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THE TESLA 500 CRYOGENIC SYSTEM LAYOUT

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ABSTRACT

The superconducting 2 x 250 GeV e^+e^- linear accelerator TESLA is composed of a series of high frequency resonators (cavities), fabricated of high purity niobium. It has to be operated at a temperature of ca. 2 K. A nominal refrigeration power of about 51 KW at 2 K, 37 KW at 4.5 K and 314 KW at 40/80 K is required. The cooling power has to be distributed over a distance of more than 30 km. Different aspects of the cryogenic system are discussed.

INTRODUCTION

The TESLA project has been presented previously [1]. Two linacs of about 15 km length, producing 250 GeV electrons and positrons respectively, will be installed collinearly, separated by a ca. 2 km long interaction zone (fig. 1). The cryogenic system, maintaining the operating temperature of 2 K, will be described in the following chapters.

GENERAL LAYOUT

Cavities

Basic elements of the linac are cavities, consisting of nine cell high purity niobium RF-resonators, welded into cylindrical containers of titanium (fig. 2). Details of this design are presented in other sessions of this conference [2; 3]. The space between the cavity and the cylinder will be completely filled with superfluid liquid He at temperatures below 2 K, in order to maintain the desired operating temperature.

Modules

A module (12.2 m length) is an assembly of 8 cavities mounted into a common vacuum cylinder together with one quadrupole and one absorber for higher order mode (HOM) losses at an end. Two concentric heat shields, one at 4.5 K, and a second one at a

temperature between 40 K and 80 K, protect the cavities. All cold supply and return lines go through the modules as well [fig. 3]. The TESLA 500 cavities will be connected directly to the 0.3 m return tube. The 100 mm two phase tube of the TTF cryostats is eliminated. The exact number of quadrupoles in the machine is not yet fixed. Probably only one quadrupole every second or every third module will be installed.

Strings

12 modules are arranged in a string. At the end of the string there will be a supply box, the other end is terminated by an end box (fig. 4, Detail A). The total length of a string including the boxes is 148 m.

Subunits

An assembly of 12 strings is a subunit (fig. 4). It will be supplied by one common refrigerator. The resulting length of 1830 m for each subunit is tolerable from the point of view of pressure drops within reasonable tube sizes.

The "geographical" length of subunits in fig. 5 differs somewhat from the "cryogenic" length in fig. 4 due to the location of the refrigerators.

The machine

Based on an accelerating gradient of 25 MV/m, for an end energy of 250 GeV an active length of 10000 m per linac is required, which means a mechanical length 14908 m (8 subunits, space factor 0.671). The total length of the system, including 2 km interaction region, amounts to ca. 32 km (Fig 5).

HEAT LOADS

An estimate of heat loads for modules and cavities has been given recently [4]. Static and total (dynamic) loads are summarized in Tab. 1. Higher order mode (HOM) losses are partially transferred to the cavity helium, a large fraction escapes out of the cavities and travels through the beam pipe from where it has to be removed by means of absorbers in the quadrupoles, cooled by the 40/80 K shield helium.

The values marked "n" in Tab. 1 represent the calculated actual estimates ("nominal"). The whole system was designed with safety factors of about 1.5 for all three temperature levels. The "design" values are marked "d".

Tab. 1

TESLA heat loads

(n = normally expected values; d = design values; stat = HF-power off; dyn = HF-power on)

Temperature	2 K		4.5 K		40/80 K		
	stat	dyn	stat	dyn	stat	dyn	W
Module n	2.8	21.4	13.9	16.0	76.8	136.0	W
d	4.2	32.1	20.9	24.0	115.2	204.0	W
String n	43.0	266.2	166.8	192.0	921.6	1632.0	W
d	64.5	399.3	250.2	288.0	1382.4	2448.0	W
Subunit n	521	3200	2007	2309	11070	19595	W
d	782	4800	3011	3500	16605	30000	W
TESLA n	8336	51200	32112	37000	177120	313500	W
d	12512	76800	48168	56000	265680	480000	W

The equivalent room temperature power inputs have been evaluated, taking into account conversion factors of 800: 250: 25 W/W for $T = 2.0; 4.5; 60$ K respectively. They are listed in Tab. 2.

Tab. 2

TESLA ambient temperature electrical power input in mega watt

Temperature		2 K		4.5 K		40/80 K		Σ input	
		stat	dyn	stat	dyn	stat	dyn	stat	dyn
Subunit	n	0.42	2.56	0.50	0.58	0.28	0.49	1.2	3.6
	d	0.63	3.84	0.75	0.88	0.42	0.75	1.8	5.5
TESLA	n	6.7	41.0	8.0	9.3	4.4	7.8	19.1	58.1
	d	10.0	61.4	12.0	14.0	6.6	12.0	28.6	87.4

THE CRYOGENIC SYSTEM

The generalized flow scheme is shown in fig. 4. A refrigerator (to be described elsewhere in this conference [5]) produces supercritical helium ($p \cong 5.4$ bar, $T \cong 4.5$ K) in point 1.

The whole mass flow enters first the 4.5 K quadrupole line at point 3, passes all quadrupoles in the subunit and returns from the end through the 4.5 K shields to point 5. A fraction is further cooled to 2.2 K in the heat exchanger HX6. It enters the 2.2 K supply line through point 2. The rest of the flow is expanded into the bath precooler HX5. ($T \cong 4.3$ K, $p \cong 1.1$ bar).

From point 6, a 40 K/18 bar flow is deviated for the 40/80 K shield cooling. After the passage through the shields and the HOM-absorbers in series it returns with $T \cong 80$ K, $p \cong 17$ bar at point 7.

At every string, about 1/12 of the 2.2 K supply flow is expanded through Joule Thomson valves into the supply boxes. From here, a two phase flow moves through the 0.3 m diameter return tube back to the end box of the string.

The heat from the cavities is transferred to the liquid in the return tube through vertical connection tubes between cavities and return tube (fig. 6) by means of the internal heat conduction process in He II [6]. In the tube, all heat flow is removed by evaporation of liquid at its surface.

For steady state operation the flow rates in the strings have to be controlled depending on the heat loads. At the end of each string, all liquid has been converted into vapor. The level is kept constant by means of a level controller LC acting on the JT-valve.

The end box of each string is mechanically combined with the supply box of the next one. A wall in the lower part separates the two adjacent liquid levels, the vapor passes through (fig.4 Detail:A).

In point 8 the vapor returns to the heat exchanger HX 6 via a connection tube (0.3 m diameter, ca. 54 m length) and a buffer tank. The return gas temperature is about 1.9 K, its pressure ca. 30 mbar.

At point 9, the helium is warmed up to ca 3.4 K. Cold compressors (4 stages) are used to raise the pressure to the inlet pressure of the main compressor group (ca. 1.0 bar).

Driving forces for the liquid through the strings are the gradients of vapor pressure $\partial p / \partial x$ and liquid level $\partial h / \partial x$. Various flow conditions have been investigated under the

assumption of independent flow of liquid and vapor in the return tube [7]. Fig. 7 displays pressure, temperature and liquid level in the return tube under different loads.

Table 3 gives massflow rates ($\dot{m}$), temperatures T and pressures p at different points in the system.

Table 3

Thermodynamic data at different points of the flow scheme

normal heat loads n				design heat loads d		
No.*	$\dot{m}$ [kg/s]	T [K]	p [bar]	$\dot{m}$ [kg/s]	T [K]	p [bar]
1	0.371	4.5	3.9	0.560	4.5	5.4
2	0.160	2.2	3.0	0.242	2.2	3.0
3	0.211	4.5	3.9	0.318	4.5	5.4
5	0.210	5.3	3.04	0.317	5.43	3.1
6	0.0945	40.0	18.0	0.142	40.0	18.0
7	0.0945	80.0	17.58	0.142	80.0	17.0
8	0.160	1.98	0.0297	0.242	1.958	0.0276
9	0.160	3.38	0.027	0.242	3.38	0.025
11	0.0133	2.00	0.0313	0.0202	2.00	0.0313

* position numbers of flow scheme Fig. 4

Cool down/warm up procedures

Cooling will be performed in several steps. Starting at room temperature, helium of about 80 K will be supplied through the 2.2 K line. At point 10 (fig. 4, Detail A) cool down lines parallel to the strings are branched. Every cavity is connected to these lines by means of narrow tubes, the flow resistances of which are large compared to all longitudinal resistances. This assures an approximately uniform flow distribution through the cavities, returning through the common 0.3 m return line. A parallel cooling of all cavities of one subunit is estimated to reach 80 K within some hours. Faster cooling, if desired, is possible, if the cooling capacity is concentrated to only one or two strings at the same time. In order to prevent cold exhausting gas penetrating to the next strings not yet to be cooled, the 2 K line must be closed at the end and the gas returns through valve VX and the 80 K return line. The cooling will be continued with running turbines and decreasing temperatures until the cavity temperatures are at about 4.5 K. At this level the filling of the cavities can be executed through the JT valves and the return line. Once having filled the whole system with 4.5 K liquid the cold compressors can start to establish final pressure and temperature.

Alternative circuit

An interesting alternative solution is presented in fig. 8. Here, the whole massflow for the string is injected through one single JT-valve at the end in point 12. Subdivision into strings is only necessary for cool down/warm up processes. The advantages of this system are: only one JT-valve with control loop hardware and software instead of 12, only 2 boxes at the ends of the subunit. The overall length of a subunit reduces to 1812 m. Flow conditions have been calculated for this system as well [6]. Pressures and temperatures are very similar to fig. 7, the much smoother level behavior is shown in fig. 9.

A disadvantage may be that a higher liquid level at the JT-valve end of the string is required for driving the total string liquid rate through the full length of the unit. This causes a higher amount of liquid being stored in the return line.

The estimated amounts of helium in a subunit are listed for both solutions in Tab. 4 under design conditions.

Tab. 4

Helium stored in different sections of a TESLA unit

Circuit section	A [kg]	B [kg]
Liquid in the return tube	262.2	1630.7
Vapor in the return tube	95.7	85.8
Cavities and other tubes	6662	6624
Total He-mass per subunit	7025	8346

A = 12 JT-valve version

B = 1 JT-valve version

SUMMARY

A possible cooling scheme for TESLA has been worked out and is proposed here. Also many requirements are unique, the limits of the present state of the art are certainly reached, but not exceeded. For future optimisation of the system, experiences from CEBAF, LEP 2, LHC and especially from TTF will be of essential value. Furthermore, it has to be investigated, whether the simplicity of the alternative scheme has drawbacks for operation or cooldown.

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Fig. 1 TESLA General Layout

Fig. 2 TESLA Cavity and Vapor Return Tube

Fig. 3 TESLA Module

05.07.1995 G.Horlitz 1.1.4.15

Fig. 4 TESLA Cryogenic Circuits
(version with one JT-valve for each string)

required: 8 Cooling stations a 2 refrigerators

capacity of one Refrigerator	total
$\dot{q}_{2.0}=5000 \text{ W}$	80000 W
$\dot{q}_{4.5}=4200 \text{ W}$	67200 W
$\dot{q}_{60}=30000 \text{ W}$	480000 W

Fig. 5 TESLA Cryogenic System
(General layout and subdivisions)

Fig. 6 TESLA Cryostat Cross Section

PRESSURE, TEMPERATURE AND LIQUID LEVEL IN THE RETURN TUBE OF A 1830 m TESLA SUBUNIT

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heat loads: 32.1 (a); 21.4 (b) W/module

Fig. 7 Flow Parameters in the Return Tube
(1 JT-valve for each 148 m string)

TESLA 1812 m SUBUNIT
with 1 JT-VALVE only.

Fig. 8 TESLA alternative Subunit Flow Scheme
(1 JT-valve for the whole unit)

LIQUID HE LEVEL IN THE 0.3 m RETURN TUBE
OF A 1 JT-VALVE, 1812 m TESLA SUBUNIT

0.000112
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Fig. 9 Liquid He-Level in the Return Tube
(only 1 JT-valve at the far end of the subunit)