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DESIGN MANUFACTURE AND TEST OF THE TESLA-TTF CAVITY CRYOSTAT

F. Alessandria¹, G. Cavallari², M. Minestrini³, T.H. Nicol⁴, C. Pagani¹,
R. Palmieri⁵, S. Tazzari⁶, G. Varisco¹

¹ INFN sez. Milano, Milano, Italy

² INFN sez. Roma2, on leave of absence from CERN, Geneva

³ INFN Laboratori Nazionali Frascati, Italy

⁴ Fermi National Accelerator Laboratory, Batavia, IL. USA

⁵ ENEA Centro di Frascati, Italy

⁶ University of Roma Tor Vergata and INFN sez. Roma2, Roma Italy

ABSTRACT

The aim of the TESLA Test Facility (TTF) is to build and to operate a superconducting (SC) linear accelerator accelerating electrons to an energy of approximately 450 MeV, to establish the technological basis for a SC accelerating structure of competitive cost, that could reliably achieve accelerating field of about 15 MV/m. Eight individual nine-cell, 1300 Mhz superconducting cavities, their RF equipment, a superferric quadrupole doublet and dipole steering coils and all diagnostic elements are combined in a 12 m long accelerator module, housed in a single cryostat. The TTF linac consists of four such modules. Cavities are cooled by superfluid two-phase Helium at 1.8 K and the quadrupole windings at 4.5 K.

The liquid Helium distribution and cold gas recovery system are incorporated into the cryostat providing additional savings by the reduction of the number of transfer lines and other hardware on the outside of the cryostat enclosure.

The TESLA project

Factors determining the high cost of present SC cavity installations are their comparatively low accelerating field and that a single or few cavities have been housed in a separate cryostat with its own refrigeration circuit, thus requiring a relatively large number of cold to warm transitions and expensive distribution cold boxes; static losses, proportional to the number of transitions are a further cost factor. The TESLA accelerating structure and cryostat design philosophy has thus been to make individual accelerating modules as long as possible and combine them in strings fed by a single cold box, a technique similar to that used for SC magnets in large proton accelerators.

In the TESLA proposal eight individual nine-cell, 1300 Mhz SC cavities, their RF equipment, a superferric quadrupole doublet and dipole steering coils and all diagnostic elements are combined in a 12 m long accelerator module, housed in a single cryostat. Twelve cryomodules are combined into a 145 m subsection, individually fed by two phase

He; finally a separate cryoplant supplies a string of 12 subsections. A cryogenic unit would have a length of 1880 meters in TESLA.

The TTF accelerating structure will consist of four such modules.

Cryostat design

The scheme for cooling the TESLA prototype modules in the TTF test linac corresponds to the cooling process which is envisioned for a future TESLA linear accelerator. The cavities are in a 1.8K helium bath. Through the string of 4 modules between the feed box and the end box, an approximately uniform helium level is maintained. The regulation of the JT valve in the entrance of the modules is via the measurement of the liquid level in the end box. The He vapor at 1.8K returns back to the feed box via a 300mm diameter return line (HeGRP), which at the same time serves as the mechanical support of the cold mass. The design of this return line and the other process line is based on the dimensions of TESLA.

The cavity production technique has been carefully designed and specified to produce absolutely clean surfaces and to keep them such throughout the whole manufacturing and assembly process. This poses significant constraints on the design and assembly together in a clean room as they have to be inserted in the cryostat as a single UHV tight unit.

The design solutions have been chosen for simplicity and ease of fabrication; thus putting some constraints onto other RF components. To minimize the costs, machining on large items such as vacuum vessel and He gas return pipe has been limited to a few vacuum flanges requiring precise positioning. The long string of accelerator modules with a common insulation vacuum minimizes the number of warm to cold transitions. All refrigeration piping runs inside the cryostat thus avoiding costly external transfer lines.

The cryostat vacuum vessel, Fig. 5, of carbon steel is evacuated to a pressure of 10^{-6} mbar. The design critical over pressure is 1.25 bar. It is the main mechanical structure and a number of constraints have been put on the shape: position of the power coupler flanges ± 1 mm, cylindricity tolerance ≤ 3 mm. The actual shape of the prototype vessel is shown in Fig. 1.

Figure 1. Vacuum vessel: Measured position errors of the Main Coupler flanges. The vessel is aligned on the x axis, on the abscissa the cavity number

The 300 mm Helium gas return pipe, required to recover the 16mbar cold gas evaporated from the 1.8K He bath, is also used as the main support beam for the accelerator module. The overall weight of items hanging from the pipe is about 2300Kg. The HeGRP operating pressure is specified to be 2 Bar, the test pressure 3 Bar.

The HeGRP is supported from above by three support posts that provide the necessary thermal insulation; posts are fastened to large flanges on the upper part of the vacuum

vessel, by means of adjustable suspension brackets. The scope of the adjusting mechanism is to allow for the accelerator module axis to be brought into its proper position, independent of the absolute position of the vacuum vessel flanges on which it rests.

In the longitudinal direction the center post is fixed to the vacuum vessel while the two end brackets are allowed to move to accommodate differential shrinkage during temperature cycling. The posts consist of fiberglass pipe terminated by two shrink fit stainless steel flanges. At intermediate positions, optimized to minimize heat leak, two additional shrink fit flanges are provided to allow intermediate heat shield connections to 4.2K and 70K.

Seven additional cooling pipes run through the cryomodule (Fig. 5):

- 1.8K two phase line forward supply
- 2.2 K pressurized He forward, to supply downstream modules
- 4.5 K pressurized He forward, to cool the quadrupole lens
- 4.5 K Pressurized He return, to cool the 4.5K shield
- 70 K He forward, also used to cool the quadrupole beam tube
- 70 K He return, also used to cool the 70K radiation shield
- a warm-up/cool-down line

All pipe connections in between modules are welded; bellows are provided to mechanical decouple modules and to allow for thermal contraction.

Alignment

Another very significant requirement, deriving from beam dynamics considerations, is the overall alignment requirements. The axes of the 8 cavities must stay aligned to the ideal beam axis to within ± 0.5 mm and those of quadrupoles to within ± 0.1 mm over the entire length of the accelerator; in addition the vertical mid plane of the lens must stay aligned to the vertical direction to $\leq \pm 0.1$ mrad. Cavity positions will be monitored during cool down with optical marks and wire positions monitors (WPM) installed on each cavity of the first prototype. The cavities and the quadrupole are aligned at room temperature before insertion in the vacuum vessel. Reference Taylor-Obson spheres on the posts are then used to align the cold mass in the vacuum vessel.

Modal analysis

The accelerator repetition rate is 10Hz and the RF cycle lasts 1.4 msec. Lorenz forces at 10Hz, induced in the cavities by the RF radiation pressure, may excite mechanical resonance. The aim of the TTF cryostat modal analysis ¹ is thus twofold. First to evaluate the static behavior, mainly deflection, due to the lumped masses of the cavities, the quadrupole and the weight of the GHe return tube itself. Fig 2 gives the results.

Figure 2 - HeGRP design: computed static deflection of the pipe loaded by the cold mass and resting on three posts

Secondly to extract all the translational modes. The accelerator repetition rate being 10Hz, all mode above 20 Hz are considered non dangerous. The analysis yielded 12 modes below 100Hz. The modes, frequencies and deflections planes are summarized in table 2. Nearly all the first 12 modes are associated with flexure of the GHe return pipe. The exception is mode 6 at 26.7Hz. This mode is almost exclusively associated with lateral deflections of the support posts. It is of course possible to determine deflections at resonance only with a specific input load spectrum.

Table 1 - HeGRP Modal Analysis

mode no.	freq. (Hz)	defl. plane
1	18,7	x-y
2	20,3	x-z
3	21,7	x-z
4	22,1	x-y
5	25,4	x-y
6	26,7	x-z
7	27,6	x-z
8	41,9	x-y
9	49,6	x-y
10	54,0	x-z
11	76,0	x-z
12	101,3	x-z

Heat treatment

Concern has been expressed about thermally induced distortions of the HeGRP. Specifically, the issue involves thermal gradients which can occur in this tube from flow stratification during cool down. These thermal gradients induce mechanical distortions and thermal stresses in the tube and impose structural loads on the support system¹. In a stress free tube the bending stresses resulting from thermal bow are small compared to the yield strength. However, residual stresses from fabrication of the tube and welding of various cryostat components to the tube imply that some parts of the tube may in fact be on the verge of yield. Any additional stresses will result in permanent deformation of the tube. The finished HeGRP has been heat treated to 550 C to relieve stresses, Fig. 4. The thermal cycle was specified such as to avoid carbide precipitation.

Figure 3. Heat treatment of the HeGRP. The time above 450C was limited to less than 3 hours.

After heat treatment, the shape of the HeGRP standing on two supports has been measured with optical means³, cooled down with LN₂ and re-measured after warm up.

Within the measurement precision of 0.15mm no permanent deformations induced by the cool down cycle have been spotted but a deviation from straight line of ± 1.5 mm. The HeGRP was closed with welded flanges, connected to inlet and outlet lines and inserted in a horizontal vacuum vessel. The inlet pipe went all along the HeGRP at the cylinder axis with nozzles every 200mm. Filling with LN₂ was stopped when liquid poured out of the exit line, i.e. when the HeGRP was half full. Temperature gauges were installed at the outer side of the pipe, three on the top and three on the bottom. While the bottom part was at the LN₂ temperature for more then 8 hours, the top part cooled down to only 160K, Fig. 4. It can be explained by a full stratification of the GN₂ inside the HeGRP due to the very slow gas speed.

Figure 4. HeGRP cooldown at LN₂. The lower part was at 78K while the upper part was limited to 180K due to stratification of the GN₂

Radiation shields

Two aluminum radiation shields are provided at intermediate nominal temperatures of 4.2K and 70K. Each shield is made in two halves. The half-shield upper sections, 5mm thick, are supported by the post intermediate flanges: they are bolted onto the center post but can slide on the end posts, to avoid build up of excessive forces on the posts during thermal cycling, when temperature differences of 100 K can develop between different points of the shield sections. The shields are cooled by means of flexible copper braids at regular intervals to the centerline of the shield upper section; the braids are directly connected to the cooling pipes and their cross section is such as to keep the ΔT between shield connection and pipe to ≤ 10 K and ≤ 2 K for the 70K and the 4.5 K levels respectively. The lower half-shields, 3mm thick, are bolted to the upper-half and are cooled by conduction.

The Al 6082 thermal conductivity been measured at 4.2K³. The 3mm and the 5mm thick Al sheets have 11 W/mK and 18W/mK respectively. Measurements on different samples cut across and along the rolling direction have given the same values: we conclude this difference to come from the bulk material itself. These values are above the figures assumed for the thermal budget design by at least a factor of 5.

Super insulation

All surfaces at 70K and 4K facing surfaces at ambient temperature or 70K respectively are covered with multi layer insulation (MLI). Ten and thirty layers of MLI are provided on

the 4 K and 70 K shields respectively. The estimated heat loads are 0.03W/m^2 and 0.9W/m^2 . The He vessel, the HeGRP and the quadrupole 4K feed lines have a 5 layer blanket, to reduce heat transmission in case of vacuum failure.

The anticipated static and dynamic heat load budget for a single cryomodule is shown in table 2.

Table 2:	Estimated cryogenic losses (W)		
	2 K	4.5 K	70 K
Static losses	2,80	13,90	76,80
Total losses at 15MV/m	15,40	15,20	125,00
Total losses at 25MV/m	21,40	16,00	136,00

Diagnostics

PT1000 and Cernox-1030 temperature sensors will be installed at various places of the cold mass. The Cernox sensors are thin film resistors, are very stable over repeated thermal cycling and can withstand the high radiation doses expected around the SC cavities. The sensors are calibrated from room temperature to 1.7K with a number of calibration points according to the final operating temperature. In the first cryomodule we will install 92 Cernox and 43 PT1000 sensors to qualify the cryogenic design.

Magnetic shield

In order to reach their nominal performance level ⁵, the superconducting cavities of TESLA must be cooled in a magnetic field $\leq 2\text{mT}$, this corresponds to a field 20 to 40 times smaller than the ambient magnetic field. To achieve this shielding level it is intended to use a mixed scheme combining a Cryoperm tube around the cavity Helium vessel and a string of Helmholtz coils around the cryomodule vacuum vessel. The former, and the carbon steel vacuum vessel will mainly shield the transverse component of the ambient field, the latter will shield the longitudinal component. The longitudinal demagnetization factor of a long cylinder, as it is the case for a string of TESLA cryomodules, approaches unity.

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- 4.- W. Weingarten: private communication, 1995
- 5.- M. Bolore et al.: Magnetic Shielding of the TESLA TTF SC Cavities; TESLA Rep. 94-23
- 6.- D.A. Edwards ed.: TESLA Test Facility Linac - Design Report; TESLA Rep. 95-01

1 VACUUM VESSEL	7 CAVITY
2 COMPOSITE POST	8 1.8 K LHe SUPPLY
3 SUPPORT BRACKET	9 MAIN COUPLER
4 70 K SHIELD	10 Cu BRAIDS
5 4.5 K SHIELD	11 ALIGNEMENT TARGETS
6 1.8 K He GAS RETURN PIPE	12 ML INSULATION