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Thermal simulation and analysis of the STF cryomodule*

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Abstract STF is a superconducting RF test facility constructed at the high energy accelerator research organization of Japan (KEK), as a main part of a R&D project for the proposed International Linear Collider (ILC) in Asia. Thermal study of the STF 1.3 GHz 9-cell cavity cryomodule was carried out within a collaboration between China and Japan. Static and dynamic thermal behaviors of the STF cryomodule were simulated and analyzed with the FEM method, and some simulation results were compared with the available experimental data. This paper presents the details.

Key words STF cryomodule, thermal simulation, ILC

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1 Introduction

As a main part of the R&D project for the ILC (International Linear Collider) in Japan and Asia, the construction of a superconducting RF test facility (STF) was decided and carried out at KEK. This facility includes eight 1.3 GHz 9-cell superconducting cavities, a cryomodule, a power source, a helium plant, the beam instrumentation, cavity surface treatment facilities, etc. In STF phase 1, starting on JFY05 (Japanese Fiscal Year) and to be ended in JFY08, eight 9-cell cavities with two different types (Tesla-like and low loss, four cavities for each type) will be installed to the STF cryomodule and horizontally tested. In the following STF phase 2, the nine cavities in one cryomodule will focus on one type[1].

Under the support of the Asian region collaboration of the ILC R&D project, several Chinese researchers started to join the construction of STF from 2006. Thermal study on the STF cryomodule is one of the most important parts of this collaboration. The static and dynamic thermal behaviors of the STF cryomodule were simulated and analyzed with the FEM software ANSYS.

2 Static thermal analysis of the STF cryomodule

The static heat load of the STF cryomodule mainly includes: heat conduction through the input power coupler, support posts, beam tube, sensor wires, RF cables and tuner, and the thermal radiation heat through the MLI (Multi-Layer Insulation) system. The radiation heat through the MLI was calculated with data based on experience: room temperature to 80 K with 30 layers MLI — 1 W/m^2; 80 K to 5 K with 10 layers MLI — 0.05 W/m^2; and 5 K to 2 K was ignored. Heat conduction through the power coupler and support posts, including temperature distributions, were simulated with the FEM 3D model, as shown in Fig. 1 and Fig. 2 (Related structure data comes from Ref. [2]).

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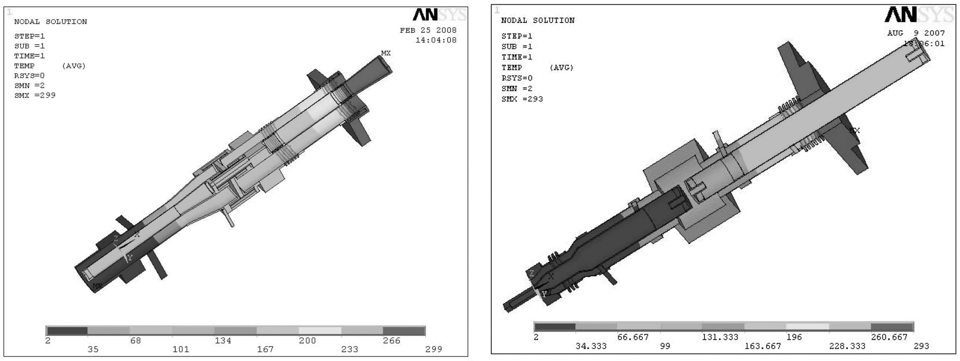

Fig. 1. Static temperature field of 35 MV and 45 MV power couplers (Unit: K).

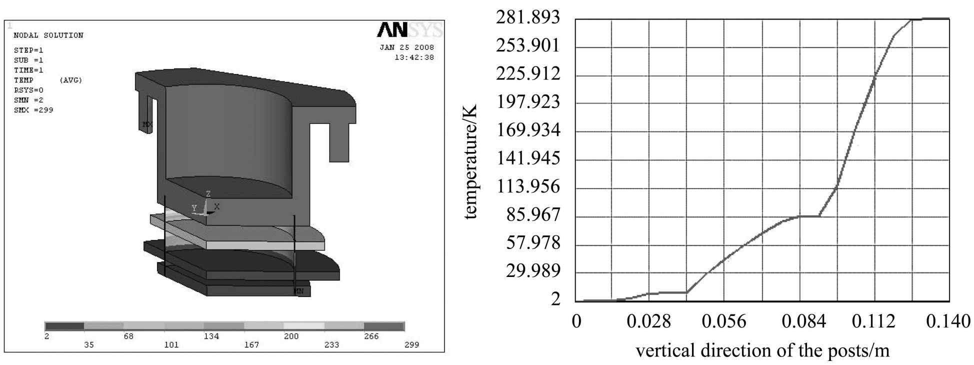

Fig. 2. Static temperature field and temperature distribution along the vertical direction of the fixed post of the STF cryomodule (Unit: K).

Figure 1 shows the static temperature fields of the 35 MV and 45 MV power couplers. For each coupler, two thermal anchors (separately connecting with two radiation shields of the cryomodule) were added to decrease the heat loads to the cryogenic system. For the 35 MV coupler, the measured data of the room temperature, first thermal anchor temperature, second thermal anchor temperature and the cavity temperature are 299 K, 83 K, 4.5 K and 2 K, respectively. With these experimental data, and the ANSYS 3D model, the calculated heat loads of the coupler are 2.41 W to the 80 K radiation shield, 1.08 W to the (5 K) radiation shield and 0.03 W to the 2 K system. It is also found from the results that the copper coating with a thickness of only several microns at the inner surface of the coupler plays a very important role in the heat conduction.

The materials of the support posts are G10 and stainless steel. From the upper side to the lower side, the posts are connected with the vacuum vessel, the 80 K radiation shield, the 5 K radiation shield and the 2 K system. Fig. 2 shows the simulation results of the static temperature distributions. The calculated heat loads are: 80 K-5.4 W; 5 K-0.81 W and 2 K-0.12 W for the fixed post, and 80 K-5.1 W; 5 K-0.81 W; 2 K-0.12 W for the sliding post. The temperature variation along the vertical direction of the posts is shown in Fig. 2.

Figure 3 shows the static temperature distributions of the 5 K and 80 K radiation shields (with 1 power coupler for each shield). The mass flow rate of helium for the 5 K shield is 1 g/s, and the inlet temperature is 5 K. With a radiation heat flux of 0.05 W/m^2, the simulation results show that the outlet temperature of the helium is about 5.25 K, and the hot spot temperature of the shield (around the coupler port) is 5.91 K. For the 80 K shield, the mass flow of nitrogen is 1 g/s, and the inlet temperature is 80 K. With the radiation heat flux 1 W/m^2, the simulation result of the outlet temperature of the nitrogen is 86.8 K, and the hot spot temperature of the shield (around the coupler port) is about 91.05 K.

A vacuum barrier structure was designed and fabricated to separate the vacuum of the cryomodule and the valve box into two independent parts, to decrease the vacuum failure possibility of the cryomodule (see Fig. 4). The materials of the barrier are stainless steel (SS316) and ETP copper. The 2 K, 5 K and 80 K cryogenic pipes of the cryomodule were welded with the barrier. To minimize the additional heat load caused by the barrier, the heat loads to the three pairs of different temperature pipes were optimized considering the heat flux through conduction and radiation. Two thermal anchors were added to the SS316 pipe which was welded with the 2 K helium pipe, and one thermal anchor was added to the pipe, welded with the 5 K helium pipe, as shown in Fig. 4. The optimized results of the heat loads are 17.32 W to 80 K, 2.18 W to 5 K and 0.057 W to 2 K.

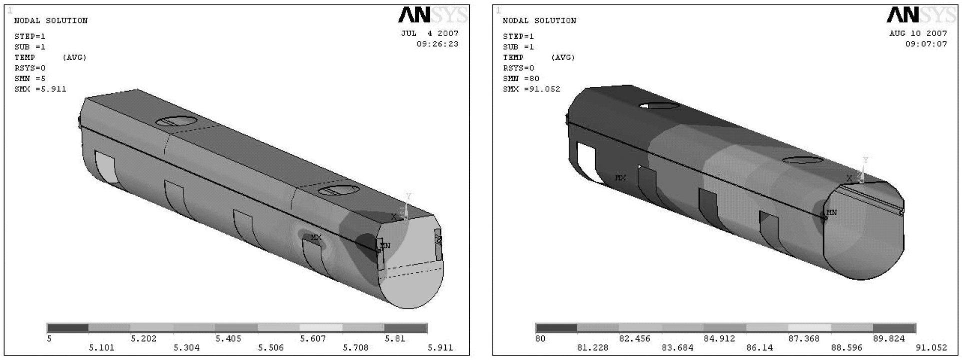

Fig. 3. Static temperature fields of the STF 5 K and 80 K radiation shields (with 1 power coupler, unit: K).

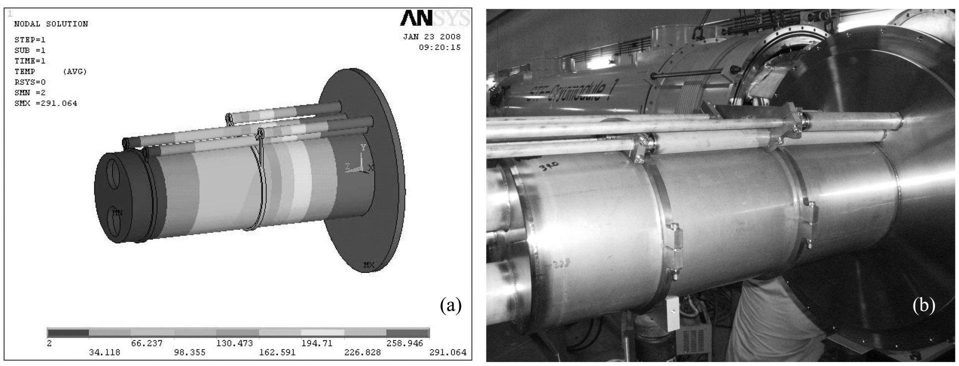

Fig. 4. Vacuum barrier of the STF cryomodule: (a) design; (b) fabrication (Temperature unit: K).

3 Dynamic thermal analysis of the STF cryomodule

During the RF power process, current flow within the skin depth of the conductor and dielectric loss in the ceramic window will generate joule heat in the coupler. A coupler-field (High Frequency magnetic and thermal) FEM simulation model was built for this dynamic thermal analysis[3]: The HF field was first calculated; with the HF distribution, surface resistance of the conductor and dielectric loss tangent of the ceramic window, the HF heat generation at the inner surface and the window of the coupler was obtained. Then the thermal simulation was carried out with the heat generation as a boundary condition.

Figure 5 shows the input power variation and the electrical field distribution of the STF 35 MV coupler during the experiment. The frequency of the input pulse is 5 Hz. At each 0.2 s cycle, the maximum power input will last 0.5 ms and then decrease to 70% during the coming 1 ms. Fig. 6 shows a comparison between the simulation results and the experimental data of the temperature rising around the window of 35 MV coupler. It shows that the experimental data approximately confirm the simulation results. The difference between them should be mainly due to the material properties error in the simulation model and the measuring error in the experiment.

The variation of heat loads of the 35 MV coupler with an increase of the input power is also shown in Fig. 6. The results show that the dynamic heat load to the 80 K shield is about 10 times larger than that to the (5 K) shield. The 2 K dynamic heat load is about one third of the second shield. The ratio of the surface loss to the dielectric loss is about 5.

The dynamic heat load caused by the cavity can be calculated according to the following equation:

$$P_{\mathrm{c}}=\frac{E_{\mathrm{acc}}^{2}*L^{2}}{Q_{0}*R/Q}\ , \tag{1}$$

where P_{c} — dynamic heat loss of superconducting cavity; E_{acc} — accelerator gradient of the cavity; L— cavity length; Q_0 — quality factor of the cavity; R/Q — shunt impedance of the cavity.

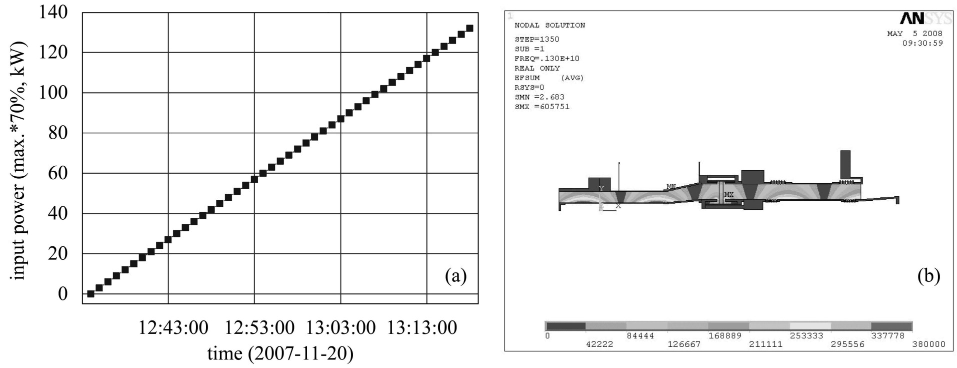

Fig. 5. (a) The input power of the STF 35 MV coupler; (b) The electrical field distribution with the maximum input power 193 kW (Electrical field unit: V/m).

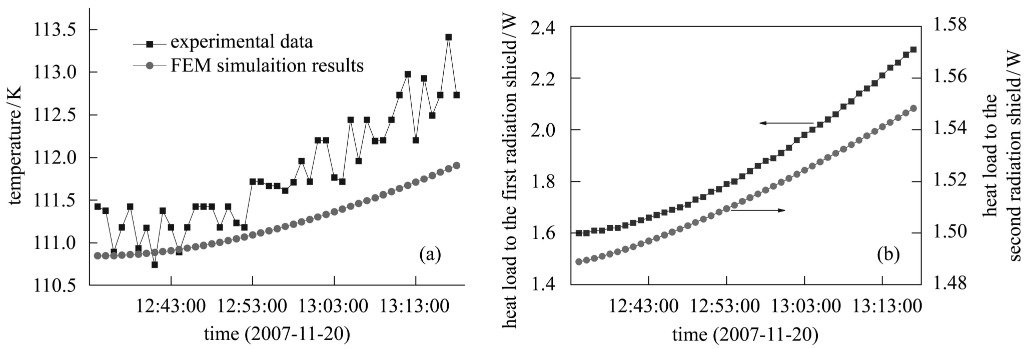

Fig. 6. (a) Temperature rising around the window of the STF 35 MV coupler caused by RF heat; (b) Variation of the heat loads of the 35 MV coupler.

4 Summary

Key components of the STF cryomodule were studied by thermal simulation and analysis with the FEM software ANSYS. Part of the simulation results have been compared with the available experimental data. A vacuum barrier structure was designed and fabricated, to separate the vacuum of the cryomodule and the valve box into two independent parts, so that the vacuum failure possibility of the cryomodule was decreased. A thermal analysis of this part was also carried out. The preliminary summary of the heat load of the STF cryomodule (35 MV part) is shown in Table 1.

Table 1. Heat load summary of the STF cryomodule (35 MV part, *data from Ref. [4]).

heat source	static/W			dynamic/W		
	80 K	5 K	2 K	80 K	5 K	2 K
radiation	14	0.6	/	/	/	/
support posts	10.5	1.62	0.24	/	/	/
input coupler (one)	2.41	1.08	0.03	2.5	0.2	0.06
cavity (one)	0.47	0.06	0	/	/	0.3
instrumentation cables*	1.25	1.64	0.05	/	/	/
vacuum barrier	17.32	2.18	0.06	/	/	/
other	1	0.3	0.2	/	/	0.1
sum	46.95	7.48	0.58	2.5	0.2	0.46

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