X-57 Electromagnetic Interference Design, Integration, and Test Consideration

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Motivation for Mod II;
Retiring Electric Propulsion Barriers

- Advance the Technology Readiness Level for aircraft electric propulsion. Aerospace has weight, safety, and flight environment challenges which complicate adaptation of COTS technologies
  - X-57 needs high voltage lithium batteries with intrinsic propagation prevention and passive thermal management
  - Establish motor/inverter ground and flight test program
  - Design crew interface and human factors approach to manage workload for complex propulsion systems
- Reduces electrified system development risk for Mod III and IV through early testing on a proven vehicle configuration
- Develop capability within NASA to design, analyze, test, and fly electric aircraft
- Pathfinder for aircraft electric traction system standards. Lessons learned used to inform FARs and standards

Two Cruise Motor Controllers (CMCs) are used to power each Cruise Motor (CM). The CMCs are located in the CM nacelles.

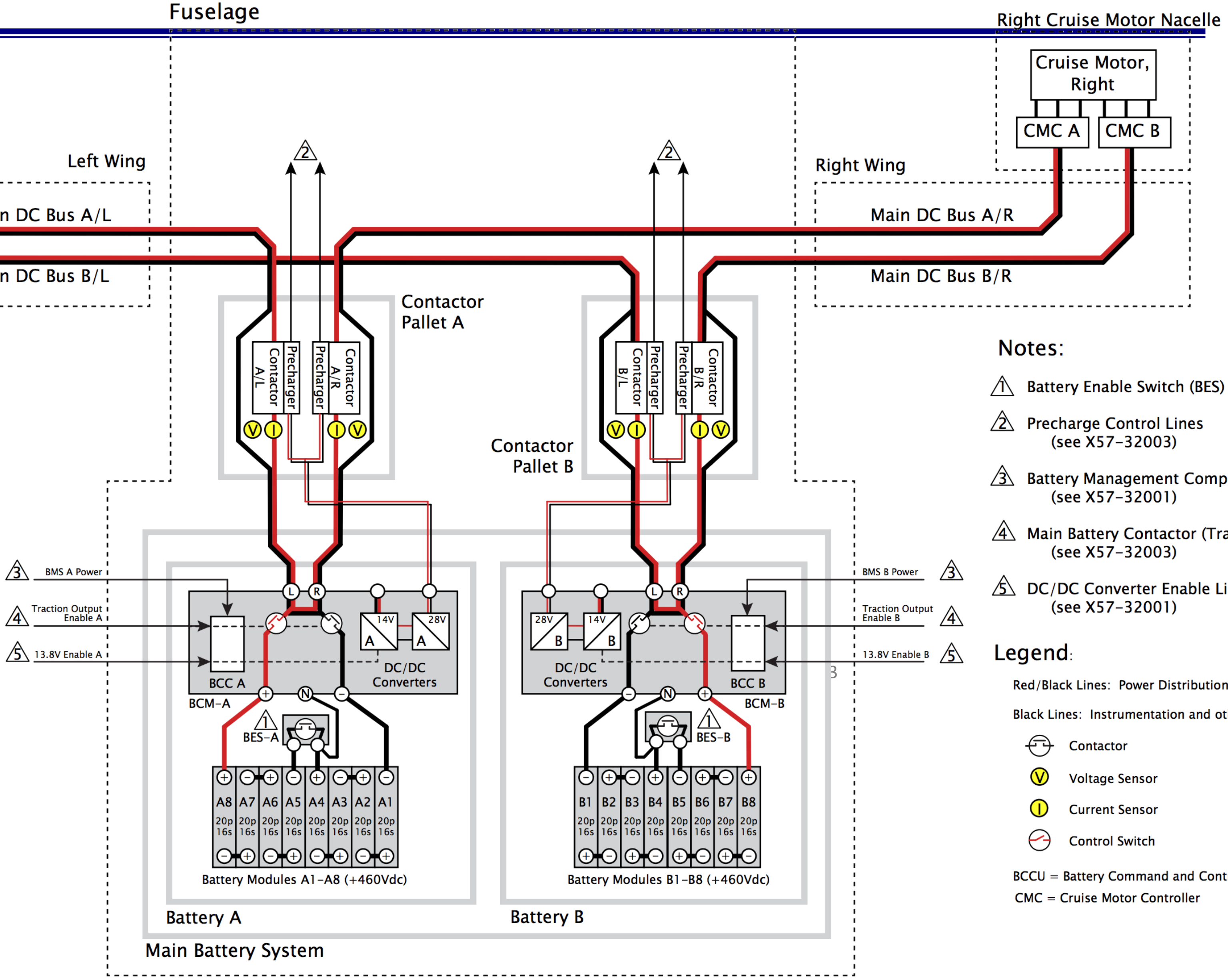
The value of X-57 lies in advancing the Nation's ability to design, test, and certify electric aircraft, which will enable entirely new markets (UAM)

Mod 2 Traction Power System

Dual inverter reduces failure severity

High voltage contactors required for hazard segmentation

Independent battery packs enables powered landing after cell failure



Notes:

1. Battery Enable Switch (BES)
2. Precharge Control Lines (see X57-32003)
3. Battery Management Computer (BMS) Power (see X57-32001)
4. Main Battery Contactor (Traction) Enable (see X57-32003)
5. DC/DC Converter Enable Line (see X57-32001)

Legend:

Red/Black Lines: Power Distribution Buses with Returns

Black Lines: Instrumentation and other Signal Wiring

Contactor

Ⓥ Voltage Sensor

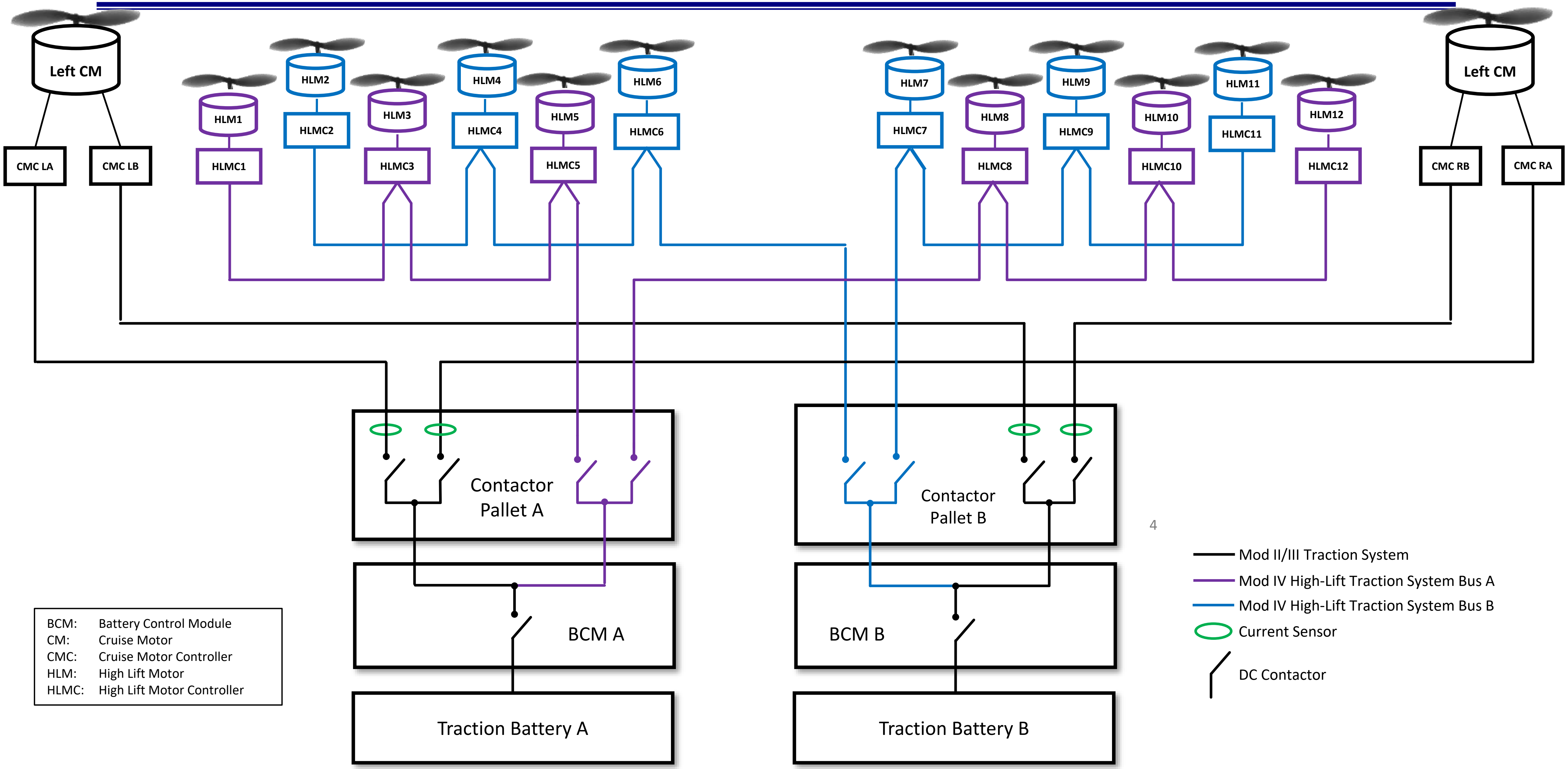
Ⓘ Current Sensor

Control Switch

BCCU = Battery Command and Control Unit

CMC = Cruise Motor Controller

Mod 4 Traction Power System



BCM:	Battery Control Module
CM:	Cruise Motor
CMC:	Cruise Motor Controller
HLM:	High Lift Motor
HLMC:	High Lift Motor Controller

Summary of BM2 CMC Flaws

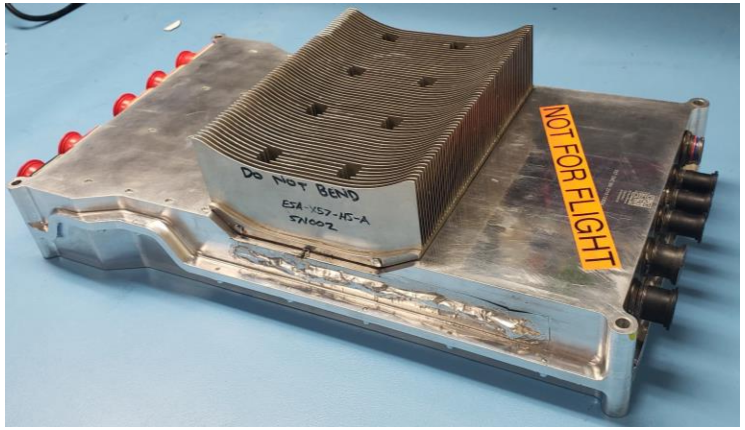
- **Thermal analysis found that the existing heat sink design would not close for MOD III/IV and was marginal for MOD II**
  - Thermal analysis showed that the existing heat sink is unable to reject enough heat to keep the MOSFET modules below their rated temperature limits
  - The analysis also showed that the excess heat would cause the low voltage electronics to overheat due to a lack of thermal isolation
  - A new heat sink design with isolation between the high and low power electronics is necessary
- **Original Cree/Wolfspeed SiC Half-Bridge MOSFET modules failed X-57 vibration acceptance tests**
  - Microsemi MOSFET modules had the same physical dimensions as the Cree modules and were selected as a drop-in replacement
  - Microsemi MOSFET modules passed vibration tests, but had degraded electrical performance and failed to meet the electrical efficiency criteria required for flight
  - No other drop-in replacements exists, requiring a redesign of the case and gate drive circuitry to accommodate a new MOSFET module
- **Phase current acquisition circuitry has unacceptable levels of noise impacting controller performance**
  - Inconsistencies found in the CMC phase current measurements led to a thorough examination of the circuit design
  - A redesign of the sensing circuit with higher accuracy and noise immunity must be implemented for the controller to perform as intended
- **Other issues found in the existing design that will be addressed in the redesign:**
  - High voltage ripple on the DC bus
  - DC Link PCB mounting scheme was unacceptable leading to high levels of vibration on the PCB
  - Not all connectors were keyed
  - Temperature sensing circuits were not optimized for maximum accuracy within the relevant temperature range
  - Boot-up transients affect operations of Vicor power supply within the CMC

Original CMC Design

CMC Designations

- The team distinguishes between the existing and new CMCs by the type of MOSFET used.
    - Existing CMC hardware designed by Joby used Cree BM2 MOSFETs and is referred to as the "BM2 CMCs"
    - New CMC hardware will use Cree XM3 MOSFETs and is referred to as the "XM3 CMCs"

BM2 CMC



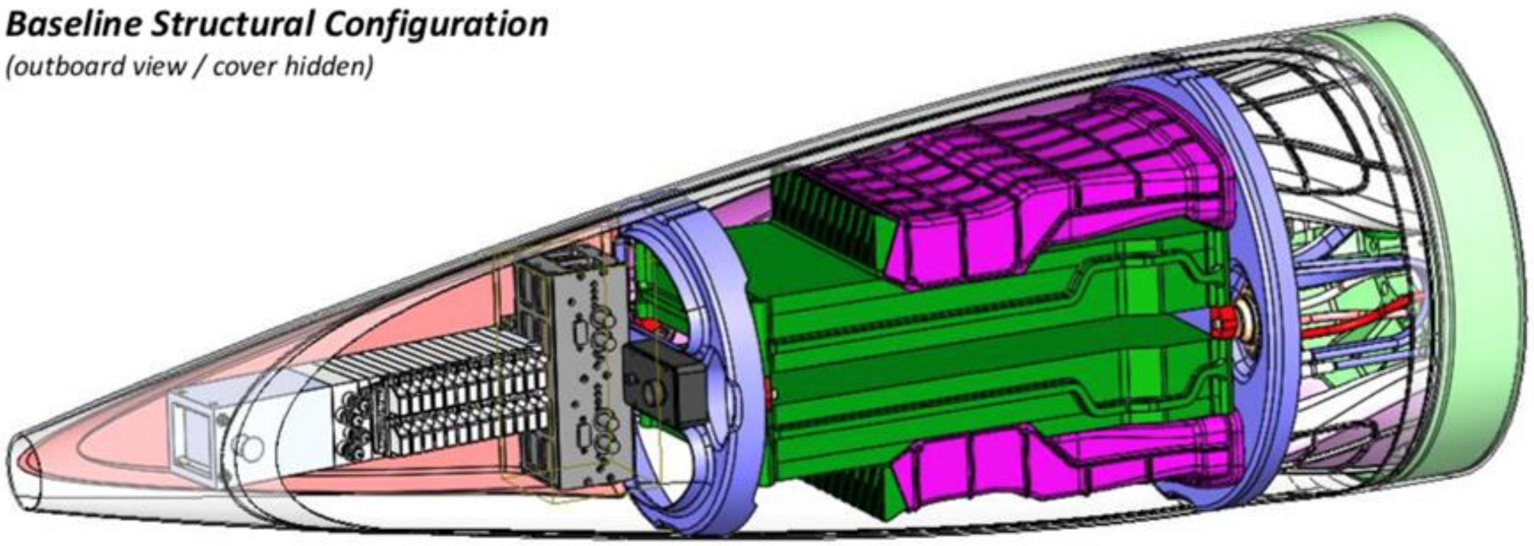
XM3 CMC

Necessity for XM3 CMC Hardware Development

- Team Moving on from the BM2 CMC hardware designed by Joby.
  - BM2 hardware will not:
    - Pass vibe testing
    - Close thermally for Mod II or Mod III cruise nacelle applications
      - Insufficient performance/efficiency to accomplish the mission.
  - Team has identified a number of design deficiencies with the BM2 CMC hardware
- Team is pursuing a NASA led redesign of the CMC with Cree XM3 MOSFETs
  - Cree XM3 MOSFETs have passed vibration testing at AFRC.
- On Aircraft Testing will continue with existing CMCs while awaiting flight CMCs
- In hindsight, the original CMC hardware from Joby should have been considered a prototype and several development cycles worked into the schedule
  - Joby moved on from this CMC hardware years ago, and they are flying a different design.
- Note: X-57 is flying the first air-cooled electric aircraft propulsion system, which is increasing the complexity of the thermal challenges.

Mod III/IV Cruise Nacelle Thermal Challenges

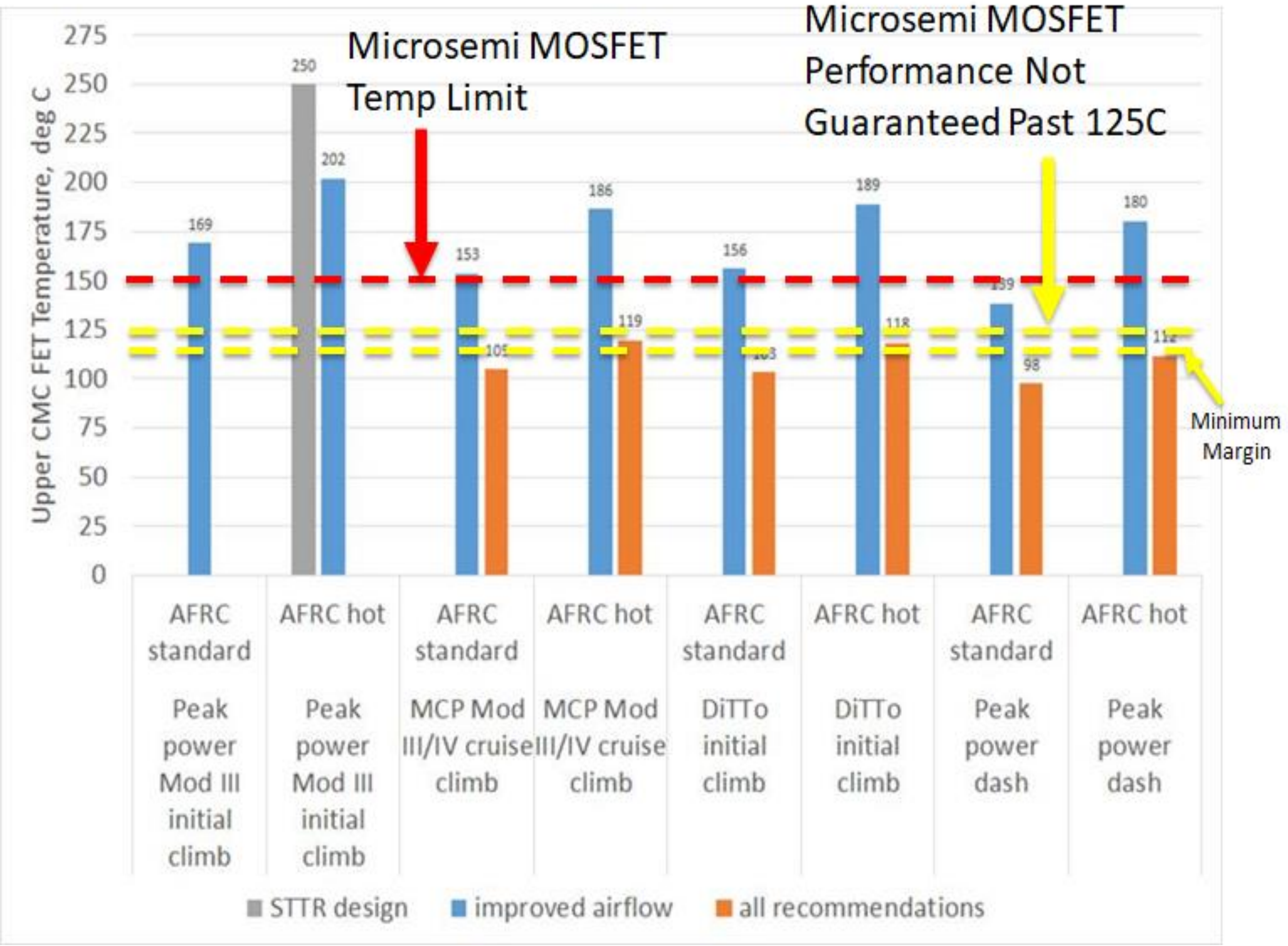
- Mod III/IV Cruise Nacelle system does not close from a thermal standpoint.
  - CMC high power (MOSFETs) and low voltage (logic board) components have inadequate or negative thermal margin.
- Cruise nacelle design is challenging from several standpoints
  - All air used to cool CMCs and all electronics first passes through the cruise motors
  - Internal massflow not optimized and is significantly reduced when compared to the Mod II design.
  - CMC low voltage electronics heat sink is in a non-optimal location aft of the high power heatsink.



Thermal Problem

Below cruise nacelle and CMC design changes required in order to drop the estimated Microsemi MOSFET temperature limit of 125C/257F

1. Increase airflow through cruise nacelle
2. Improved heat sink for more effective MOSFET heat rejection
3. Internal nacelle ducting to direct external cooling air to CMC High Voltage heat exchanger
4. Internal nacelle ducting to direct external cooling air to CMC Low Voltage heat exchanger (only affects low-voltage electronics, not CMC MOSFETs)
    - Requires modification to the CMCs to add low voltage electronics heat sink
5. Reduce hot day temperature requirement for flight operations from 46C/117F to 30C/86F
6. Baseline high lift propeller system operation for all takeoffs (Distributed Thrust Takeoff – DiTTo) – removes peak power Mod III takeoff operations
    - Implementation of all recommendations does not provide adequate thermal margin for Microsemi CMC MOSFET operations.
    - Environmental test plan calls for:
    - 5 to 11 C Acceptance test margin
    - Additional 5 to 10 C Proto-qual test margin
    - *Minimum* of 10C is required for acceptance test and Proto-qual test thermal margins
    - Case Redesign required in order for the Mod III/IV cruise nacelle CMC design to close



Microsemi MOSFET

- Testing showed excessive gate voltage over/under-shoot and ringing with the Microsemi modules
- The team established derated “Do Not Exceed” requirements to bound the problem
- Increasing gate resistance, capacitance, and dead time improved gate voltage quality at the cost of CMC efficiency/thermal performance
- Using a verified model the team was able to show that the Microsemi module would not meet the efficiency/power dissipation requirement of 97%/1224W for takeoff and climb
- The Wolfspeed 425 Ampere XM3 module (CAB425M12XM3) was chosen for the new CMC design and showed > 98% efficiency and < 500 W of total power loss

MOSFET Derated Requirements

Module	Gate V_{min} [V]	Gate V_{max} [V]	Cross Talk (Turn Off) V_{max} [V]	Cross Talk (Turn On) V_{min} [V]	Mod2 Takeoff CMC Eff_{min} [%]	Junction T_{max} [°C]*
Microsemi	-7	22	0	-7	97	125
XM3	-6	17	0	-4	97	150

*Mod III/IV Heat Sink design coupled with this metric

Architecture	$t_{turn-on} + t_{turn-off}$ (τ=RC) [ns]	Switching Freq. [kHz]	R_{DSon} [mΩ]	Switching Power Lost [W]	Conduction Power Lost [W]	Total Power Lost per FET (DNE 204) [W]	Total CMC Power Lost (DNE 1224) [W]	Estimated Inverter Efficiency [%]
Baseline: BM2	158	52	4.2	107.3	5.1	119.5 (-41%)	717	98.21
Microsemi	340	52	8.0	230.9	9.8	243.0 (+20%)	1458	96.44
XM3 (400 A)	110	52	4.0	74.7	4.2	81.8 (-60%)	490	98.77
XM3 (425 A)	110	52	3.2	74.7	3.4	81.5 (-60%)	489	98.78

Assumptions:

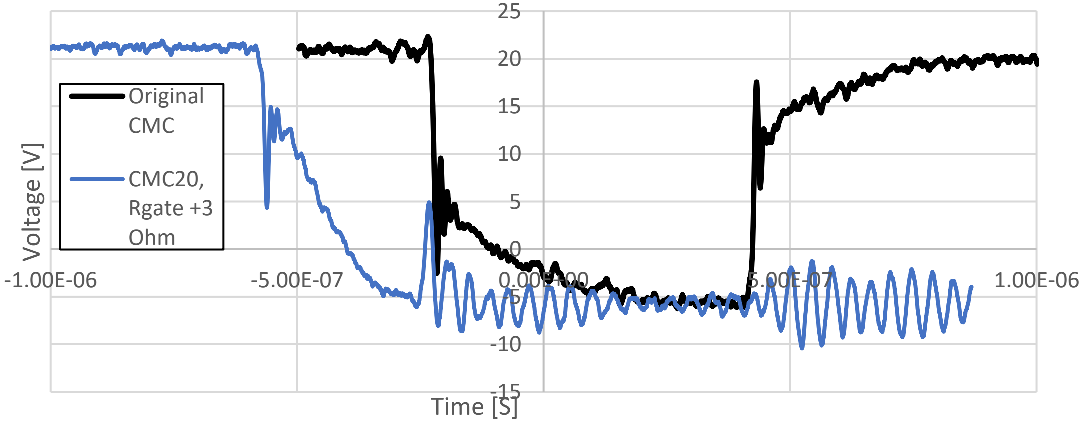
Battery Bus Voltage: 461 V
Operating point: 2700 rpm/127 Nm (72 kW shaft)
MOSFET Equivalent On Current: 80.3 A
CMC Output (aka Motor Input) Power: 39.5 kW (per CMC)
Absolute max CMC Power Loss: 1224 W

BM2 and Microsemi Gate Voltage Testing

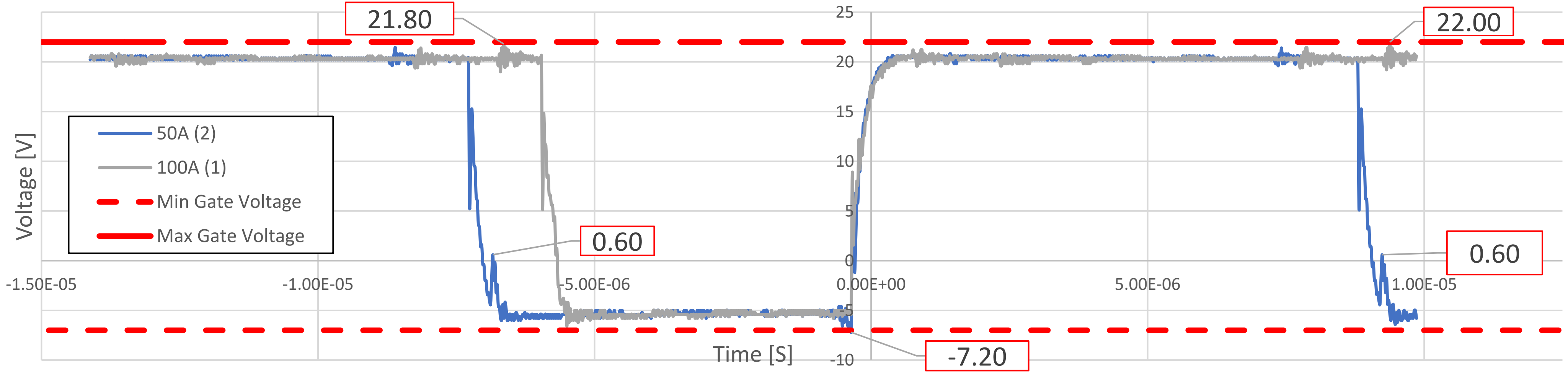
- Gate voltage waveform quality is crucial for proper MOSFET switching, module efficiency, and the overall health of the modules
  - Over/undervoltage can degrade the MOSFETs gate oxide layer causing degradation over time
- Original CMC (BM2) waveform quality was marginal, but acceptable
  - However, BM2 modules could not withstand vibration
- Gate signal quality was poor after the initial installation of the Microsemi modules
- The overall signal quality improved with modifications to the gate drive circuit hardware, but was still unable to meet the derated Max/Min/Cross Talk requirements

Module	Gate V_{min} [V]	Gate V_{max} [V]	Cross Talk (Turn Off) V_{max} [V]
Microsemi	-7	22	0
XM3	-6	17	0

Vgs, Low Side, Fsw = 31.25kHz, Vbus = 270Vdc, Iout = 5Aout

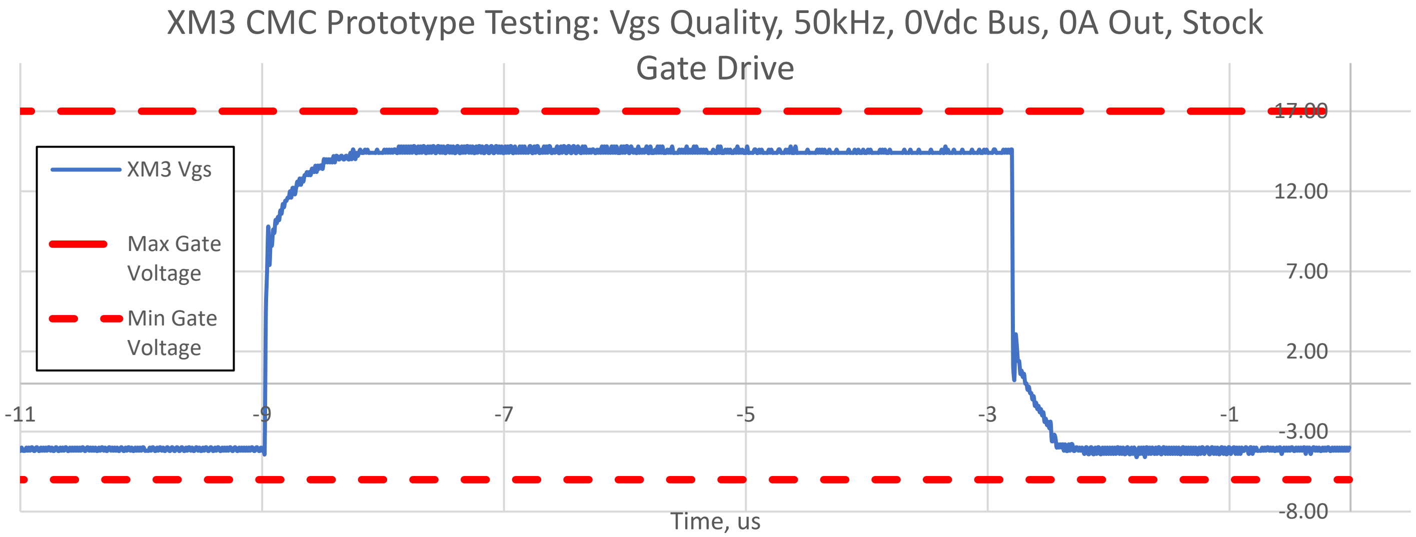


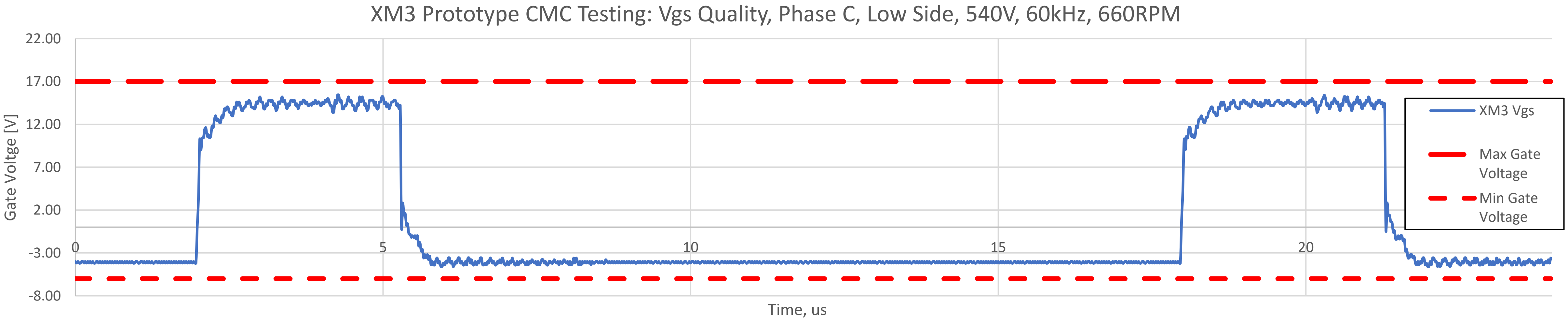
Vgs Quality by Output Current, Microsemi, Low Side, Rgate 7.6 Ohm, 540 Vdc, 62.5kHz



Initial Gate Voltage Quality with XM3 Prototype

- The gate drive circuit in the XM3 CMC design is based off of Cree's COTS gate drive
- Cree's gate drive was used in the XM3 prototype
- Initial experiments showed higher quality gate voltage waveforms compared with the Microsemi and BM2 modules
- We expect to see equal or greater performance from the new XM3 CMC gate drive design



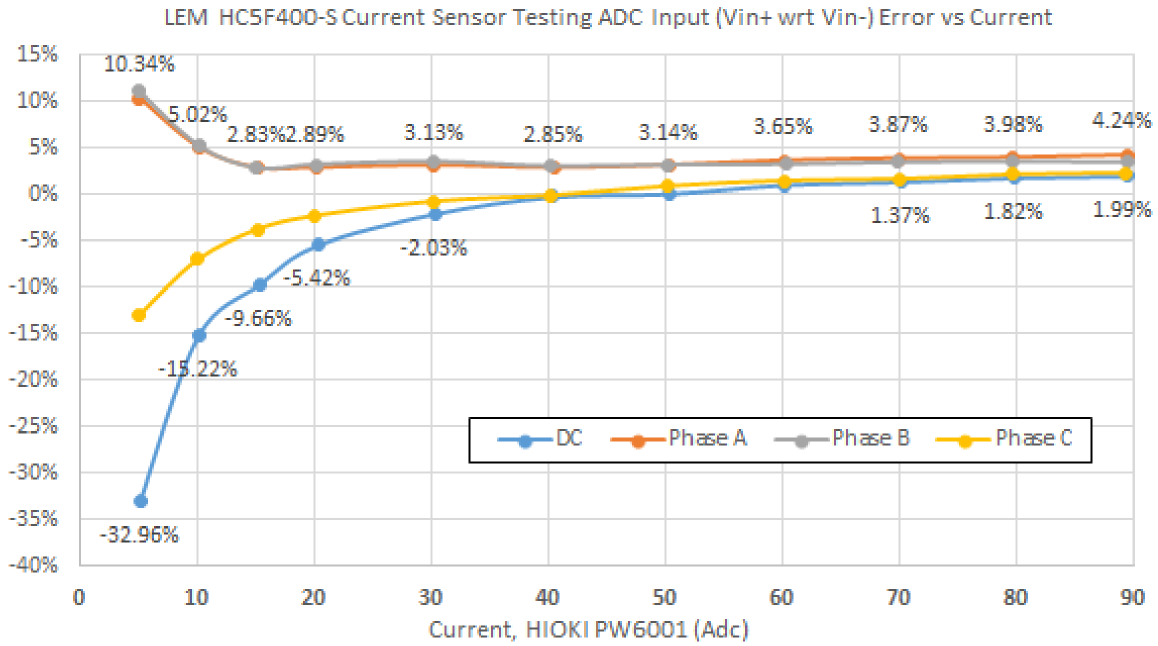


DC and Phase Current Sensing Circuit

- Phase current is the only feedback path in high-performance sensorless control; measurement quality is critical to CMC stability and performance
- Existing Hall-Effect sensor is oversized and voltage output which leads to higher noise susceptibility
- Test data shows signal error is up to 4.4% at high current, but is 10-30% at low current (e.g. motor startup and idle)
- Error in the current acquisition equates to error in the control law

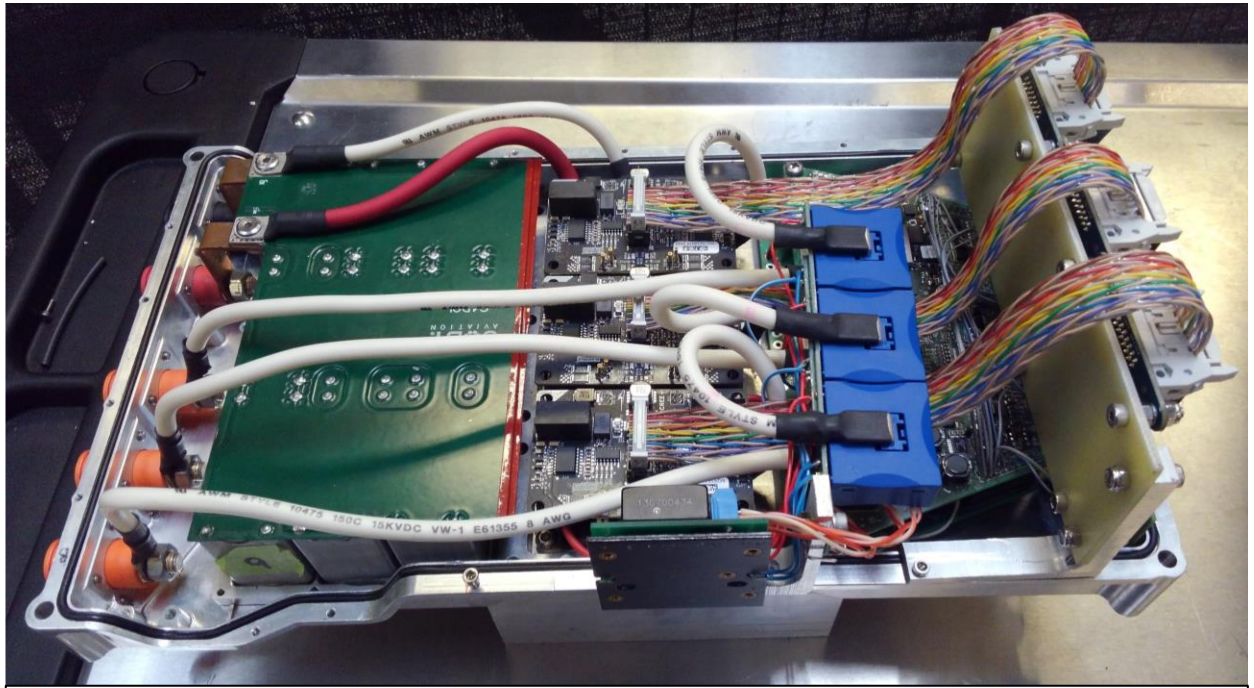
Required Fix:

- Modify analog signal design on LEM and CPU circuit boards to improve signal integrity
- Change packaging layout of CMC to better co-locate sensor and DAQ without noise source between them
- Select higher performance DAQ with better noise immunity
- Select a shunt or current output Hall-Effect current sensor with higher noise immunity

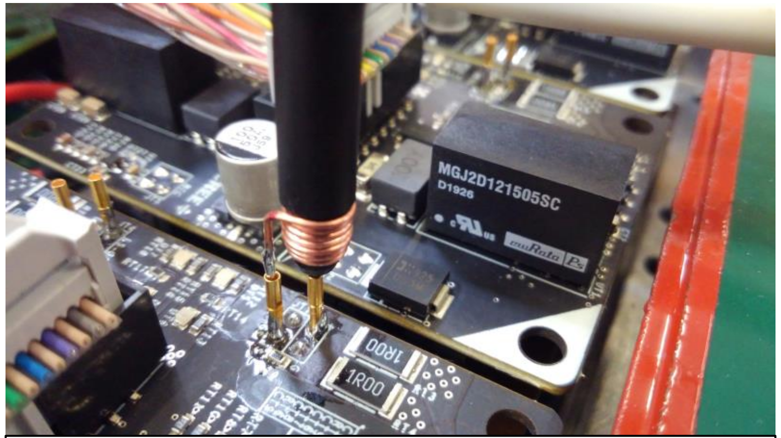


Modified Ground CMC Prototype (Frankinverter)

- A prototype inverter was fabricated at ES AERO with XM3 modules, Cree gate drivers, and LEM LA 150-TP current sensors
- The prototype is used to test circuits representative of the new CMC XM3 design
- Initial tests looked at the DC-Link voltage ripple filtering and the gate voltage waveform quality
- Further testing will be performed on the dynamometer and measure electrical and thermal efficiencies



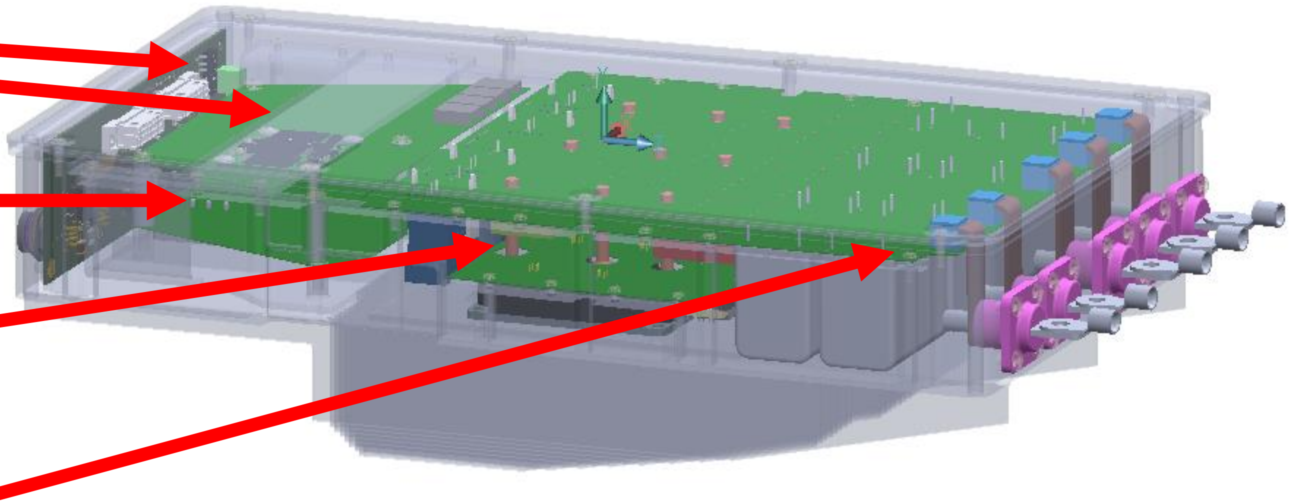
Prototype Inverter incorporating XM3 CMC representative hardware



Gate Voltage Measurement Methodology to Reduce Induced Noise

GRC CMC XM3 Design

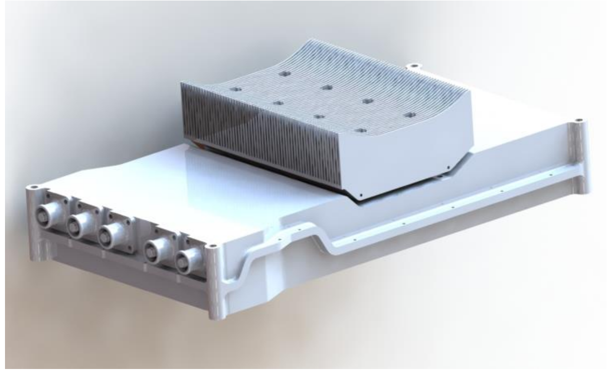
- CPU/Connector Board
  - Both PCBs are being reused on XM3 CMC
- Power Board
  - Auxiliary Power Distribution
  - Supporting Circuitry
- Driver Board
  - Gate Drive Circuitry
  - Shoot Through Protection
- AC-DC Board
  - Current Sense Circuitry
  - Bus filter
  - High Power Connections



- New PCBs – Power, Driver, AC-DC
- AC and DC traction has been combined into one PCB
- Driver PCB is tightly integrated with MOSFET module minimizing stray inductance
- Current sense circuits we fully redesigned and placed as close as possible to acquisition circuit.

CMC Change

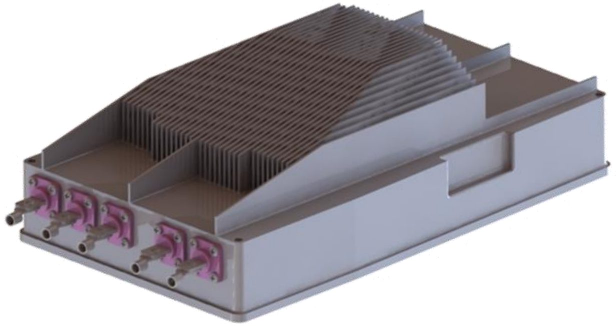
Old CMC Design



Original CMC design presents multiple design issues:

- No separation of high and low power thermal management.
    - This produces case temperatures of 100 deg C and exceeds temperature limits of low power components during target operation.
- Passive heat management system (fin array) is undersized to adequately dissipate waste heat of electronic systems.
- No internal support of high-mass capacitor boards.
    - Insufficient stiffness for vibe environment.

New CMC Design

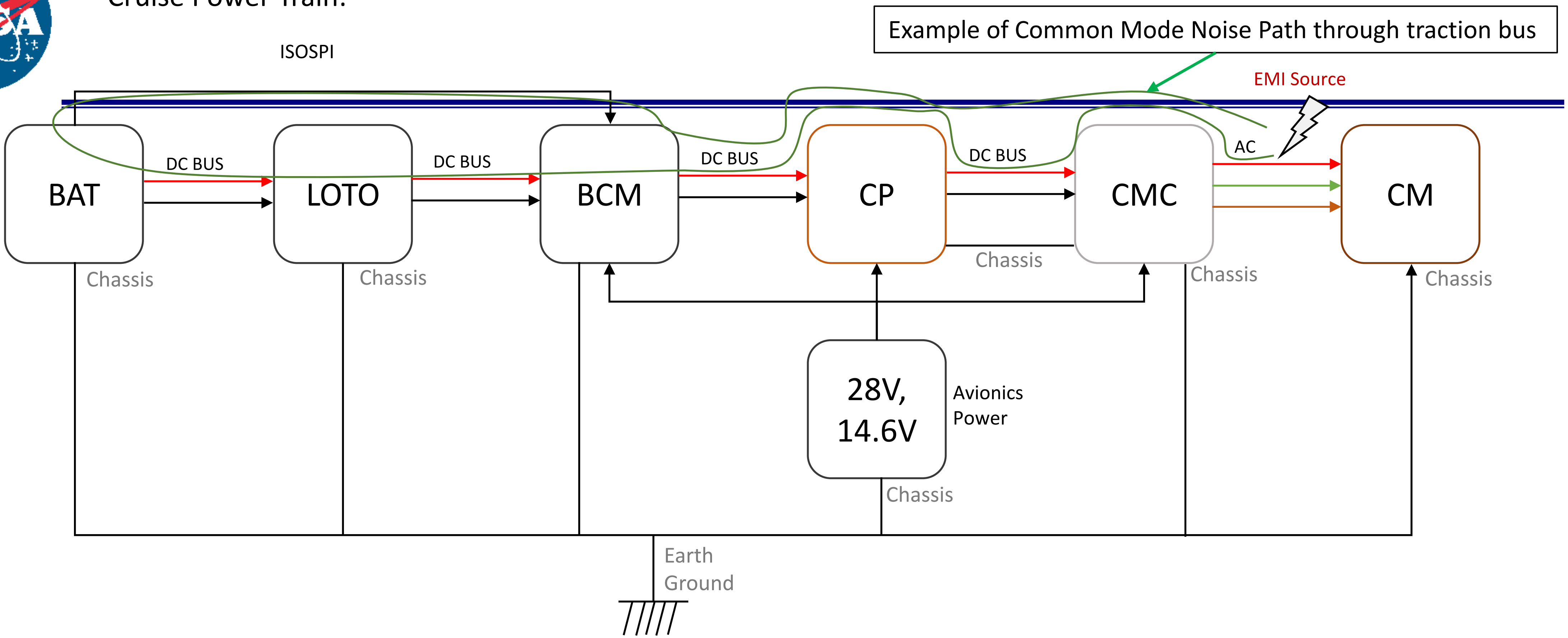


Original CMC design presents multiple design issues:

- Complete separation of high and low power thermal paths.
    - High power electronics are cooled through fin array while low power components are channeled through case lid.
- Fin array is integrated to case structure to allow for much higher overall surface area.
- Support structures incorporated into case design for stiffness under vibe environment.

EMI Problem and Potential Solutions

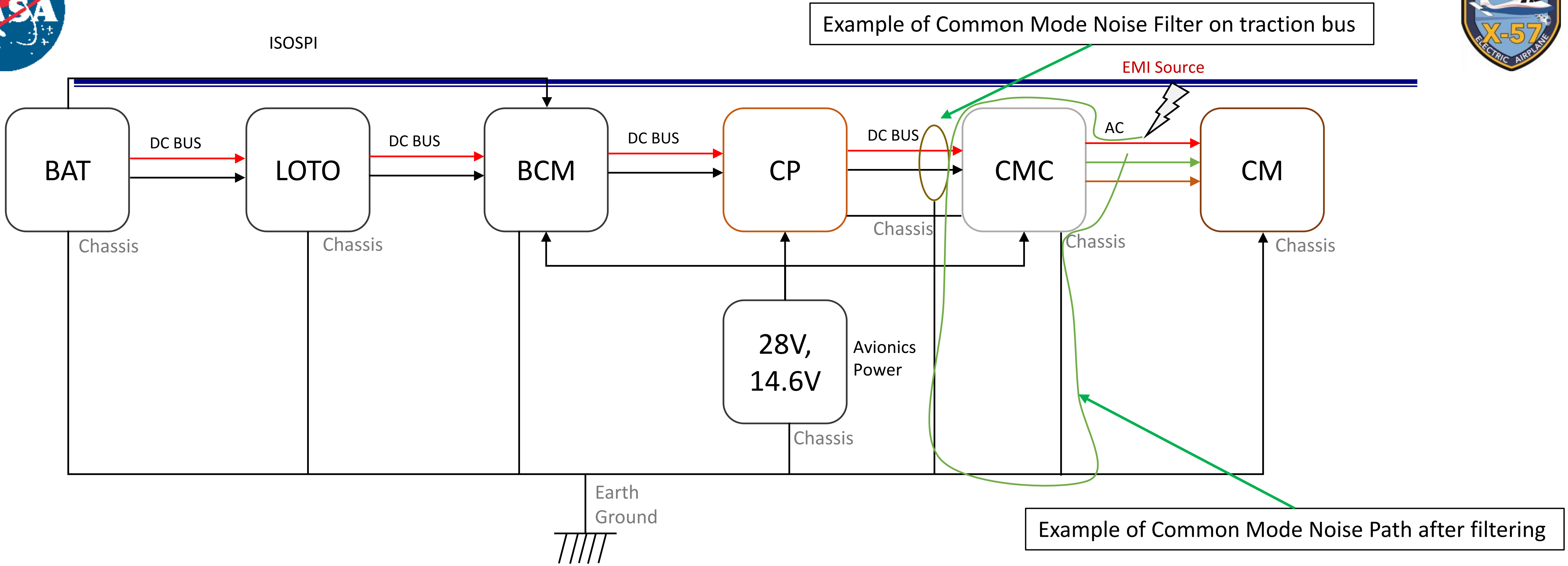
Cruise Power Train:



- CMCs generate EMI noise due to switching events. Square wave pulses are “riding” on top of AC waveforms going into a motor
- Due to coupling capacitance in the power train, the EMI noise starts to propagate throughout the system and comes back to source
- EMI noise is represented mostly as a common mode current, which finds path of least resistance through the system
- Once common mode current finds path to sensitive electronics (control boards, communication lines, etc), it will disrupt the regular operation of such systems causing drop outs, shutdowns, etc.
- In a cruise power train, EMI will propagate from any copper connections out of CMCs (Traction or Avionics) through capacitive coupling between subsystems and back through path of least resistance

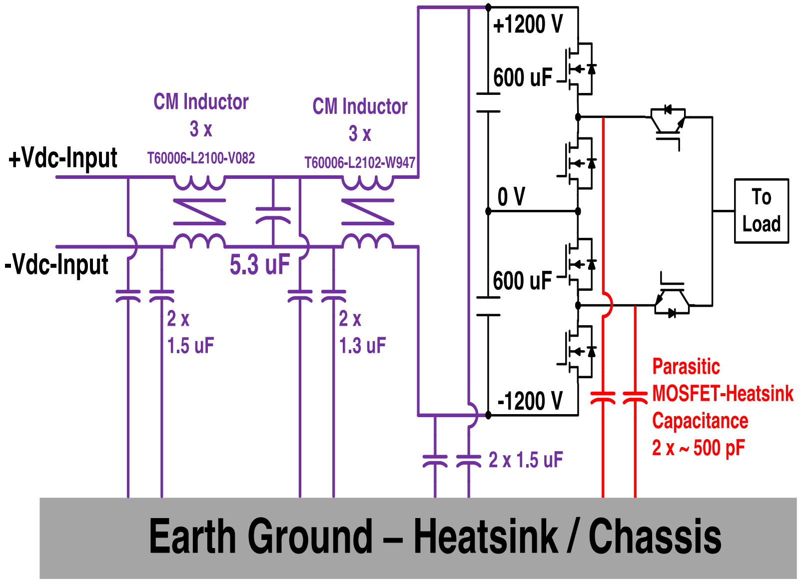
EMI Problem and Potential Solutions

Cruise Power Train:

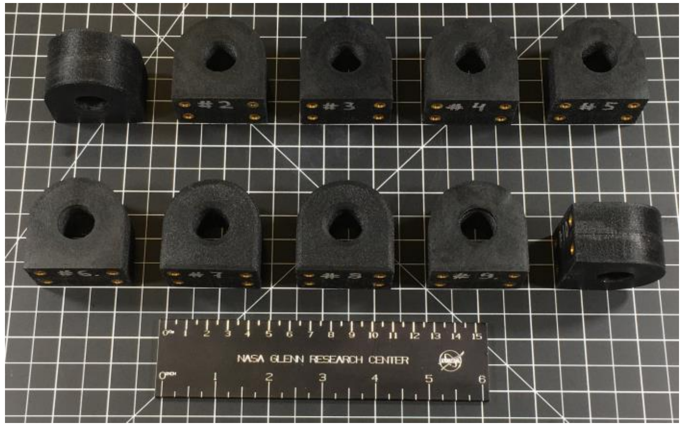


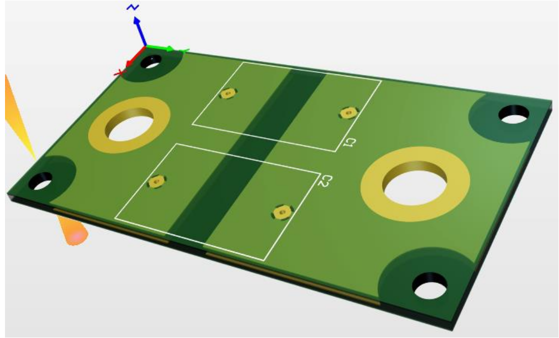
- There are two common methods of minimizing EMI problems: Isolation or Filtering
- Isolation techniques were tried and did not yield enough benefits for stable operation
- Implementation of toroid on traction cables yield excellent results, but its not enough to minimize EMI for the entire power train
- Implementation of Pi filters (capacitors and inductors) yields best results in simulations and were successfully tested on the off A/C configuration to verify results

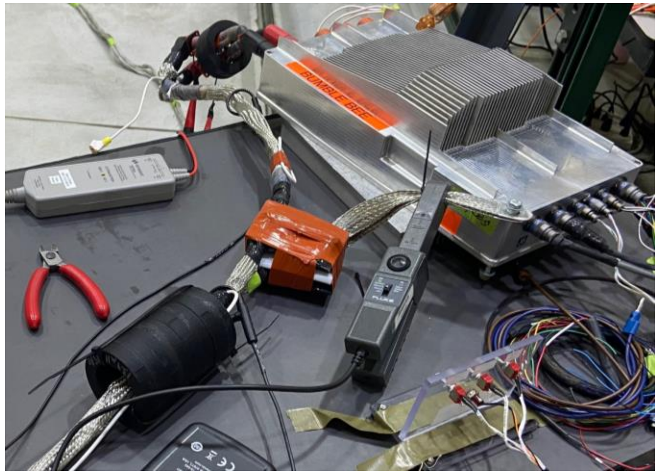
CMC EMI Filter Electrical Design



- Custom soft core magnetic material inductors have been produced by GRC for common mode inductance
- 2uF capacitors have been picked with lowest ESL for capacitance of the filter
- Full PI filter will be used on each traction input of the CMCs
- Stand alone soft core magnetics will be used on all other copper interfaces coming out of a motor
- Total of 20 inductors will be used in a cruise system







Filter Mechanical Design

Initial Functional Prototype

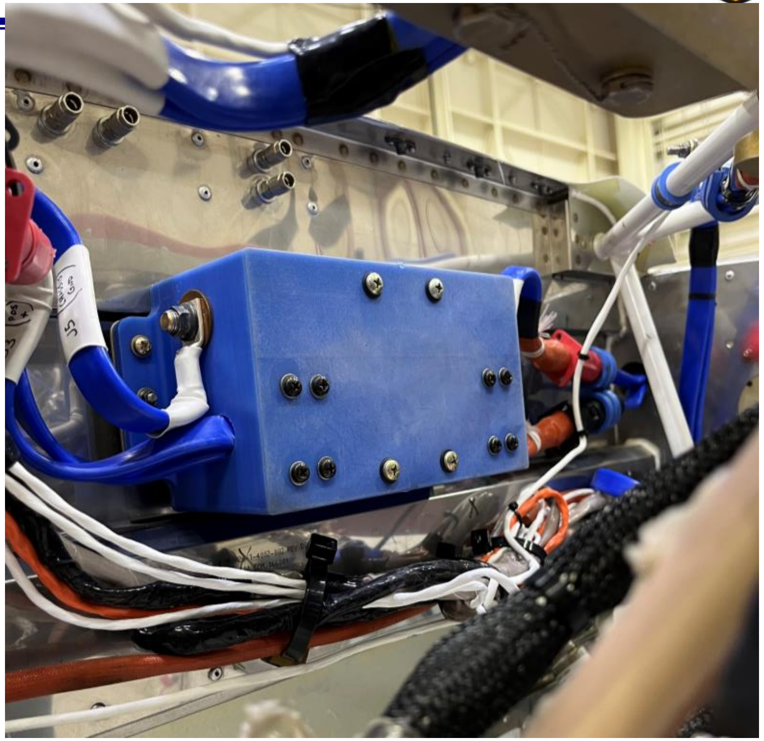
-Initial functional prototype demonstrated without housing.

-Layout favored simplified routing for traction cables.

Design Fit-Check

-Iterative design process was followed with technician team.

-Due to stiffness of traction cable, final housing design heavily leveraged functional prototype layout.



Final Design

-Design envelope verified with fit check on aircraft.

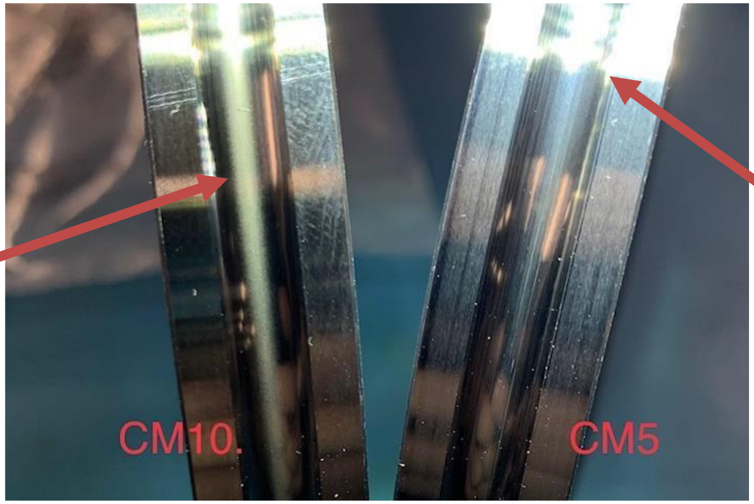
-Internal components verified through fit-check on prototype.

Motor bearing design gaps

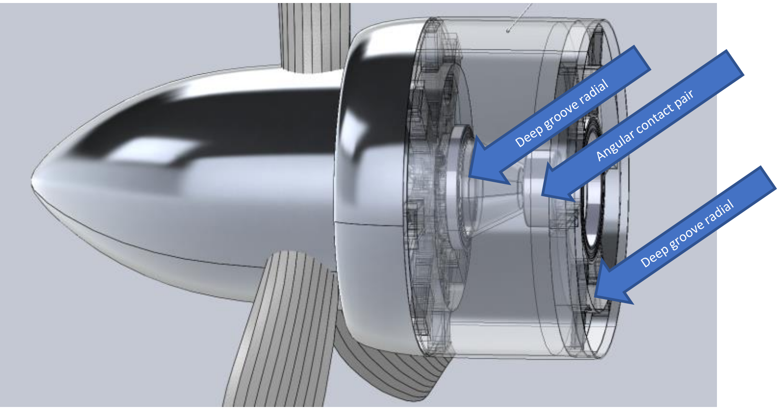
- Forward guide bearing not rated for X-57 motor speed range. Conflicting data from manufacturer and distributors. Replacement part is not sealed and may be less resistant to FOD.
- Bearings are not preloaded by rotor design. Thrust, inertial, and gravity loads add some bearing load, but not enough to meet spec, and not in bench configuration (e.g., dyno). Expect this to lead to increased wear and early failure (imposes additional monitoring and maintenance overhead).
- Baseline plan is to replace bearings before flight

Cruise Motor endurance testing on NASA Airvolt stand at AFRC

Teardown inspection after an overspeed event shows 'frosting' wear pattern



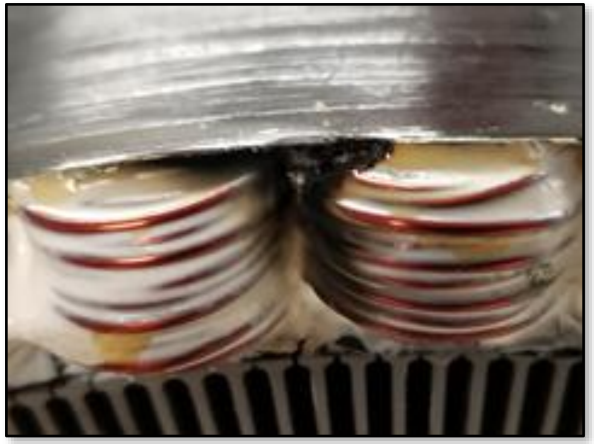
CM5 rotor inspected after fewer hours. Wear shows sliding / wiping pattern due to poor loading contact



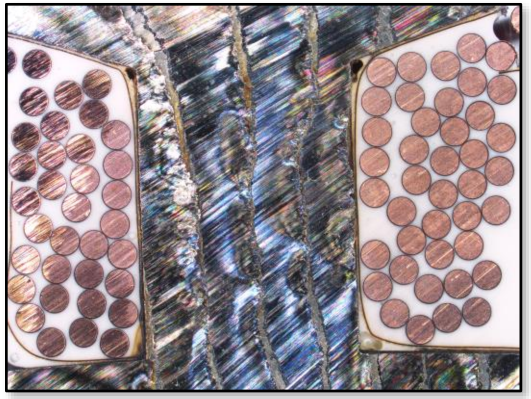
Rotor with Bearings

Stator Insulation Improvements

- Fabricated new stators in 2019/2020 to correct winding isolation defects
- Stator laminate stack up design introduced high-stress at end-turn areas. Phase-to-structure isolation faults after prolonged operation.
- Potting process control did not ensure sufficient penetration into winding bundle. New fabrication run improved from ~20% to ~90% penetration, but void pockets still exist are are accounted in the thermal analysis.
- Performance/thermal void analysis of updated potting reduces stator thermal margin, but still positive in the ICPT model discussed in Performance slides.

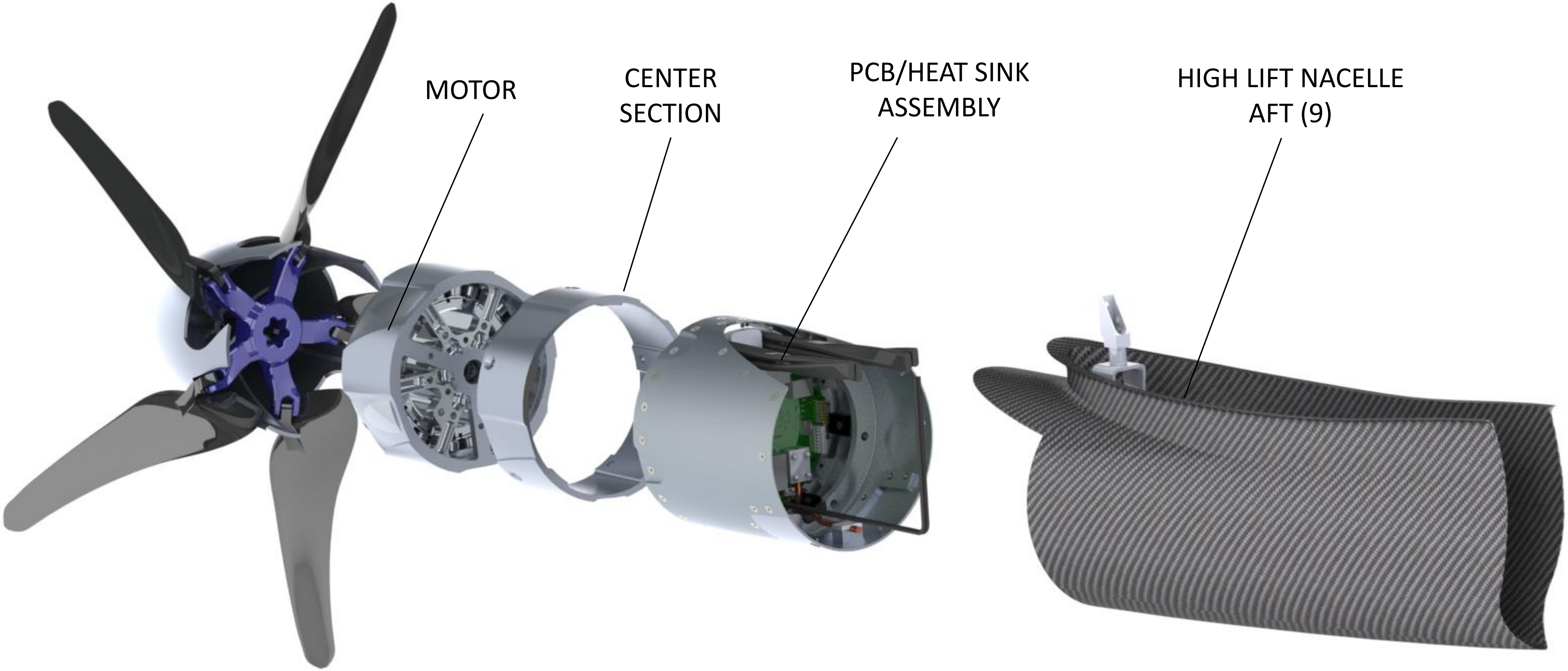

Electrical isolation failure during HV vehicle test produced internal arc fault


Original motor winding poor epoxy penetration (typical throughout)

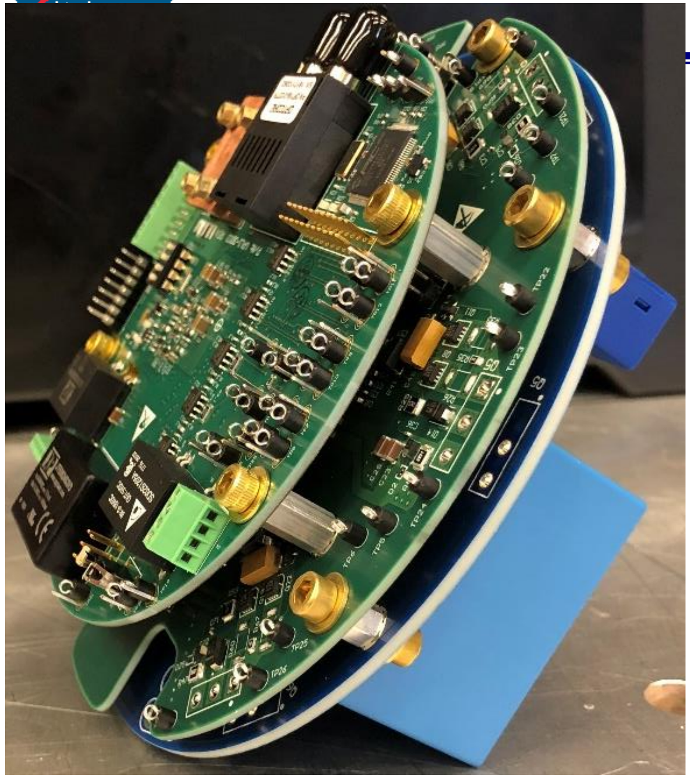
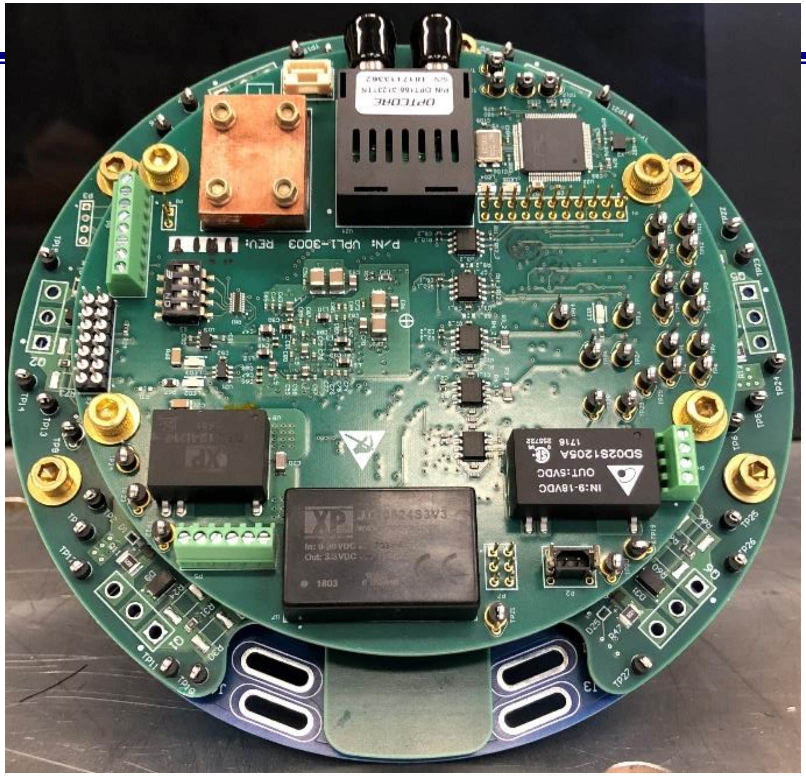

Improved fabrication process (typical for 80% of samples)

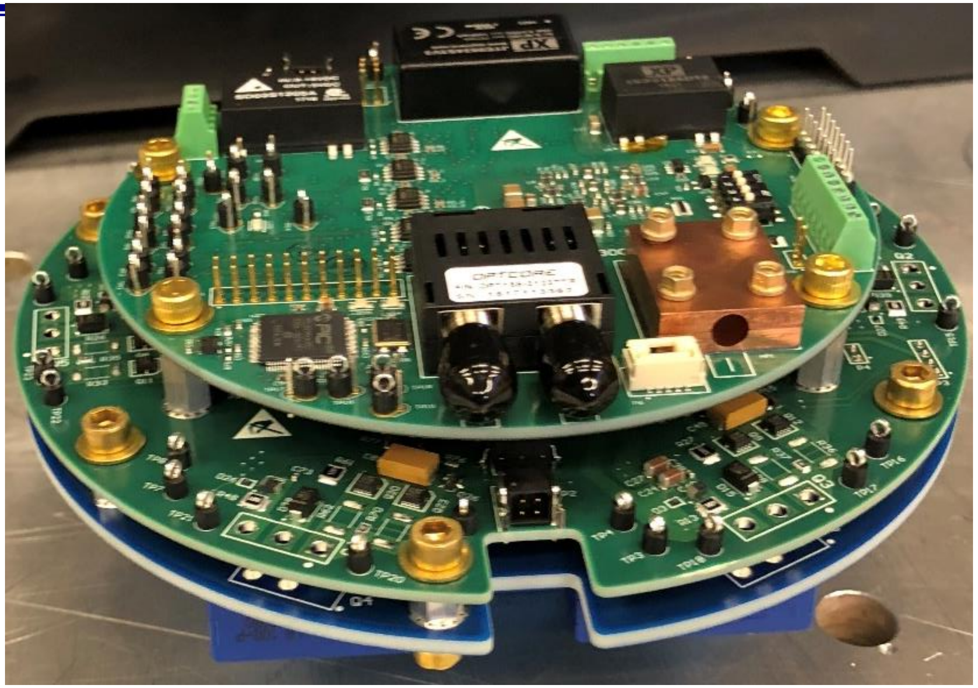

Improved fabrication process still exhibits some voids

Nacelle HLMC Integration



Electrical Design Integration



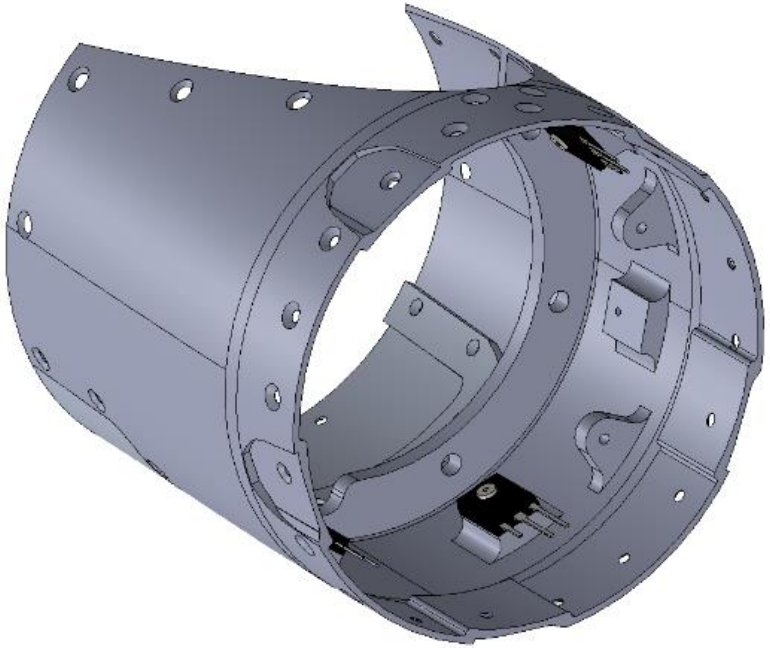
HLMC Qualification Cooling Design

High Power Electronics

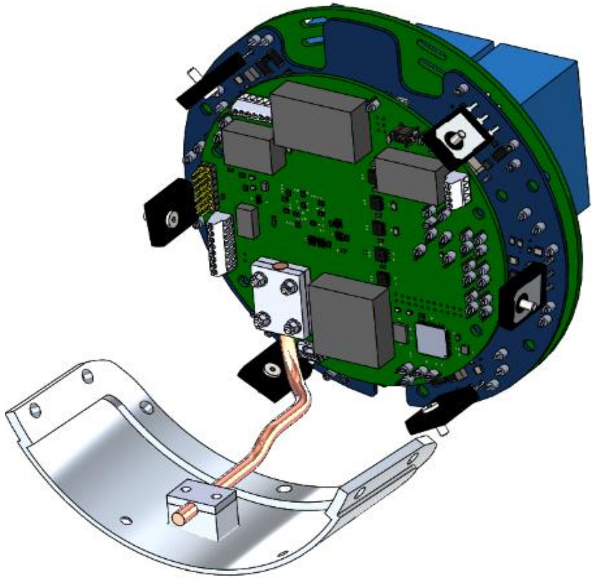
- 6 MOSFETS (FETs) have a direct thermal conduction path to external flow, and are distributed around the circumference to minimize temperature gradient and maximize sink area per unit.
- Aluminum external sink conforms to OML to eliminate additional parasitic drag

Low Power Electronics

- Two 1.4 mil copper thermal planes on each PCB to distribute heat
- PCBs are thermally linked together through aluminum standoffs which are in contact with the thermal planes
- Secondary isolated low power heat sink with COTS sintered wick heat pipe conductor

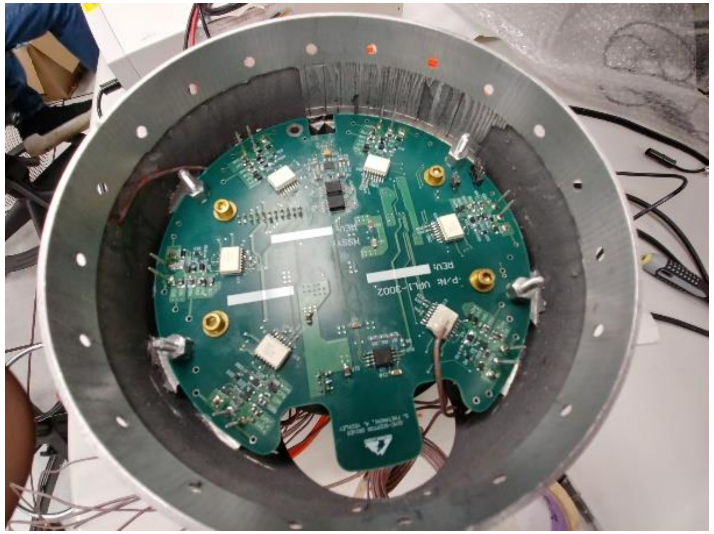


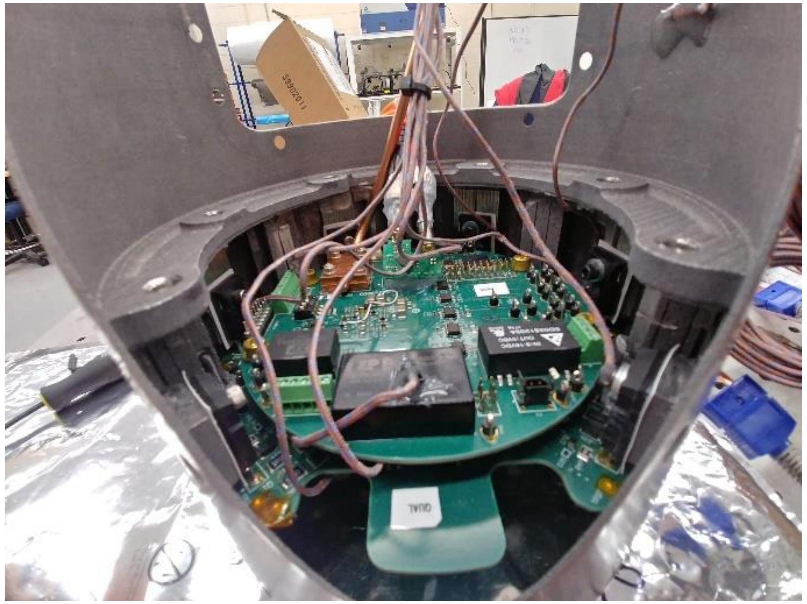
High Power Electronics & External Sink

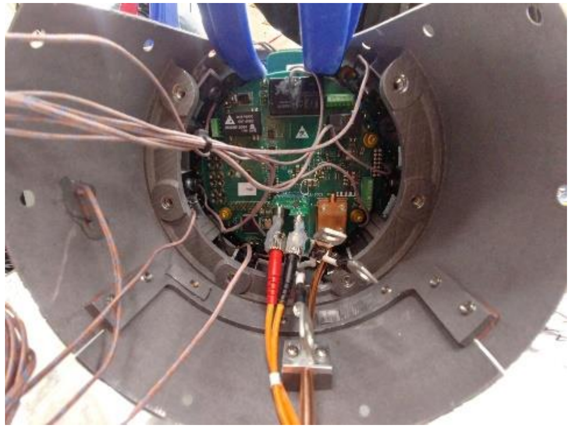


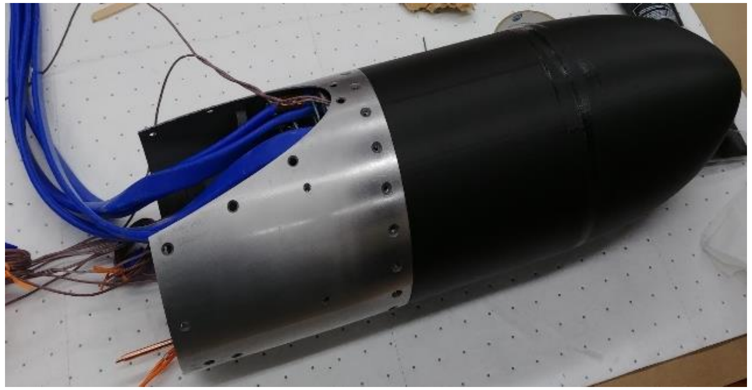
Low Power

HLMC Mechanical Integration

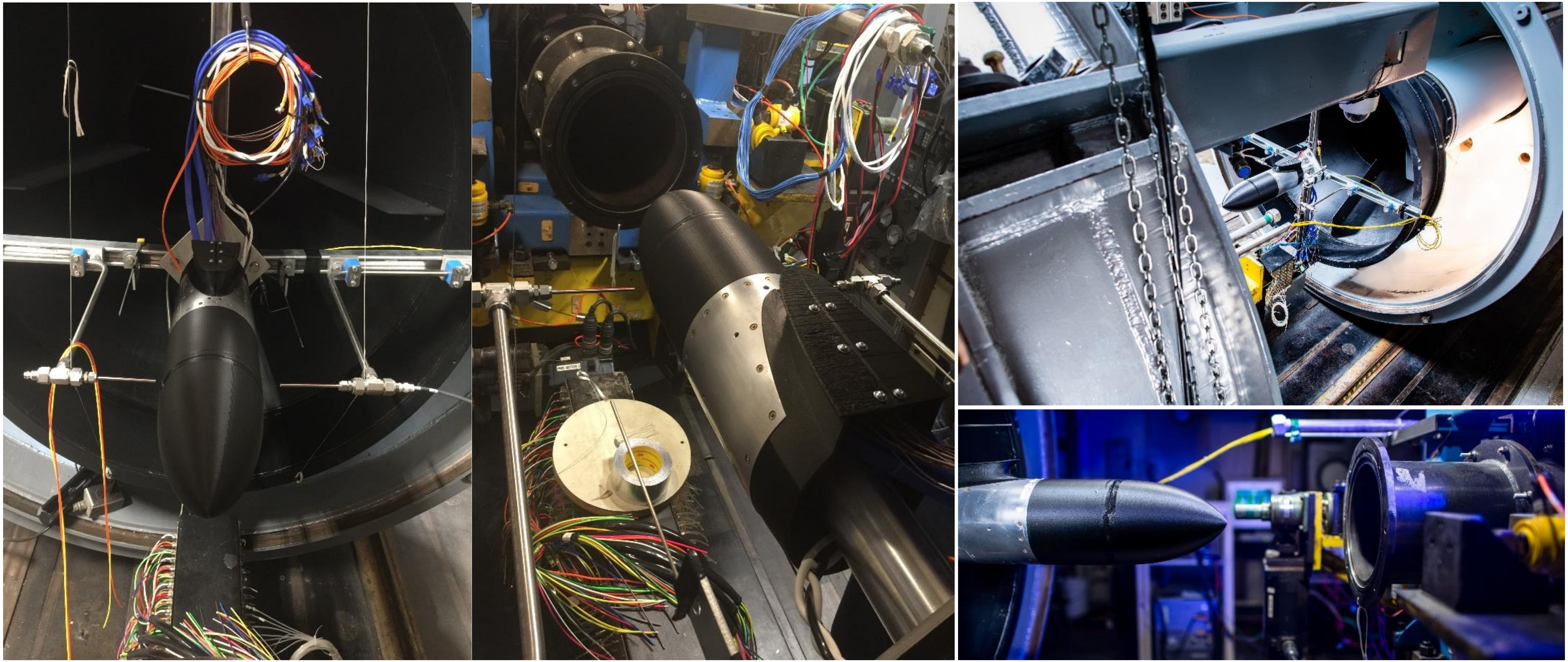






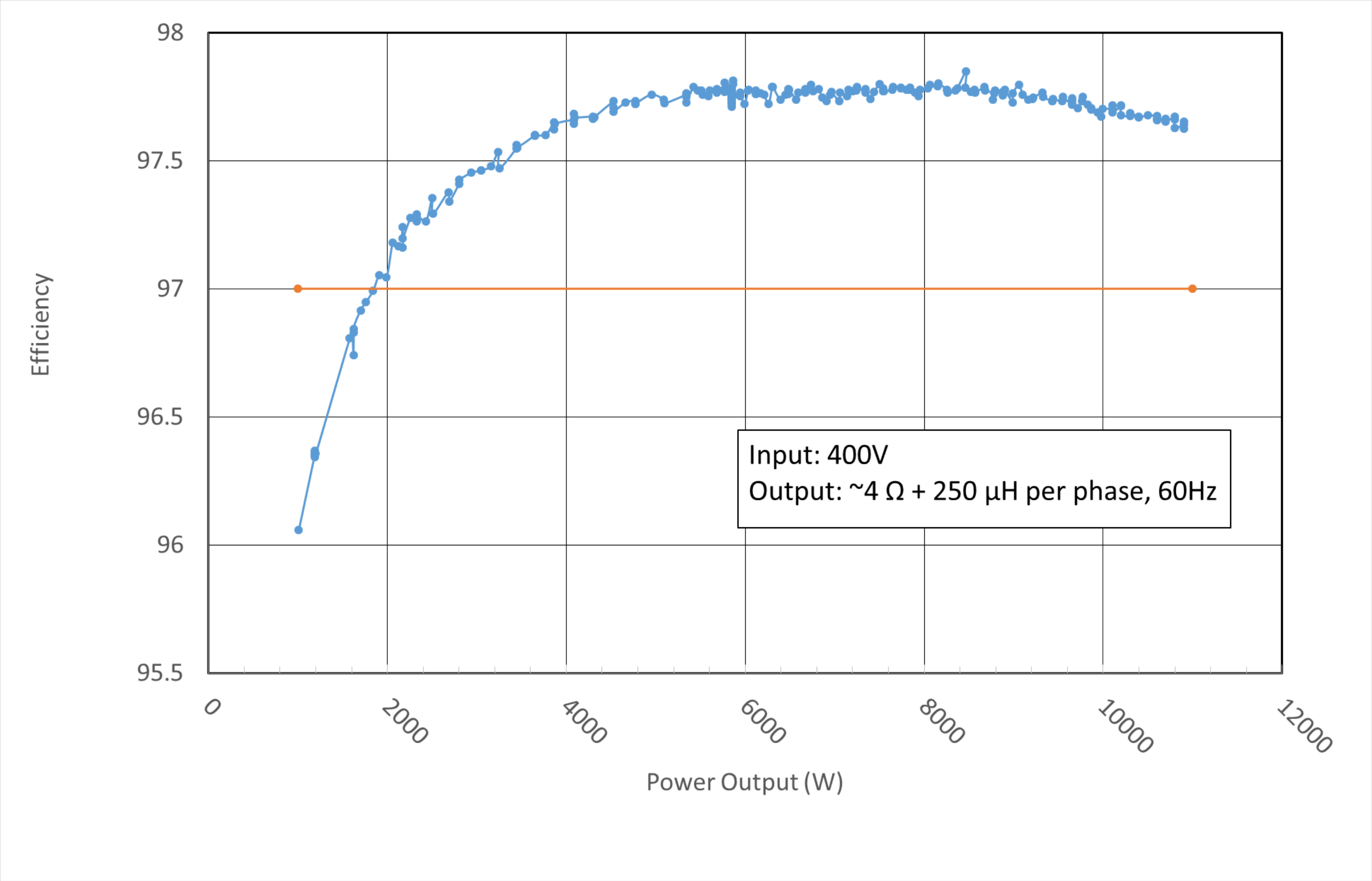


HLMC Altitude CE-22 Test Set Up

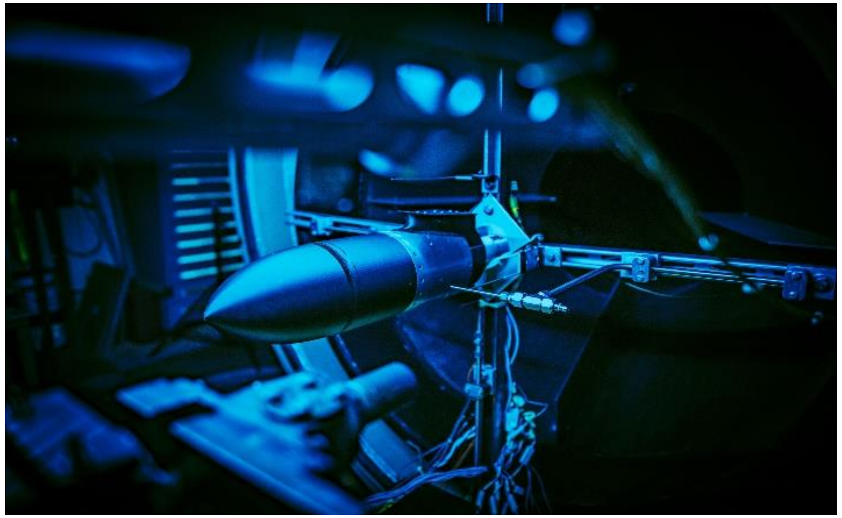


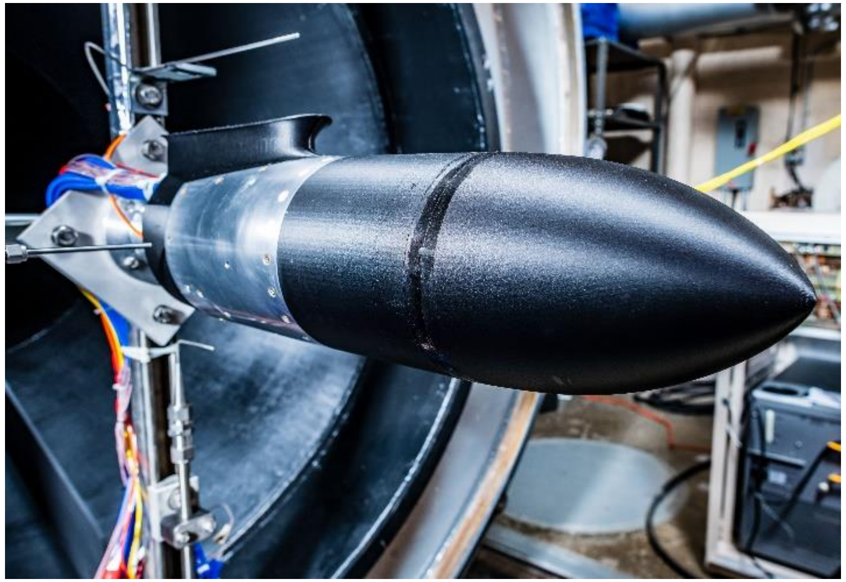
HLMC Altitude Test Efficiency

Exceeded 97.5% Efficiency in Altitude Testing at GRC Advance Nozzle Test Facility



Input: 400V
Output: ~4 Ω + 250 µH per phase, 60Hz





Backup

CMC
Controller
Motor
Cruise
Inspection
Requirements
Test
SPEC-CEPT-001
Requirement
requirements
requirement
temperature
Method
measure
maximum
required
cruise
Parent
board
power
voltage
bus
motor
aircraft
Analysis
interface
current
input
output
traction
Verification
design
X-57
MOSFET
order
controller
external
operation
components
avionics
temperatures
defined
meet
ensure
comply
range
AFRC
structure
remain
connector
efficiency
verification
Assurance
limit
Parts
Plan Quality
3112
VDC
Command
CMCs
QAP-CEPT-008
selection
system
without
used
connectors
quality
data
Date
rated
needs
per