THE TESLA CRYOGENIC ACCELERATOR MODULES

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Abstract

The Tera-eV Energy Superconducting Linear Accelerator (TESLA), a 32 km long superconducting linear electron/positron collider of 500 GeV (upgradeable to 800 GeV) centre of mass energy, presently in the planning phase at DESY, will consist of about 21000 superconducting RF 9-cell cavities of pure Niobium. Each cavity of about 1 m length has to be cooled in a 2.0 K helium bath and operated at 1.3 GHz with 5 Hz beam repetition rate. The cavities, equipped with their individual helium vessels made from titanium, RF input couplers , tuners and magnetic shielding, will be assembled in groups of 12 in about 16 m long cryostats (cryomodules) with thermal radiation shielding at 5-8 K and 40-80 K. Part of the cryomodules will also be equipped with superconducting quadrupoles and steering coils. About 10% of the cryomodules will contain cryogenic valves and instrumentation required for cooling purposes.

The paper presents design, construction and assembly details of the cryomodules, which are based on the experience with somewhat shorter cryomodules, already in use at the TESLA Test Facility (TTF) at DESY.

1 INTRODUCTION

The design of the cryomodule for the TESLA project [1] has been essentially driven by the cost cutting with respect to the existing superconducting systems. The module design is based on the 3rd generation of the TESLA test facility (TTF) one [2]; the length, which has been increased to 16 m (17 m for the modules with a quadrupole package), has been the major change. The driving criterion followed in order to decrease the production cost has been to significantly reduce the number of cryogenic components (especially cryogenic supply boxes and cold-warm transition). This is obtained by having a single long continuous string of about 2.5 km, called cryogenic unit [1]. Each long module contains twelve 9-cell cavities (and a cold quadrupole package in approximately 1/3 of the modules). The modules are directly connected each other into a cryogenic unit.

2 CRYOSTAT

Figure 1 shows a cross section of the cryostat. The cryostat outer vacuum vessel is constructed from carbon steel and has a standard diameter of 38''. Adjacent vacuum vessels are connected each other by means of a cylindrical sleeve with a bellow, which is welded to the vessels during installation.

Pumping stations every 250 m will provide the insulating vacuum.

The following helium lines are integrated in the cryomodule:

· 2 K forward line of single phase pressurized helium,
· 2 K two phases supply line,
· 2 K Gas Return Pipe (GRP) which returns the gas pumped off the saturated He II,
· 5-8 K forward and return lines for cooling the inner thermal shield and for heat flow intercept of the main coupler,
· 40-80 K forward and return lines for cooling the superconducting current leads and the outer thermal shield [3].
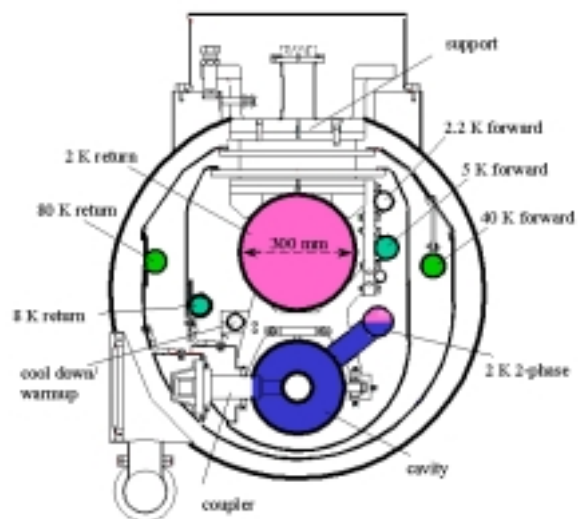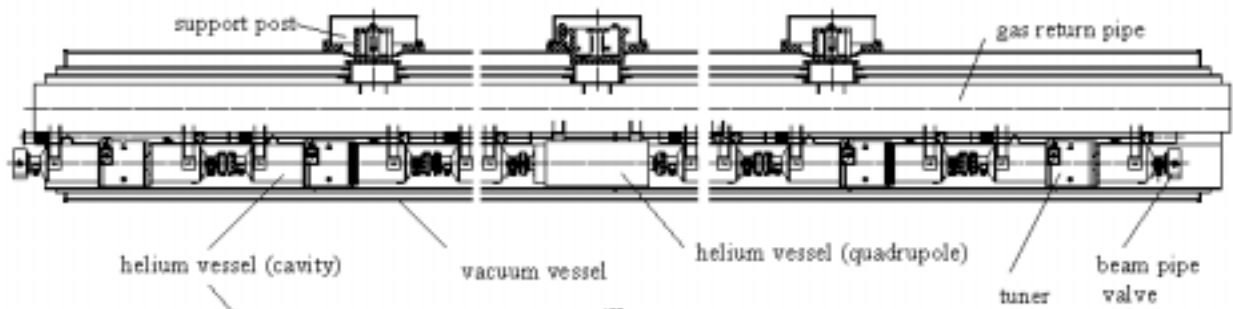

Fig. 1: Cryostat cross section.

Fig.2: Longitudinal cross section of a 17 m long cryostat with 12 cavities and a central quadrupole. The GRP behaves as the supporting structure and it is suspended to the vacuum vessel through three fiberglass posts.

2.1 GRP and cryogenic supports

The GRP acts as a reference beam to which cavities and quadrupoles are attached. Three cryogenic supports connect the GRP to the external vacuum vessel, the central one is fixed while the two laterals can slide to compensate for the thermal differential shrinkage. Each cryogenic support includes, for thermal insulation, a fiberglass pipe, the post, that is terminated by two shrink-fit stainless steel flanges. Two other intermediate aluminum flanges are also integrated in the post design, to support the thermal shields. The diameter of the fiberglass pipe is larger than what strictly required, in order to raise the mechanical eigenfrequencies of the system. During cooldown the two edges of the ~ 17m long GRP move towards the center of the module by up to 26 mm. To keep the cold input coupler head of each cavity longitudinally fixed within an accuracy of 1 mm, each cavity is anchored to the GRP via a sliding fixture, while its longitudinal reference is given by an independent system of invar and stainless steel rods [2]. The longitudinal position of the two external posts has been set to minimize the GRP top-down deformation, whose value is affecting the fabrication cost. Finally, because the quadrupole package tolerances are stricter than those of the cavities, it has been positioned just below the fixed central post. In this position the GRP deformations, induced by the unavoidable forces generated by the bellow at the welded connection between two consecutive cryostats [3], are minimal.

2.2 Thermal Shields

The cryogenic optimization of TESLA [1,3] requires two thermal shields at 5-8 K and at 40-80 K respectively. Both shields are manufactured in aluminum (1050 alloy) and include a stiff upper part (divided in two sections) that supports 12 lower panels, one in front of each cavity (13 in the modules with quadrupoles). An aluminum pipe, finger-welded to the shield roof and to the panels [4] cools each shield. Bimetallic junctions are used to connect the aluminum pipe to the stainless steel transition between cryomodules. The shield geometry and partitioning have been checked by a finite element code to test for cooldown deformations and thermal inertia. As

a reference, a 12-hour fast linear cooldown induces deformations all limited to less than 10 mm, which are compatible with the geometric free space in the section. In this extreme case, due to the asymmetric cooling, each shield is bent laterally ("banana" effect), while all stresses are below 30 MPa.

The shield panels are also used to indirectly cool other components of the cryomodule as: the fiberglass post intermediate plates and the body of the power couplers. The post plates, which support the cold mass and the shield roofs, need to be kept at different temperatures. In particular, the lateral post plates are connected to the shields with sliding supports that do not assure a good heat exchange. To achieve the post cooling, short and very flexible copper braids have been developed and used. The same solution has been applied for the coupler heat intercepts (called cones for their original shape). This solution has been already qualified during the cooldown of the second cryomodule. Data from the temperature sensors showed that all behaviors are as predicted.

Blankets of multi-layer insulation (MLI) are placed on the outside of the 5-8 K and the 40-80 K shields. A 10 layer blanket is sufficient on the lower temperature shield while a 30 layer one is required on the other. In addition 5 layers of MLI are wrapped on the cavity and quadrupole helium vessels, the gas return pipe and the 5-8 K pipes to reduce heat transfer in the event of a vacuum failure.

The experience gained through the design and operation of TTF 12 m cryomodules has been used to evaluate the static (without RF and magnet current) and dynamic heat load of the TESLA cryomodules [1]. Table 1 summarizes the quoted results. It is worthwhile to note that, even at the chosen RF duty cycle of 0.5%, the cavity Q being as high as $1 \cdot 10^{10}$, the total cryogenic losses are dominated by the RF dynamic losses at 2 K.

Table 1. Heat load of the 17 m long cryostat (12 cavities and a quadrupole).

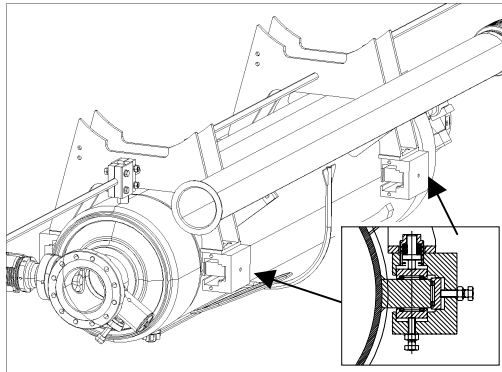| Temp	Static [W]	Dynamic [W]
2 K	1.74	7.31
5-8 K	11.32	4.62
40-80 K	90.13	92.89

Fig 3. The cavity sliding system. The rod defines the longitudinal position. The low friction support frees the longitudinal motion during cooldown-warmup cycles.

2.3 Sliding cavities supports

The experience gained during the assembling of the first three TTF cryomodules suggested to improve the cavity fixture design [2,5] in terms of maintaining the cavity alignment [3]. Due to the geometry of the system, it was too complicate to keep cavities and quadrupole positions within the alignment requirements. The necessity to develop a system that could, in principle, be compatible with superstructure [1] or semi-fixed couplers [2] lead to the decision of a complete redesign of the cavity supports. The solution that has been studied and implemented keeps the cavity transverse position fixed, while leaving the cavity longitudinal position independent from the GRP thermal contraction and extension during the cooldown-warmup cycles. This objectives have been reached with a set of low friction sliding supports [5]. These supports, whose section is presented in Fig. 3, consist of a C-shaped stainless steel element that clamps a titanium pad, welded on the cavity helium tank. The connection is mediated by a sequence of rolling needles, runners and reference screws. In each constrained direction (vertical and lateral) a reference screw defines the cold position of the cavity axis, and a spring washer package, loaded at 800 N, and keeps the pad into contact. To qualify the new fixture scheme, the friction coefficient, between the cavity pad and the sliding fixture, has been measured reproducing all the possible extreme operational conditions [5]. The static and dynamic force required to move the system was always below 6 N. This low friction value results in a good decoupling of the cavity longitudinal position with respect to the supporting GRP. Moreover, In order to be compatible with semi-rigid couplers and superstructures [1] the longitudinal position has to be fixed. As for the TTF-Phase2 cryomodules [2], the six more internal cavities are clamped to an Invar rod, that is fixed at the center post position and runs along the module. Conversely, to compensate for the excessive contraction of the Invar rod in the case of a 17 m cryomodule, the most external cavities are indirectly connected to the Invar rod via a stainless steel rod, to limit the overall longitudinal displacement of the cavity positions to less than ±1mm, as required.

2.4 Assembly and alignment

The cryomodule design, including fabrication procedures and tolerances, is the key factor to obtaining the required alignment precision for cavities and magnets, while at the same time limiting the costs. The alignment of the individual active components, cavities and quadrupoles, is performed once they are anchored to the supporting GRP. The alignment of the GRP, via three Taylor-Hobson spheres, is used as a reference for the axis of the active components. Assembly and cool down do not affect this external reference, except for a predictable and reproducible parallel vertical motion.

A crucial step in cutting the production cost was to relax the general tolerances of the GRP and of the vacuum vessel, while using a long milling machine to precisely reference (after welding of ancillary components) all the important axes and planes.

The GRP is now fabricated according to the standard high-quality welded pipe tolerances (5 mm), including straightness. After welding of the cavity supports, lower post flanges and end flanges, the axis is defined on the milling machine according to the end flange centers and transferred to the lower post flanges. The interconnection bellows, properly fastened, are already included to minimize the inter-module lateral forces. The pipe is then turned and the cavity supports are referenced to the defined GRP axis. A similar procedure is also applied to the vacuum vessel to reference the coupler ports and upper flanges to the vessel axis. After welding and before milling, a stress relief is performed on the GRP to avoid permanent deformations induced by thermal cycling.

The module assembly is performed in three major steps:

1. The cavity string is prepared in the class 10 clean room, pre-aligned and closed;
2. The string is then transferred to the assembly area where it is attached to the aligned GRP;
3. Each cavity and quadrupole is aligned with respect to the GRP using the three optical targets on the posts Taylor-Hobson spheres) and then fixed.

The module can now be moved and the alignment can be recovered through the external targets. The last step is performed in a third assembly station where, after the assembly of the thermal shields, a long fixed cantilever and a movable cart are used to insert the cold mass into the vacuum vessel. Module alignment in the linac is made using three optical targets placed on the vacuum vessel and referenced to those on the GRP.

6 REFERENCES

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