Deep Space Cryocooler Control Electronics for the Ricor K508

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ABSTRACT

In this paper, Iris Technology in cooperation with Southwest Research Institute (SwRI) and Ricor present the design and test of the MASPEX Cryocooler Electronics Board (MCEB) for SwRI's MAss Spectrometer for Planetary EXploration (MASPEX) instrument for NASA's Europa Clipper mission to Jupiter's moon Europa. The challenges of developing deep space electronics are discussed along with the challenges of driving rotary cryocoolers. An overview of the MCEB development process from conceptual design to deep-space electronics implementation is also given. MCEB performance data are presented along with lessons learned along the way. In addition, the testing and qualification of the Ricor K508 cryocooler performed by Ricor and SwRI is discussed.

INTRODUCTION

To support the MASPEX instrument of the Europa Clipper, SwRI selected the Ricor K508 cryocooler to chill captured samples for later analysis. Subsequently, SwRI selected Iris Technology to develop Cryocooler Control Electronics (CCE) for the K508 that would survive the harsh conditions presented by the Europa Clipper mission.

Both Ricor and SwRI tested the flight K508 cryocoolers and both Iris Technology and SwRI tested the MCEB. This paper addresses this testing along with the MCEB development.

OVERVIEW

Europa Clipper Overview[1]

Europa Clipper will be the largest spacecraft NASA has ever developed for a planetary mission. The spacecraft will be about 16 feet (5 meters) in height. With its arrays deployed, the spacecraft spans more than 100 feet (30.5 meters) and has a dry mass (no propellant in the tanks) of 7,145 pounds (3,241 kg). Because Europa is bathed in radiation trapped in Jupiter's magnetic field, Europa Clipper's payload and other electronics will be enclosed in a thick-walled vault. The vault walls – made of titanium and aluminum – will act as a radiation shield against most of the high-energy atomic particles, dramatically slowing down the degradation of the spacecraft's electronics. An illustration of the Europa Clipper is shown in Figure 1.

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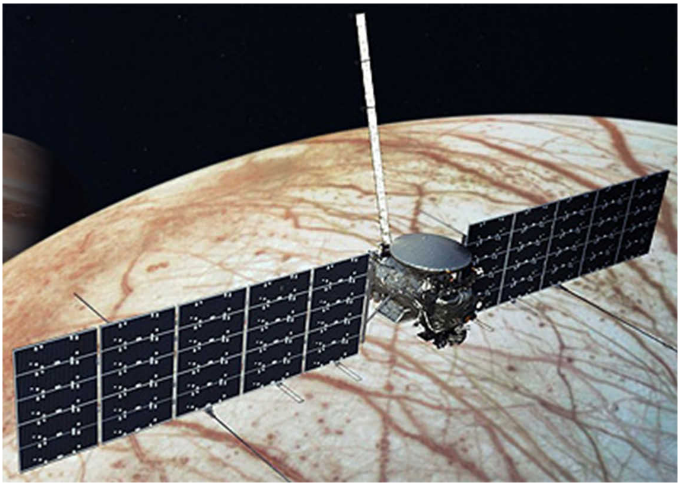

Figure 1. NASA's Europa Clipper will conduct a detailed reconnaissance of Jupiter's moon Europa and investigate whether the icy moon could harbor conditions suitable for life. The mission will place a spacecraft in orbit around Jupiter to perform a detailed investigation of Europa — a world that shows strong evidence for an ocean of liquid water beneath its icy crust and which could host conditions favorable for life. The mission will send a highly capable, radiation-tolerant spacecraft into a long, looping orbit around Jupiter to perform repeated close flybys of the icy moon.

Jupiter's moon Europa shows strong evidence of an ocean of liquid water beneath its icy crust. Besides Earth, Europa is considered one of the most promising currently habitable environments in our solar system.

Europa Clipper has three main science objectives:

- Determine the Thickness of Europa's Icy Shell and How the Ocean Interacts with the Surface
- Investigate Europa's Composition
- Characterize the Geology of Europa

Europa Clipper will carry science instruments more advanced and sensitive than anything that's explored this Jovian moon before. There are nine unique instruments:

- Imagers
  - Europa Imaging System (EIS)
  - Europa Thermal Emission Imaging System (E-THEMIS)
- Spectrometry
  - Europa Ultraviolet Spectrograph (Europa-UVS)
  - Mapping Imaging Spectrometer for Europa (MISE)
- Plasma and Magnetic Field
  - Europa Clipper Magnetometer (ECM)
  - Plasma Instrument for Magnetic Sounding (PIMS)
- Radar & Gravity
  - Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
- Chemical Analysis
  - MAss SPectrometer for Planetary EXploration/Europa (MASPEX)
  - SUrface Dust Analyzer (SUDA)

Whatever Europa Clipper reveals could change our understanding of the solar system, and other planetary systems, forever.

MASPEX Overview[2]

The space near Europa teems with gases. Some get knocked off Europa's surface by Jupiter's relentless radiation. Others might vent into space from Europa's suspected subsurface ocean, or from water

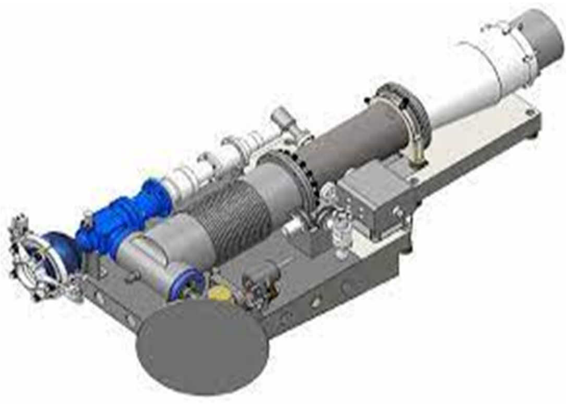

Figure 2 MASPEX generates high-energy (fast-moving) electrons to strip electrons from incoming gas molecules. That makes the gas molecules into positively charged ions. The instrument accelerates the ions to a uniform amount of energy. The ionized gases are pulled into the "drift tube," which gives MASPEX its baguette-like length. The lighter the ion, the faster it can move through the drift tube.

trapped in the moon's ice shell. The MAss Spectrometer for Planetary EXploration /Europa, or MASPEX, will identify those molecules with unparalleled precision. An illustration of the MASPEX is shown in Fig. 2.

MASPEX collects gases and converts them into charged particles called ions. It bounces the ions (atoms and molecules missing an electron) back and forth within the instrument. By timing their transit through the instrument, MASPEX determines the ions' mass. The mass reveals each molecule's identity to help determine whether Europa is habitable.

MASPEX will gain crucial answers from gases near Europa, such as the chemistry of Europa's surface, atmosphere, and suspected ocean. MASPEX will study how Jupiter's radiation alters Europa's surface compounds and how the surface and ocean exchange material.

The MASPEX Cryotrap[3]

MASPEX, shown in Fig. 3, also has excellent sensitivity due to an ion source that stores 200,000 ions every half-millisecond before the ions are released into the ion optical path. Even with its great sensitivity,

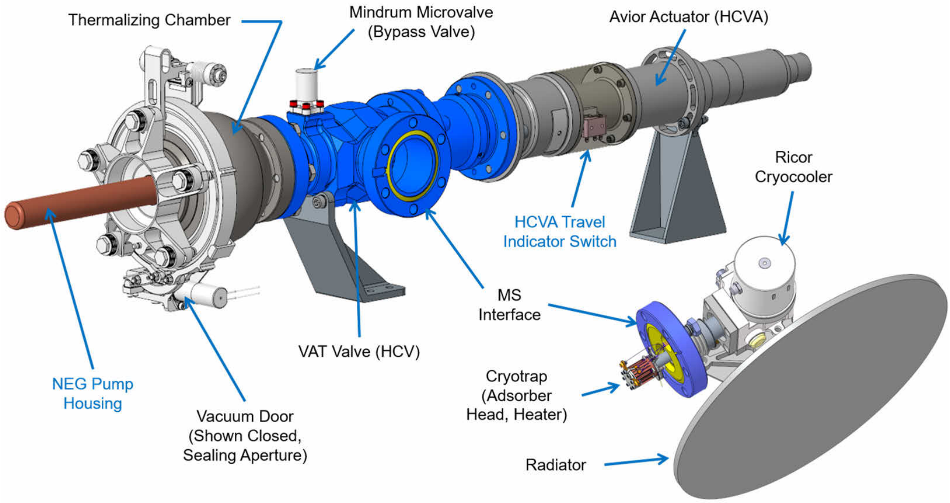

Figure 3. MASPEX uses a Ricor K508 cryocooler to provide cryo-trapping of volatiles from the exosphere of Europa that occurs simultaneously with the in-situ sampling during the flyby thereby increasing the sensitivity to trace volatiles by over three orders of magnitude.[4]

however, MASPEX has difficulty collecting enough gas to see the rarest molecules. For that, SwRI engineers incorporated a cryotrap into the instrument. This device freezes and concentrates gas samples, boosting the instrument's sensitivity by a factor of 10,000. On every flyby, MASPEX will both directly sample the atmosphere and concentrate a sample of the atmosphere, using a frigid surface to trap the gas. After the flyby, this cryotrap releases the sample into MASPEX's detectors, providing a concentrated sample of Europa's atmosphere and effectively increasing the instrument's sensitivity. The MASPEX cryotrap is cooled by a Ricor K508 cryocooler.

Ricor K508 for Space[5]

RICOR refrigerators have been involved in various space missions, starting with the "Clementine" Moon mission in 1994. Ricor tactical rotary refrigerators have been incorporated in many space instruments, after passing qualification, lifetime, thermal management testing, and flight acceptance.

The tactical to space customization framework includes an extensive characterization and qualification test program to validate reliability, the design of thermal interfacing with a detector, vibration export control, efficient heat dissipation in a vacuum environment, robustness, mounting design, compliance with outgassing requirements, and strict performance screening.

Engineering Model Unit Selection

The first step in the selection process is the Ricor standard screening process of all production units, more than 1000 per month (Fig. 4). Since the primary failure mode of rotary machines is a piston rod bearing, or crankshaft bearing, Ricor's first task is to define the lowest pressure for which adequate cooling power can be obtained. The refrigerator is then operated open loop for 48 hours. It is expected that refrigerators having the lowest values of cold finger temperature and input current would have the lowest average operating speed, and those having the lowest noise and vibration levels would cause the least amount of wear on the bearings. Ricor selects refrigerators having a high probability to meet mission specifications, only 2-3% of the refrigerators produced each month, on average.

Each candidate refrigerator is then placed in a climate chamber for performance testing at various ambient temperatures. The refrigerator will then be run closed-loop and tested for stable operation. This test is repeated twice for each candidate refrigerator. The best candidate refrigerators selected by this screening are processed on an accelerated schedule as the Engineering Model (EM) and then shipped to the customer. Ricor experts choose a pool of the "best" refrigerators from a batch manufactured over three months, for further testing and selection as Flight Model (FM) units.

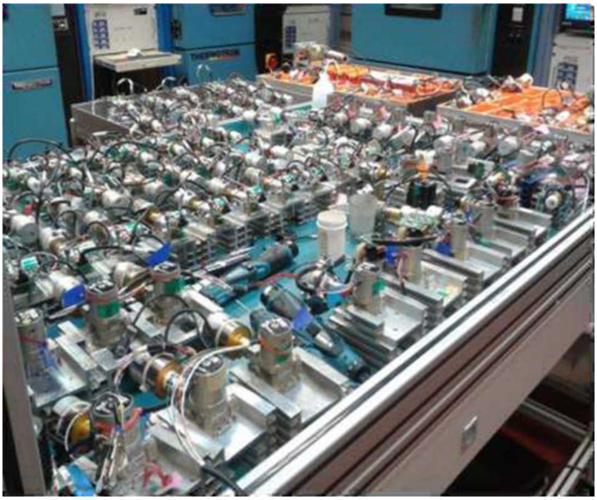

Figure 4. Candidate refrigerators before selection testing for space application.[5]

Flight Model Unit Selection

The selected pool of candidate refrigerators is further tested in a climate chamber to measure their performance more precisely over the full range of ambient temperatures, to differentiate them, and select the "best" flight-quality refrigerators. Continuous histories of the compressor and cold-finger temperatures, refrigerator input power, voltage, current, and heat load for each unit under test (UUT) are measured and recorded. Motor speed is also measured for each candidate refrigerator for specific sets of parameter values that are the same for each refrigerator.

When the entire measurement sequence is completed for all candidate refrigerators, Ricor experts thoroughly analyze the data and prepare a comprehensive report recommending which refrigerators a customer should select as the "best". Ricor can send this report to a customer along with all data on all candidate refrigerators, to aid the customer in making the final selection of which refrigerators to procure as Flight Model units.

Additional K508 Screening at SwRI

SwRI performed environmental lifetime testing on a group of three cryocoolers from the same lot. This environmental lifetime test included vibration testing, exposure to ionizing radiation to a level of 4 Mrad TID, and thermal vacuum testing representative of thermal cycles expected during flight. The order of operations was pre-vibe testing (~10 ON/OFF) cycles to establish the baseline performance of the coolers in terms of the time it takes to reach the setpoint temperature and then the power draw during the regulated mode. The coolers were subjected to vibration and then ~50 ON/OFF cycles. The coolers then were irradiated to 1 Mrad TID and exposed to ~200 ON/OFF cycles, then irradiated again to 1 Mrad TID for a total cumulative dose of 2 Mrad TID and then subjected to another ~200 ON/OFF cycles. Then thermal vacuum testing was performed. During the thermal test, the coolers were turned ON at -30 deg C and 100 ON/OFF cycles were performed. The last step was a 2 Mrad TID to a cumulative TID of 4 Mrad and then more than 400 ON/OFF cycles. During each ON/OFF cycle, the cooler was run until it reached 65 K on the cold tip and then held at that temp for ~93 minutes.

The vibration testing requirements for the cryocoolers were established from simulations representing the PSD (g^2/Hz) response at the base of the cryocooler as transmitted from the S/C vault interface to the MASPEX Instrument panel, using the JPL/NASA ERD Rev B vibration inputs. From these spectra, a set of ASD input curves was developed according to NASA FEMCI accepted practice (https://femci.gsfc.nasa.gov/) for creating a random vibration component test specification.

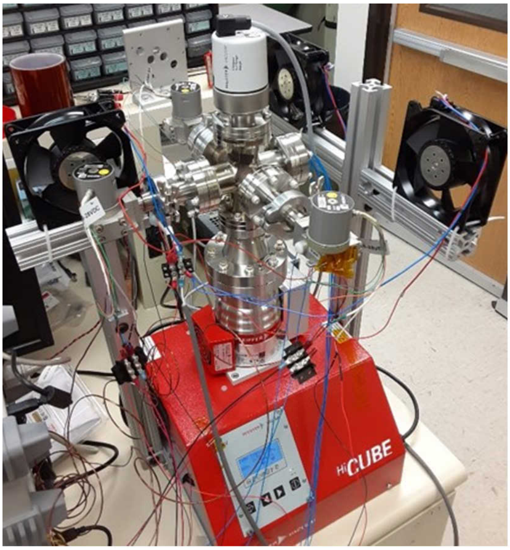

Figure 5. This test setup was used at SwRI for Ricor K508 testing.

Figure 6. The fully assembled MASPEX Cryocooler Electronics Board (MCEB).

MASPEX Cryocooler Electronics Board (MCEB)

The MASPEX Cryocooler Electronics Board (MCEB) is an electronics board designed by Iris Technology to drive a Ricor K508 rotary cryocooler. The electronics design was based on the Low-Cost Cryocooler Electronics – Rotary (LCCE-R) which in turn was based on the Low-Cost Cryocooler Electronics (LCCE) design to drive a two-piston cryocooler. The fully assembled board is shown in Figure 6. The most significant change in the electronics from the LCCE-R was the removal of the Hall effect sensor interface because the Hall effect sensors would not survive in deep space. Back Electro-Motive Force (BEMF) was used to monitor and initiate commutation in place of the Hall effect sensors. In addition to the capability of driving the K508, the MCEB also had to survive the harsh environment experienced by the Europa Clipper and only use the area of half of a PCI board.

A block diagram of the MCEB is shown in Figure 7. The blue blocks in the diagram were used as-is from the LCCE-R, the green blocks are modified designs from the LCCE-R and the yellow blocks are new designs for the MCEB. Note that unlike most Iris Technology cryocooler control electronics (CCE) the MCEB requires several discrete power voltages to the board along with an external clock.

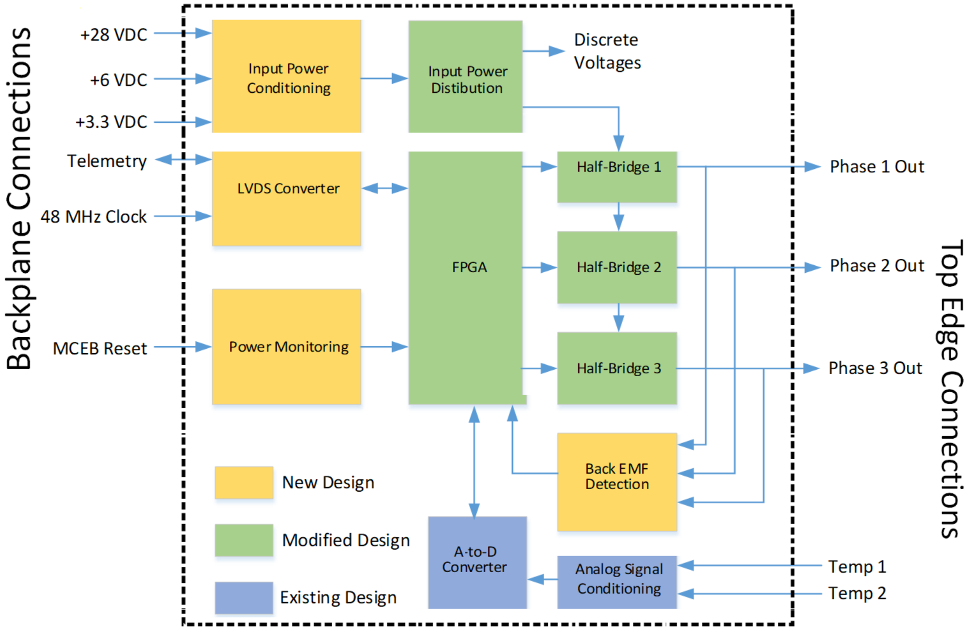

Figure 7. Block diagram of the MASPEX Cryocooler Electronics Board (MCEB).

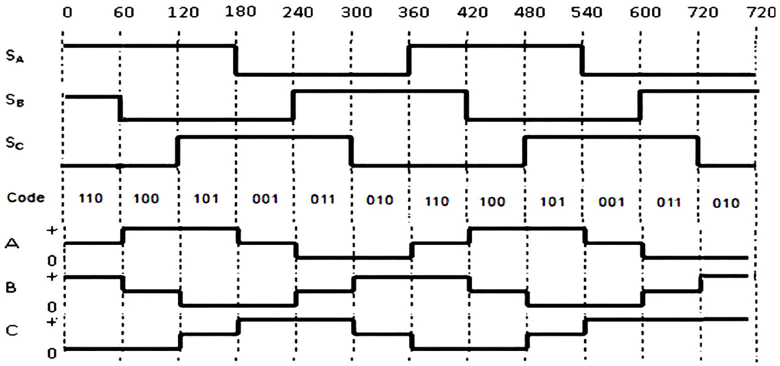

Figure 8. Commutation using Hall Effect Sensor

Developing Commutation Techniques for the Ricor K508

Since the Hall effect sensor could not be used for the MCEB, other methods had to be considered. Different methods were tried before a solution was settled upon. Several methods are described in the following paragraphs.

BLDC Motor Control with Hall-Effect Sensors

To set the context, we will discuss Hall effect sensor commutation and some rotary motor basics as a way of review. The Ricor K508 is a brushless DC motor (BLDC) with a permanent magnet rotor. The rotor is inside the gas chamber of the Stirling-type micro cooler, while the stator windings are outside. The rotor has 3 pole pairs, and the stator has 18 poles wired at a 3-phase star configuration. The commutation is controlled by 3 Hall-effect sensors on the stator windings that sense the rotor field. The basic switching scheme is shown in Figure 8. Hall-effect sensors are subject to radiation damage and cannot be used on long-duration or deep space missions.

BLDC Motor Control with DC/2-Centering with Virtual Neutral

Iris initially tried using the DC/2 BEMF detection method. The details are shown in Figs. 9a and 9b. Instead of detecting a zero-crossing, as is done with Hall sensor commutation, the voltage across a motor coil is used. When the motor voltage is zero volts, its BEMF voltage is DC/2. This method worked well with an unloaded COTS BLDC motor. However, the K508 is not unloaded and the BEMF was not consistent enough for this method to work reliably.

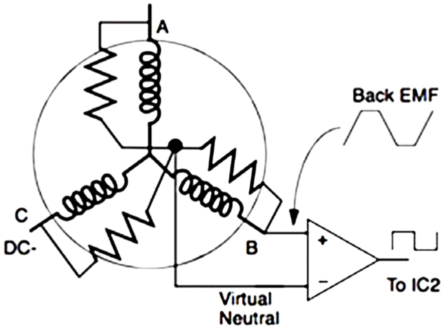

Figure 9a. Zero crossing detection using DC/2 BEMF

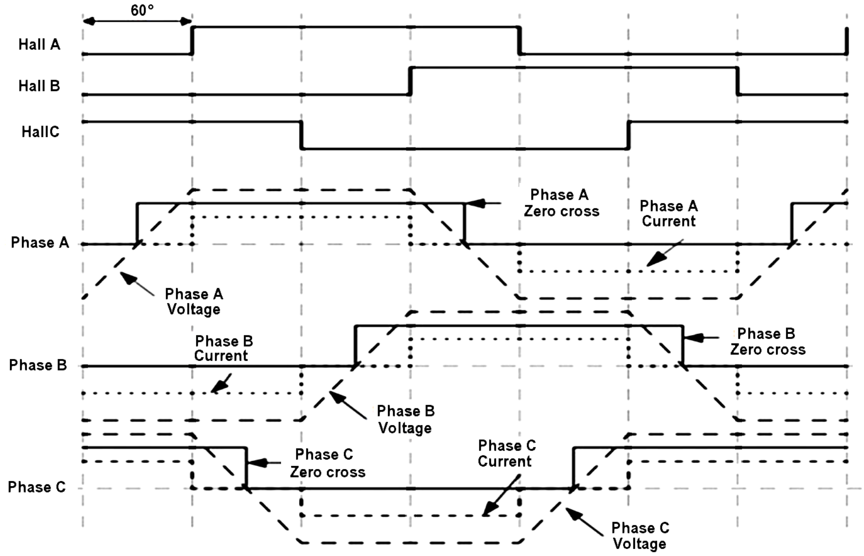

Figure 9b. Commutation using DC/2 BEMF

BLDC Motor Control with Phase to Phase (P2P) BEMF Detection

Phase to Phase P2P BEMF detection is handled much like Hall sensor detection. In this method, differential BEFM Phase crossings are compared to control commutation. This is shown in Figure 10. The greatest challenge was filtering the BEMF signals to minimize ripple voltage without causing the motor drive signals to ring excessively. Time-based digital filtering was also introduced to only allow state changes in the expected state change windows.

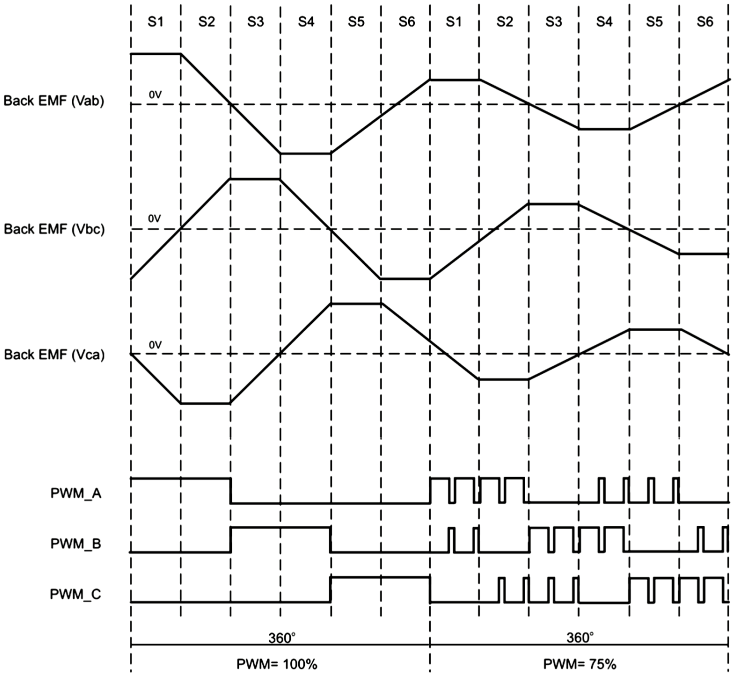

Figure 10. Commutation using Phase to Phase (P2P) BEMF Detection.

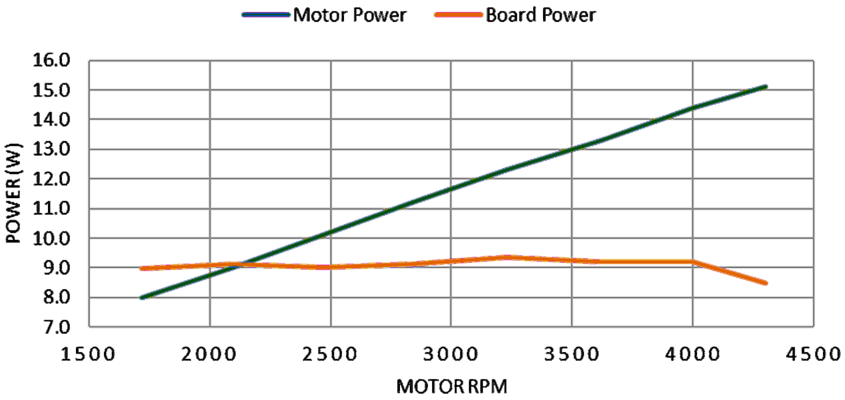

Figure 11. MCEB Board Power versus Motor Power.

Other Design Challenges

Electrical, Electronic, and Electromechanical (EEE) components are the fundamental building blocks of any spacecraft. For Europa Clipper, EEE components were required to meet 300 krad total ionizing dose (TID). This severely limited the components that could be considered for the MCEB design. In addition, the lead times for this class of components were extremely long.

Early testing of the engineering model (EM) MCEB revealed that the 28-volt power supply unexpectedly could not handle the current ripple induced by commutating the K508. Since there was very limited time and board area to facilitate a change, a simple passive ripple filter was added to the flight model (FM) design. This had the unfortunate effect of significantly increasing the power draw to the MCEB and therefore reducing efficiency.

MCEB Performance

Testing of the MCEB showed good results. The MCEB met all mission performance requirements. It was found that the minimum rotational speed at which the K508 could be reliably started was around 1700 RPM. Basic commutation and quiescent power of the MCEB required about 9 watts of power, however, this value did not increase with motor RPM. The power provided by the MCEB to the K508 motor increased linearly with motor RPM. This is shown in Figure 11.

CONCLUSIONS

While the MCEB was specifically designed to support the MASPEX mission, the design could be used to produce a more generalized solution for the K508 or other rotary cryocoolers. Like other Iris CCE products, we could produce a solution in a box rather than plugging it into the PCI backplane.

Based on lessons learned, efficiency improvements could be made by: (a) proper IRF would reduce quiescent power consumed by the RC filter, (b) snubber optimization could improve some of the efficiency losses, (c) modifications to the PWM rate could further enhance efficiency, and (d) cycle by cycle current limiting could ensure more consistent torque and therefore less low-frequency input ripple current.

This effort not only provided cryocooler control capability for the MAPEX instrument but also provides a basis for a design to offer control of the Ricor K508 and its variants in less harsh geocentric orbit environments.

ACKNOWLEDGMENTS

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