AIP Conference Proceedings

Study of thermal radiation shields for the ILC cryomodule

Norihito Ohuchi, Tug Arkan, Serena Barbanotti, Harry Carter, James Kerby, Hirotaka Nakai, Carlo Pagani, Thomas J. Peterson, Paolo Pierini, Kiyosumi Tsuchiya, Akira Yamamoto, and Zhanguo Zong

Citation: AIP Conference Proceedings **1434**, 929 (2012); doi: 10.1063/1.4707009
View online: http://dx.doi.org/10.1063/1.4707009
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1434?ver=pdfcov
Published by the AIP Publishing

STUDY OF THERMAL RADIATION SHIELDS FOR THE ILC CRYOMODULE

N. Ohuchi[1], T. Arkan[2], S. Barbanotti[2], H. Carter[2], J. Kerby[2], H. Nakai[1], C. Pagani[3], T. J. Peterson[2], P. Pierini[3], K. Tsuchiya[1], A. Yamamoto[1] and Z. Zong[1]

[1]KEK High Energy Accelerator Research Organization
Tsukuba, State, 305-0801, Japan

[2]Fermi National Accelerator Laboratory
Batavia, IL, 60510, U.S.A.

[3]INFN L.A.S.A
Segrate, Milan, I-20090, Italy

ABSTRACT

The main linacs of the International Linear Collider are composed of 1824 cryomodules. As part of the R&D on the cryomodule, simplifications of the design were considered to reduce the construction and installation costs, including the possibility of removing a portion of the 5 K thermal shield. For this investigation the heat load measurements of a 6 meter cryomodule with and without the 5 K shield were performed, and used to determine emissivity coefficients. A thermal model of a full cryomodule was then created, and the heat loads of the cryomodule with the full set of the 5 K shield and without the lower 5 K shield were calculated with these parameters. By using a modified cooling scheme for the high temperature thermal shielding, we showed that the heat loads at 2 K between two models are substantially equivalent, and indeed, the thermal model without the 5 K lower shield requires 2% less work from the refrigerator.

KEYWORDS: ILC cryomodule, 5 K thermal shield, thermal radiation

INTRODUCTION

The design of the ILC main linac cryomodules has been studied in the framework of the ILC Global Design Effort [1]. The baseline ILC cryomodule design is that of a DESY

Advances in Cryogenic Engineering
AIP Conf. Proc. 1434, 929-936 (2012); doi: 10.1063/1.4707009

TTF-III cryomodule [2], however the efforts of the ILC team have focused on improved cavity performances and other modifications to better industrialize the design according to the large number of cryomodules that will be required for the linacs. The ILC cryomodule baseline design can accommodate either 9 cavities or 8 cavities plus 1 quadrupole, always retaining the slot length of 12.652 m in the main linac. FIGURE 1 shows the cross section of the cryomodule. The main components in the cryomdule are the superconducting cavities which are cooled to 2 K, the gas return pipe which acts as the structural backbone, the support posts, the 5 K and "40 K" (40 K–80 K in the ILC concept, and ~80 K in the test) shields, the integrated cryogenic piping, the input couplers and the vacuum vessel. The ILC main linacs require 1824 cryomodules, almost 20 times more than any other Superconducting RF Linac ever built, therefore the industrialization of the cryomodule is an important subject. Simplifying the design by removing the 5 K shield, or a major portion of it, has been suggested as a means of cost reduction. By removing the lower parts of the 5 K shield, the following points can be expected to contribute to the cost reduction; 1) the fabrication and material cost of the removed components of the 5 K shield; 2) the assembly of the 5 K shield including welding process; and 3) the assembly of the other components, like the input coupler and the magnetic shield, due to the simple configuration around the superconducting cavity package. In order to reduce the heat loads at 2 K derived by the removal of the shield parts, a revised cooling scheme has been proposed and has been evaluated with the modified cryomodule shield design.

In this discussion, the 5 K cooling line and the 5 K shields upper parts are retained to cool the intercepts of input couplers, current leads, HOM couplers, HOM absorber and RF cables, and to provide mechanical support to the intercepts. This study concentrates on the heat load analysis comparison between the two solutions of the full 5 K shield and the removal of the lower components of the 5 K shield, and they are performed experimentally with a 6 meter cryomodule [3, 4] and a 3 dimensional model created by ANSYS [5].

This paper consists of two sections. In the first section, the heat load measurements using the 6 meter cryomodule are reported. This includes two types of heat load measurements, one performed with the complete thermal shield and the second one with the lower parts of the 5 K shield removed, in order to show the differences in the heat load at the 2 K cavity vessel level. In the analysis, the emissivity coefficients of the cold components in the cryomodule are obtained from the measurements. In the second section, the heat loads in the ILC cryomodule are modeled using the proposed shield modifications, using the defined emissivity coefficients and the revised cooling scheme.

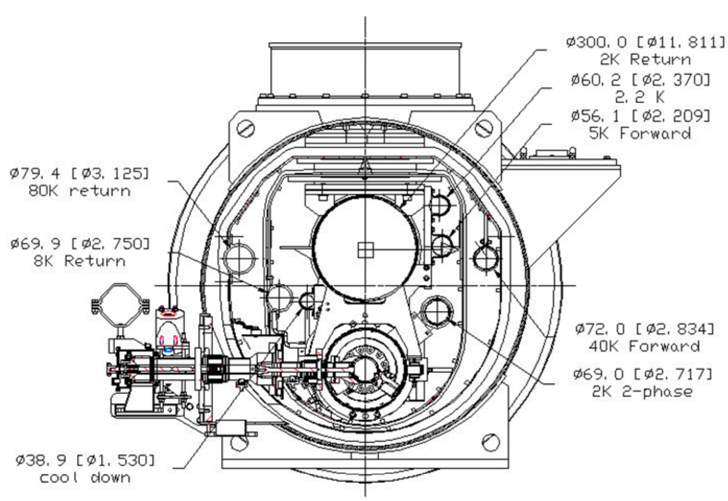

FIGURE 1. Proposed cross section of the ILC cryomodule based on the DESY TTF-III design.

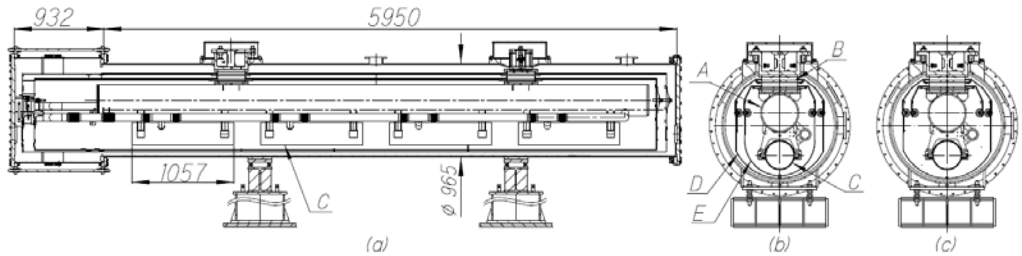

FIGURE 2. Six meter test cryomodule, the longitudinal cross section (a), the cross section with the full set of thermal shields (b) and the cross section without the lower parts of the 5 K shield. In the figures, A=gas return pipe, B=support post, C=dummy helium vessel, D=80K thermal shield and E=5K thermal shield.

MEASUREMENT OF THERMAL RADIATION HEAT LOADS BY 6 METER CRYOMODULE

Test Cryomodule

In order to estimate the heat loads by thermal radiation for the ILC cryomodule, a series of heat load measurements under different configurations of the 6 m long cryomodule were performed. The cryomodule is shown in FIGURE 2. The basic design concept is same as the TTF-III cryomodule. The parameters of the test cryomodule are listed in TABLE 1. The length of the vacuum vessel is 5.95 m, corresponding to the almost half the length of the ILC cryomodule design, and therefore accommodates four 9-cell cavities. In order to concentrate the cold test on measuring the heat loads by thermal radiation, four dummy vessels the same size as the jacketed 9-cell cavities but without input and HOM couplers were assembled in the cryostat. Each vessel was made of SS304L, and measured 1057 mm long, and 236 mm in outer diameter. The vessels, the gas return pipe and the 2 K liquid helium supply pipe were located inside the 5 K and 80 K thermal shields. The vessels had bare surfaces of SS304L without multi-layer insulation “MLI” while the gas return pipe and the helium supply pipe were each wrapped with 5 layers of MLI. The 5 K and 80 K shields were wrapped with 10 layers and 30 layers of MLI, respectively. By design it was possible to separate the shields at the cooling pipes into the upper and lower parts.

Heat load measurements at 2 K dummy vessels

The heat load of four dummy vessels was evaluated by measuring the 2 K LHe evaporation in the vessels, and details of the thermal measurements are presented in [4]. The measurements were performed at operating temperatures with the full 5 K shield, and with the lower components of the 5 K shield removed, as shown in FIGURE 2 (b) and (c). The evaporating helium was measured with a volumetric mass flow meter, and temperatures of the components were measured with Cernox sensors from 2 K to 30 K, PtCo sensors from

TABLE 1. Parameters of test cryomodule

Cryomodule component	Material	Parameter
Vacuum vessel	Steel-SS400	Length=5950 mm, Outer Dia.=965.2 mm,
80 K thermal shield	Al	Cold mass=220 kg
5 K thermal shield	Al	Cold mass=190 kg
Dummy helium vessel	SS304L	Length=1057 mm, O/I Dia.=236/230 mm
Gas return pipe	SS304L	Outer/Inner Dia.=318.5/297.5 mm
2 K LHe supply pipe	SS304L	Outer/Inner Dia.=76.3/72.1 mm

TABLE 2. Summary of the heat load measurements at four dummy vessels

5 K shield condition	Temp. LHe, K	Temp. 5K shield, K	Temp. 80K shield, K	Evaporation of LHe, g/s	Heat load, W
Full 5 K shield	1.93	4.82	84.5	0.132	3.07
Without 5 K lower shield	1.96	4.51	84.2	0.167	3.85
Full 5 K shield	1.93	4.81	84.9	0.048	1.11
Without 5 K lower shield	1.96	4.51	84.0	0.083	1.91

4 K to 100 K and Cu-Constantan thermocouples from 70 K to 300 K, respectively.

The measured results are summarized in the TABLE 2. In the table, the LHe temperature in the dummy vessels, the average temperature of the 5 K and 80 K thermal shields, the mass flow rate of the evaporated He gas and the calculated heat load from the latent heat of LHe [6] were listed. The heat load measurements were performed under two static bias heat loads by controlling the LHe level. The first included the heat loads by the four vessels, the 2 K phase separator in the 2 K cold box and the connection cryo-tube between cryomodule and the 2 K cold box, and the second included the heat loads only by the vessels and the 2 K phase separator [4]. In the first case, displayed by the first two rows of TABLE 2, the heat loads at the 2 K components with the full 5 K shield and without the lower 5 K shield were 3.07 W and 3.85 W, respectively. The difference was 0.78 W and it was induced by removing the lower 5 K shield. The same measurement was performed for the second case, with a smaller bias heat load, and resulted in a difference of 0.80 W in the heat loads, showing good agreement between the two experiments.

Heat load measurements at 5 K and 80 K shields

The heat loads to the 5 K and 80 K thermal shields were calculated by measuring the temperature rise of these shield plates by stopping the LHe and LN_2 flow to each shield, independently, while holding all other conditions constant. During the measurements, the vacuum pressure in the cryostat was kept at less than 5×10^{-5} Pa. FIGURES 3-(a) and 4-(a) show the temperature changes of the thermal shields as a function of time. The temperature profiles of the 5 K and 80 K shields were measured by 12 PtCo sensors and 8 Cu-Constantan thermocouples, respectively. The temperature changes plotted are the average of the measured values. The enthalpies [7] of the shields were calculated from the average temperatures, and their changes are shown in FIGURES 3-(b) and 4-(b). The masses of the 5 K and 80 K shields are 190 kg and 220 kg, respectively.

The temperature of the 5 K shield rose by 8.8 K from 8.6 K to 17.4 K, in a period of 1790 seconds, which is indicated by arrows in FIGURE 3. The enthalpy increase of the 5 K shield was 5.02 kJ, and therefore the average heat load can be evaluated at 2.80 W. The temperature rise of the 80 K shield was slower than the 5 K shield, and was 5.9 K, from 85.0 K to 90.9 K, over 4 hours. The enthalpy increase was 511.3 kJ, and the average heat load was 35.5 W. These values include the conduction heat loads of two support posts and through all the sensor wires that instrument the module. The temperatures of the thermal intercepts of the posts were 85 K and 5 K, respectively. The analysis models of the posts

TABLE 3. Summary of the heat load to the 5 K and 80 K shields

	Measured heat load, W	Two support posts, W	Sensor wires, W	Residual (thermal radiation), W
5 K shield	2.80	1.69	0.53	0.58
80 K shield	35.5	10.42	0.007	25.1

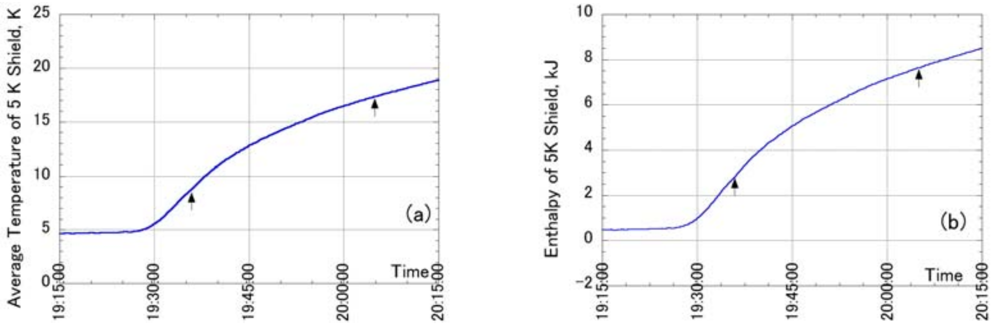

FIGURE 3. The temperature and the enthalpy change of the 5 K shield in Fig. (a) and (b), respectively. The temperature is the average of 12 PtCo sensors on the 5 K shield.

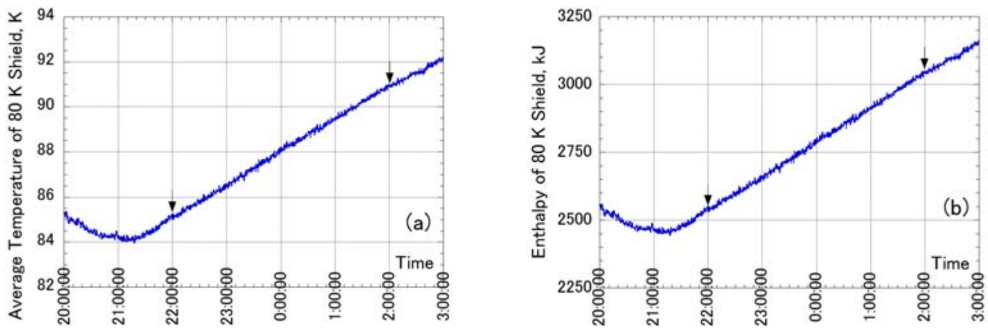

FIGURE 4. The temperature and the enthalpy change of the 80 K shield in Fig. (a) and (b), respectively. The temperature is the average of 8 Cu-Constantan thermocouples on the 80 K shield.

were built using ANSYS, and the calculated heat loads for the movable and fixed posts were 5.03 W and 5.39 W at the 80 K intercepts and 0.853 W and 0.833 W at the 5 K intercepts, respectively. The conduction along the sensor wires accounts for 0.007 W to 80 K and 0.53 W to 5 K. In TABLE 3, the measured and calculated heat loads are listed. Subtracting the conductive exchange from the measurements, the radiation heat loads on the 5 K and 80 K shields are estimated to be 0.58W (=0.041 W/m^2) and 25.1 W (=1.51 W/m^2), respectively.

In order to derive an effective emissivity of the thermal shields with MLI for further design investigation, we have used the basic equation of thermal radiation,

$$Q = \frac{\sigma A_1 \left(T_1^4 - T_2^4\right)}{1/\varepsilon_1 + \left(A_1/A_2\right)\left(1/\varepsilon_2 - 1\right)} \ , \qquad (1)$$

where σ: Stefan-Boltzmann constant, ε_1 and ε_2: emissivity coefficients of the surface areas A_1 and A_2, respectively, and T_1 and T_2: temperatures of the areas A_1 and A_2. In calculation, the emissivity coefficients of the inner surfaces of the vacuum vessel and the shield plate are assumed to be 0.2 and 0.06. They are the coefficients for the machined surface of Fe and Al [8]. By using these values in equation (1), the calculated effective emissivity

TABLE 4. Effective emissivity of the thermal shields with MLI

	SI Layer #	A_1, m^2	A_2, m^2	T_1, K	T_2, K	ε_1	ε_2 [effect. emissi.]
5 K shield	10	16.6	14.0	84	5	0.06	0.022
80 K shield	30	22.3	16.6	300	84	0.2	0.0036

TABLE 5. Calculated heat loads by thermal radiation with 3 dimension model.

	Vacuum vessel	80 K shield outer/inner	5 K shield outer/inner	GRP LHe sup.	Dummy vessel
Temperature, K	300	84	5	2	2
Emissivity	0.2	0.0035/0.06	0.02/0.06	0.03	0.2
Heat load [with 5K shield], W	NA	27.2	0.68	0.19E-3	0.57E-3
Heat load [w/o 5K low shield], W	NA	26.7	0.74	0.20	0.76

coefficients of the 5 K and 80 K thermal shields with MLI result in 0.022 and 0.0036, respectively, as shown in TABLE 4.

CALCULATION OF THERMAL RADIATION HEAT LOADS OF 6 M CRYOMODULE

The heat loads by thermal radiation of the test cryomodule was also calculated using a 3D model in ANSYS. The calculations were performed with the full 5 K shield and without the 5 K lower shield as shown in FIGURE 2 (b) and (c). Because the gas return pipe and the 2 K LHe supply pipe were wrapped with 5 layers of MLI, the emissivity coefficient of 0.03 was applied for these components. The calculation parameters and the results are summarized in TABLE 5.

The measurement of the test cryomodule in the two thermal conditions with the full 5 K shield and without the 5 K lower shield, reported in the previous section, have shown a difference of 0.78~0.80 W. From this thermal calculation, the difference was 0.76 W, agreeing very well with the experimental results.

HEAT LOADS OF ILC CRYOMODULE

The cooling scheme of the ILC cryomodule is completely described in [1]. For the discussion of the heat load to 2 K and/or 5 K regions with the full set of 5 K shield and without the lower 5 K shield, the cooling scheme of the 40 K line plays a key role. In the present cooling design, helium gas in the 40 K line is used to cool the intercepts for HOM couplers, HOM absorbers and input couplers at the average temperature of 54 K along the main linac, and after the turnaround, the helium gas at the average temperature of 74 K cools the thermal radiation shield and intercepts for supports, current leads and cables, as shown in FIGURE 5. The heat loads of the components were calculated with this temperature profile, and they are listed in TABLE 6. The heat loads of the support posts

TABLE 6. Static heat load of the ILC cryomodule.

	Full set of 5 K shield			Without 5 K lower shield		
	2 K	5 K	40 K	2 K	5 K	40 K
Thermal radiation	< 0.001	1.14	54.4	0.10	0.18	54.6
Supports	0.32	2.06	16.6	0.23	1.06	19.0
Input coupler	0.26	1.29	17.6	0.26	1.60	16.8
HOM coupler (cables)	0.01	0.22	1.81	0.01	0.27	2.03
HOM absorber	0.14	3.13	-3.27	0.14	3.13	-3.27
Current leads	0.28	0.47	4.13	0.28	0.47	4.13
Cables	0.12	1.39	2.48	0.12	1.39	2.48
Sum	1.13	9.70	93.8	1.14	8.10	95.8

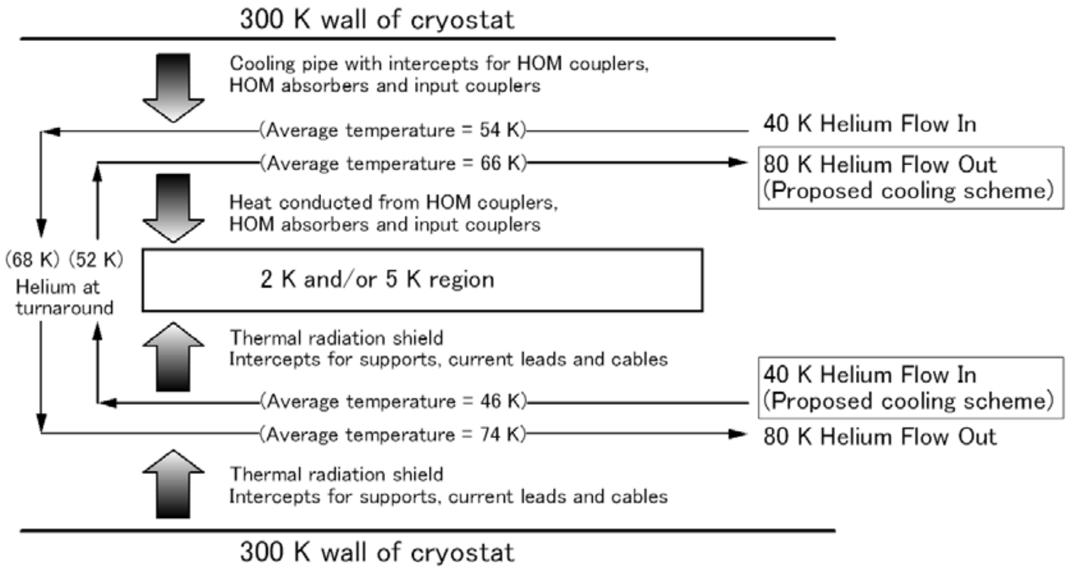

FIGURE 5. Allocation of thermal loads to 40 K－80 K circuit.

were calculated using the ANSYS model. The heat load of input coupler was taken from the TESLA coupler design, with the static heat load by thermal conduction corrected linearly according to the temperature profile in [9]. The heat load by thermal radiation at each temperature level was calculated with the empirically obtained emissivity coefficients. In this calculation, 5 layers of MLI were assumed to be wrapped on the cavity helium vessel and the effective emissivity coefficient was 0.03. As the result, the total static heat loads at 2 K, 5 K and 40 K for one ILC cryomodule are 1.13 W, 9.70 W and 93.8 W, respectively.

For the thermal model where the 5 K lower shield is removed, a new cooling scheme [10] was applied. Helium gas in the 40 K circuit is reversed, and it first cools the thermal radiation shield and the intercepts for supports, current leads and cables at the average temperature of 46 K. After the turnaround, the gas cools the intercepts for HOM input couplers, HOM absorbers and input couplers at the average temperature of 66 K. In this cooling model, the 5 K circuit is retained. By reducing the average temperature in the forward line to 46 K and wrapping MLI around the cavity helium vessel, the heat load by thermal radiation to the cavity vessels, the gas return pipe and the 2 K LHe supply pipe is calculated to be 0.10 W. Because the heat load through the support posts is reduced from 0.32 W to 0.23 W due to the lower intercept temperature, the total static heat load at 2 K is calculated in 1.14 W. By modifying the cooling scheme, the difference of the heat load at 2 K between an assembly including the full 5 K shield and one without the lower 5 K shield is negligible.

TABLE 7 summarizes the static and dynamic loads for one cryomodule in the configurations described above. The dynamic loads are assumed to be identical between the two thermal models. In this table, the effects on the cooling power of the refrigerator are shown. The transfer coefficients of work at each temperature level to work at 300 K are the same assumed for the ILC cryoplant: W_{300K}/W_{2K} = 702.98, $W_{300K}/W_{5\text{-}8K}$ = 197.94 and $W_{300K}/W_{40\text{-}80K}$ = 16.45 [1]. Between the two thermal models, the required work of the refrigerator at 300 K with respect to the heat load of one cryomodule are almost the same, and rather, the thermal model without the 5K lower shield shows slightly less work by applying the new cooling scheme.

TABLE 7. Summary of static and dynamic heat loads of the ILC cryomodule.

	Full set of 5 K shield			Without 5 K lower shield		
	2 K	5 K	40 K	2 K	5 K	40 K
Static load, W	1.13	9.70	93.8	1.14	8.10	95.9
Dynamic load, W	10.02	7.06	83.0	10.02	7.06	83.0
Sum (static +dynamic), W	11.15	16.76	176.8	11.16	15.16	178.9
Work at 300 K, W	7838.2	3317.5	2908.4	7845.3	3000.8	2942.9
Sum (2K+5K+40K), W		14064			13789	

CONCLUSION

The thermal model of ILC cryomodule was created to study the effect of removing the 5 K shield for the purpose of reducing the construction and assembly cost. The study concentrated on the comparison of the heat loads between an assembly with the full set of thermal shields and one without the lower 5 K shield and including the new cooling scheme of the 40 K helium line.

From the heat load measurements performed with the 6 meter cryomodule, the emissivity coefficients of the cold components were defined. With these parameters, the heat loads of the ILC cryomodule were calculated for the two cases.

By introducing a new cooling scheme based on the flow reversal of the 40-80 K circuit which reduces the average temperature of the thermal shield, the radiative heat load to the 2 K region can be limited to 0.1W, and total heat loads at 2 K between the two thermal conditions are almost identical. As a result of the calculations, the ambient work needed from this new cryomodule and cryogenic lines configuration is decreased by 2 % with respect to the present configuration presented in the ILC RDR [1], and it will be further investigated in view of the ongoing work towards the Technical Design Report of the ILC.

ACKNOWLEDGEMENTS

We thank Y. Kojima, H. Hayano and the KEK-STF cryogenic group for completing the cold test of the 6 meter cryomodule.

REFERENCES

1. ILC Reference Design Report, http://www.linearcollider.org, Vol.3 (Accelerator), (2007), III-165-174.
2. Pagani, C., et al., The TESLA cryogenic accelerator modules, TESLA report 2001-36.
3. Ohuchi, N., et al., "The first cool-down test of the 6 meter-long cryomodules for Superconducting RF Test Facility (STF) at KEK," in *Proc. of the EPAC2008*, Genoa, 2008, pp. 892-894.
4. Ohuchi, N., et al., "Experimental study of thermal radiation shield for ILC cryomodule," in *Proc. of the International Cryogenic Engineering Conf. 23 (ICEC23),* Wroclaw, 2010.
5. ANSYS is trademark by CYBERNET. Inc.
6. HEPAK is trademark by CRYODATA, INC, http://www.cryodata.com.
7. Corruccini, R., and Gniewek, J., "Specific Heats and Enthalpies of Technical Solids at Low Temperatures", in NBS Monograph 21, (1960), p.7.
8. Hands, B.A., In: Cryogenic Engineering, Academic Press, USA (1986), pp. 107-112.
9. Dohlus, M., et al., "TESLA RF POWER COUPLER THERMAL CALCULATIONS," in *Proc. of LINAC2004,* Lubeck, Germany, 2004, pp. 174-176.
10. Peterson, T., "Cryomodule Thermal Intercept Optimization Strategy", presented in TILC08, Sendai, (2008), http://www.awa.tohoku.ac.jp/TILC08/.