ABSTRACTS (PH D THESIS)

Study on High Temperature Superconducting Coil System for Magneto Plasma Sail Spacecraft

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Superconducting coils can revolutionize space propulsion systems. The performances, e.g., acceleration and thrust to power ratio, of space propulsion systems can be greatly improved with a superconducting coil by generating a larger magnetic field with less power consumption and weight. A magneto plasma sail is a space propulsion system with a higher fuel efficiency or specific impulse for future deep space explorations. The thrust of the magneto plasma sail is produced by the transfer of momentum from a solar wind plasma to a strong magnetic field generated by a High Temperature Superconducting (HTS) coil as shown in Fig. 1. The thrust of the sail is proportional to the magnetic moment of the coil (coil turn number × coil current × area enclosed by the coil). To obtain a large thrust to mass ratio, or acceleration, enough for space missions, our target is to increase the magnetic moment to mass ratio of the HTS coil system ten times larger than that obtained by a previous study. The HTS coil system is optimized to maximize its magnetic moment to mass ratio within the capacity of a launch vehicle.

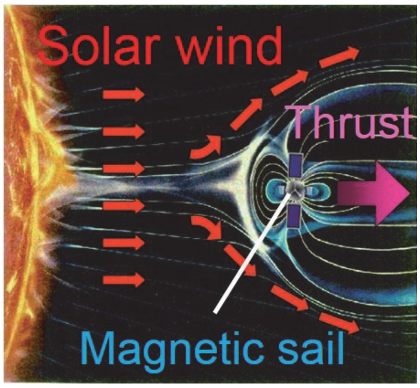


Figure 1. Thrust generation mechanism of the magneto plasma sail.

To design an HTS coil for the magneto plasma sail, we first investigated a quantitative current transport performance and thermal behavior of an HTS coil, and the effect of the critical current inhomogeneity along the longitudinal direction of HTS tapes on the coil performances. We measured the current transport property and temperature rises during current applications of a scale-down model HTS coil using a Bi-2223/Ag tape in a conduction-cooled system, and analytically reproduced the results on the basis of the percolation depinning model and three-dimensional heat balance equation. As a result, we precisely estimated the critical currents of the HTS coil within 10% error for a wide range of the operational temperatures from 45 to 80 K, and temperature rises on the coil during current applications as shown in Fig. 2. These results showed that our analysis and conduction-cooled system were successfully realized. The analysis also suggested that the critical current inhomogeneity along the length of the HTS tape deteriorated the current transport performance and thermal stability of the HTS coil.

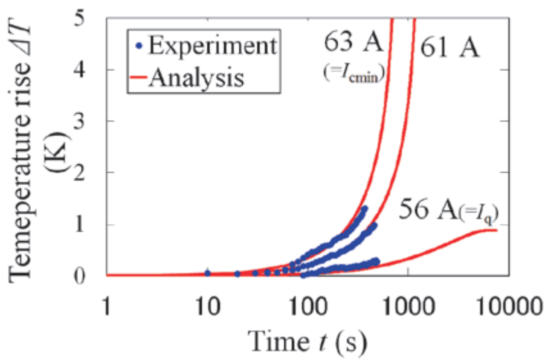


Figure 2. An example of the estimation of temperature rises of the HTS coil.

We also modeled screening currents I_s induced in HTS coils to investigate the effect of I_s on the coil magnetic field and a transport AC loss in an HTS coil for space applications of the HTS coil. We compared analysis results with experimental data obtained from the Bi-2223/Ag scale-down model coil. The experimental residual magnetization due to I_s in the Bi-2223/Ag coil can be effectively modeled assuming an equivalent loop length of approximate 9 mm for I_s in the coil. The values calculated from the method quantitatively agreed with the results for various experimental conditions as well as the hysteresis of the magnetization due to I_s. These results demonstrated the validity of our model for screening currents I_s, which considers the effects of flux creep and smaller I_s loops in the multi-filamentary Bi-2223/Ag tape. The transport AC loss in an HTS coil under AC ripple currents with DC offsets was also investigated to use a DC/DC converter for space applications of the HTS coil. Our analysis clarified that larger DC offsets greatly increase the effective AC loss even under a smaller AC current. In addition, we showed that the AC loss decreased the thermal stability of the conduction-cooled coil in case that HTS tapes in the coil are in the flux-flow state such as the load factor of 80%. These results suggested that, in order to apply the AC ripple current to HTS coils, the operational load factor must be properly selected.

To design an optimal HTS coil for use in space, we analyzed the characteristics of HTS coils using a Bi-2223/Ag tape or YBCO coated-conductors. The suitable configuration of the HTS coil was searched within a diameter of 4 m to obtain a larger magnetic moment and clarify the obtainable propulsive force from the magneto plasma sail. We analyzed the current transport properties, thermal behavior, and applied stresses of the HTS coils, and compared these characteristics for each coil configuration. As a result of a sensitivity study, we showed that a thin-walled racetrack coil or multi-pole coil with YBCO coated-conductors could achieve the larger magnetic moment (as shown in Fig. 3) with allowable stresses and high thermal stability for space missions.

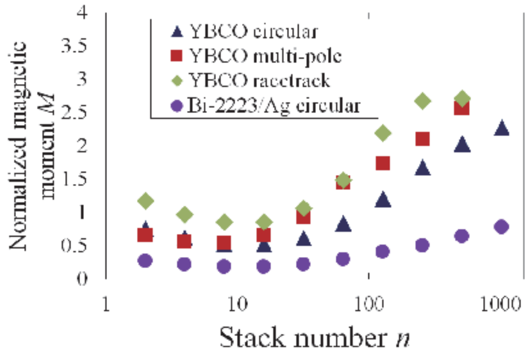
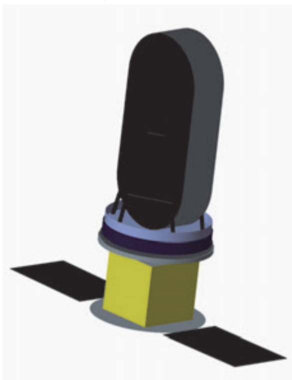


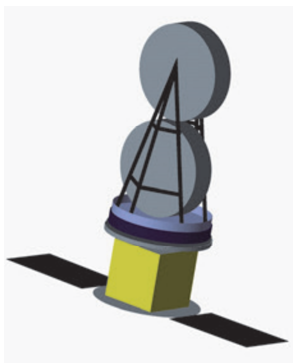
Figure 3. Dependence of the magnetic moment of the coils in the case of an outside radius of 2.0 m on the coil configuration.

The whole HTS coil system including the cooling system was also optimized to maximize the magnetic moment to mass ratio or acceleration, of the magneto plasma sail. The weight of the cooling system was considered for each coil configuration. We optimized the configuration of the coil using the genetic algorithm in the case of YBCO circular, multi-pole and racetrack coil at a variety of the operational temperatures from 10 K to 50 K on the condition of the perpendicular or parallel direction of the magnetic axis to the sun direction. Figure 4 shows the optimal coil system with the racetrack coil or multi-pole coil. For all kinds of the coils, the magnetic moment to mass ratio reaches the highest value at the operational temperature of around 20 K. On the other hand, in the case of using the HTS coil at less than 20 K, the magnetic moment to mass ratio rapidly decreases because a larger radiation cooling system is required. This study finally revealed that the racetrack coil system can maximize the magnetic moment to mass ratio of the system which is approximate three times larger than that of the minimum requirement for the magneto plasma sail.

The present study proved the possibility to increase the thrust to mass ratio of the magneto plasma sail greatly, and leads to realizing a space propulsion system using an HTS coil.



(a) Racetrack coil



(b) Multi-pole coil

Figure 4. Overview of the optimal system of the magneto plasma sail with (a) racetrack coil or (b) multi-pole coil.