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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.

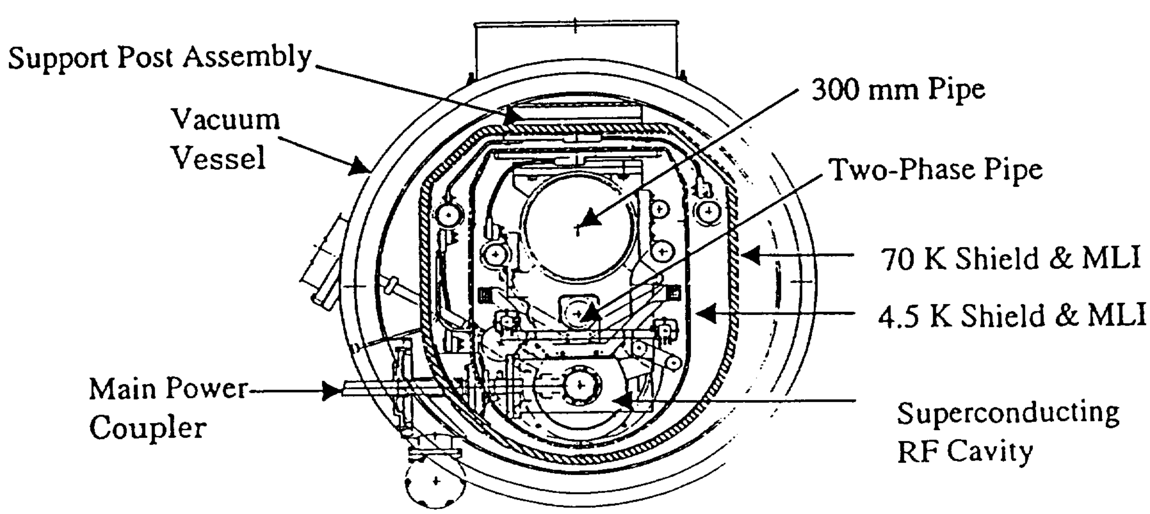

Figure 1 Cross Section of Cryomodule

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.

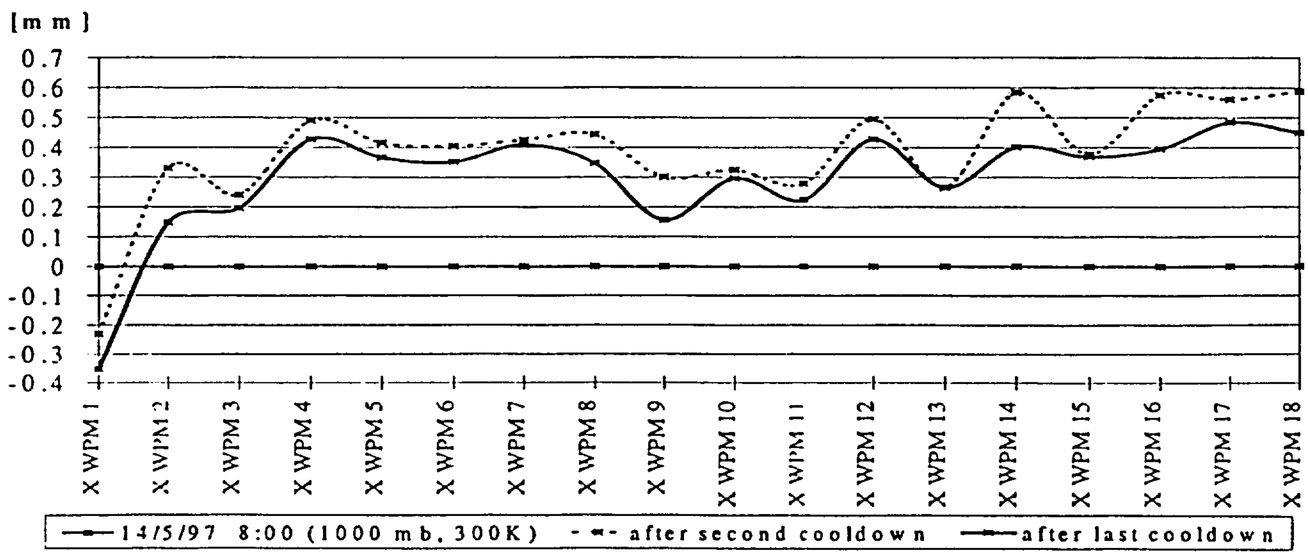

Figure 2 Horizontal Offsets of Cavities and Quadrupole as Measured by the WPM System

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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