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The TESLA Test Facility (TTF) Cryomodule: A Summary of Work to Date

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ABSTRACT

The proposed TeV Superconducting Linear Accelerator (TESLA) is a 30 km long electron / positron collider. The cryomodule is one of the principal building blocks of TESLA. The cryomodule contains the superconducting RF cavities that accelerate the beam along with superconducting focusing quadrupoles and associated cryogenic piping and thermal shielding. The cryomodules must meet strict requirements for alignment, heat leak vibration and cost. Approximately 2500 of these cryomodules are required for TESLA 500. Since 1997, three prototype cryomodules (of two different designs) have been built and tested in the TESLA Test Facility linac. This paper sums up the design, construction and operating experience with these prototypes. Measurements of alignment, heat leak and vibration of both designs are reported. The installation and performance of the new style thermal shields on the second prototype design are compared to the shields on the first prototype as well as to computer model predictions. Future cryomodule designs, allowing for fixed power couplers, are also discussed.

INTRODUCTION

An important aspect of the ongoing TESLA [1] project is the development of the cryomodules. Since 1997, a total of three cryomodules representing two different designs have been built and tested in the TESLA Test Facility Linac. The purpose of this paper is to summarize the experience with these prototypes and indicate the future direction of TESLA cryomodule design.

Role of the Cryomodules in TESLA

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The proposed TeV Superconducting Linear Accelerator (TESLA) is an electron / positron collider roughly 30 km long. The accelerating portion of the machine is built up of cryomodules. Each module contains 8 superconducting niobium cavities cooled to 2 K. Many modules also contain a superconducting magnet package consisting of quadrupoles and steering dipoles. The modules provide support, alignment and thermal shielding for the cavities and magnets as well as feed throughs for the RF power and instrumentation. The cryomodule is the fundamental building block for the TESLA machine. Approximately 2500 cryomodules are required for TESLA. These modules must meet strict requirements for alignment, heat leak, vibration and cost.

Cryomodule Requirements

Alignment. In order for TESLA to function properly as both a collider and a FEL driver, the cavities and magnets must be aligned to within certain tolerances. These tolerances must be maintained throughout transport, vacuum pumping and thermal cycling. For reasons of cost and complexity, there is no plan to allow adjustment of individual cavities once the module is assembled. Table 1 lists the alignment tolerances for the TESLA cryomodules. The axial tolerance is parallel to the accelerated beam while the transverse tolerance is in the plane perpendicular to the beam.

Static Heat Leak. As a superconducting RF device, the majority of the cryogenic load in TESLA comes from the RF power. However, the size of TESLA dictates that the static heat leak into the cryomodules also be kept as small as reasonable. Table 2 gives the expected static heat leaks at the 2 K, 4.5 K and 70 K levels.

Movable Couplers. The fixed point of the cryomodule is at the center. Thus the ends of the 12 m long module move 15 mm towards the center during cool down. This leaves the designer with a choice. Either fix the power couplers (and thus the cavities) with respect to the 300 K vacuum vessel and let them move relative to the rest of the cold mass or fix them to the cold mass and design the coupler to move relative to the 300 K vacuum vessel. Early on in the TESLA project it was decided to take the second option (that of movable couplers). Couplers [2] have been designed to meet these requirements. It may however be preferable to use fixed couplers and the third generation cryomodule design in principle permits the use of both fixed and movable couplers.

Vibration. Excessive vibration can affect the cavity tuning and resulting beam performance. The cryomodule should be designed to reduce the vibration to the cavities and magnets. The resonant frequency of the cryomodule should be far away from the 10 Hz repetition rate of the accelerator.

Table 1 Alignment Tolerances for TESLA Cryomodule

Component	Transverse tolerance	Axial tolerance	Rotational tolerance
Cavity	+/- 0.5 mm	+/- 5 mm	-
Quadrupole	+/- 0.1 mm	+/- 5 mm	0.1 mrad

Table 2 Predicted TESLA Cryomodule Static Heat Leaks

Temperature Level	Predicted Static Heat Leak (W)
70 K	76.8
4.5 K	13.9
2 K	2.8

Cost The size of TESLA dictates that the cost of each cryomodule must be kept as low as possible. While there is not a specific goal, reducing the cost of the cryomodule has been a consideration from the beginning. This has lead to the design of long cryomodules to minimize the number of expensive interconnects. Cost was the principal reason for changing the thermal shield design between cryomodule #1 and cryomodule #2.

CRYOMODULE DESIGN

1st Prototype

The cryomodule is 12 m long and contains 8 superconducting RF cavities. All cryomodules built so far also contain a superconducting quadrupole and steering dipole package. The cavities are bath cooled by saturated He II at 2 K. The cavity baths are supplied by a parallel two-phase He II line. The heat deposited in the He II evaporates vapor at the surface of the two-phase line and the resulting helium gas is returned to the refrigerator via a large diameter (300 mm) gas return pipe. The gas return pipe and two-phase line are connected together at the end of each module. The superconducting magnets are cooled by a separate 4.5 K flow. The same flow also cools the 4.5 K thermal shields. A second set of shields is cooled by a separate 70 K flow. The cryomodule also contains multilayer superinsulation (MLI) blankets on the 4.5 K and 70 K thermal shields and a separate warm up / cool down pipe parallel to the cavity string. All process lines are contained within the cryomodule.

Figure 1 shows a cross section of the first prototype cryomodule. The outer diameter of the vacuum vessel is approximately 1.2 m. The cavities and quadrupole package are directly attached to the 300 mm gas return pipe. This pipe is itself attached to the 3 composite support posts arranged axially along the length of the module. The middle post is fixed. The 2 outer posts along with the 300 mm pipe, cavities, magnets and shields move towards the center of the cryomodule as a result of thermal contraction during cool down.

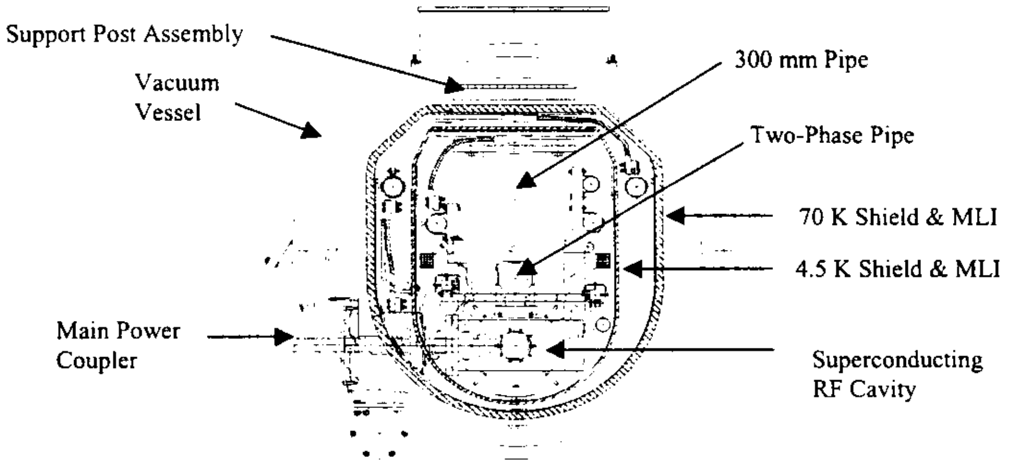


Figure 1 Cross section of 1st prototype cryomodule

The gas return pipe is the structural backbone of the cryomodule and is key to the alignment of the cavities and quadrupole. The gas return pipe is aligned relative to the ideal beam axis via adjusting screws on the support posts. The cavities and quadrupole are then each aligned relative to the ideal beam axis via adjustment screws attaching them to the 300 mm pipe. Once this is accomplished, the cavity alignment is determined by the pipe alignment. As long as the gas return pipe is in the proper position relative to the beam axis, the cavities will be as well. This design only works properly if the cavities don't move relative to the 300 mm pipe once aligned and the 300 mm pipe doesn't move in an unexpected manner once aligned relative to the beam axis. Upon cooling, thermal contraction will cause the 300 mm pipe, 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.

In the first prototype cryomodule, the thermal radiation shields at 4.5 K and 70 K are constructed from aluminum and the cooling pipes are stainless steel. Large copper braids fastened between the shields and the cooling pipes cool the shields. Each thermal shield is divided into 18 pieces connected together by thread fasteners.

One example (cryomodule #1) of this first prototype design has been built.

2nd Prototype

The second prototype design is virtually identical to the first prototype with the exception of the thermal radiation shields. There were two problems with the initial shield design. First, the copper braids used to cool the shields were bulky, expensive and not completely reliable. Second, the use of threaded fasteners to connect the shield pieces together was very expensive in both material and manpower. To solve these problems, it was decided to cool the shields with aluminum cooling pipes that were directly welded to the shields. Welding was also used instead of fasteners to connect the shield pieces together. In order to prevent excessive stress and deformation of the welded joints during thermal cycling a finger welding technique was used. Extensive FEA modeling was performed [3] to predict the behavior of the new shield design. The use of welded shields does place limits on the cryomodule cool down rate, but these limits are consistent with those imposed to prevent excess deformation of the gas return pipe during cool down.

Based on the experience of cryomodule #1, the mechanical tolerances of the second prototype design were adjusted. Those tolerances that were tighter than necessary were relaxed and the reference points of all the tolerances were adjusted to better match the manufacturing and assembly process.

The changes to the thermal shield design and the tolerances resulted in a cost savings of almost 50 % for the cold mass (that is everything except the cavities, quadrupole and their related components) between the first and second prototype design. Two cryomodules (cryomodules #2 and #3) were built to this second prototype design.

CRYOMODULE ASSEMBLY

So far, 3 cryomodules have been assembled at DESY. The assembly process begins when the assembled string of eight cavities and one quadrupole is removed from the clean room. The two-phase He line connecting the cavities is then welded and leak checked. Next MLI, magnetic shields and temperature sensors are added to the cavities. The cold mass (provided by INFN) is then placed on the assembly tooling above the cavity string. The three support posts of the cold mass are adjusted so that the 300 mm gas return pipe is level straight and aligned with the reference beam axis. The cold mass is then carefully lowered onto the cavity string and attached to it. The resulting assembly is then lifted off the string support carts. A precision screw gear linkage system in the assembly tooling permits this to be done with damaging the cavities. Next the cavity tuner linkages and motors, remaining sensors, cables and magnetic shielding are installed. The system is now ready for final alignment.

The alignment is one of the most critical steps in the assembly. Each cavity and the quadrupole are aligned to the reference beam axis using adjustment screws that connect them to the cold mass. Experience showed that tightening the supports after the alignment in some cases altered the alignment. Thus, it is necessary to measure the alignments after the supports are tightened and realign the components as needed. In cryomodules #1 and #2 the alignment was not done to within the required tolerances to avoid damaging the cavities. However, in assembling cryomodule #3, all the components met the final alignment tolerances. The alignment takes 3 days.

After the alignment is finished, the beam tube vacuum is leak checked and the cryomodule is moved to another assembly position. Here the 4.5 K thermal shields, 4.5 K MLI, the 70 K thermal shields and 70 K MLI are installed. Temperature sensors are installed as needed on the thermal shields. Next the 300 K vacuum vessel is slid over the cold mass and attached to it via the support posts. The support posts are then realigned to bring the gas return pipe (and thus the cavities and quadrupole) back into alignment with the ideal beam axis. Lastly, the warm parts of the main couplers, the quadrupole current leads and all the instrumentation feed throughs are installed. The cryomodule is now ready for installation in the linac.

The assembly of the welded thermal shields used in cryomodules #2 and #3 went very well. One team of two welders was able to install all the shields of a module in less than 2 days. No damage was done to any of the cryomodule components during the welding.

Eight weeks were needed to assemble cryomodule #1. Cryomodule #2 and #3 each required 6 weeks. Additional time savings should be possible in the future with elimination of the sensors now needed for research and some automation of the assembly process.

OPERATING EXPERIENCE

Introduction

Two cryomodules (CM #1 and CM #2) have been cooled down and operated with RF power and beam. Cryomodule #1 has been in operation since June 1997 and has undergone 5 thermal cycles. Cryomodule #2 was first cooled down in November of 1998 and has undergone 2 thermal cycles. The performance of the cryomodules was measured during these experiments.

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 2 K result was calculated by multiplying the latent heat of helium at 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.

Table 3 compares the predicted and measured static heat for the two cryomodules. Note that there are two sets of results given for cryomodule #1. When cryomodule #1 is operated alone, the end of the cryomodule is connected to a special cryostat known as the

Table 3 Static Heat Leak Results

Temperature Level	Predicted Heat Leak (W)	Measured Heat Leak (W) Cryomodule #1 (alone)	Measured Heat Leak (W) Cryomodule #1 (with #2)	Measured Heat Leak (W) Cryomodule #2
70 K	76.8	90	81.5	77.9
4.5 K	13.9	23	15.9	13
2 K	2.8	6	5	4

Endcap. When cryomodule #1 and #2 are operated together the end of cryomodule #1 is connected to cryomodule #2 via 12 m long bypass transfer line. This transfer line is simpler in function than the original endcap and causes less heat leak to cryomodule #1. In particular, the old end cap contained optical windows which penetrated to the 2 K space and added heat to both the 4.5 K and 2 K levels. The absence of these windows is seen in the data. The heat leak in cryomodule #2 is smaller than that of cryomodule #1 and closer to the predicted values. This results from the smaller number of sensors in cryomodule #2 and a corresponding reduction in heat leak due to instrumentation cables.

Performance of new shield design

Figure 2 shows the measured temperature distributions on the 4.5 K and 20 K shields in cryomodule #2. The shields performed quite well. The temperature at each level is quite uniform and the temperature of the shield is within a Kelvin or two of the desired level. No damage was done to the shields during the controlled cool down and warm up of the cryomodule. The results here are consistent with the FEA predictions [3]. In particular, the temperatures on either side of the predicted thermal neutral line (180° from the cooling pipe) are equal as expected. The 8 K and 9 K temperatures at the end of the 4.5 K shield are most likely a result the heat sinking of wires to the shield in that region.

The performance of the new shields in cryomodule #2 shows that the simpler, less costly design will meet the cryomodule requirements.

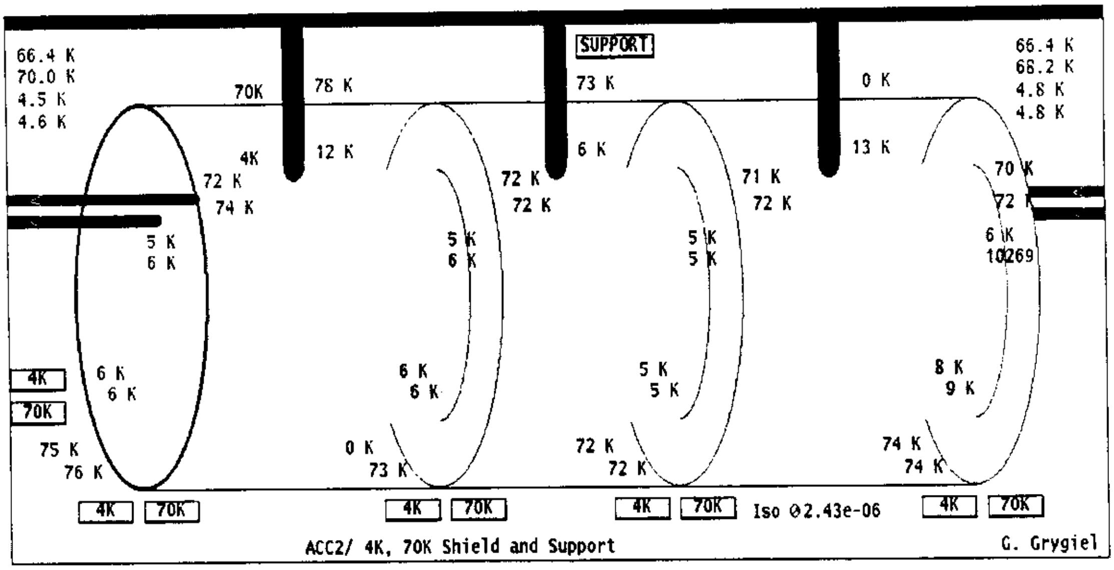


Figure 2 Measured temperature distributions on the 4.5 K & 70 K shields for cryomodule #2

Alignment

The change in the alignment of the cavities and quadrupole is measured by a wire position monitor system [4] produced by INFN. This system permits the real time measurement of position of the components with a resolution of 50 microns. Figures 3 and 4 shows the change in horizontal position for the cavities and quadrupole in cryomodules #1 and #2. Similar results are seen for the change in the vertical system. In these plots, the quadrupole is the rightmost data point. The remaining points represent cavity positions. Notice that the greatest deflection comes at either end of the cryomodules. This results from unbalanced forced generated on the 300 mm gas return pipe during vacuum pumping and cool down. These forces deflect the pipe and thus the attached cavities. Unfortunately, the quadrupole which has the tightest alignment tolerance (+/- 0.2 mm) is located at the end of the cryomodule. Thus, it is always out of tolerance. The cavities, by contrast, are almost always within their tolerance of +/- 0.5 mm. Note also, that the 300 mm pipe does not return to its original position after being warmed up. Some residual forces remain. While the changes in the quadrupole position do not effect the performance of the TTF linac they will be too large for proper performance of the TESLA 500 machine. One of the changes in the 3rd generation cryomodule is designed to solve the alignment problems.

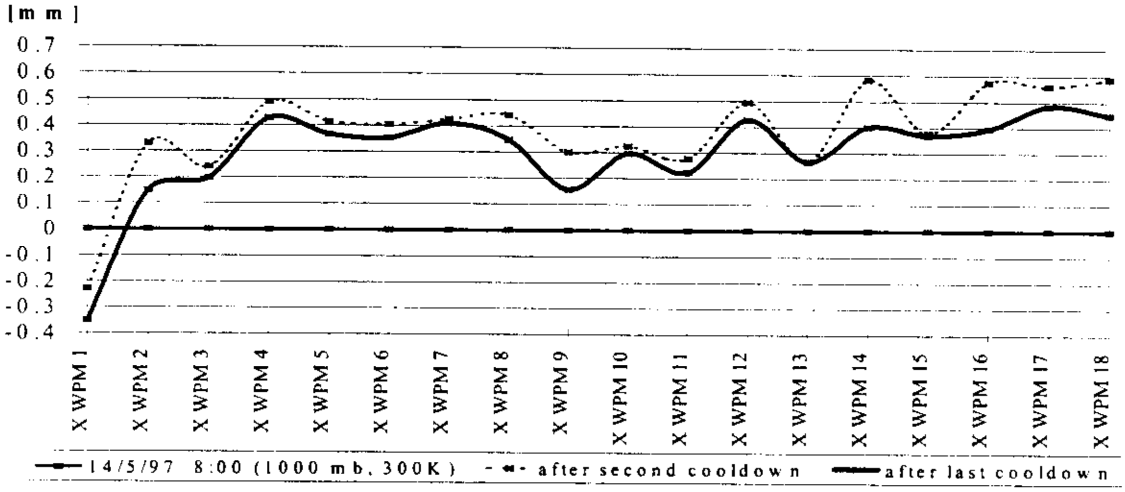


Figure 3 Horizontal displacements of the cavity string for Cryomodule #1 as measured by the WPM system

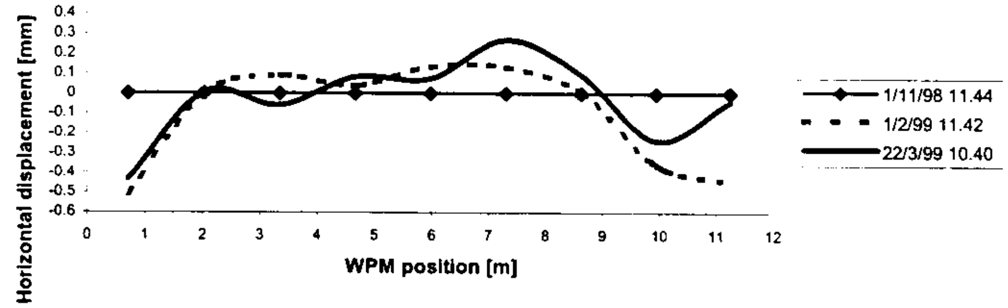


Figure 4 Horizontal displacements of the cavity string for Cryomodule #2 during cooldown (1/2/99) and warmup (22/3/99) compared to the original position (1/11/99)

Vibration

The best test of the cryomodule's resistance to vibration is operational. Excessive vibration will result in a detuning of the cavities off their resonant frequencies or perhaps in beam jitter and defocusing. None of these effects have been seen during several years of operation despite the cryomodules operating over a range of helium flow rates and heat loads. The cryomodules thus meets the vibration requirements.

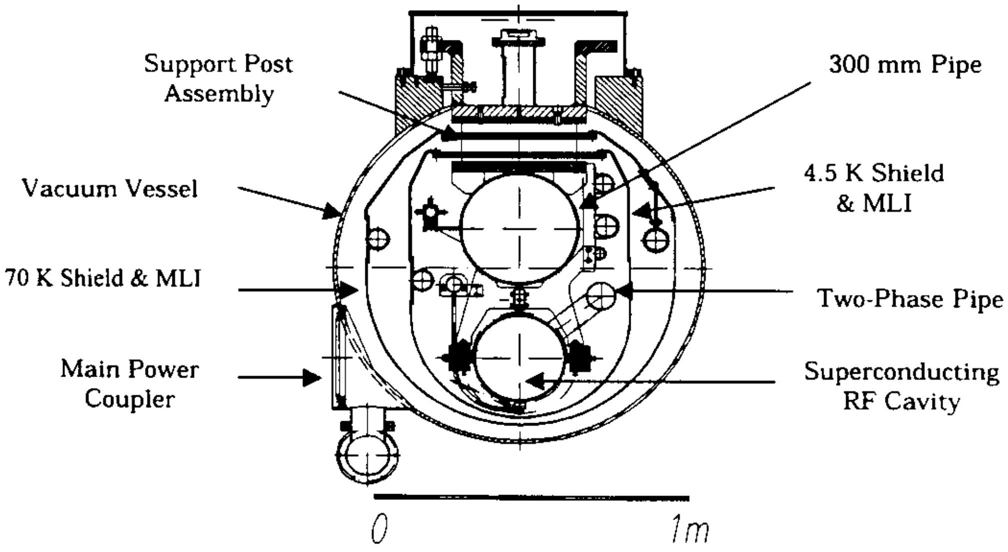
3RD GENERATION DESIGN

Based on the results from the first two generations of cryomodule design, a 3rd generation design has been developed. This new design:

- Reduces the outer diameter of the cryomodule from 1.2 m to 0.98 m. This was accomplished by changing the connection of the cavities to the cold mass and by slightly moving the two-phase pipe. The smaller size frees up room in the proposed TESLA tunnel.
- Stiffens the 300 mm tube near the quadrupole by moving the support posts . Analysis shows that this should permit the quadrupole to stay within its alignment tolerance with unbalanced forces of up to 1000 N
- Allows the use of rigid or semi-rigid main couplers by connecting the cavities to the cold mass by a series of roller bearings and a parallel Invar rod. This may result in significant cost savings for the main coupler as well as an easier and less expensive cryomodule assembly procedure
- Uses the improved thermal shield design tested in cryomodules #2 and #3.

Figure 5 shows a cross sectional view of the new design. The first of these new cryomodules should be built at the end of 1999. More details about the design are presented elsewhere in this conference[5]

Figure 5 Cross section of the 3rd generation cryomodule design



SUMMARY

In the past 5 years, significant progress has been made in the development of cryomodules for TESLA project. 3 cryomodules representing 2 different designs have been constructed. By changing the thermal shield design and adjusting the mechanical tolerances, the 2nd generation cold mass is significantly less expensive than the 1st. Two of these cryomodules (one of each design) have been tested in the TTF linac. The results show that the design meets or comes close to meeting the requirements for vibration and heat leak. The alignment of the quadrupole tends to exceed the tolerances. In order to solve this problem as well as to reduce the outer diameter of the cryomodule and allow for the possibility of fixed power couplers, a 3rd generation design has been created.

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