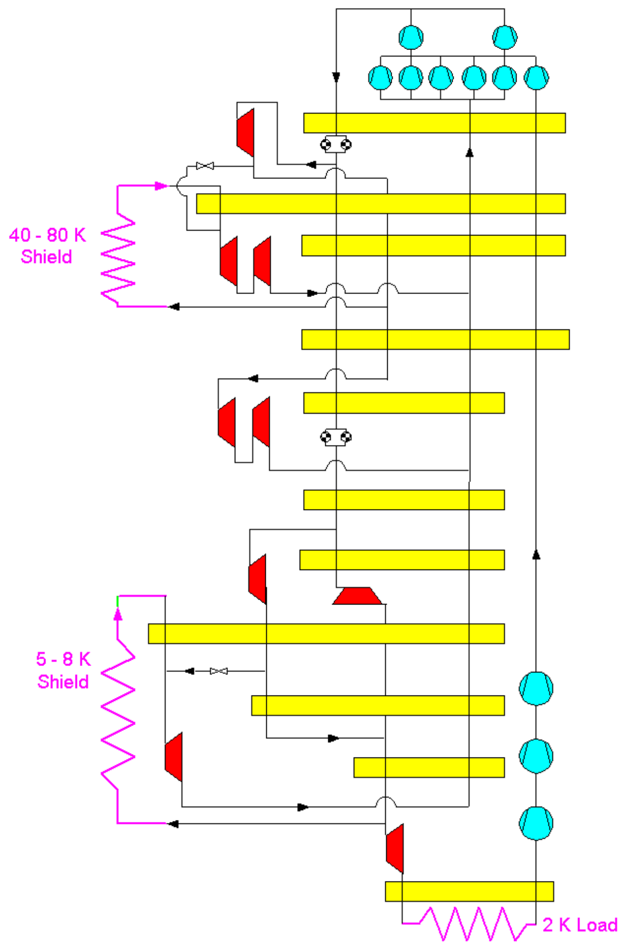

Fig. 7: Model refrigerator

The electrical power consumption in each cryogenic hall is shown in Table 4.

Table 4: Required el. power at refrigeration halls [MW]

	hall1	hall2	hall3	hall4	hall5	hall6	hall7
500 GeV 5 Hz	2.40	2.33	3.40	3.38	3.13	3.74	3.39
800 GeV 4 Hz	3.42	3.88	6.35	6.33	5.65	6.62	6.28

4.4 Upgrade Philosophy

For operation at 800 GeV centre-of-mass, the cavities will have to be operated at about 37.4 MV/m or only 35 MV/m provided that the new superstructure scheme [7] presently in development at DESY for a more compact assembly of cavities in the cryomodules is used. The refrigeration capacity has to be doubled in each cryogenic hall in that case. For this purpose a second cold-box must be installed in the refrigeration halls and the halls must be extended to give space for a second set of warm compressors (Fig. 8). A third cold compressor chain is also necessary for redundancy. The distribution box is already prepared for the energy upgrade. Making use of safety margin for the primary installed plants (for 500 GeV centre-of-mass energy operation), a beam pulse repetition rate of ~ 4 Hz will be possible (see Table 4).

5 SUMMARY AND OUTLOOK

The planning of the cryogenic system for TESLA is well advanced. The system is based on the well established design of superconducting 1.3 GHz cavities and cryomodules developed for the TESLA Test Facility at DESY. A concept for the cryogenic distribution through 2.5 km long cryogenic units supplied by a total of seven refrigerators has been found. The refrigerators are based on a sound technology similar to the one used at LHC. An upgrade for operation up to 800 GeV centre-of-mass energy is foreseen. Costing of all components has been done and has been submitted to authorities for approval. More detailed work is necessary, however.

6 REFERENCES

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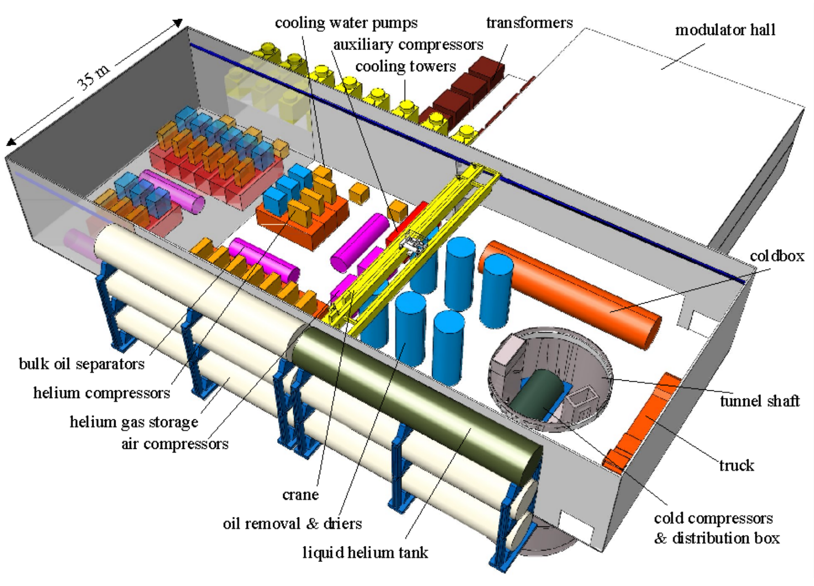

Fig. 8: Cryogenic hall for 800 GeV operation