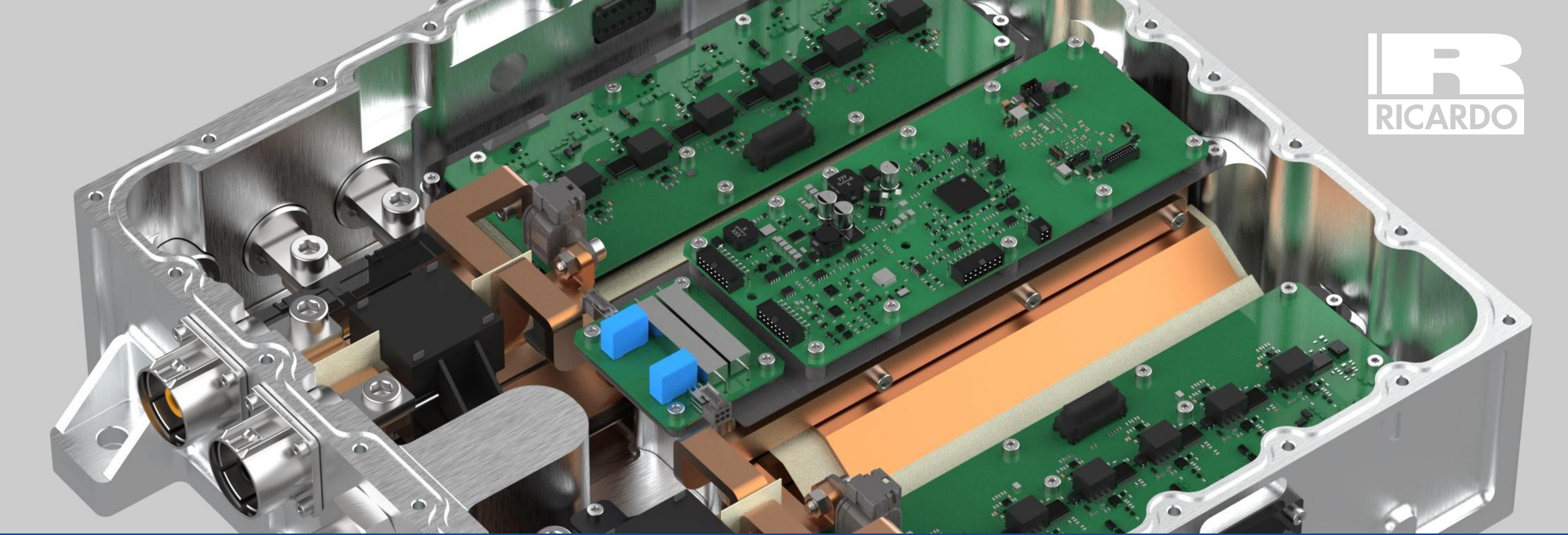


Dual Output SiC Inverter Drive for High Power Applications

Dr Temoc Rodriguez

Dr Chao Ji

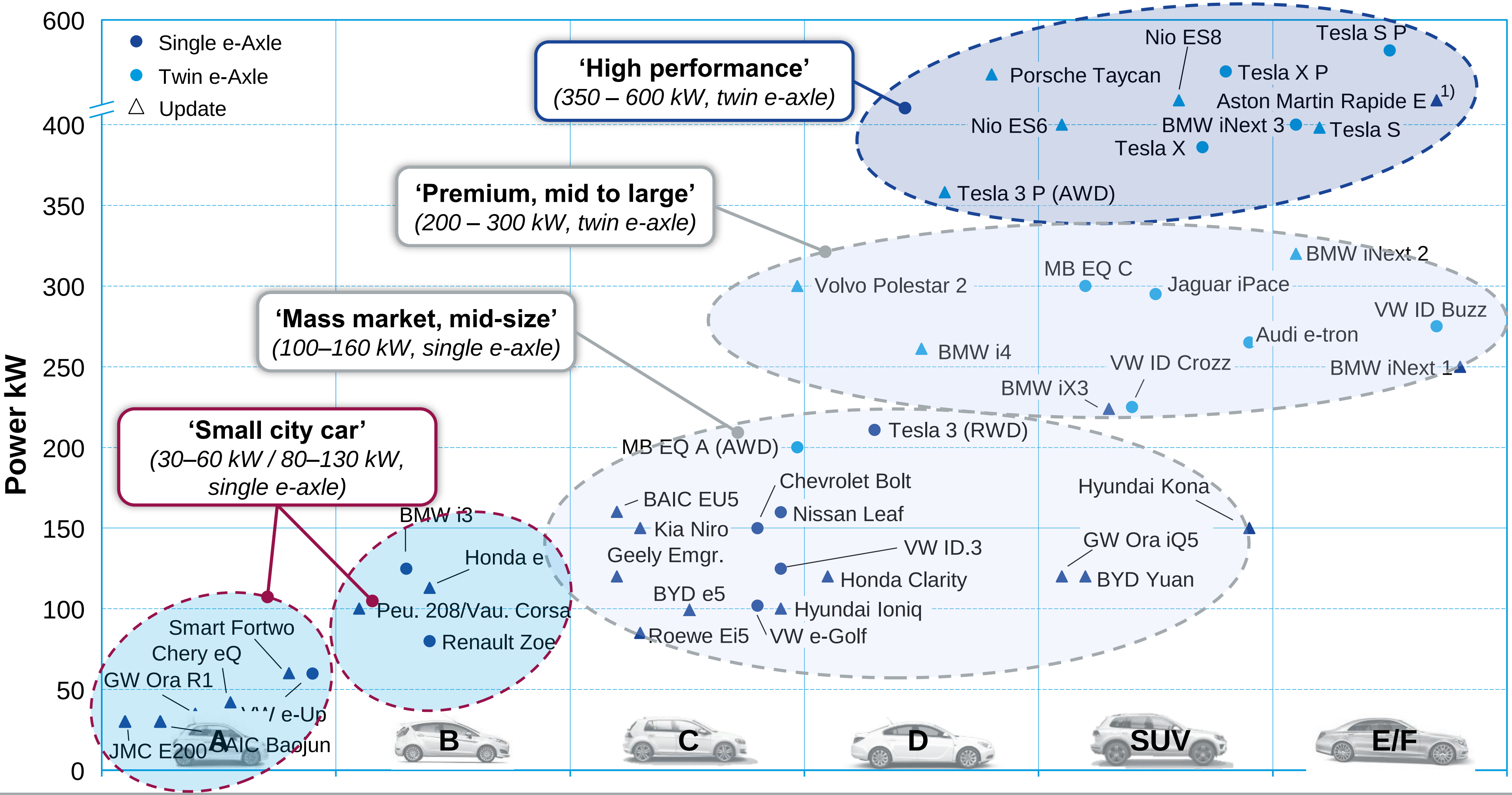
Multi-motor EV Architectures

- Electric Vehicles are now ubiquitous in many markets, from passenger cars to commercial vehicles and off-highway vehicles
- Depending on market segment power requirements can range from 50kW to 300kW in passenger cars and up to 500kW in heavy duty vehicles
- High performance and heavy-duty vehicles use multiple inverters and motors to achieve higher power ratings, often up to 800kW per axle
- To improve system mass and packaging, integrated drive units incorporating dual motors and dual inverters can be used in each axle

Ricardo’s 800V, 250kW, SiC Inverter

EV Market – Passenger Cars

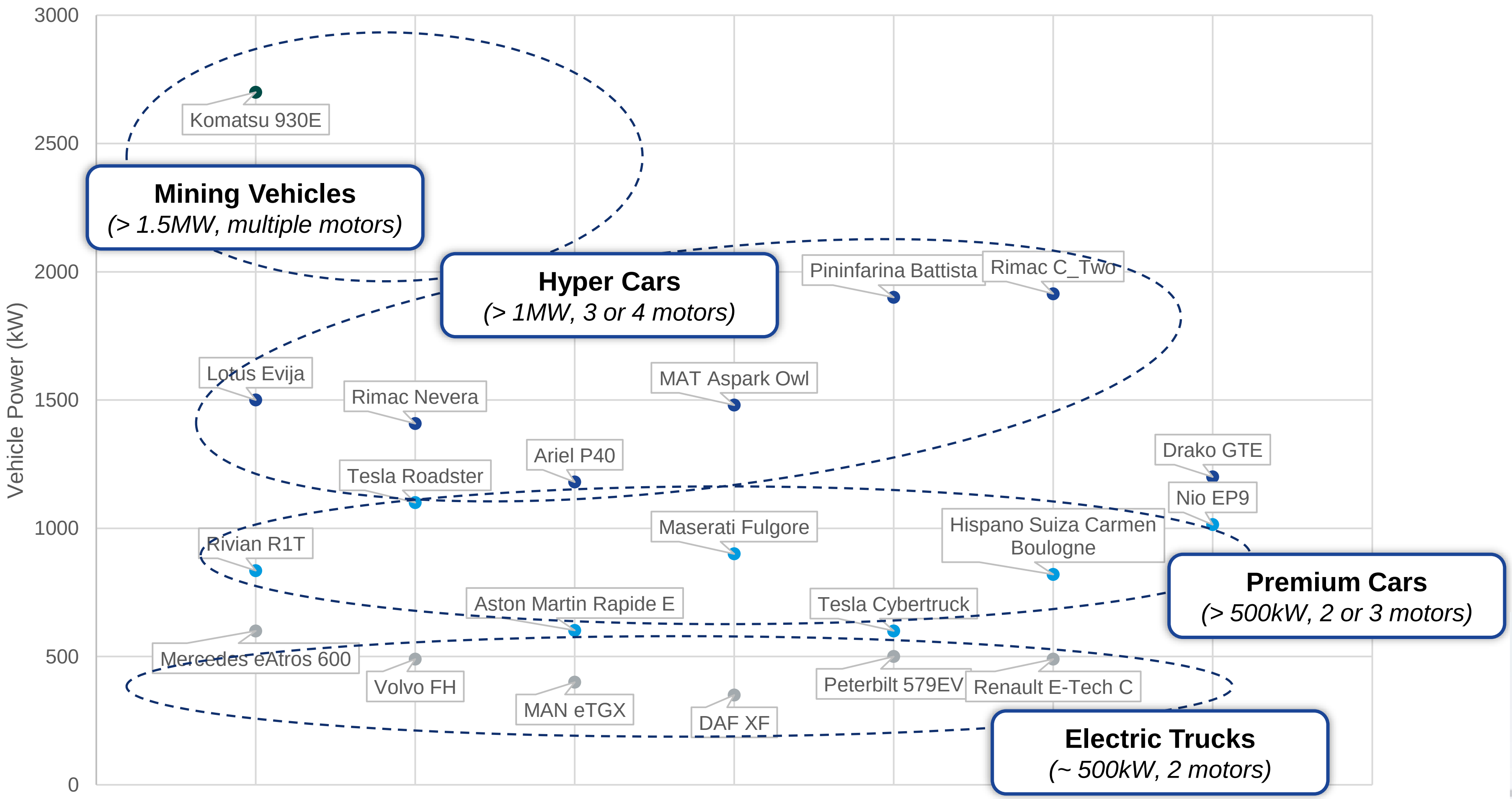
Power output for selected BEVs (total motor power)



Source: Ricardo Analysis, press releases and public domain sources

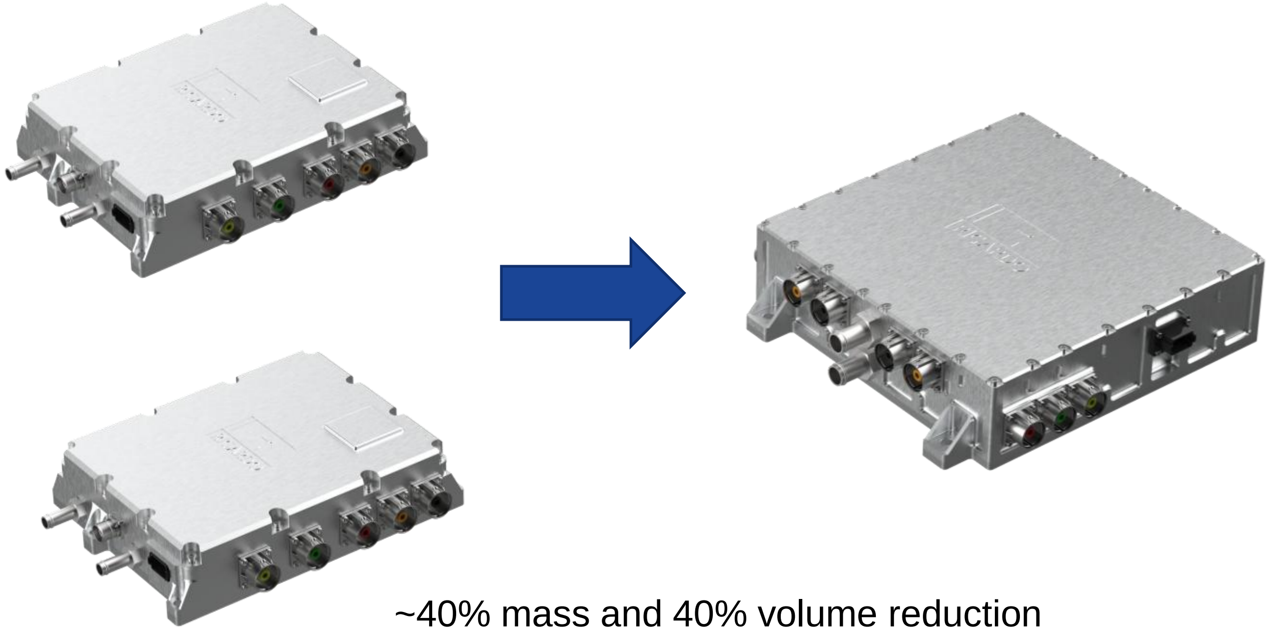
Note: 1) Aston Martin Rapide has two rear-mounted electric motors

EV Market – Other Segments

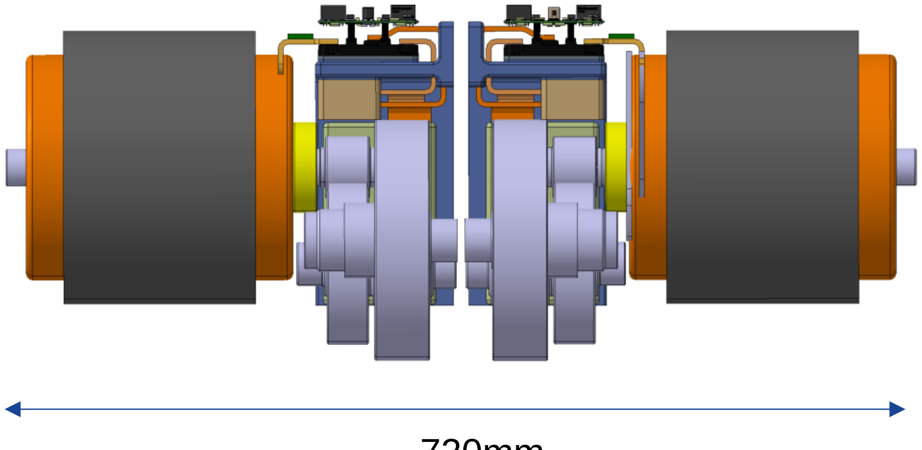


Dual Drive Unit Axle Solution

- A dual drive unit has a shorter dimension compared to two independent drive units
- Control coordination between the two motor drives is easier to achieve, for example torque vectoring and fail-safe states
- Dual motor drive integrated into single unit has lower mass and volume



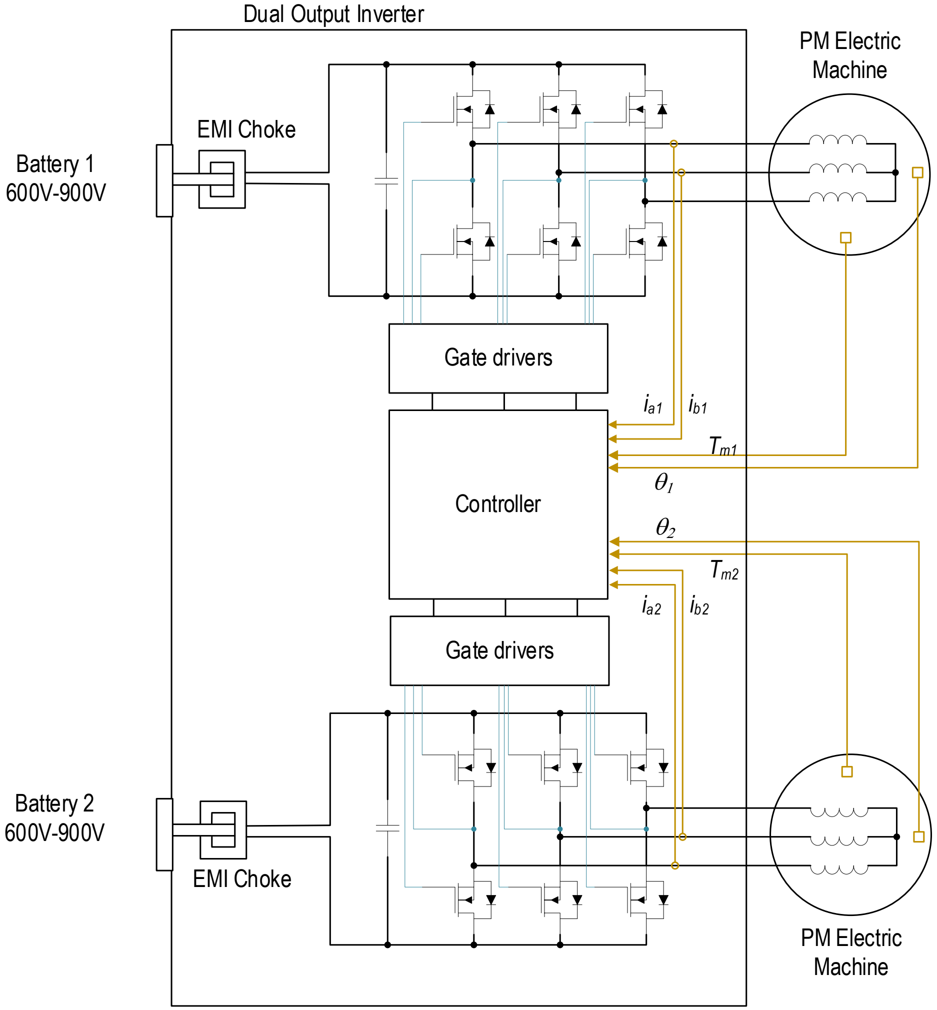
~40% mass and 40% volume reduction



Ricardo's Dual Motor Drive eAxle

Dual SiC Inverter Electrical Design

- The dual output SiC inverter incorporates mirrored power stages and gate drives
- A single control board with a multi-core processor is used for both inverters
  - This offers easier integration and control of differential torque control in case of two separate motors; OR
  - Easier integration and control of a 2x3phase single motor
- DC inputs can be powered from two different battery packs for a higher level of independence and integrity; OR can be wired together to power from the same battery pack
- SiC inverter gate drive design
  - Dual power supply of control electronics (from vehicle 12V battery and from HV battery via a dc/dc converter)
  - DESAT protection, active clamp, active miller clamp, diagnostics etc.
- Adjustable gate drive strength to reduce EMI at low loads



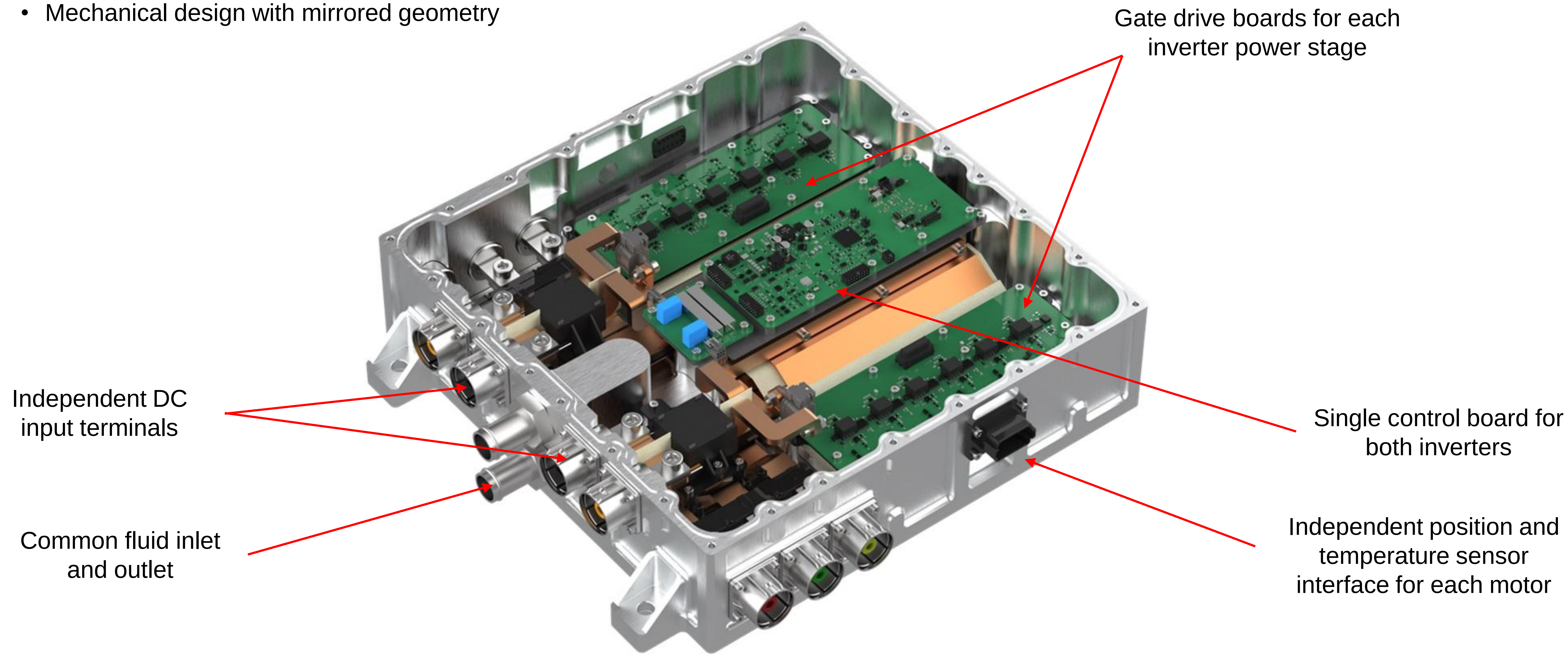
Dual SiC Inverter Functional Safety

- There are two possible safe states for the inverter
  - 6-switch open: where all 6 transistors in the 3-phase inverter are turned off
    - Triggered in detection of short circuit events
  - Active Short Circuit (ASC) 3 high/low side switches on: this effectively shorts the motor windings
    - Triggered when a shorted high/low side switch is detected
    - Activated when over-speeding, due to loss of control in field weakening region, and regeneration voltage is higher that the battery voltage
- Response of the second inverter upon detection on the first inverter
  - Maintain symmetric torque in the axle
  - Coordinated braking or rolling control
- Limp-home operation
  - Isolate a faulty inverter/motor in the axle
  - Operate second inverter/motor in limited torque/speed conditions to limp home

Hazards	Safety Goal	ASIL	Rationale
• Unintended motor torque results in unintended vehicle motion • Unintended motor torque results in damage to drivetrain	The inverter shall control motor torque in response to vehicle commands	D	In dual motor drive drivetrains incorrect torque application can result in loss of vehicle (rolling, spinning)
• Inverter or motor failure propagates to the system to create an electrical hazard	The inverter shall detect and manage electrical faults	B	System level (e.g. in battery disconnect unit) redundant detection of isolation breakdown or overcurrent events lead to inverter disconnection

Dual SiC Inverter Mechanical Design

- Mechanical design with mirrored geometry



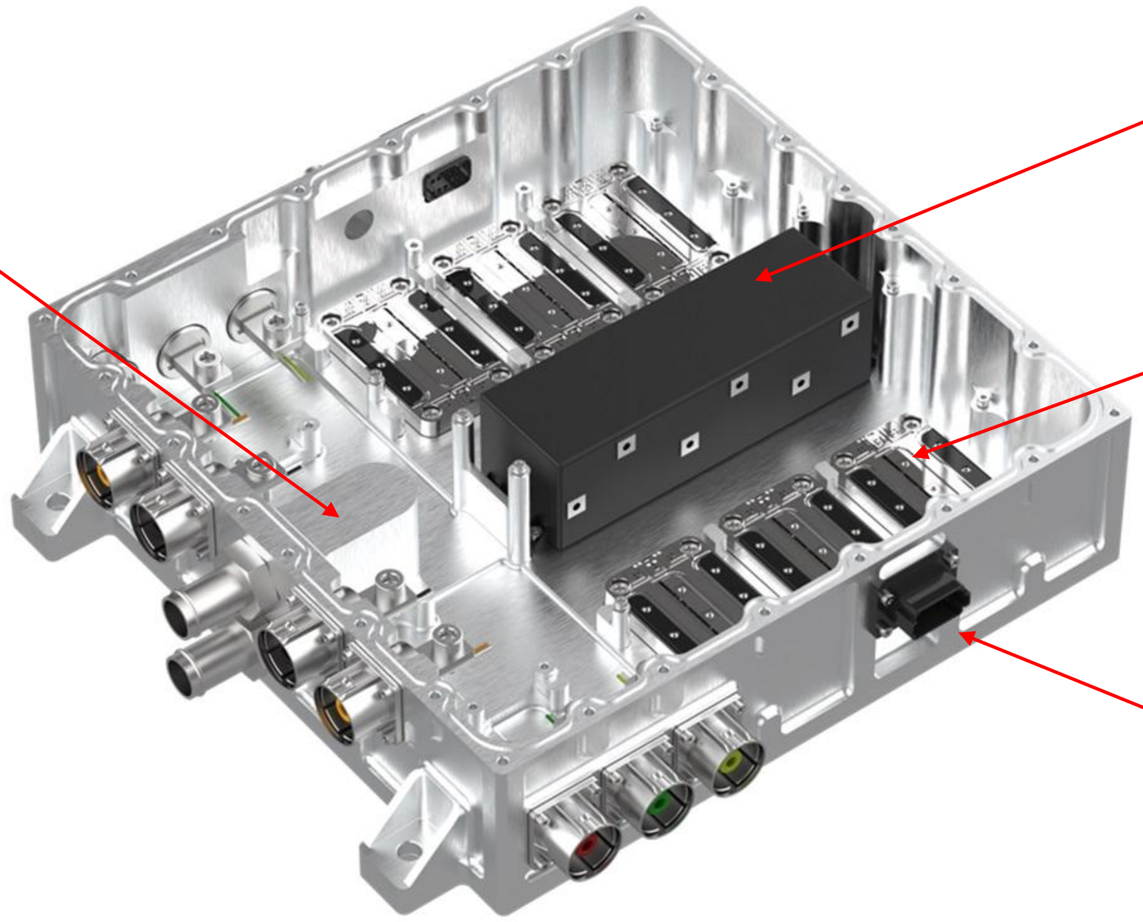
Dual SiC Inverter Mechanical Design

Cooling circuit and galleries machined into chassis

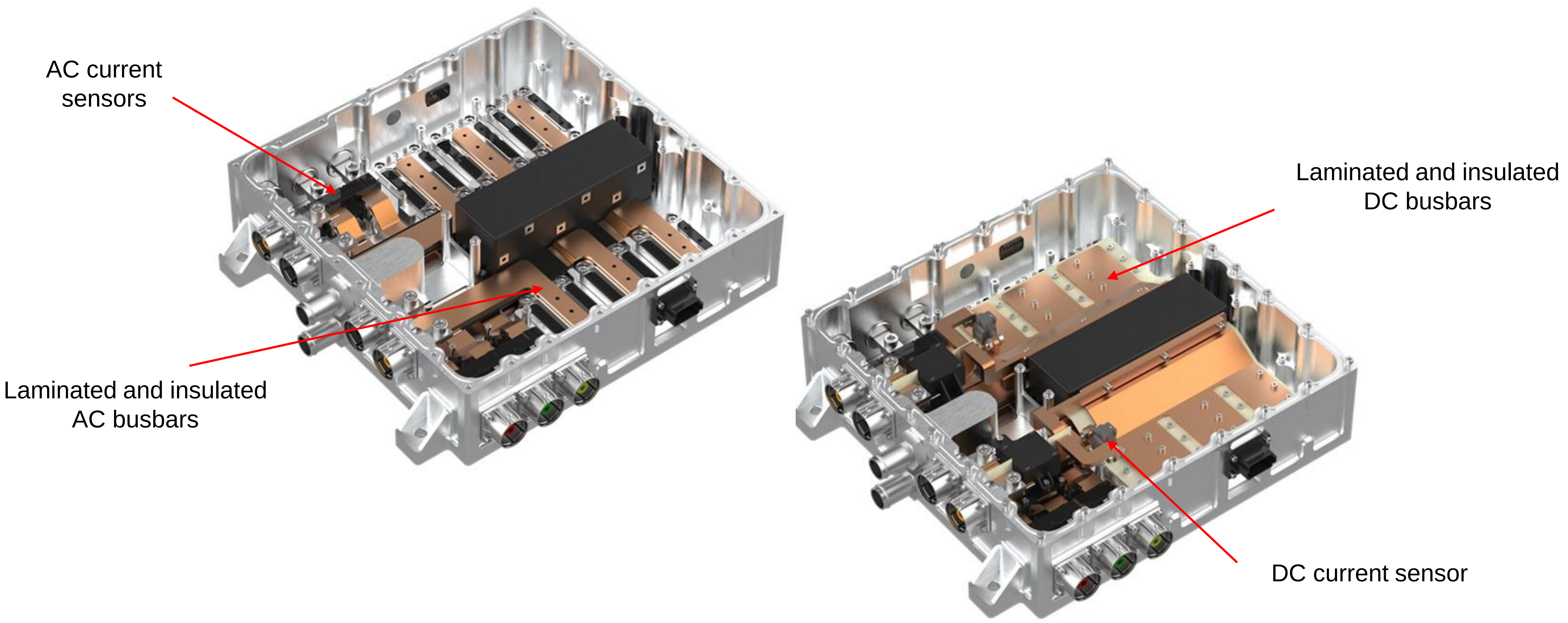
Split dual capacitor bank

Wolfspeed HM4 power modules secured against cooling circuit

Independent position and temperature sensor interface for each motor



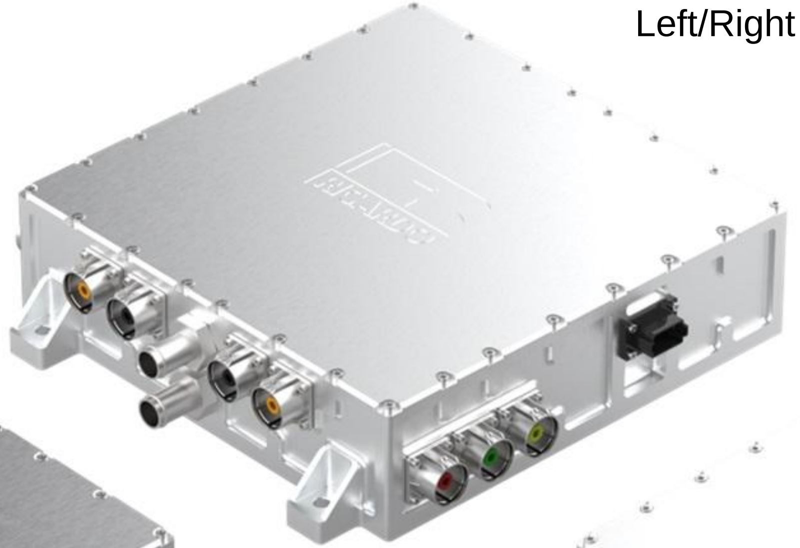
Dual SiC Inverter Mechanical Design

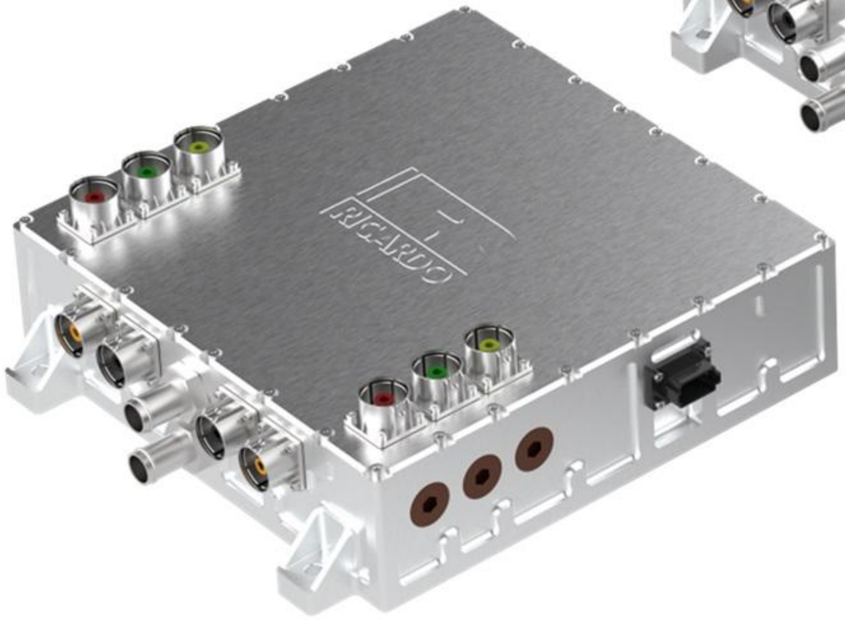


Dual SiC Inverter Mechanical Design

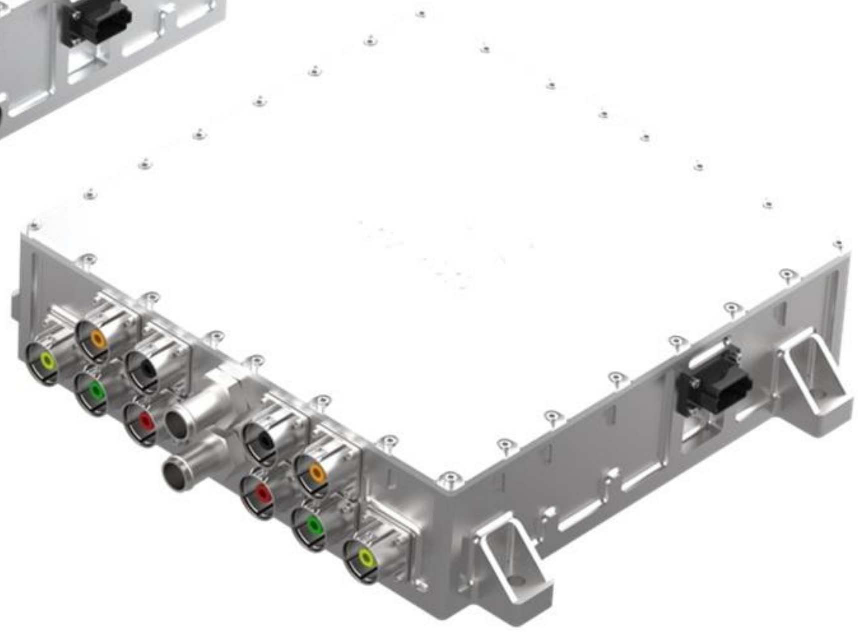
- Possible AC terminal exits

Left/Right Side Exit





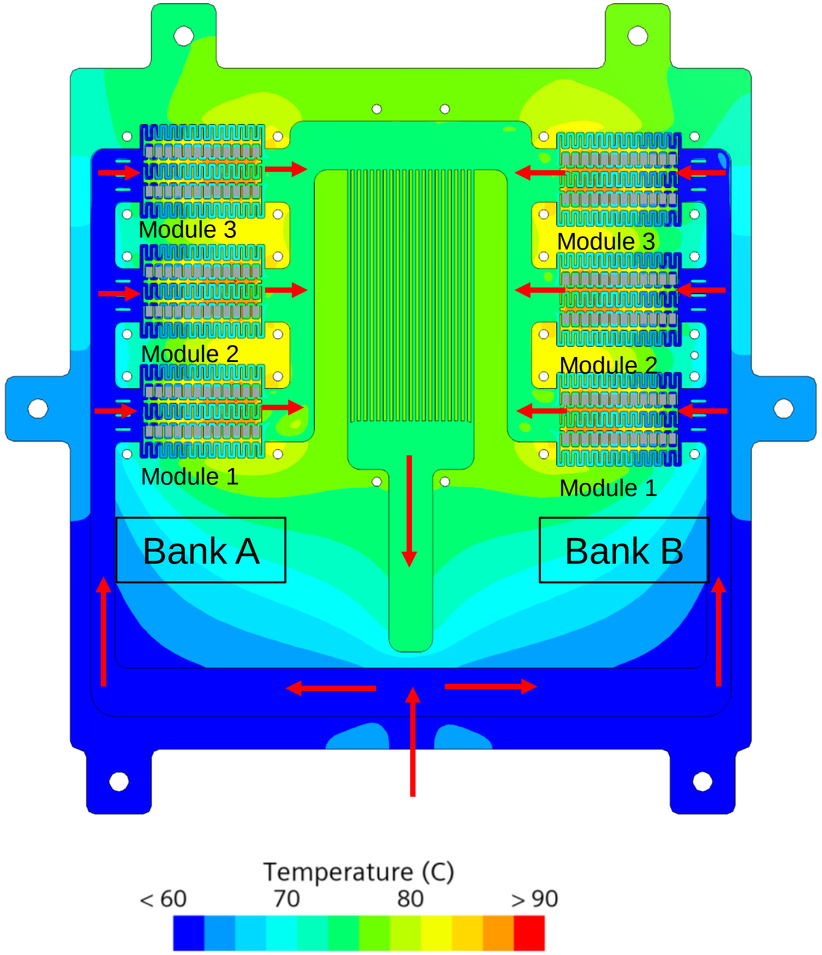
Top Side Exit



Front Side Exit

Dual SiC Inverter Thermal Design

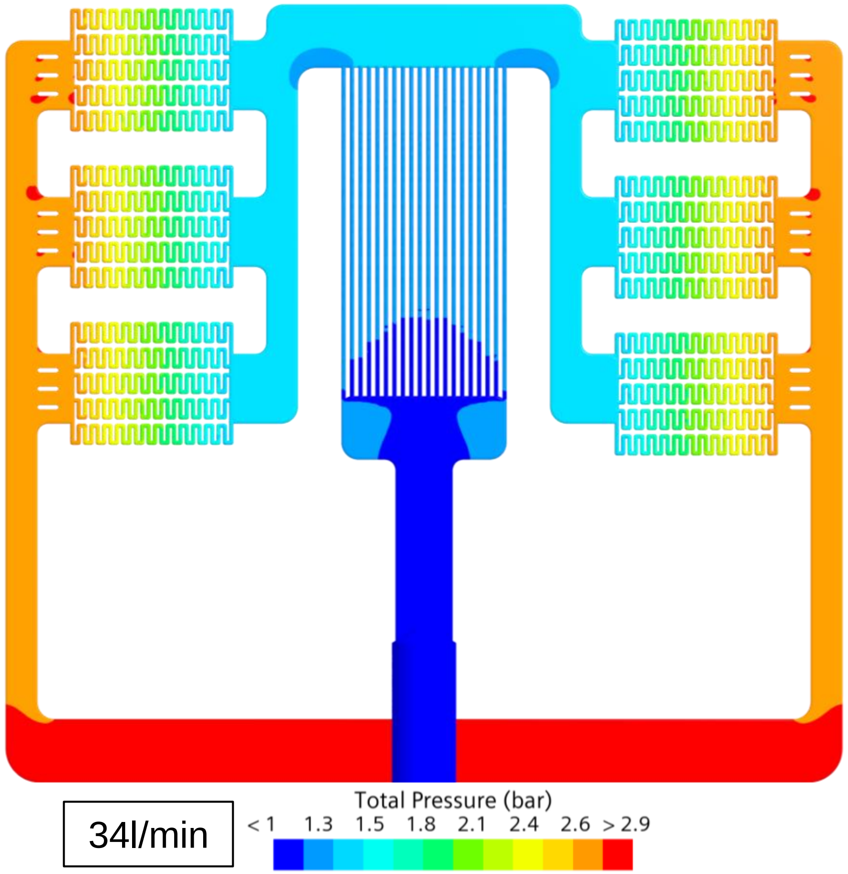
- Heat exchanger designed into the chassis
- Common inlet and outlet coolant spigots for flow rates of up to 34LPM
- Incoming fluid is split symmetrically between left and right inverters
- Cooling galleries and channels for each power module half-bridge
  - The three modules in parallel
  - The return flow then flows under the dc-link capacitor



Coolant Flow Rates and Pressure Drop

- Result for various flow rates are shown in the table below

	With Fins			
Total Flow Rate [l/min]	20	26	30	34
Maximum Temperature MOSFET [°C]	174	169	167	165
Average Maximum Temperature MOSFET [°C]	167	163	161	159
Maximum velocity through Micro-channels [m/s]	2.4	3.2	3.7	4.1
Outlet Temperature [°C]	74	71	70	68
Pressure Loss [bar]	0.68	1.11	1.46	1.84



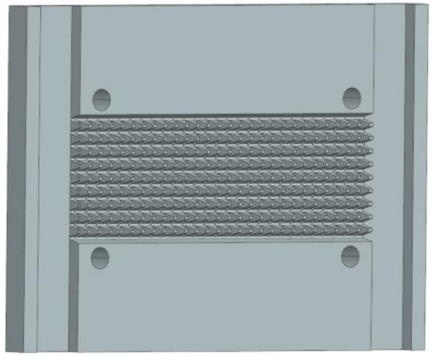
- Note that at very high flow rates >26LPM the pressure drop may become excessive and be highly dependent on system design.
- At 20LPM the semiconductors junction temperature reaches its specified maximum limit (175degC)

Cold Plate Designs

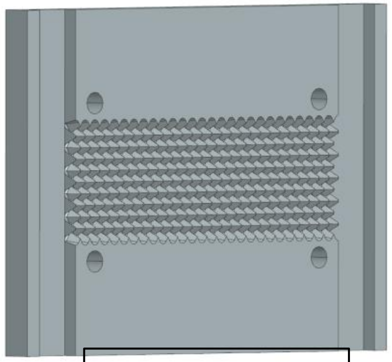
- Several cold plate arrangements were explored, including channels and pins of different dimensions
- The objectives are to maximise surface area and fluid turbulence

	Coolant Interface Area [mm2]
V channels	27600
Linear Pins	24900
Angular Pins	24900

V channels

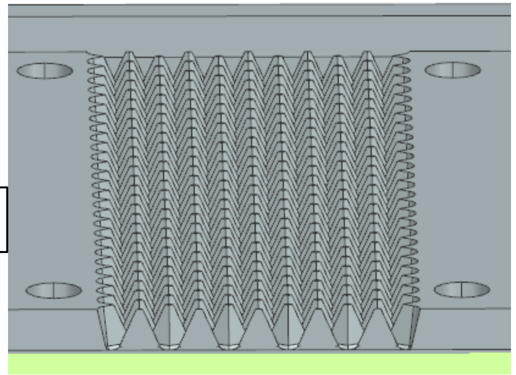


Linear Pins

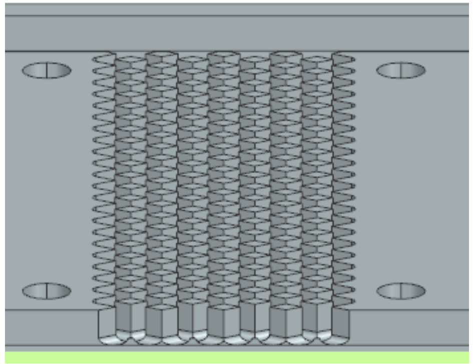


Angular Pins

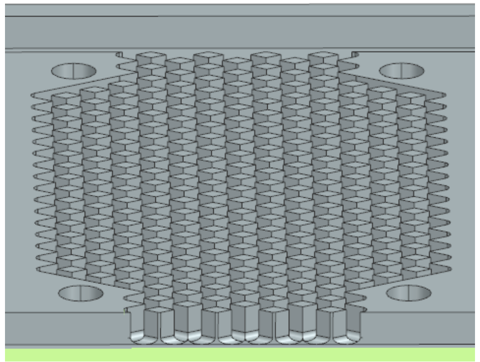
Sharp Pins



Square Pins



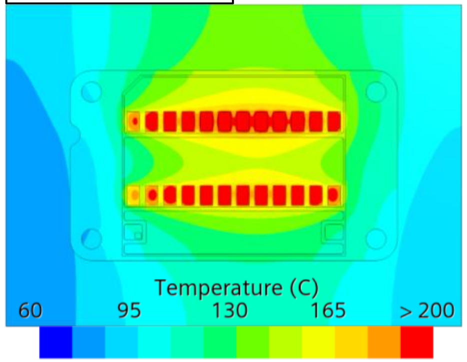
Square Pins- Extent Channels



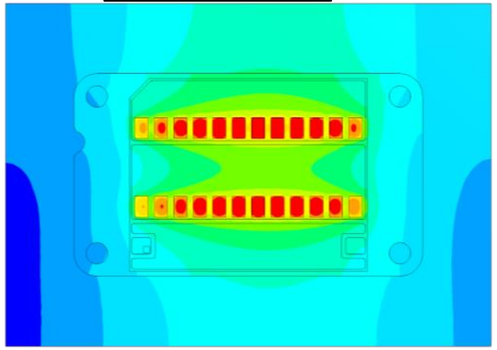
MOSFET Temperature Distribution

- Summary temperatures are listed in the table for selected geometries
- Temperature distribution over the module shown below
- The concentrated heat is observed within the central region of MOSFET rows

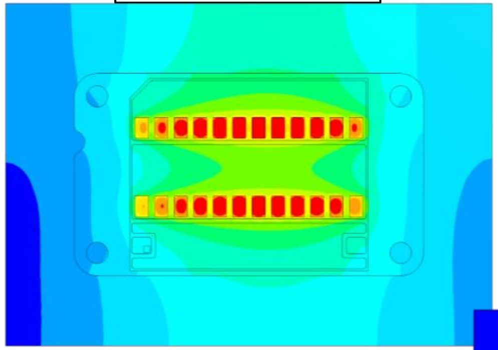
V channels



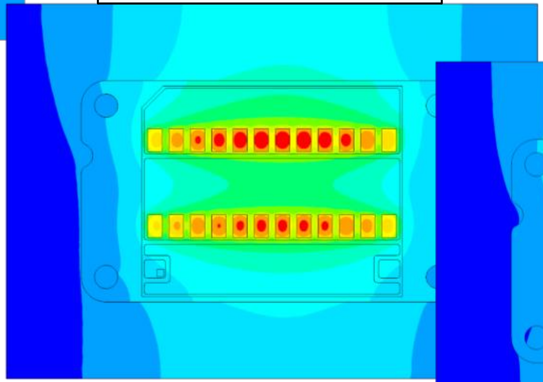
Linear Pins



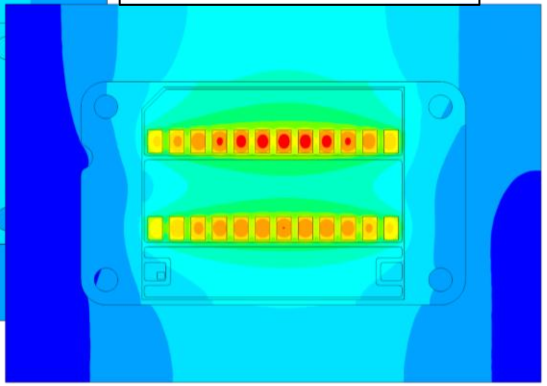
Angular Pins



Double Flow Rate

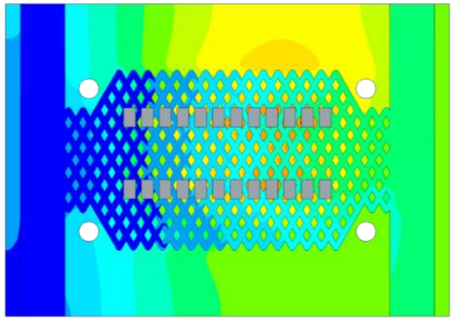


Thinner Cold Plate

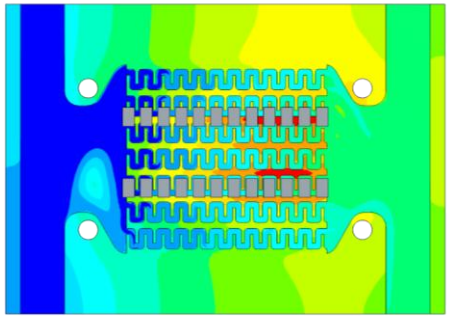


Lateral Wave Channel MOSFET Temperature Distribution

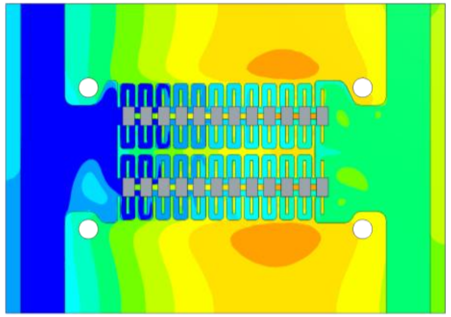
- A comparison of results is carried out between the Square Pin and Lateral Wave channel at mass flow rate of 10LPM
- Significant enhancements in term of temperature are observed in the Lateral Wave with MOSFET temperatures remaining below 175°C
- Notably, the Aligned arrangement showcases nearly identical MOSFET temperatures across both rows with a maximum T of 172°C



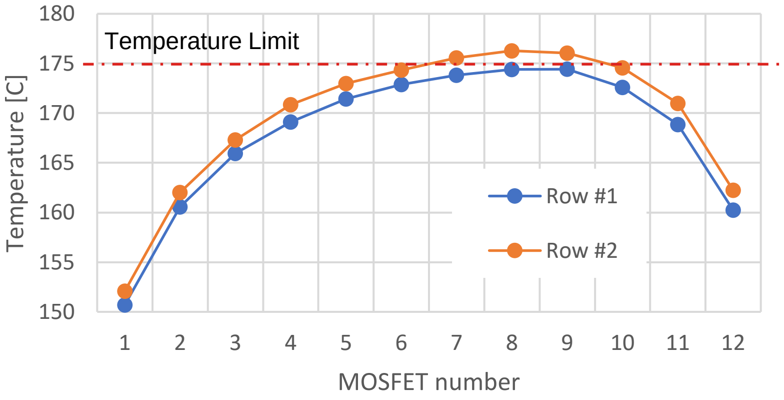
Square Pin Channels

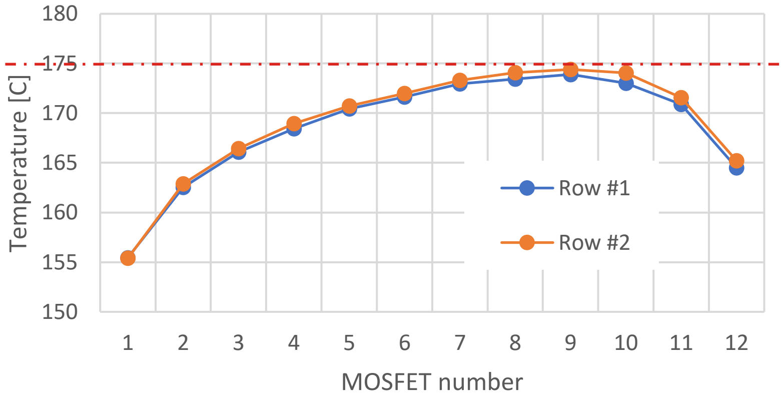


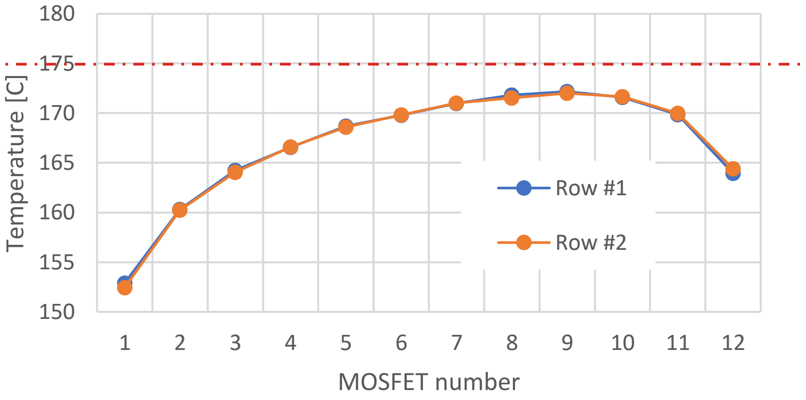
Offset-Lateral Wave Channels



Aligned- Lateral Wave Channels



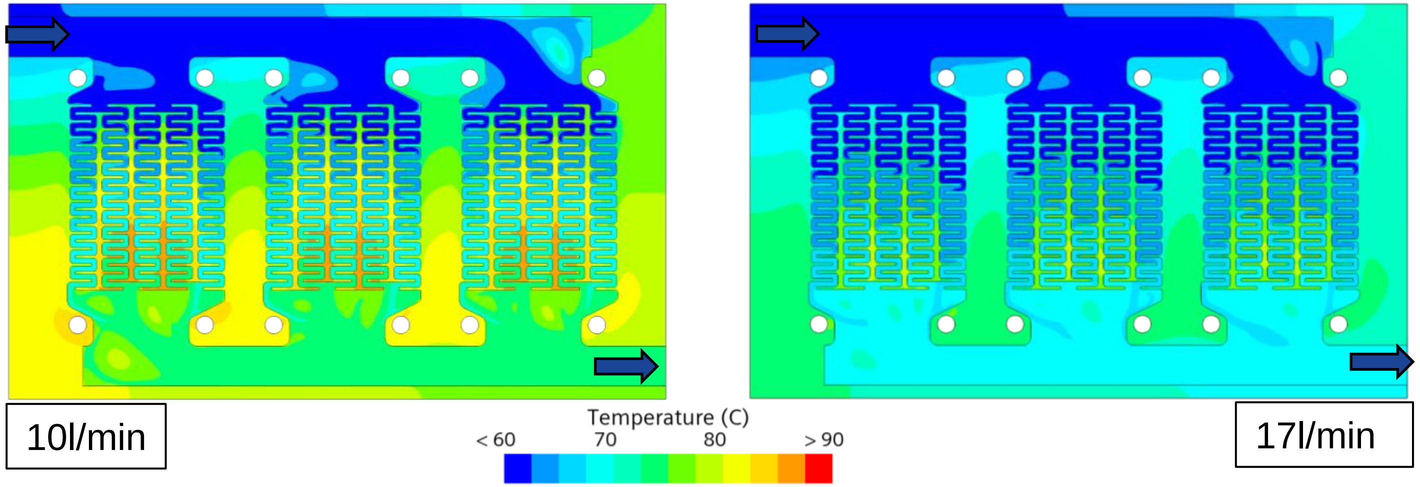




Flow Distribution Across Modules (1/2)

- An assembly of three modules positioned with opposite ends were assessed at flow rates of 10 and 17LPM (total of 20-34LPM combined)
- The results are presented in the table on the right
- At a flow rate of 10LPM, the results obtained for a single module closely resemble those from the assembly of modules
- As expected at 17LPM the module attains the target temperature with a 11°C margin and the maximum velocity under the MOSFETs remains within acceptable limits
- The elevating the flow rate to 17LPM results in a coolant temperature outlet is 5°C lower

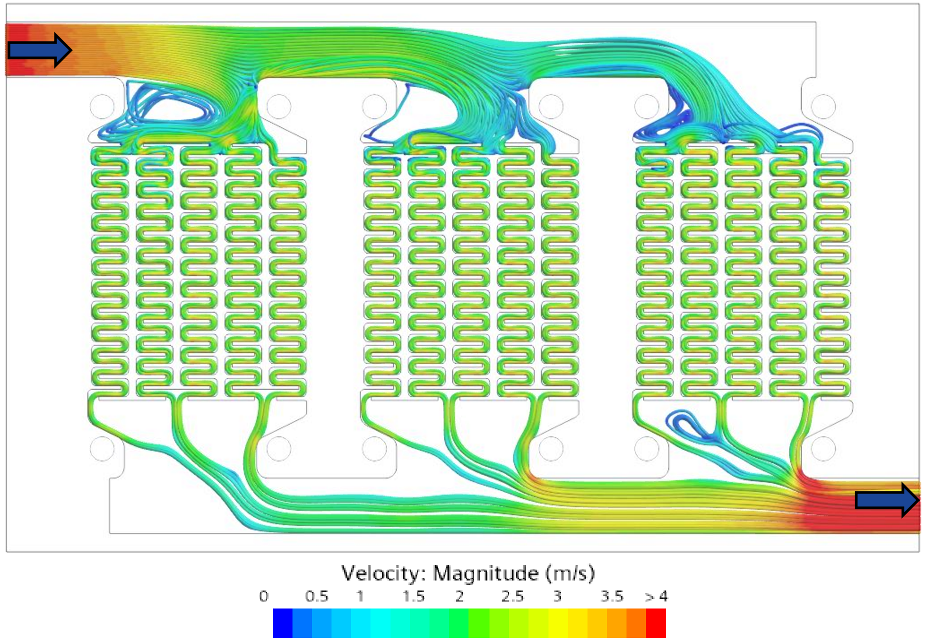
Three Modules- Vertical Channel V05b		
Total Flow Rate [LPM]	10	17
Inlet Temperature [°C]	60	60
Outlet Temperature [°C]	73.1	68.3
Maximum Temperature MOSFET [°C]	173	164
Maximum velocity through Micro-channels [m/s]	2.3	3.9
Pressure Loss [Bar]	0.38	1.07

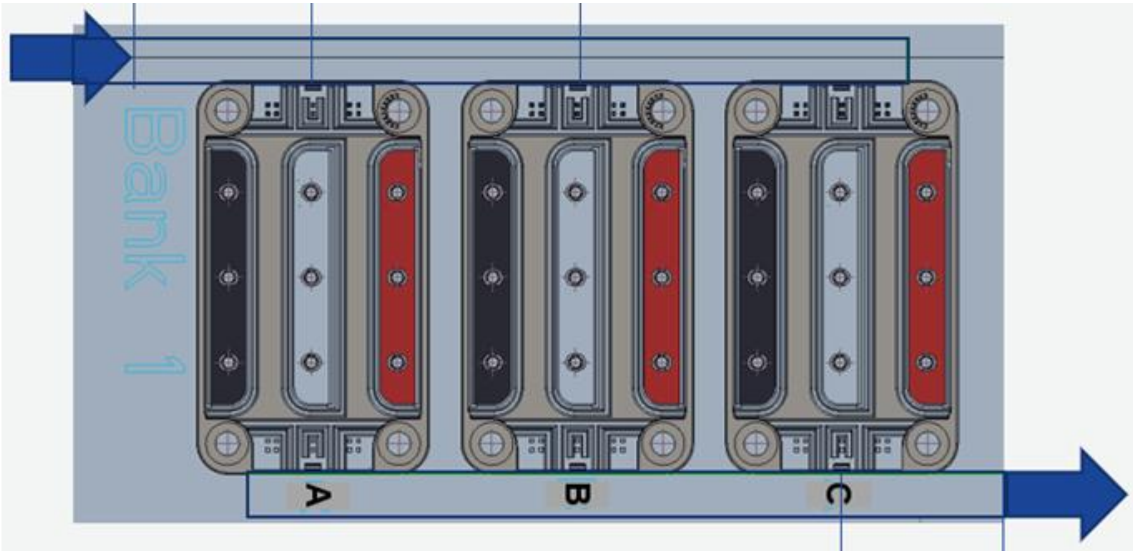


Flow Distribution Across Modules (2/2)

- Table on the right shows the maximum MOSFET temperature for each module with the module names correspond to picture below
- Temperature remain consistently uniform across all three modules with a deviation of less than 0.5°C regardless of the flow rate
- Flow streamlines are generated for the flow rate of 17l/min at inlet and contoured with velocity
  - The highest velocity reaches 5m/s observed at both inlet and outlet regions

Maximum MOSFET Temperature [°C]	Flow rate 10l/min	Flow rate 17l/min
Module A	173.4	164.1
Module B	173.1	163.7
Module C	173.1	163.8





Dual SiC Inverter Efficiency Map

- Inverter efficiency (one of two subsystems) when paired with a 400kW, 500Nm, 15000RPM PM synchronous motor

Current limited operation

Motor Speed (RPM)

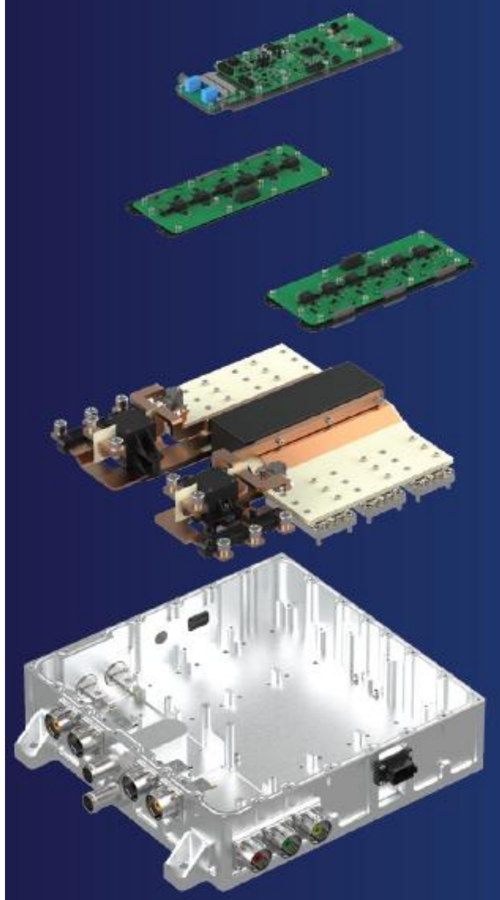
Motor Torque (Nm)	1000	3000	5000	7000	9000	11000	13000	15000
500	0.9103	0.9733	0.9799	0.9857				
450	0.9103	0.9731	0.979296	0.985376	0.988552			
400	0.910642	0.972676	0.978486	0.984714	0.988158			
350	0.909481	0.972065	0.977352	0.983892	0.987467	0.989792		
300	0.911227	0.971909	0.976566	0.983316	0.986974	0.989401	0.98446	
250	0.906098	0.970058	0.974164	0.981565	0.98567	0.98827	0.982307	0.984707
200	0.898226	0.966809	0.970402	0.978792	0.983511	0.986512	0.979079	0.981827
150	0.886621	0.961945	0.96471	0.974687	0.980244	0.983773	0.97419	0.977577
100	0.855189	0.949202	0.951258	0.964891	0.972533	0.977465	0.963227	0.968058
50	0.767557	0.910567	0.91197	0.935598	0.949226	0.958136	0.931292	0.940168

Voltage limited operation, flux weakening

Switching losses dominate

Variable switching frequency based on motor speed and electrical frequency

Concluding Remarks



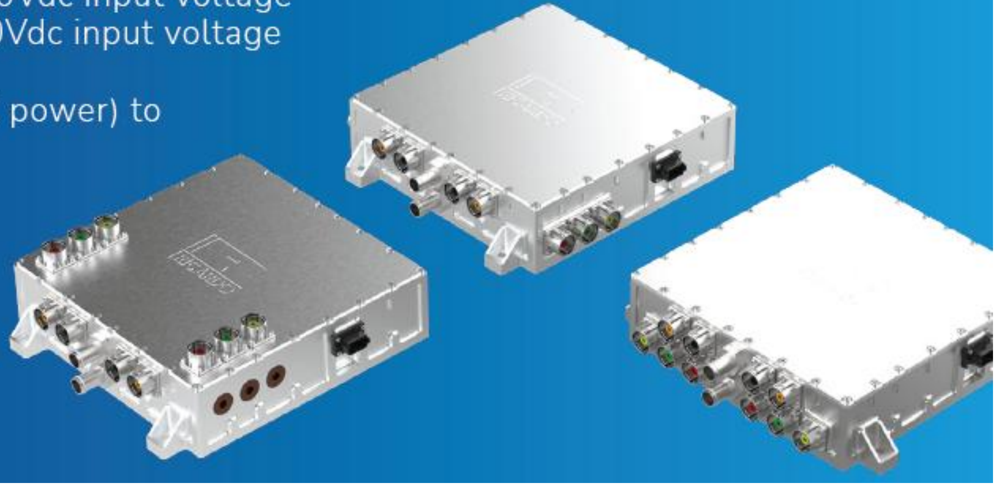
DUAL INVERTER SOLUTION

Ricardo’s dual output Silicon Carbide inverter offers high continuous and peak power levels required for high performance applications. Specifically designed for dual motor electric axles where high power levels are required as in performance cars or heavy-duty vehicles.

Ricardo’s dual output inverter enables platforms with traction power levels in excess of 1MW per axle at a power density of 34kW/kg (50kW/L).

SPECIFICATIONS & FEATURES:

- Dual input DC Bus Voltage 500V to 850V each
- Continuous RMS line current up to 500Arms
- Peak RMS line current up to 650Arms
- Continuous output power 400kW per output @750Vdc input voltage
- Peak output power 525kW (10s) per output @750Vdc input voltage
- Operating temperature -40°C to 70°C
- Water/glycol coolant temperature range 60°C (full power) to 90°C (de-rated power) at 34LPM
- Torque or Speed control
- Dual CAN interface
- Multiple safe states depending on fault condition (Active Short Circuit or 6 bridge open)



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