Thermal analysis of a prototype cryogenic polarization modulator for use in a space-borne CMB polarization experiment

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Abstract. We report a thermal analysis of a polarization modulator unit (PMU) for use in a space-borne cosmic microwave background (CMB) project. A measurement of the CMB polarization allows us to probe the physics of early universe, and that is the best method to test the cosmic inflation experimentally. One of the key instruments for this science is to use a half-wave plate (HWP) based polarization modulator. The HWP is required to rotate continuously at about 1 Hz below 10 K to minimize its own thermal emission to a detector system. The rotating HWP system at the cryogenic environment can be realized by using a superconducting magnetic bearing (SMB) without significant heat dissipation by mechanical friction. While the SMB achieves the smooth rotation due to the contactless bearing, an estimation of a levitating HWP temperature becomes a challenge. We manufactured a one-eighth scale prototype model of PMU and built a thermal model. We verified our thermal model with the experimental data. We forecasted the projected thermal performance of PMU for a full-scale model based on the thermal model. From this analysis, we discuss the design requirement toward constructing the full-scale model for use in a space environment such as a future CMB satellite mission, LiteBIRD.

1. Introduction
One of the most important research topics in the current cosmology and high-energy particle physics is to study the cosmic inflation, which predicts a rapid expansion of the universe ~10^{-38} seconds after the beginning of the universe [1, 2]. The inflation solves several mysteries of our universe and it can provide a foothold for a new physics microscopically and macroscopically in particle physics and cosmological physics. The cosmic microwave background (CMB) is electromagnetic microwave

radiation that contains the information before and after the last scattering surface. The CMB has a uniform temperature of 2.7 K with a black body spectrum: the CMB is polarized with the amplitude of a few microkelvin fluctuation across the whole sky. There are two types of polarization: one is E-mode and the other is B-mode. The E-mode naturally arises from the density perturbations in the early universe. On the other hand, the B-mode only originates from gravitational waves by the cosmic inflation. Thus, the CMB polarization contains the fingerprint of the cosmic inflation. In recent years, a world-wide race toward the detection is ongoing. Correspondingly, the instrumental developments have progressed rapidly.

One of the key instruments for a precise measurement of the CMB polarization is a polarization modulator. It consists of an optical element, a half-wave plate (HWP), and a rotational mechanism. The rotating HWP modulates the CMB polarization signal, and thus, the signal appears above the low frequency detector noise after it is demodulated. An ordinary spinning method of the HWP using ball bearings is difficult in a cryogenic environment due to heat dissipation induced by mechanical friction. Our proposed modulator employs a superconducting magnet bearing (SMB). Even though the SMB is a contactless bearing with minimal heat dissipation from friction, there is a potential heat dissipation due to the magnetic interaction, e.g. hysteresis and eddy current. In this paper, we discuss the estimation of the impact to the HWP temperature from these heat dissipations.

2. Overview of the polarization modulator
A scaled model of the rotating HWP system is constructed to demonstrate the thermal feasibility. The overview of the system is shown in Figure 1. It consists of four main parts: the rotor (top and bottom sections), the superconducting magnet bearing (SMB) and the three grippers. The entire system is installed inside of the cryostat that is kept below 10 K using a GM cooler.

The SMB consists of a ring-shaped permanent magnet, NdFeB, and a ring-shaped high temperature superconductor array, YBCO. The permanent magnet is encased in a holder at the bottom of the rotor. The rotor is held by the three grippers while the entire system is cooling. We wait until the stator YBCO becomes below its critical temperature. Furthermore we wait until the rotor is thermalized to the lowest temperature of about 7 K. Then, the gripper is actuated by each cryogenic stepping motor and the rotor is released in space. The magnetic field of the rotor magnet is pinned in the YBCO due to the field cooling, and thus the rotor levitates and spins freely due to the symmetry of the magnetic field. The YBCO is mounted by a G10 holder in order to minimize a metal to avoid the eddy current. The rotor is driven by a drive mechanism that consists of an alternating magnetic rail on the rotor side and the magnetic gear on the stator side. The magnetic gear is mounted on a shaft that is connected to a drive mounted outside of the cryostat. The rotational position is encoded by an optical chopper and an LED and Silicon photodiode. The HWP is mounted at a center of the ring-shaped rotor and stator. The HWP is the first optical element of the telescope. Thus, it is exposed to outer space and pointed to the 3 K deep space.

The heat dissipation due to the rotational loss is estimated by conducting the spin-down measurement. The rotor is span up to the initial frequency and let the rotor freely spin down. The expected heat dissipation from the spin down is about 1 mW. We also estimate the heat dissipation from the drive mechanism by computing the heat dissipation of the AC coils. While the detailed design of the drive mechanism is yet to be finalized, the estimation is in the order of 1 mW.

During the nominal observation, the HWP spins at about 1 Hz. In order to meet the sensitivity requirement, the HWP is required to maintain below 10 K. Any energy loss becomes a source of heat. A part of the energy loss of PMU goes to the rotor. The rotor supported by the levitating system at cryogenic temperature has only poor heat exchange by radiation. Thus, the small energy input can increase the temperature of the HWP that is mounted on the rotor. Once the temperature of the HWP exceeds 10 K, the rotor is held by the three grippers and cooled down by the conduction. The further detailed description for this system can be found in Sakurai et al. and Matsumura et al. [1, 2]. The required observational time is 24 hours that is set by a recycle time of Adiabatic Demagnetization Refrigerator (ADR). The cooling time is aimed to be less than 4 hours.
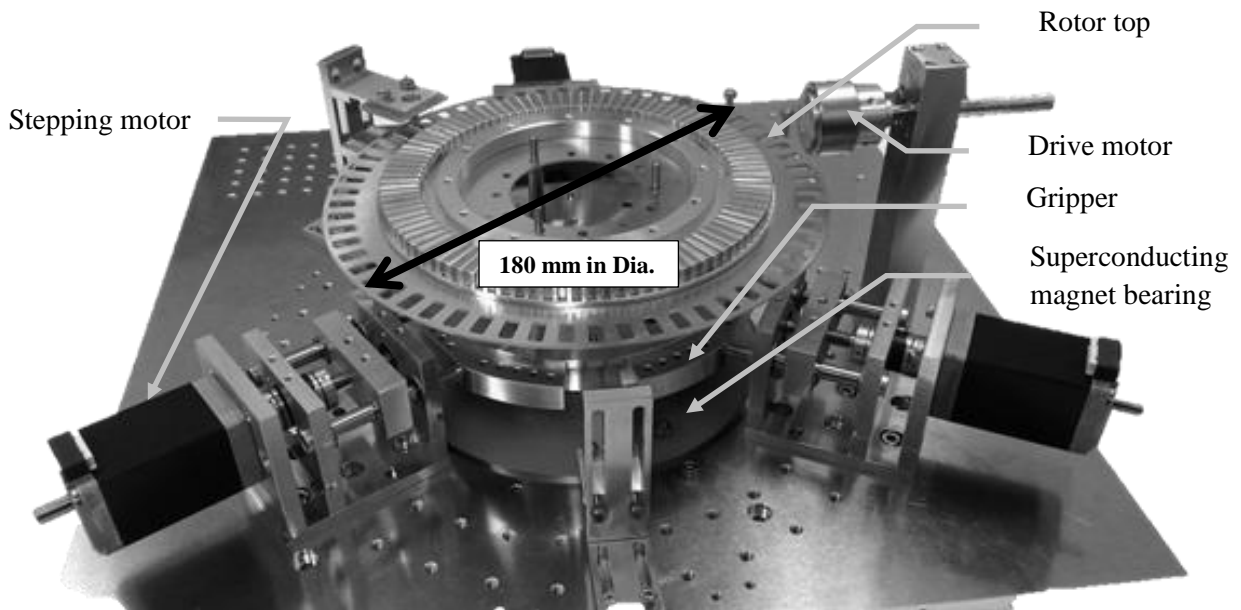
Figure 1. A photo of the scaled rotating HWP system. The bottom side of the rotor and the HWP are not shown in the photo.

3. Thermal simulation

3.1. The workflow
We conducted the two types of the thermal simulation. First we estimate the temperature rise of HWP by heat loads, which is corresponding to energy losses in a rotor operation. Second we estimate how long it takes for HWP to cool from 10 K to 4 K by mechanical conductive heat through the grippers.

   The thermal simulation workflow is as followings. First, we built a thermal model of scaled rotor system. We verify this model experimentally by applying an energy input to a levitating rotor using a heater. In this test, the levitating rotor is not only thermally coupled by the radiation but also the conduction due to the Manganin wires to apply a heat by a heater resister and wires for a Cernox. We account the thermal conduction due to the wire in the model. The transient temperatures were measured in the different heat input to the rotor. Finally, the experimental results are compared with the thermal simulation using Thermal Desktop ver. 5.8.

3.2. Thermal model
We built a thermal model of the scaled rotor, as shown in Figure 2. The material list for each component is shown in Table 1. The thermal properties, thermal conductivity and specific heat, are set as a function of temperature on the model. The surface finish of the most assemblies is a metal colour as aluminium and its infrared emissivity is 0.11 while the surface of YBCO holder is G10 and its emissivity is 0.96.

Table 1. Assembly material list

Assembly name	Material	Remarks
Rotor top	Aluminium 6061	
Permanent magnet	NdFeB	For rotation
Rotor bottom	Aluminium 6061	
HWP	Sapphire	
Permanent magnet	NdFeB	For levitation
Superconducting magnet bearing	YBCO	
SMB holder	G10	
Grippers	Aluminium 6061	
Gripper arm	SUS304	

The entire rotor system is placed on the 4 K cold plate which is cooled by a 4 K GM cooler. The system is enclosed by a vacuum chamber with box-type shrouds. The five shrouds around the system except the 4 K cold plate are also cooled with a thermal connection with the cold plate. Thus, the cold plate and shrouds are thermal boundaries for simulation. The thermal boundary conditions as a function of time are measured at the experiments and are input on the thermal model. Wires to a heater and temperature sensors are also included only when it is relevant.
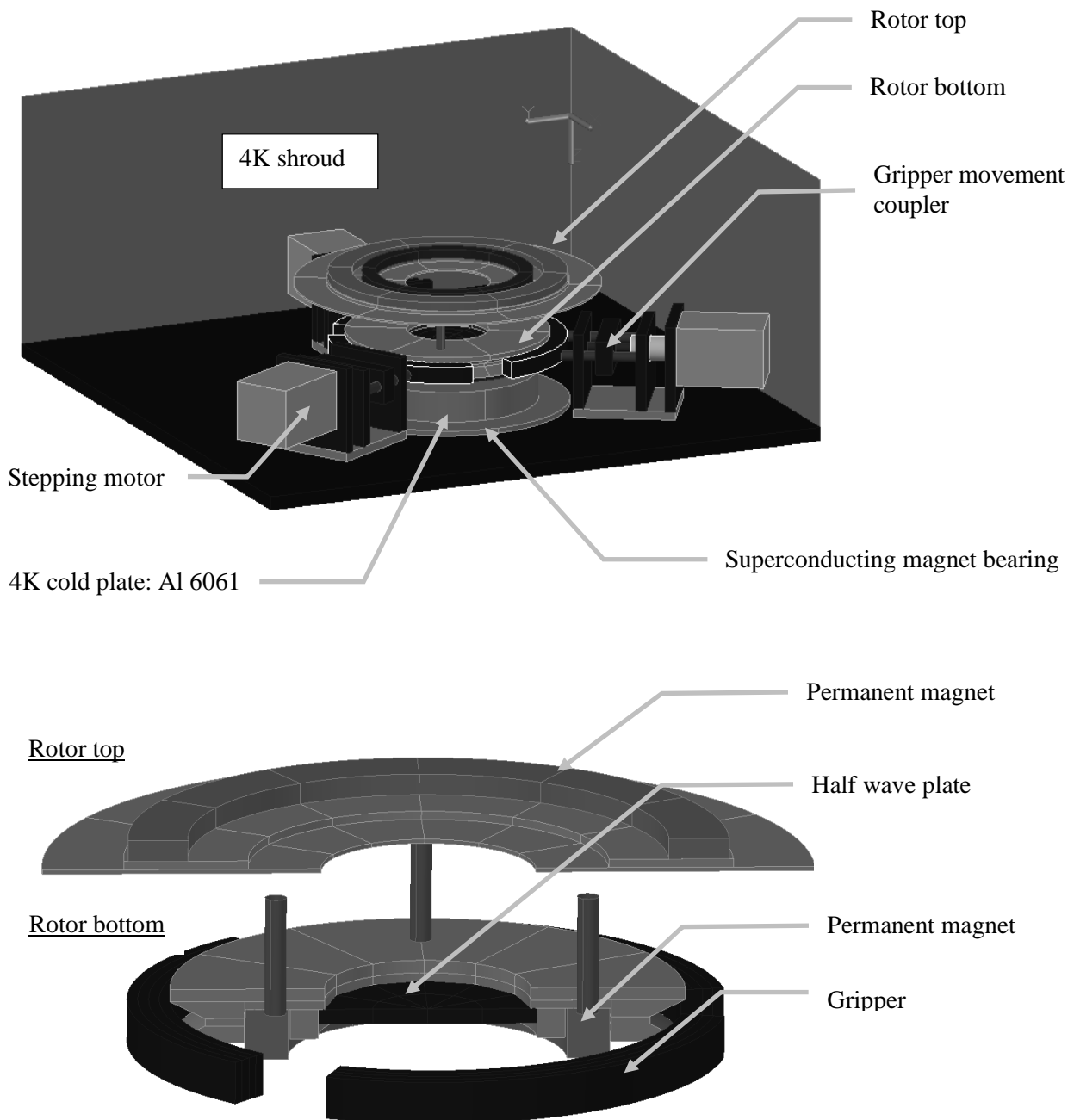

Figure 2. Thermal model of the scaled rotating HWP system. The rotor is separated into two parts, Rotor top and Rotor bottom. The rotor holds the two permanent magnets and the HWP. The dark color, labeled as gripper, is an arm of the gripper which is a part of the stator.

3.3. Verification of the thermal model using the experimental results

We compared the simulation results with the experimental data using the scaled model. Figure 3 shows the temperature of the HWP as a function of time. The rotor system has no HWP in the configuration. The solid lines are the experimental results and the broken lines are the simulation results. The heat load is applied by a heater resister that is mounted on the rotor. The constant power input by the heater resister is applied sequentially from 0.25, 0.50, 1.0 to 3.5 mW during the measurements of the rotor temperature.

When the thermal model is built, we included the thermal conductivity λ, specific heat C_p of all the materials except a NdFeB magnet at cryogenic temperatures. Thus, we let these parameters free and fit them from the experimental data. A time constant, τ_f, is proportional to $C_p(T)$. From the fit, we extract the time constant as $\tau = \alpha \tau_f$, where $\alpha = 0.61$ while τ_f is fixed using the numbers from stainless steel. However, $\lambda(T)$ of stainless steel is used instead of $\lambda(T)$ of NdFeB in the simulation.

In Figure 3, the curves from the simulation and the experimental are over-plotted and they show a good agreement each other. The fractional difference between the data and the model are 3%. Thus, we successfully reproduced the experimental results on the simulation. The temperature curves around 20 hr. after the start of heating have a slightly large difference between the data and the simulation. This is due to the calibration error of the temperature sensor.
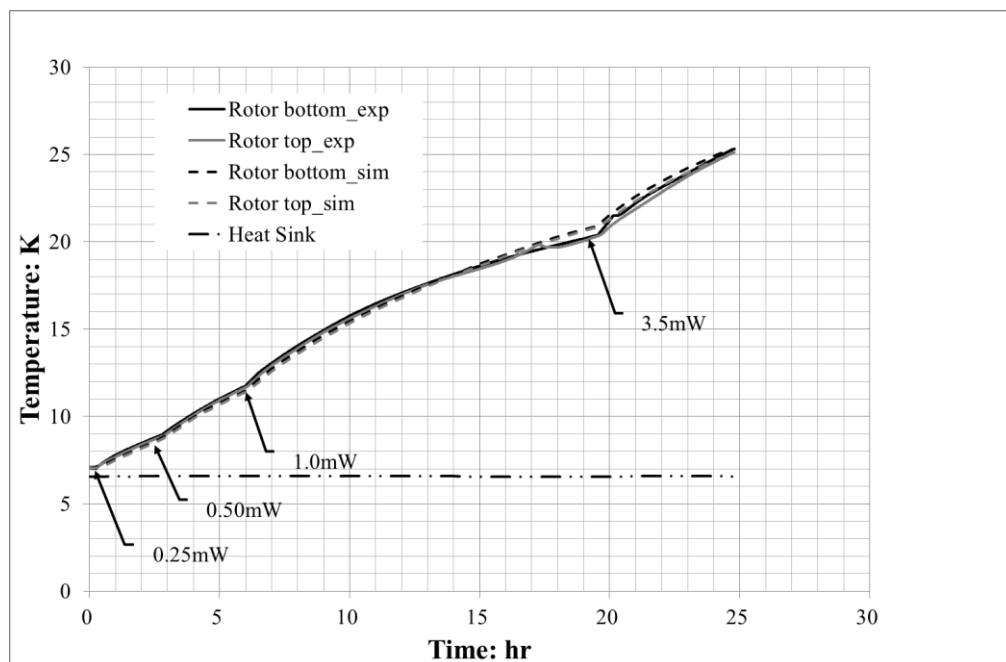

Figure 3. The experimental and simulation results are over-plotted with different heat loads.

4. Simulation results of full-scale rotor

We now apply our verified thermal mode to a full-scale PMU. We computed the maximum heat input that is allowed for the HWP to maintain below 10 K over 24 hours. We also estimated the time it takes for the HWP to cool down from 10 K to 4 K.

4.1. Full scale rotor configuration

Figure 4 shows the thermal model of the full-scale rotor configuration. The differences between the scaled and full-scale rotors are mainly their dimensions and weights, as shown in Table 2. The materials used on the both rotors are the same. Thus, the temperature response on the rotor with a heat load only depends on the dimensions. The contact area between the rotor and the gripper is also increased by a factor of 9.5 due to the increase of the overall diameter. The value is used to estimate the cool-down time of HWP later described in *Subsec. 5.3*.
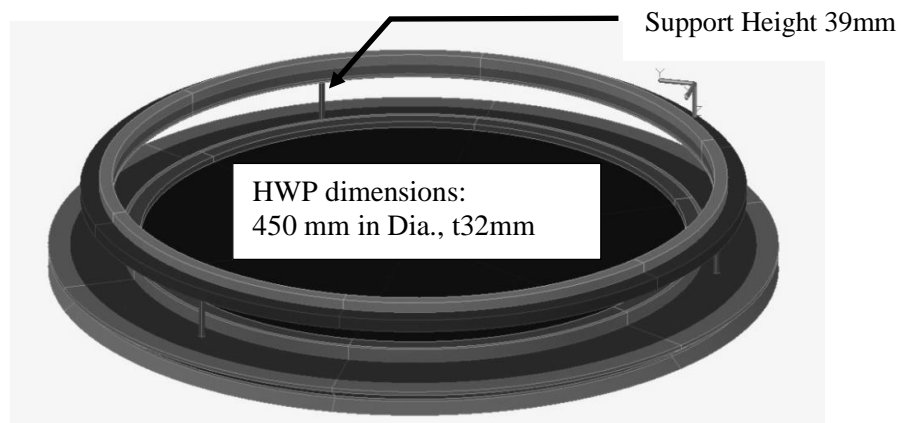
Support Height 39mm

HWP dimensions:
450 mm in Dia., t32mm

Figure 4. Thermal model of the full-scale rotor configuration.

Table 2. Differences between the scaled and full-scale rotors

	Scaled	Full-scale
Dimensions		
# Outer diameter of rotor bottom	120 mm	570 mm
# Height	53.3 mm	81.0 mm
Weight	0.76 kg	28.72 kg
Gripper contact area ratio	1	9.5

4.2. Maximum heat dissipation to be allowed in operation

The thermal requirement is that the HWP is not allowed to exceed 10 K during the hold time of ADR, which is 24 hrs. We estimated the maximum heat dissipation is allowed for the HWP not to exceed 10 K over 24 hrs. after we start heating the rotor from 4 K using the thermal model.
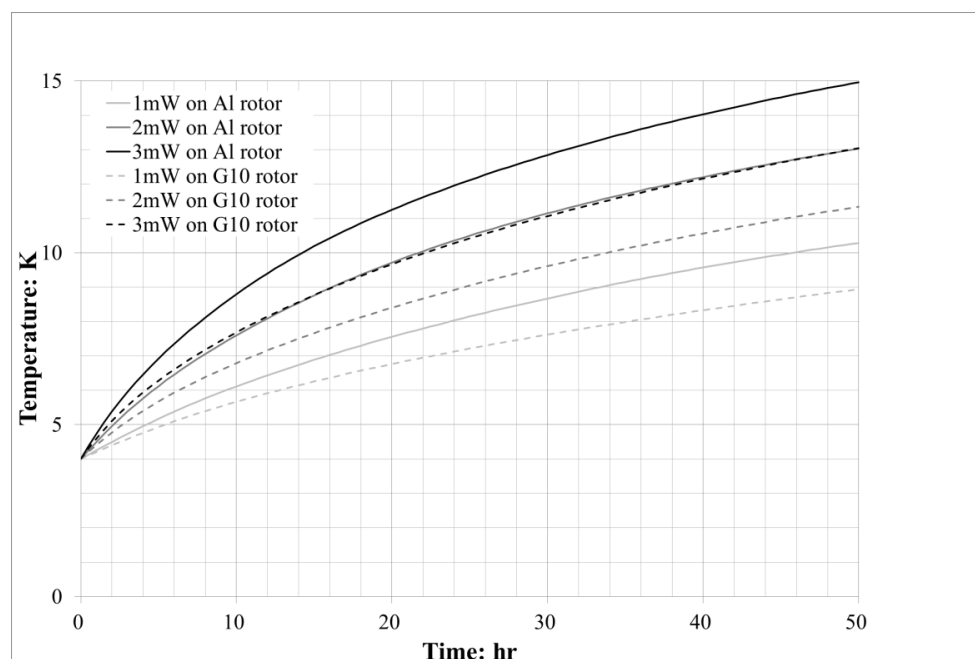
Figure 5. The temperature of the HWP with different heat inputs.

The simulations are conducted by considering different materials of the rotor, Rotor top and Rotor bottom: aluminium 6061 and G10. The former C_p is much smaller than the latter C_p at cryogenic temperatures. The transient temperature of HWP with the rotor of each material is simulated with different heat loads as 1 mW, 2 mW and 3 mW, as shown in Figure 5. The simulation results are summarized in Table 3. It is found by interpolating the simulation results that the heat dissipation of 1.82 mW for Al rotor and that of 2.76 mW for G10 rotor are allowed. Thus, we should take a rotor of G10 if we keep its temperature below 10 K for a longer time period.

Table 3. Summary of the HWP temperatures at the time of 24 hrs.

	1 mW	2 mW	3 mW
Rotor material: Aluminium 6061	8.03 K	10.35 K	11.96 K
Rotor material: G10	7.13 K	8.93 K	10.28 K

4.3. Cool-down time prediction for the HWP to recover 4 K

We experimentally measured a thermal contact conductance between the scaled rotor and gripper. The conductance was 1 mW/K [1] for each gripper. The full-scale size is expected to have a larger contact area, and thus, we employ the area ratio of 9.5, that is simply scaled by the difference in contact area. We can also easily foresee to increase the contact area, and thus we also run the simulation with the contact conductance of 19 and 67 mW/K too. The cooling profile of the HWP temperature is simulated before and after the rotor is grabbed by the grippers, as shown in Figure 6. Two different materials, aluminium 6061 and G10, are compared as a rotor material in the simulation. The appropriate heat load, 1.82mW for Al rotor and 2.76mW for G10 rotor, is applied onto the HWP as the HWP temperature goes to 10 K at 24 hours after the beginning of heating. In Figure 6, the rotor is grabbed by grippers at the time of 24 hours. The rotor is thermally shorted to the 4K cold plate through the three grippers. The simulation results are summarized in Table 4. It is found from the results that the cool-down time for the Al rotor is about 1.5 hours and that for the G10 rotor is about 3 hours in the worst cases although the cool-down time depends the thermal contact conductance. Either way, any cases are within the ADR recycle time, which is 4 hours. Thus, we can recover the 4 K temperature on the HWP of the full-scale rotor within 4 hours. even if the temperature is increased by some energy losses in operation.
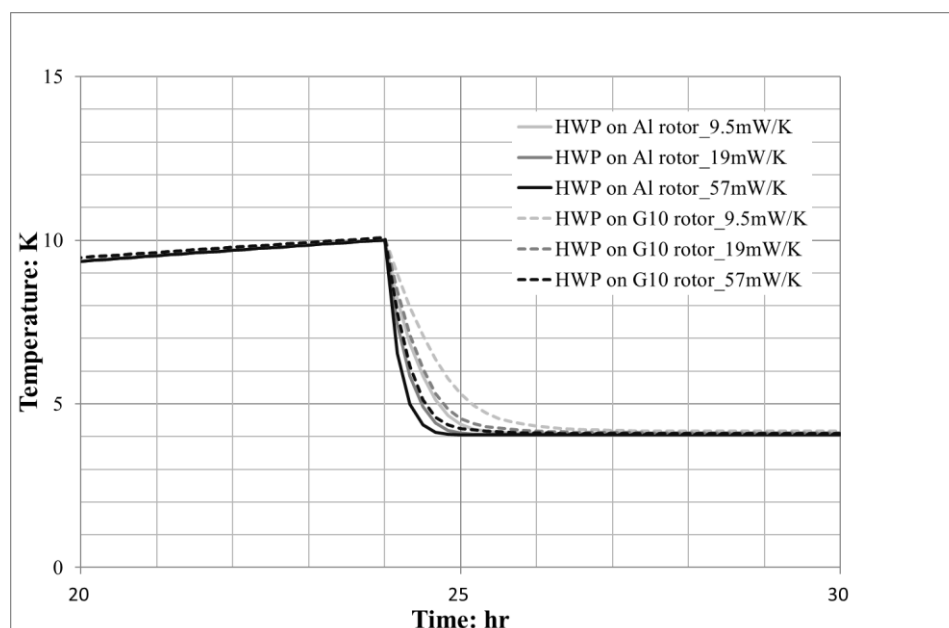

Figure 6. The HWP temperature as a function of time when the rotor is grabbed by the three grippers and the HWP is cooled down to 4 K.

Table 4. Cool-down time prediction to recover 4K on HWP

Material	Al	Al	Al	G10	G10	G10
Thermal contact conductance: [mW/K]	9.5	19	57	9.5	19	57
Time: [hours]	1.51	1.19	0.89	3.17	2.58	2.22

5. Conclusions

We built a thermal model of the PMU. We verified our thermal model by comparing the simulation to the experimental data. We show the agreement between the model and the data within 3%. We used this thermal model and computed the projected performance with a full-scale model. In particular, we computed the maximum power that can be dumped to the levitating rotor to keep the HWP temperature to be below 10 K for 24 hours. We showed that a few mW of power can be dumped to the rotor. We also confirmed that the cool-down time from 10K to 4K on the present rotor design, even if either material is taken, is within the ADR recycle time, 4 hours.

References

1. Sakurai Y, Matsumura T, Kataza H, Utsunomiya S, Yamamoto R, *IEEE Transactions on Applied Superconductivity* vol. 27, no. 4, June 2017, no. 3601904
2. Matsumura T, Sakurai Y, Kataza H, Utsunomiya S and Yamamoto R. *Physica C: Superconductivity and its applications.* **530** (2016) 138-141

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