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DESIGN AND MANUFACTURING OF A HIGH-PERFORMANCE BATTERY MODULE FOR AN ELECTRIC RACING VEHICLE

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Abstract: This paper presents the design and development of a high-performance lithium-polymer battery module for a Formula Student electric racecar. The goal was to reduce weight, improve manufacturability, and enhance integration compared to the previous generation. A 14s2p configuration was chosen based on energy and power requirements, with pouch cells selected for their high power density and favorable packaging characteristics. The mechanical layout, electrical interconnections, and casing design were optimized with support from benchmarking of other teams. Manufacturing was carried out using 3D-printed flame-retardant parts and laser welding of cell tabs. The final system was successfully integrated into the target vehicle, confirming its proper functionality.

KEYWORDS: electric racing vehicle, battery module, pouch cell, laser welding, 3D printing, Formula Student

1 Introduction

The rapid expansion of electric mobility has placed unprecedented demands on the design and integration of lithium-ion battery systems. In both mass-produced electric vehicles (EVs) and high-performance racing prototypes, battery packs must deliver high power and energy densities within minimal weight and volume, while ensuring mechanical safety, thermal stability, and electrical reliability. In motorsport applications, these requirements are even more stringent due to space constraints, aggressive load profiles, and strict safety regulations [1], [2].

Modern battery modules integrate cells with materials and components for structural reinforcement, electrical isolation, thermal management, and safety, with many trends and technologies specific to this domain. Soft cushioning foams are used to protect fragile pouch cells from vibrations and shocks. As Wünsch et al. [3] found, applying appropriate pressure on pouch cells can extend their lifetime by up to 80 %. Thermal interface materials (TIMs) improve heat transfer between sources and cooling elements [4], while flame-retardant polymers and ceramic barriers reduce fire propagation risk during thermal runaway [5]. Connections made via laser or ultrasonic welding are often designed and optimized by advanced methods, such as in [6], to ensure low resistance while maintaining mechanical robustness [7]. According to Lee [8], the stiffness of battery packs strongly depends on the contact area and fastening method, especially in Cell-to-Pack designs. Additive manufacturing with flame-retardant filaments is increasingly adopted for enclosures, offering flexibility, weight savings, and fast prototyping [9], with mechanical behavior strongly influenced by fiber orientation, as shown in [10].

Thermal management remains critical, particularly as cell power density increases. Poor thermal regulation shortens lifespan and accelerates degradation, especially when local cell temperatures exceed 50 °C or vary by more than 5 °C across the module [11]. Zhao et al. [12] report innovations in liquid cooling, such as aluminum jackets, composite gels with graphite particles, and mini-channel cold plates with optimized coolant paths. Air-based cooling remains attractive for small or weight-sensitive modules due to its simplicity. Authors of [13] highlight

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approaches like ducted airflow, turbulence-inducing fins, and compartmentalized channels to enhance convection in compact layouts.

Motorsport applications serve as a unique proving ground for lightweight, compact, and robust battery systems that are increasingly relevant to mainstream EV development. In this context, we present the electromechanical design and prototyping of a high-performance battery module intended for integration into the 600 V battery system of a Formula Student racecar built by the STUBA Green Team – the longest-running university team in Slovakia developing a Formula Student (FS) vehicle [14]. Each season, a new vehicle is developed as an iteration of the previous one (shown on Fig. 1). The battery module presented in this paper was developed for the current season, with the goal of demonstrating the design approach and technological improvements compared to the previous generation. The focus was placed on the selection of lithium-polymer pouch cells, compact mechanical layout, safe electrical interconnections using laser welding, and manufacturability using flame-retardant 3D-printed structures. The new module, compared to the previous generation, aims to reduce weight without compromising thermal performance, while also improving manufacturability and simplifying assembly.

All work presented in this paper was carried out by the authors, with the following contributions: Martin Baťa – mentoring, consulting, and paper writing; Alexander Lazorík – mechanical and electrical design; Samuel Mazúr – technical leadership and coordination of manufacturing activities. Supporting contributions were also provided by other members of the STUBA Green Team during development and assembly.

Fig. 1 STUBA Green Team racecar SGT-FE22 from season 2022

2 Requirements and methods

The first step was to understand the specific requirements of the application, evaluate the limitations of the previous design, and outline viable improvements.

2.1 Application context and design constraints

Formula Student is an international engineering competition where student teams design, manufacture, and race small-scale electric vehicles [15]. The competition imposes strict technical rules [16], including limits on maximum voltage, energy content, and mechanical robustness of battery systems. In this context, modularity, weight optimization, manufacturability, and serviceability become essential design goals. To meet these performance, safety and manufacturing demands under real-world constraints, the design must be tailored specifically to the conditions and capabilities of a student racing team.

Our target application is a racecar with a 4-wheel-drive architecture and a fully custom battery system. The FS rules define strict technical constraints to ensure safety, serviceability, and standardization across teams. The system needs to be separated into modules (called segments in the rules), each of them below 120 V and 6 MJ of energy and 12 kg of mass. The whole system must not exceed 600 V and 80 kW of output power. The modules must withstand accelerations of 40 g in lateral and longitudinal directions and 20 g vertically. System and module housings must use flame-retardant materials and prevent propagation of thermal runaway. Pouch cells, due to their mechanical sensitivity, must be protected from edge loads and supported across their broad surfaces using compliant materials. The casing needs to be made of steel or aluminum; composite materials are allowed only if equivalency is proven.

From a practical perspective, all manufacturing, testing, and assembly is performed by undergraduate students within a single academic season. This necessitates a design that is simple to produce, yet structurally sound and safe. Component selection is limited to locally available materials and technologies with short lead times. Specialized tooling, processes, and parts are often infeasible due to cost or access limitations. The design must accommodate student skill levels while maintaining the robustness expected from an EV battery system.

2.2 Electrical performance targets

The electric vehicle is equipped with the AMK Racing Kit, consisting of four independent electric motors and corresponding inverters [17]. The team has been using this powertrain architecture since 2018, gaining extensive experience with its energy consumption and dynamic behavior under race conditions. While the system supports voltages up to 720 V (see Fig. 3), 600 V is the target maximum battery voltage, due to competition rules. The target battery system energy was set between 7.5 and 8.0 kWh, similar to previous iteration. This value is based on data from previous seasons, reflecting the typical energy consumption of the current powertrain and the vehicle's expected mass, which is anticipated to decrease only marginally.

The efficiency map of the motors, as well as the corresponding mechanical and electrical power curves – including the average inverter efficiency of 98 % – are shown in Fig. 2. To fully utilize the maximum potential of all four motors simultaneously, the battery would need to supply approximately 180 kW of electrical power. However, this scenario cannot occur in practice due to the competition's 80 kW output power limit. As such, the primary design objective for the battery is to reliably deliver 80 kW, with some performance margin, even at low states of charge (SOC). The full capabilities of the motors can still be exploited through torque vectoring strategies, where individual motors can be operated at high power levels, though never all at once.

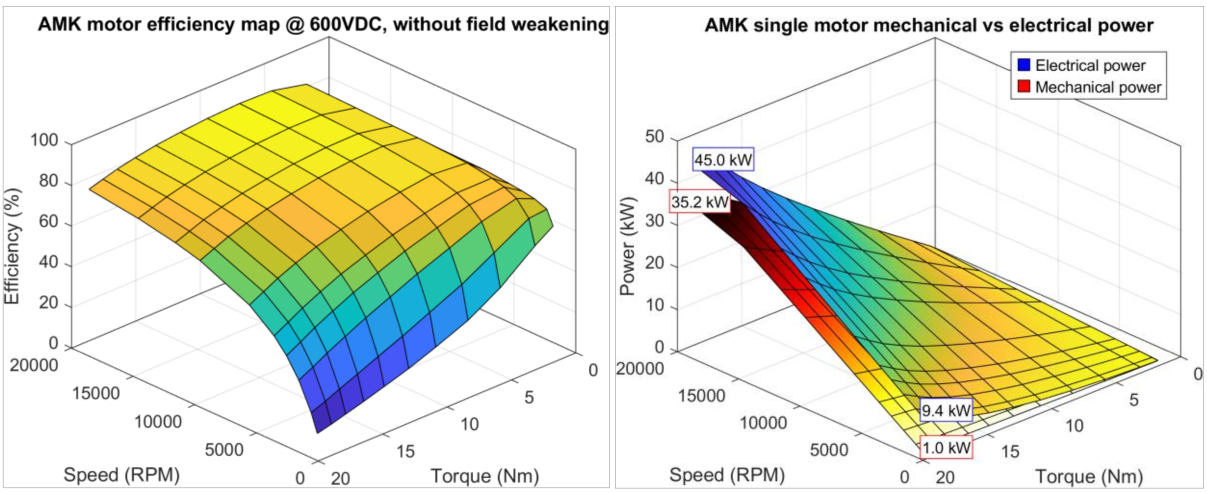

Fig. 2 AMK drivetrain characteristics

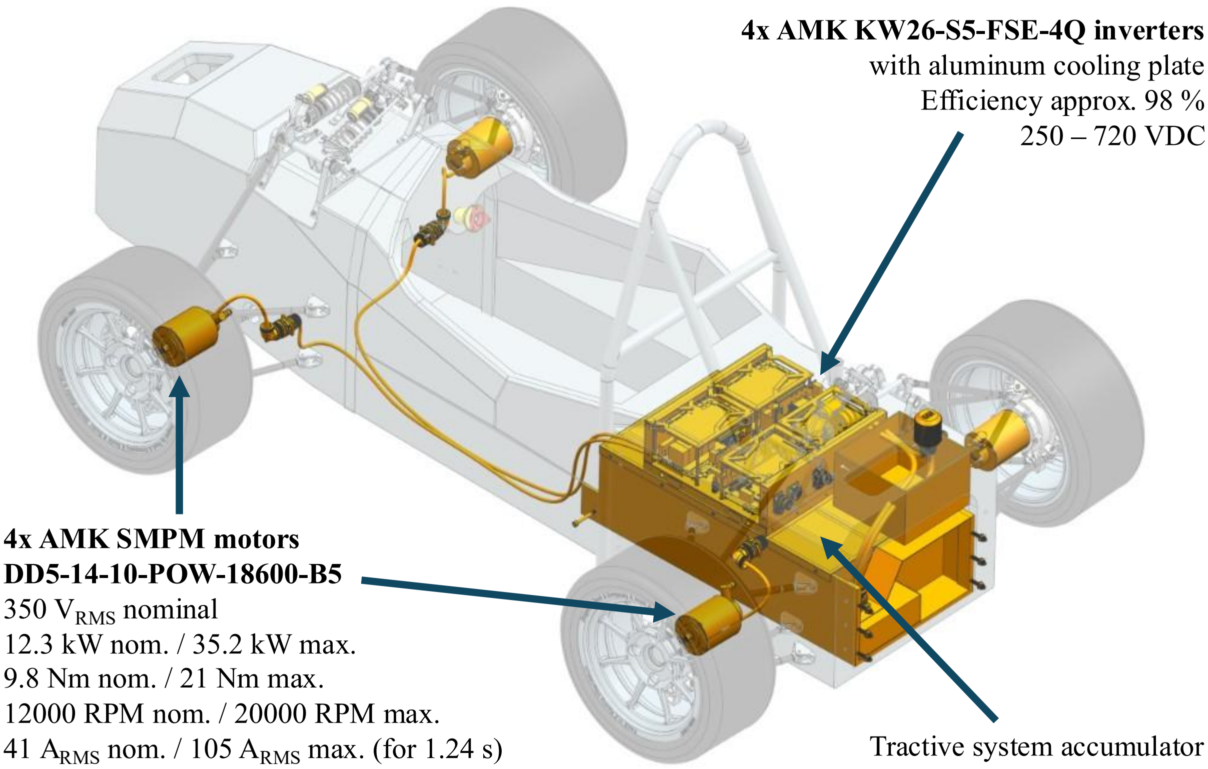

Fig. 3 Tractive system of the vehicle with motor and inverter parameters [17], [18]

2.3 Analysis of previous battery system generation

The previous battery system, developed for the 2022 vehicle, employed a 140s3p configuration based on Melasta SLPB694513HV lithium-polymer pouch cells. The system consisted of ten modules, each containing 14s3p cells, assembled on CNC-cut FR4 baseplates. Cells were mounted on layers of flame-retardant adhesive silicone foam to enable soft mounting and support airflow-based cooling (see Fig. 4 and Fig. 5).

This casing approach was cost-effective, but significantly limited design flexibility. The manual gluing process was labor-intensive and susceptible to alignment errors. Furthermore, the chosen airflow-based cooling concept proved to be oversized and ultimately unnecessary for the actual thermal loads encountered.

Electrical interconnections were implemented using ultrasonic welding, which turned out to be overly complex – particularly because multiple welds were required on a single busbar. This has caused de-joining of first welds after adding others and ultimately meant that all the contacts had to be reworked using laser welding (see Fig. 6). Although this provided sufficient electrical resistance in the end, the process was not ideal, highly sensitive to alignment accuracy and only a temporary last-minute solution. It required a custom fixture for ultrasonic welding and another for laser welding. This, combined with frequent manual adjustments, resulting in inconsistent weld quality across the modules and very labor-intensive process.

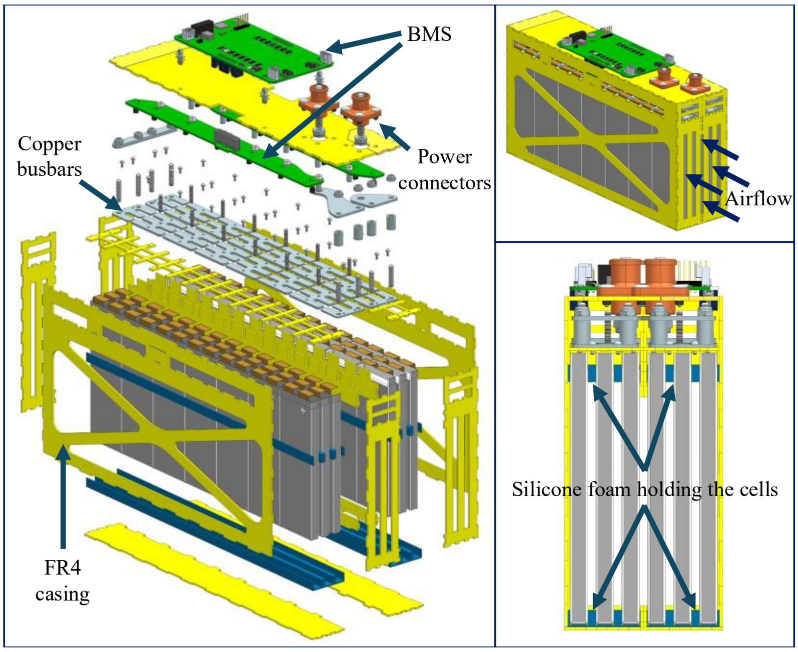

Fig. 4 Visualizations of previous generation battery module

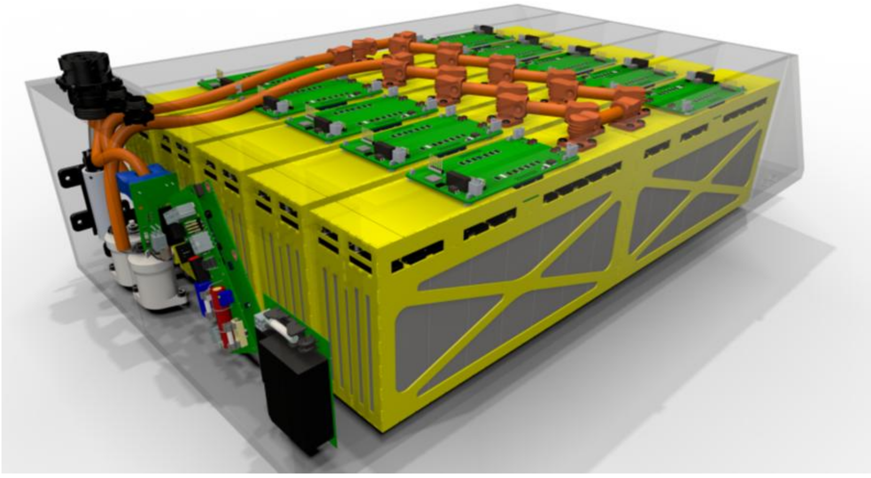

Fig. 5 Visualization of previous generation battery system

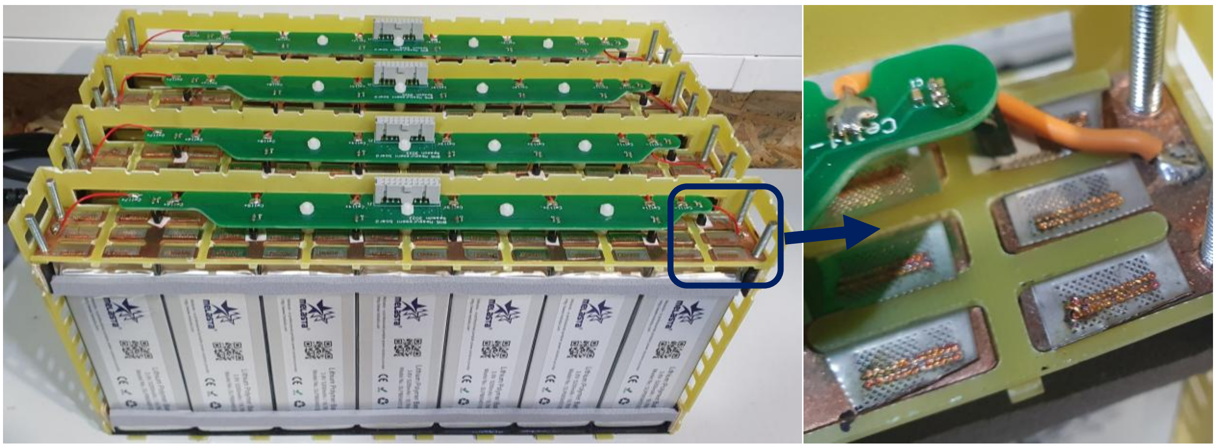

Fig. 6 Previous generation of battery half-modules after manufacturing, with ultrasonic and laser welds in detail

2.4 Design methodology and goals

The design process with a new module followed an iterative, constraint-driven approach. Requirements were derived from the FS rules, available components, packaging envelopes, and powertrain specifications. An initial configuration was drafted on paper and validated using a spreadsheet-based electrical model. Cell grouping and interconnect layouts were refined to balance current paths and minimize voltage drops.

Mechanical design was developed using 3D CAD modeling in Siemens NX, including all busbars, housings, and cell placeholders. Key dimensions and tolerances were reviewed through peer inspection and physical mock-ups. Manufacturing decisions were made based on available suppliers, including laser welding and 3D printing support from partner companies.

The battery module was designed with a focus on repeatability, service access, and seamless system integration. Key goals of the new generation included reduced weight, simplified mechanical layout, and elimination of inter-cell cooling gaps. Although this was expected to slightly reduce thermal performance, the previous design had sufficient headroom, and no thermal issues were observed in practice. The trade-off was therefore considered acceptable, as it promised improved long-term pouch cell reliability through consistent pressure. Additional objectives included better manufacturability via optimized packaging, fewer components, and more robust contact joining. The concept featured 3D-printed casings, with laser welding planned from the outset as a replacement for the previously used ultrasonic method.

3 Electrical design

Once the system requirements were defined, the focus shifted to selecting a suitable battery cell and configuring the electrical layout to maximize its performance.

3.1 Cell format and chemistry

Selecting the appropriate battery cell format is a fundamental step in the design of a high-performance battery module, especially in environments with strict spatial constraints and demanding load profiles such as Formula Student. The chosen cell must offer not only high energy and power density, but also facilitate compact integration, reliable thermal management, and mechanical stability under dynamic conditions. On the other hand, the life cycle is not that crucial in this case, as the battery system usually serves only one season with a few competitions and not more than 100 cycles.

After many internal considerations and market research, pouch lithium-ion polymer (Li-Pol) cells were selected for this application due to their high discharge capability, low internal resistance, and excellent packaging efficiency. As found from market research and emphasized in recent literature [19], [20], pouch cells typically exhibit the lowest internal resistance among commercial formats, enabling low voltage drop and efficient high-current operation with minimal losses. Their flat geometry allows for dense stacking with packaging efficiencies of up to 90–95 %, which is essential when working within a space-limited car chassis. Although more mechanically sensitive than cylindrical cells, these limitations can be effectively managed through compliant mounting and rigid structural support.

The team’s long-standing experience with pouch cells played a key role in this decision, allowing the design to build upon proven integration methods rather than introducing additional risks through a major format transition. As further illustrated in the next section, pouch-type LiPol cells remain a common choice among competitive Formula Student teams, highlighting their continued relevance for space- and performance-critical applications.

3.2 Cell selection and electrical configuration

The selection of suitable battery cells began with an evaluation of multiple pouch-type lithium-polymer candidates, primarily from Melasta [21], a long-standing supplier previously used by the team, and Grepow [22], a more recent manufacturer gaining popularity within the FS community. Both offer high-discharge LiPo cells with parameters compatible with our requirements.

The design process was guided by the maximum system voltage permitted by competition rules – 600 V. This constraint defines the number of series-connected cells, typically around 143 for standard cells with a fully charged voltage of 4.2 V, or fewer when using high-voltage variants. High-voltage variants were preferred during cell selection, as they allow a reduction in the total number of series-connected cells. Nominal voltage was in either case expected to be approximately 530 V, with the minimum voltage under load defined at 420 V, based on the common 3.0 V lower limit of LiPo chemistry and these manufacturers.

Parallelization strategy was also critical. A single cell in parallel was ruled out due to reliability concerns – it presents a single point of failure, where even one weak weld or contact could limit overall performance. On the other hand, using more than three cells increases complexity, reduces packaging efficiency, and adds dead volume due to extra interconnecting and structural needs. A configuration of two or three cells in parallel was therefore considered optimal, leading to the derived cell parameter requirements presented in Table 1.

Table 1 Battery system and cell requirements

Target system energy	*7.5 – 8 kWh*
Maximum cell voltage	*4.2 V (preferably higher)*
Nominal system voltage	*≈ 530 V*
Minimum system voltage	*≈ 420 V (3.0 V per cell)*
Required system capacity	*8 kWh / 530 V ≈ 15 Ah*
Resulting individual cell capacity	*≈ 7.5 Ah (2p) or ≈ 5.0 Ah (3p)*
Peak system power	*80 kW × 1.1 (safety margin) = 88 kW*
Peak system current at minimum voltage	*88 000 W / 420 V = 210 A*
Peak cell C-rate	*210 A / 15 Ah = 14 C*

These performance targets were used only as primary filter when comparing available cells. All candidate cells were then benchmarked in terms of capacity, voltage, current handling, and resulting system configuration, with summary data presented in Table 2. The most relevant are highlighted using color scales, with green indicating the most favorable values, red the opposite.

After comparing multiple viable options, the final selection was the Grepow GRPA74214-15C (7450 mAh), as it fulfilled all technical requirements, including voltage and current specifications, and offered a significantly lower cost compared to the Melasta alternatives. The resulting maximum voltage of 609 V in this configuration will be limited by the BMS to the rule-defined maximum of 600 V. The associated capacity loss is negligible. On the other hand, cells will not be charged to their absolute maximum, which also contributes to improved safety. Additionally, the chosen number of series-connected cells (140) is more modular-friendly and easier to divide evenly into battery modules compared to alternatives like 139 or 138, making the slight overvoltage well justified. The decision was to divide the resulting system into 10 series-connected modules, considering manufacturability and BMS limitations.

Table 2 Cell selection and resulting system configuration (chosen cell highlighted)

	Melasta 8542126 (used in 2018)	**Melasta** 6945135HV (used in 2022)	**Grepow** 742124	**Melasta** 742124HV	**Melasta** 942126HV
Capacity (mAh)	5200	5200	7450	7450	7900
Discharge rate cont. (C)	15	10	10.8	15	10
Discharge rate peak (C)	20	23	15	20	15
Continuous current (A)	78.0	52.0	80.5	60.0	79.0
Peak Current (A)	104.0	119.6	111.8	149.0	118.5
Internal resistance (mΩ)	2.2	2	1.8	1.5	1.5
Nominal voltage (V)	3.7	3.8	3.8	3.8	3.8
Maximal Voltage (V)	4.2	4.35	4.35	4.35	4.35
Minimum Voltage (V)	3	3	3	3	3
Mass (g)	102.5	88	124	124	129
Energy density gravimetric (Wh/kg)	187.71	224.55	228.31	228.31	232.71
Energy density volumetric (Wh/L)	427.73	485.47	518.50	516.43	528.87
Power density gravimetric (kW/kg)	2.82	2.25	2.47	1.84	2.33
Power density volumetric (kW/L)	6.42	4.85	5.60	4.16	5.29
SYSTEM PARAMETERS:					
Cells series	140	140	140	140	140
Cells parallel	3	3	2	2	2
Number of cells	420	420	280	280	280
Maximum voltage (V)	588	609	609	609	609
Nominal voltage (V)	518	532	532	532	532
Minimum voltage (V)	420	420	420	420	420
Continous current (A)	234	156	160.9	120	158
Continous power @nom. volt. (kW)	115.6	80.7	82.3	62.3	81.4
Continous power @min. volt. (kW)	92.7	63.2	64.3	48.9	63.7
Peak current (A)	312	358.8	223.5	298	237
Peak power @nom. volt. (kW)	151.6	178.9	112.6	149.2	120.2
Peak power @min. volt. (kW)	131.0	150.7	93.9	125.2	99.5
System capacity (Ah)	15.6	15.6	14.9	14.9	15.8
Energy (kWh)	7.86	7.96	7.60	7.60	8.06
Cell mass (kg)	43.1	37.0	34.7	34.7	36.1

4 Mechanical integration and CAD design

With the battery cell format and electrical configuration defined, the next step focused on the mechanical integration and CAD design of the battery module. This stage addressed the spatial arrangement of cells, design of the structural enclosure, and overall packaging strategy within the constraints of the vehicle chassis. Emphasis was placed on mechanical robustness, serviceability, and manufacturability—ensuring that the resulting module could be reliably assembled by students and integrated into the full battery system.

4.1 Benchmarking of Formula Student battery module electromechanical designs

To better understand the design landscape, we analyzed public sources, technical documentation, and team websites to identify battery module solutions developed by other Formula Student teams using pouch cells and operating under comparable constraints. From our research and available published materials, pouch cells are the most commonly used format in this field, followed by cylindrical cells in a second place. Some of the published solutions are:

- **TU Wien Racing** (Austria) and **Team WOB Racing** (Germany) used Melasta pouch cells in 3D-printed casings with bolted connections and no inter-cell spacing, see Fig. 7a [23], [24]
- **Race Up Team** (Italy) employed Melasta SLPBA843126 6350 mAh 15C 3.7 V pouch cells in a 144s2p configuration, housed in milled epoxy-glass parts with aluminum busbars and bolted cell connections, see Fig. 7b [25]
- **Ecurie Aix** (Germany) designed a 144s2p pack using 5.6 Ah Melasta pouch cells, 3D-printed casings, bolted joints, and air cooling focused on busbar areas rather than between cells, see Fig. 7c [26]
- **Formula Electric Belgium** implemented a 144s2p, 600 V, 6.9 kWh system with 3D-printed lightweight casings and laser-welded cell interconnections [27]
- **University Racing Eindhoven** (Netherlands) developed an integrated PCB for BMS monitoring and direct laser-welded cell connections [28]
- **VUB Racing** (Belgium) built a 72s, 300 V system with single-parallel 8 Ah Melasta pouch cells in a PolyMax PC-FR 3D-printed enclosure with integrated nuts for bolted contacts [29]
- **Racetech Racing Team** (Germany) used pouch cells in 3D-printed casings without inter-cell gaps [30]
- **BIT Racing Team** (China) constructed their system from polycarbonate plates with air gaps between pouch cells for enhanced cooling [31]
- **MIT Motorsports** (USA) employed compressed A123 pouch cells with fire-retardant neoprene padding, mechanically clamped connections, and side-directed fan cooling [32]

Based on these trends, the team opted for a similar approach using pouch cells, 3D-printed casings, and laser-welded tab connections. Benchmarking confirmed that compact layouts and simplified mechanical integration are common in successful designs and helped guide early development choices.

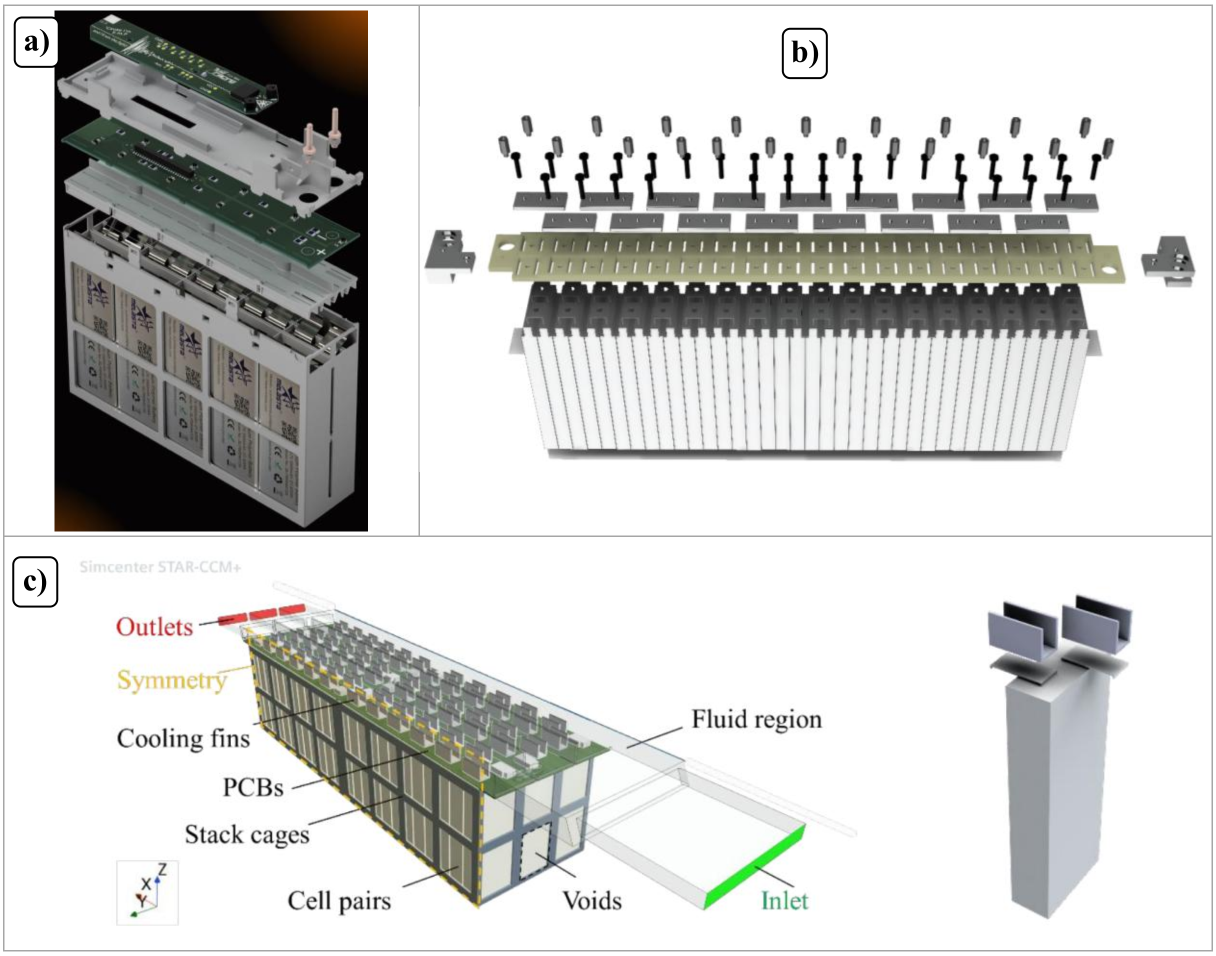

Fig. 7 Benchmarked FS battery module solutions: a) TU Wien Racing (Austria) [24], b) Race Up Team (Italy) [25], c) Ecurie Aux (Germany) [26]

4.2 Cell layout selection

Each battery module was designed in a 14s2p configuration. The selected cell was fully 3D modeled based on datasheet dimensions and real-world measurements of supplied samples. Special attention was given to modeling the tab geometry and surrounding area, as previous experience showed variations in tab placement and shape between individual cells. The model was designed to accommodate these deviations.

Two mechanical layouts were considered for the cell stack: an electrically linear and a U-shaped configuration (see Fig. 8). The U-shape, very similar to previous years, would present challenges in achieving uniform cell compression and maintaining mechanical stability. The resulting module would be longer and narrower, more prone to bending, and would require longer structural walls in the battery system casing, reducing overall stiffness. This layout would also mean similar busbar configuration to previous years, which was not ideal and meant to be revised this year.

Initially longer and narrower, the linear layout was later revised into a more compact half-module configuration (see Fig. 9), with direct alignment of copper tabs. This enabled minimalistic electrical connections, where the tabs are in direct contact and the busbar serves primarily as mechanical support (further detailed in Section 4.3). The half-module approach also simplified assembly and allowed for partial service or replacement in the future.

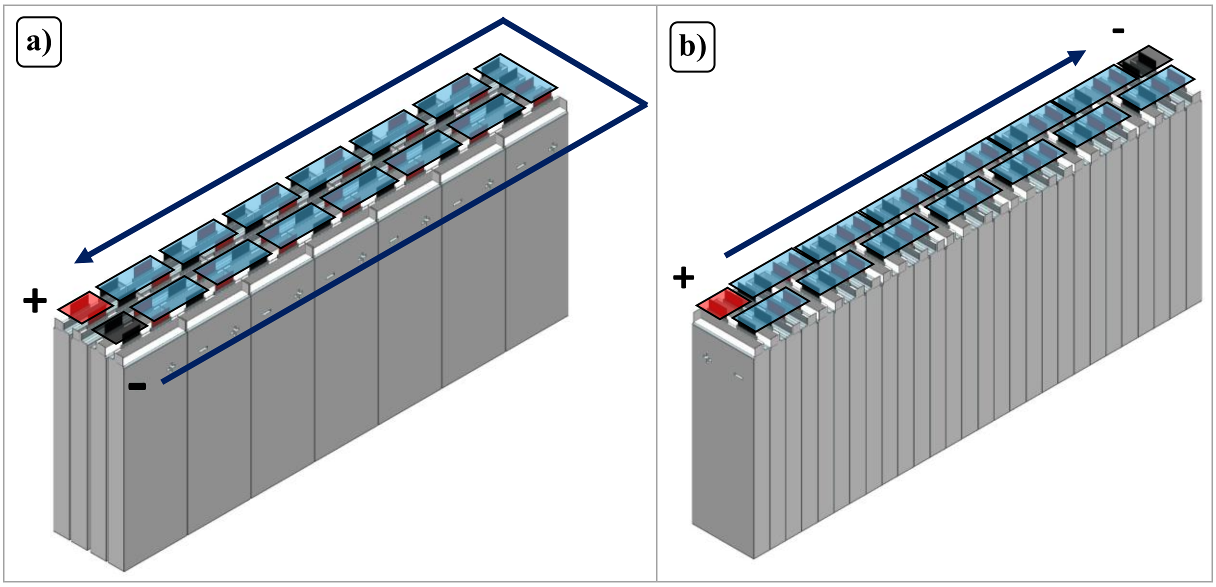

Fig. 8 Two primary layout configurations – a) U-shape, b) linear

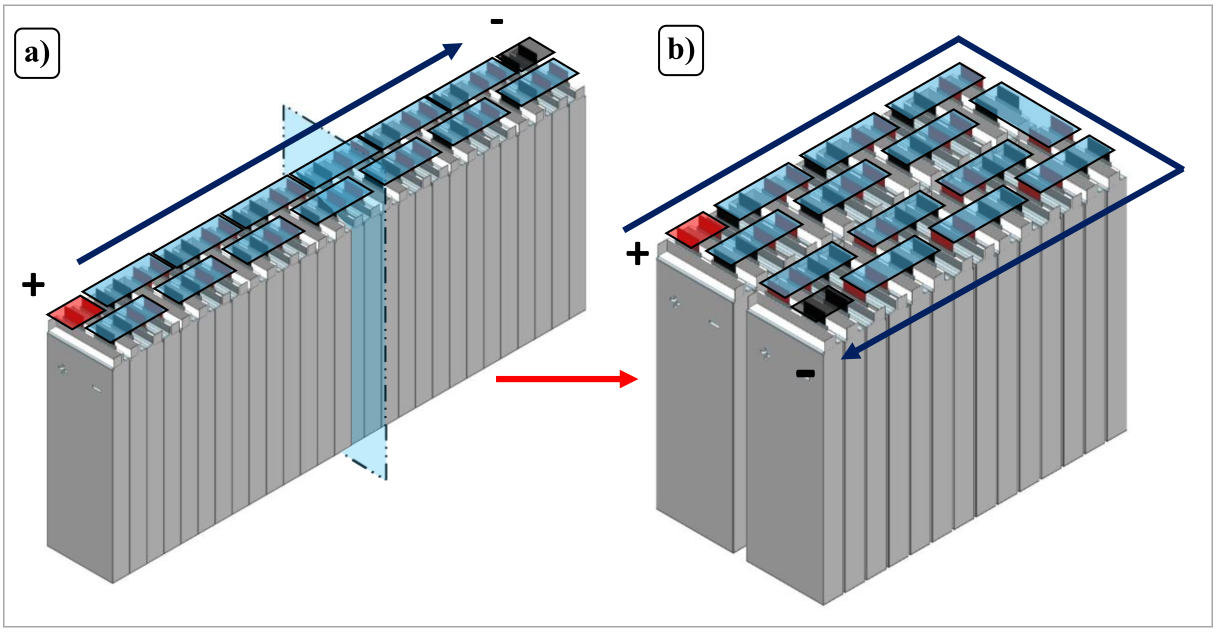

Fig. 9 Secondary layout configuration (b) created from the original linear configuration (a)

4.3 Electrical interconnection design

From the beginning, the goal was to implement laser welding as the preferred joining method. It is non-contact, less invasive, and allows the module to be fully assembled prior to welding. In contrast, ultrasonic welding, used in previous designs, requires strong mechanical support (usually from below) to withstand high sonotrode forces. Additionally, vibrations from the welding process can damage nearby components or weaken already welded joints.

Despite this, several ultrasonic welding configurations were explored (see Fig. 10a, b, c), as this method can yield excellent contact quality when properly executed. However, the mechanical requirements – especially the need for large anvil and sonotrode access – proved excessive for the compact integrated module design. Accommodating such tooling would have required enlarging the module, which was not acceptable.

Laser welding was therefore selected as the final solution, applied from the top to simultaneously join all four tab layers at each connection point. The busbar acts as the mechanical support and weld base. This method is visualized on Fig. 10d. To further optimize the layout, the busbars were designed to be integrated with or placed directly on top of the PCB, as discussed in the following sections.

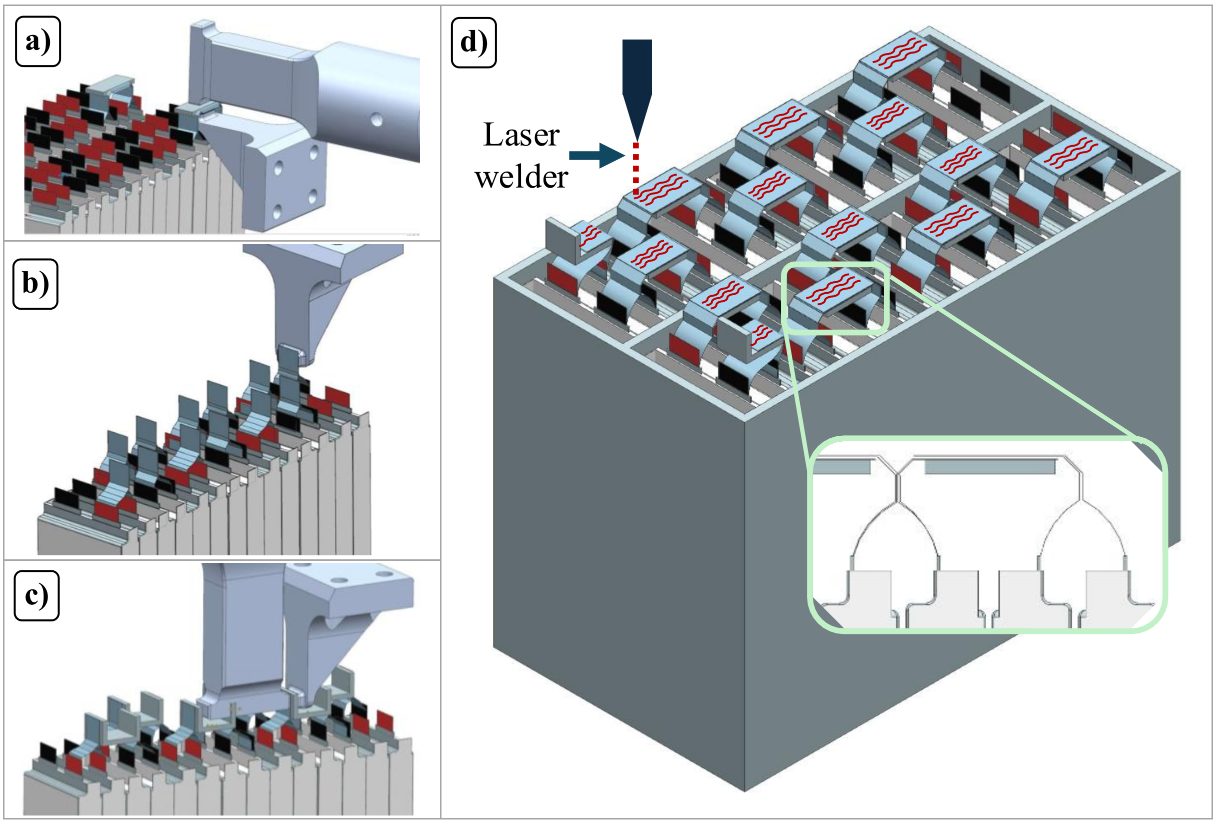

Fig. 10 a) b) c) Comparison of various considered ultrasonic welding concepts, d) selected laser-welded interconnection concept

4.4 Mechanical and casing design

The mechanical enclosure of the battery module was designed as a four-part 3D-printed casing, comprising left and right halves, an internal divider plate, and a removable top cover (see Fig. 11a). The material used was flame-retardant filament suitable for functional prototyping. To protect the pouch cells, 1–3 mm flame-retardant foam Schlegel S30 [33] was placed between and around cells, serving both as mechanical cushioning and thermal interface (pink material in Fig. 11b). The structure was designed to resist pouch swelling and provide protection against vibration and external impact.

The top-mounted PCB includes voltage measurement traces from busbars to connector, as well as integrated temperature sensors, positioned directly above each welded tab connection (see Fig. 11b, c). The module layout was optimized for airflow efficiency and weight distribution, with active air cooling directed across the contact area and the PCB surface, rather than between individual cells. Fig. 12 shows the final module design along with a side view illustrating the cooling strategy. Due to packaging constraints, a more optimal placement of the PCB connector was not feasible, therefore it is expected to partially obstruct airflow. However, airflow is still present both beneath and above the PCB, and the design relies on induced turbulence to extract heat even from the partially blocked region.

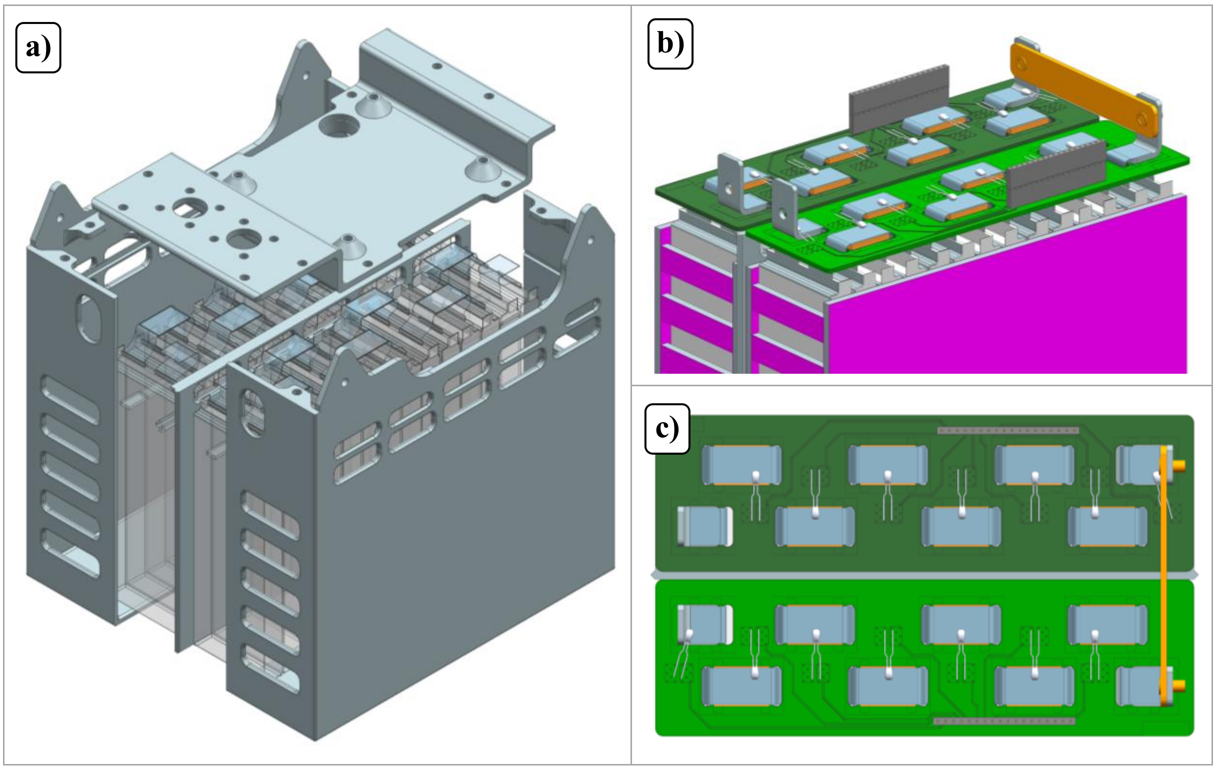

Fig. 11 Mechanical design of the module – a) 3D printed 4-part casing, b) c) cell joining PCB with temperature sensors

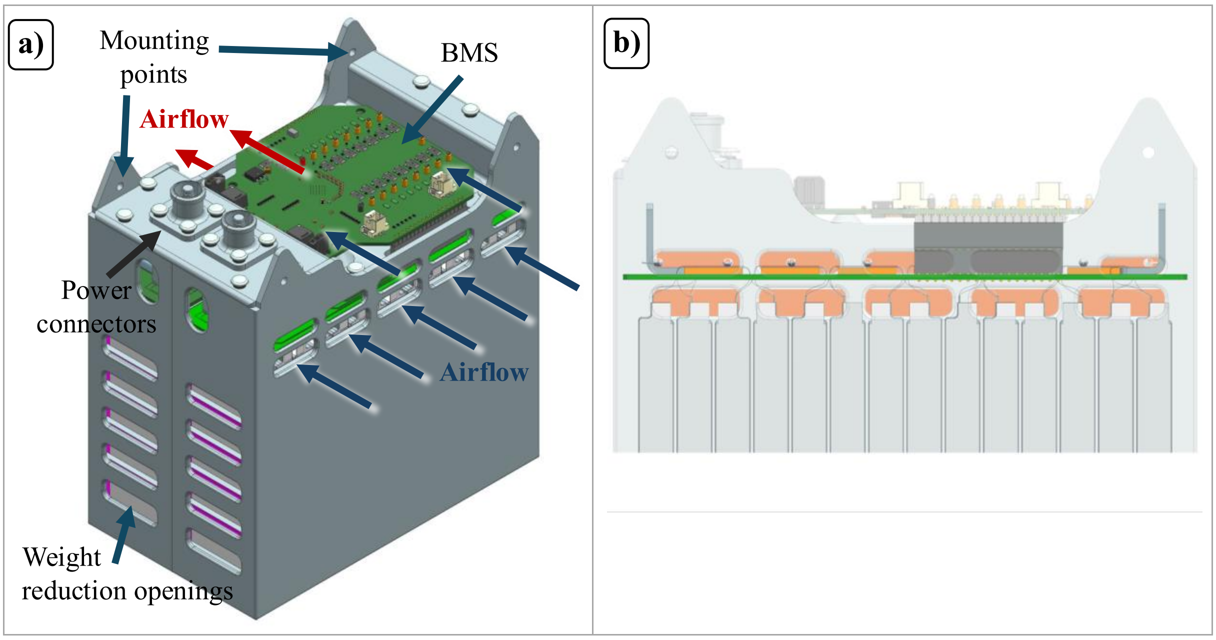

Fig. 12 a) Final module CAD design, b) cooling ducts through the module (orange color)

The module was designed with the entire battery system in mind, which – due to scope limitations – is not described in detail in this paper. However, the final system-level configuration with all connections (called “maintenance plugs” by the rules) is illustrated in Fig. 13.

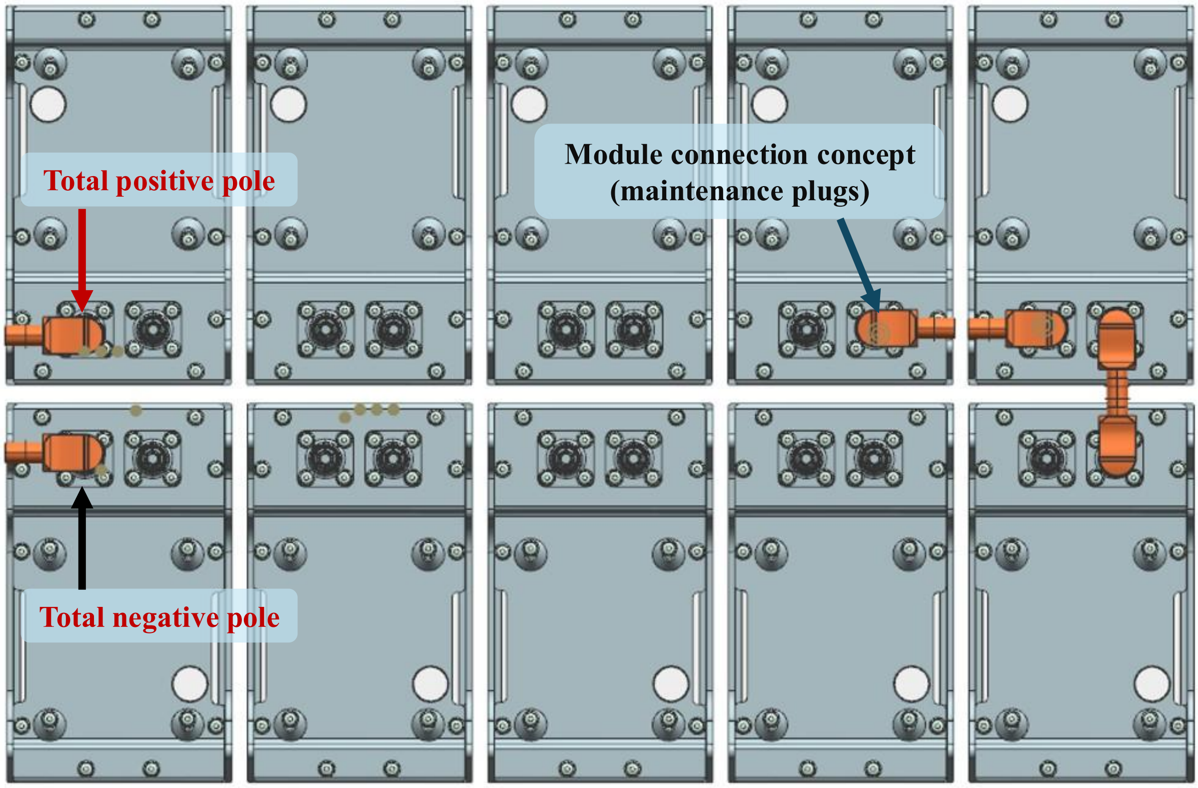

Fig. 13 Battery system complete layout

5 Manufacturing, results and discussion

The module manufacturing began with Fused Deposition Modeling (FDM) 3D printing of the four-part enclosure. After considering multiple technologies and suppliers, Z-240 flame-retardant filament [34] was selected due to good availability from partner company ZF Slovakia. The original team's preference for Stereolithography (SLA) or Selective Laser Sintering (SLS) printing was unfortunately not feasible due to budget and supplier constraints. Due to the complex material properties of the filament used (containing 40% glass fiber), several issues were encountered, including dimensional inaccuracy, low mechanical strength, and layer delamination, particularly on small features and supports. Two additional iterations of the printed design were required. Manual post-processing of the parts was necessary (see Fig. 14a).

After all casing parts were prepared, the assembly process began by joining the battery cells into a single stack with 1 mm foam layers between them and taping the contact tabs together (Fig. 14b). The PCB was then positioned directly on top of the cell contacts. Outer silicone foams were installed around the stack, and the entire assembly was inserted into the casing. The PCB was glued into a prepared groove in the casing to ensure fixation. Finally, the cell tabs were bent into position to make contact with the copper busbars, completing the half-module preparation for welding (Fig. 14c).

To support the welding process, a custom laser welding fixture was developed in-house using 3D-printed plastic for fast iteration. Flexible silicone foam was used to press the contacts down, which is important for weld quality and feasibility (Fig. 14d). The laser welding was performed in cooperation with the partner Prvá zváračská, an established welding company based in Slovakia, using a programmable robotic arm and external laser source (Fig. 15a and 15b). Several welding imperfections were observed during the process, including soot contamination, burned plastic and foam, and most notably, tab deformation and lifting (Fig.

15c). The lifting was caused by accumulation and displacement of molten material beneath the contact area, which led to partial separation of some welded layers before solidification. Fortunately, the tabs always maintained electrical contact with each other, as in most cases, the lift-off occurred only from the busbar, which serves solely for voltage sensing and does not carry current. Despite these issues, the welding process was successfully completed for all 10 modules.

After welding, temperature sensors were fixed in place using thermally conductive potting compound. The two half-modules were then assembled together, including internal busbar connection, power terminals, and BMS integration (Fig. 16a and 16b).

To summarize the lessons learned from the manufacturing process, the new module design – compared to the previous generation – achieved simplified assembly, reduced labor intensity, and a lower overall weight and component count. It also offered a higher level of integration, better compliance with competition rules, and fewer manual operations, which helped minimize potential sources of error.

Challenges included limitations of the 3D printing process and underestimated contact pressure requirements during welding. Future iterations should focus on improving casing material and manufacturing, welding fixture and contact pressing strength, and airflow design. The current cooling layout is partially compromised by the PCB connector placement, which blocks the airflow, though its impact on actual temperatures remains to be verified.

Despite these issues, the modules were successfully integrated into the system (Fig. 16c) and later into the vehicle. Initial in-car testing confirmed full functionality and no faults. Thermal and electrical validation is currently ongoing and planned further.

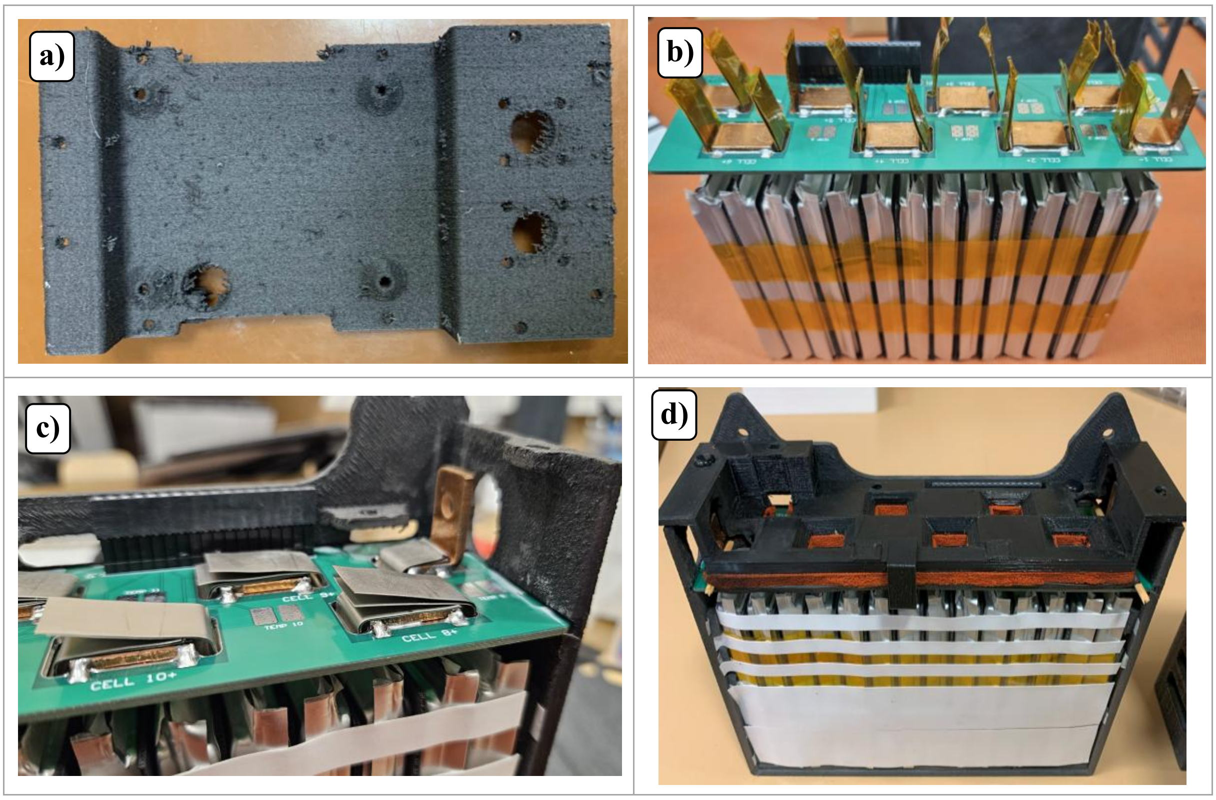

Fig. 14 Module assembly details – a) printing quality example, b) cell stack with PCB, c) cell contacts ready for welding, d) half-module with welding fixture, ready for welding

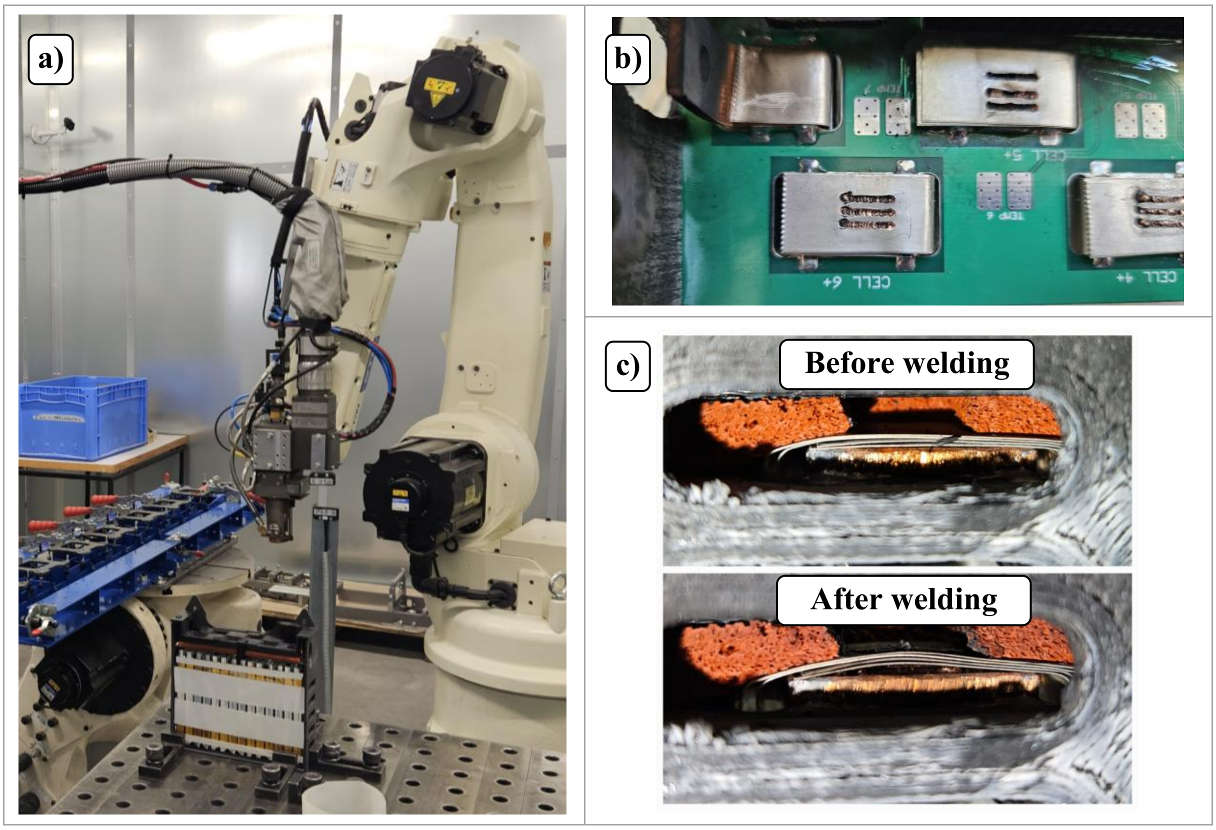

Fig. 15 Laser welding details – a) welding setup, b) completed welds, c) contact lifting

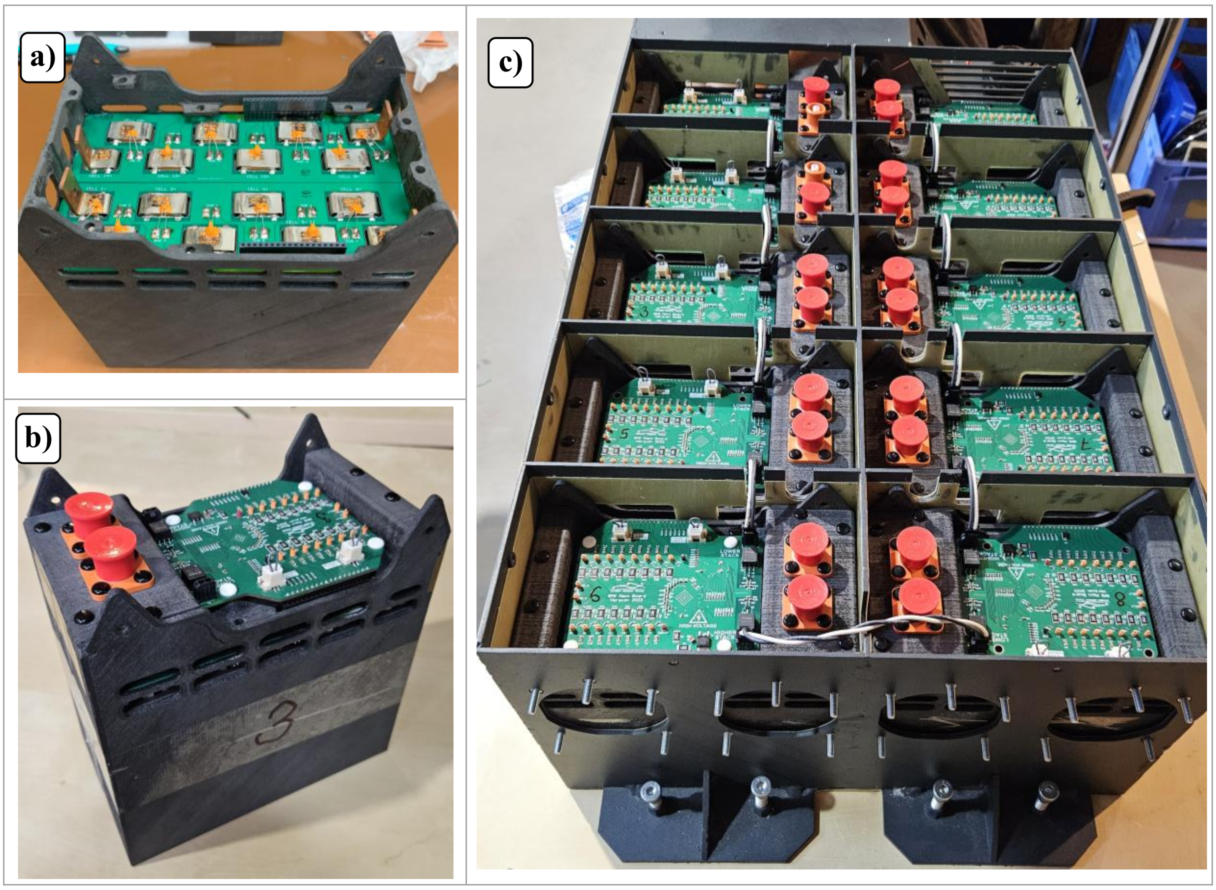

Fig. 16 After-welding assembly – a) module with temperature sensors before cover placement, b) final assembled module, c) final assembled battery system

CONCLUSION

The presented battery module was developed to address the specific needs of student electric racing, where performance, reliability, and manufacturability must be balanced within limited resources and strict technical rules. Through targeted improvements in electrical configuration, mechanical layout, and production approach, the new generation offers a more compact, lightweight, and integrated solution while maintaining serviceability and robustness. For the first time in the team's history, the concept fully eliminated point-to-point wiring, relied on laser-welded tab connections, and employed flame-retardant 3D-printed casings. This approach has proven to be less error-prone and more space- and weight-efficient than previous generations.

Despite some identified weak points – particularly in welding fixture design and airflow obstruction – these are considered solvable in future iterations. The overall module represents a high technological level within the context of student-built systems. Planned validation steps include targeted thermal and electrical testing under realistic load conditions, with the aim of further refining the design. The methods and outcomes presented in this paper can serve as a practical reference for other academic teams or low-volume EV developers seeking efficient and cost-effective battery system solutions.

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