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Designing a High Voltage Battery for a Formula Student Vehicle

Metropolia University of Applied Sciences

Bachelor of Engineering

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The purpose of this thesis was to document information on designing and manufacturing process of a high voltage battery for a Formula Student competition vehicle. The thesis discusses component selection, design of the battery container, material selections and electrical design. The manufacturing methods, for example composite work, 3D-printing and machining are described as well as possible alternative possible design solutions.

Most of the safety aspects of the design come from the Formula Student Rules. This thesis explains the principles behind the rules which give a good background for safe battery design. Some examples of electrical properties of the materials are provided.

Designing an electric vehicle battery is largely component selection, and the most important part is battery cell selection. Several alternative battery cells are compared to each other in order to find the most suitable battery cell, and the reasons for selecting certain battery cell are documented. The thesis explains with the selection of several parts, which could help in the selection of other corresponding parts needed in similar projects.

The thesis includes examples of a high voltage battery that was used by Metropolia Motorsport for two consecutive competition seasons 2018 and 2019. The data logged by the battery management system and the vehicle data logger was used to evaluate the success of the design and provide more information of the battery in use.

Keywords	Formula Student, Battery, High Voltage

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Tämän opinnäytetyön tarkoituksena on dokumentoida Formula Student -ajoneuvoon kuuluvan korkeajänniteakuston suunnittelu- ja valmistusprosessi. Aihealue sisältää komponenttivalintaa, akuston kotelon suunnittelua, materiaalivalintoja ja sähköistä suunnittelua. Valmistusmetodeina on käytetty komposiittitöitä, 3D-tulostusta ja koneistetusta.

Useimmat käyttö- ja sähköturvallisuuteen liittyvät ominaisuudet akustossa tulevat suoraan Formula Student -säännöistä. Opinnäytetyö esittelee sääntöjen perustana olevia periaatteita, jotka ovat hyvä perusta turvalliseen korkeajännitteiseen akkuteknologiaan.

Korkeajänniteakun valmistaminen on suurelta osaltaan komponenttivalintaa, joista tärkeimpänä on akkukennojen valinta. Valittuja kennoja on verrattu vaihtoehtoisiin malleihin valinnan perustelemiseksi. Työ kattaa useita osia, jotka ovat sovellettavissa muihin vastaaviin tuotteisiin.

Työssä käytetään esimerkkinä Metropolia Motorsportin akkua, jolla on ajettu kaksi kilpailukautta 2018 ja 2019. Näillä kilpailukausilla tallennettua dataa on käytetty akuston käyttötarpeiden ja suunnittelun onnistumisen määrittämisessä.

Avainsanat	Formula Student, akku, korkeajännite.

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List of Abbreviations

144s2p	Commonly used abbreviation referring to 288 battery cells connected 144 in series and 2 in parallel.
Accumulator	Name used in Formula Student Rules (1) for high voltage battery.
AIL	Accumulator Indicator Light. Led indicating if there is HV present outside battery container.
AIR	Accumulator Indication Relay. Main contactor isolating and connecting HV.
BMS, AMS	Battery Management System. Safety system monitoring voltages and temperatures of battery cells
AWG	American Wire Gauge. Wire size unit
CAE	Computer-aided Engineering
CC-CV	Constant current – Constant voltage
DNF	Did not finish. Term used in competitions for participant who is not able to finish the event.
FS	Formula Student
FSG	Formula Student Germany
HPF018	Metropolia Motorsport 2018 competition season formula car
HPF019	Metropolia Motorsport 2019 Competition season formula car
HV	High Voltage. Refers to maximal 600 Volt system isolated from vehicle frame.
IVT	Current and voltage measurement device for high voltage.

IMD	Insulation Monitoring Device. System measuring resistance between HV and LV Ground and indicating if there is isolation problem.
LV	Low Voltage. Refers to 24 Volt system grounded to frame of the vehicle.
MM	Metropolia Motorsport
NC	Normally Closed
NO	Normally Open
PCB	Printed Circuit Board
SPI	Serial Peripheral Interface Bus
VCU	Vehicle Control Unit

1 Introduction

The purpose of the thesis was to describe the design of a high voltage battery for a Formula Student vehicle. Formula Student is a car designing and building competition for universities and it is governed in Europe by the Formula Student Germany organisation. Many of the design aspects come from the rules (1). However, the purpose of this thesis was not to explain the rules but mainly to clarify principles behind the rules and point out why they are also good practices and applicable to other similar battery designs.

1.1 Metropolia Motorsport

Metropolia Motorsport is a project of Metropolia University of Applied Sciences competing in Formula Student competitions. The project has been active with 20-40 students participating since the year 2000. This thesis explains the battery design of Metropolia Motorsport and the working methods applied by the team during 2018 and 2019. Metropolia Motorsport has been running electric formula cars since 2013 and the design of high voltage batteries for the cars has been improving by each new iteration. In a competition vehicle an improvement of the battery design means more compact dimensions, lighter weight and more capacity while still providing sufficient power ratings for required use.

1.2 Goals of the Thesis

The goal of the thesis was to produce a conceptual design and manufacturing of the battery. The study of the different design phases and discussion were narrowed down, and therefore, these phases are often described only in a reasonable amount of depth. This allows to describe the complete battery conceptual design and give a better overall picture of the design principles for a high voltage battery that is suitable for an electric vehicle. For example, information and work carried out by Metropolia Motorsport on cell testing, battery management or material testing would easily be worth a thesis of their own.

2 Requirements and Design Goals

The power capability and the capacity of a battery are generally defined by required use -scenario. In Formula Student there is a power limit of 80 kW which defines requirement regarding maximum discharge power. Maximum power requirements are needed in the acceleration part of competitions, which is a 75-meter acceleration from standstill lasting less than 4 seconds. The capacity requirement is mostly related to the endurance part of the competitions, where 22 kilometers is driven with 30-80 km/h speeds on a twisty approximately 1 km per lap asphalt racetrack.

2.1 Improvement Areas & Requirements

From testing and observing the competing teams during the previous years the team had learned that approximately 7 kWh of nominal capacity would be needed to get through the endurance event while keeping lap times with the powertrain at a competitive level. This would require dropping power of the vehicle from full power events to around a half, so with extra capacity more power could be used. However, when weight reduction of the battery was considered as a more important factor, capacity would have to be defined taking that into account.

The following principles were defined as design guidelines compared to the previous design:

- Lighter battery
- Increased capacity
- Lower center of gravity

2.2 Electrical Requirements

The maximum voltage allowed in the Formula Student rules (1) is 600 volts. Using higher voltage decreases currents needed to achieve the rated power. Smaller current allows smaller and lighter components to be used in high current path. Because of this a decision was made to use the highest possible voltage. This can be easily achieved with Li-ion batteries by using 144 cells in series which gives Maximum voltage of 144 x

4.2 Volts = 604.8 Volts. The actual maximum voltage in use was then limited to 597.6 volts by software not allowing to charge individual cells over 4.15 Volts.

2.3 Mechanical Concept

The mechanical design for the battery consists of designing the container for all the components and the attachments to keep them firmly in place. The FS rules (1) define that aluminium should be used in the construction of the battery container. Alternative materials can be used if their equivalency is proved by destructive testing. Metropolia Motorsport decided to produce equivalent composite materials to save weight.

The battery container design was CAD-modeled simultaneously with the rest of the vehicle. Packaging of the vehicle including the battery was done as tightly as possible. Combined tolerances for the accumulator container and the steel frame surrounding it needed to be within 5 mm to ensure no interference with the other parts. This required that all the manufacturing methods had to have enough accuracy. Regarding the battery container this meant that the composite parts and the aluminium parts were water jet cut and CNC-machined to achieve the tolerances.

3 Cell Selection

Two commonly available cell types were tested and considered to be used: Lithium-ion polymer pouch type or cylindrical 18650 type.

3.1 Cell Types and Testing

The team made a battery tester using fast switching MOSFET as a load. The tester created constant current discharge of 15 Amps to the cells. Three Samsung INR18650-30Q cells connected parallel with combined capacity of 9000 mAh were compared against 15C 6000mAh pouch cell from previous battery (Figure 1). The conclusion of the testing was that internal resistance of 18650 cylindrical type cells was much higher. This introduces several problems for a Formula Student car.

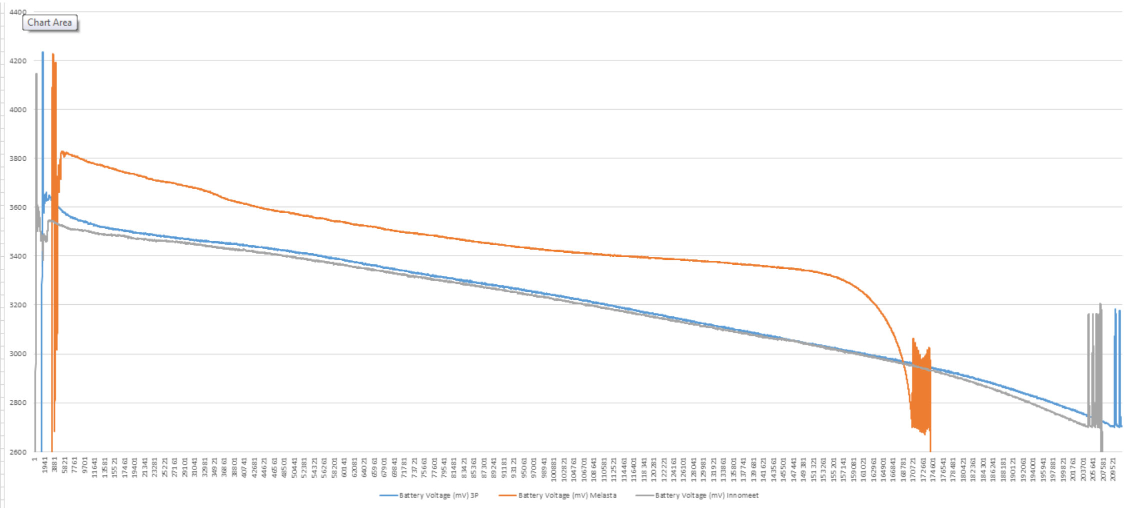

Figure 1. Discharge test with constant 15 A current from full charge to manufacturers recommended minimum. Blue line presenting voltage of 3 parallel connected Samsung INR18650-30Q cylindrical cells of combined capacity of 9000 mAh 5C and Orange line Melasta 6000 mAh 20C pouch cell. X-axis representing time and Y-axis cell voltage during discharge.

The first problem was voltage drop under large discharge. The team already knew that if they had had 50 Volt drop with the previous car and it was limiting how well they could use battery capacity because cells would hit the lower cut-off limit earlier with higher voltage. One basic way to describe how much a battery can handle discharging is C-rating. There the nominal capacity of the battery is multiplied by continuous C-rate equaling to maximum recommended continuous current (2).

Another problem also could also be caused by resistance. Higher internal resistance heats up the cells more under load. Using cylindrical cells would require more cooling capacity, and therefore, more complex cooling design. There would be an easy solution to both problems, and it would be using more cells in parallel. This would gain more capacity and not discharge each cell as much. This was, however, discarded as one of the main design objectives was to make a lighter battery to improve performance of the car.

3.2 Voltage Drop

A relatively large drop in voltage under load can be seen in Formula student vehicles. This has had the most effect during a long endurance drive. Voltage drop has a role when the battery is almost empty. The goal is to use whole capacity of the battery but only one and slightly worse cell can easily drop the voltage below the safety limits. Exceeding the limits results in battery management stopping the car and causing DNF for this part of the event. To prevent this the overall quality of all the cells has to be equal.

In Figure 2 the maximum power load figure that a Formula Student car creates to a battery can be seen. Battery voltage drops from 593 volts to 546 volts in 4 seconds. Maximum discharge is 143 amps and power is limited to 78,2 kW. After the load is removed, the voltage rises back to over 580 volts, so the battery is still approximately 90% charged.

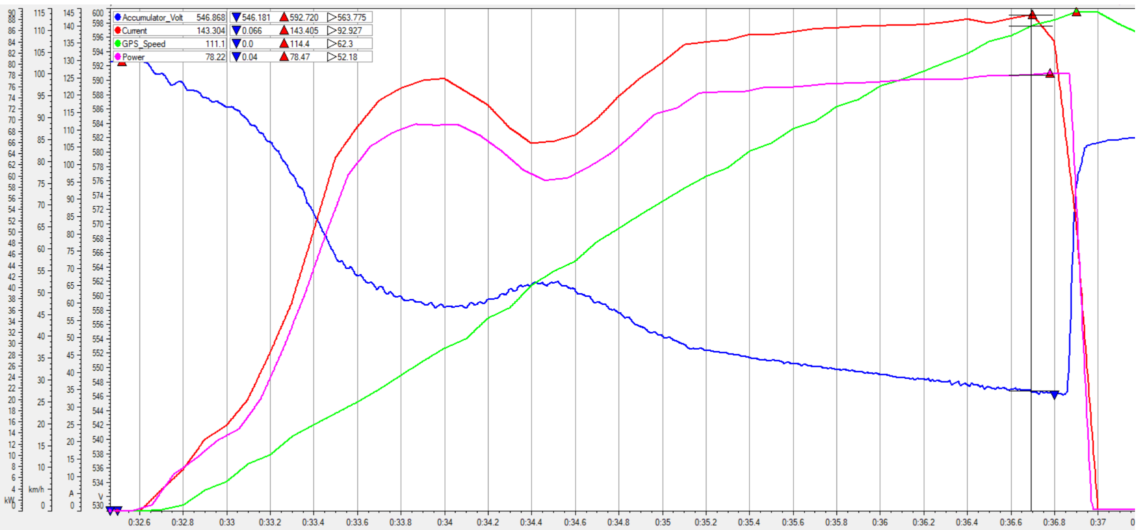

Figure 2. Typical Formula Student 75 meter acceleration event from 0 to 111 km/h. Blue line is presenting battery voltage and red is current. Voltage drop under 78 kW load being 46 volts from battery rest voltage.

3.3 Optimal Weight and Capacity

Formula Student has two main types of using the battery in competitions. Some require the maximum limited 80 kW power from the battery, and others require maximum capacity from the battery. As increasing the capacity of a battery in general adds weight to the vehicle, it is a balancing act between maximum performance and increasing capacity or an endurance event.

To get a better overall picture of what kind of battery would be optimal for an endurance event some lap time simulations were carried out. The main purpose of simulation was to compare weight change against changing the full torque request of the car in an endurance event. Previous years track testing gave enough information that it was possible to assume that increasing available energy by 10 percent would make it possible to use approximately 5-10 percent more power during the 22 km drive.

3.4 Selection of Cell Manufacturer

After deciding to go for pouch cells the next challenge would be to decide where to buy them. European manufacturers seemed to have a habit of pricing themselves out of the picture and most Chinese manufacturers were not producing consistent enough quality.

Formula student batteries have a specification of a high voltage but quite small capacity in ampere hours. Physically this means a cell configuration where there are many cells in series but only 1-3 small cells in parallel when using pouch cells. The total capacity available is extracted from the battery to drive the vehicle in competitions most efficiently. If one of the cells is lower in capacity, it will decrease the usable capacity of the whole battery the same amount of Ah it is missing.

3.4.1 Individual Cell Testing as Part of Manufacturing

Metropolia Motorsport had successfully used cells manufactured by Melasta in the previous car. What differentiated Melasta as a manufacturer from other companies available for this purpose was individual cell testing. The manufacturer tests the individual cells and matches the capacities and internal resistances before shipping them.

3.4.2 Cell Selection

Over 200 possible cells manufactured by Melasta were compared focusing on energy density, capacity, internal resistance and nominal discharge rating. The comparison revealed that having smaller C-rating and higher internal resistance allowed cells to be lighter but would result in more heat produced and have a larger voltage drop under load.

After balancing these factors and comparing different cell sizes it was found out that cell dimension of 42 mm width and 127.5 length had slightly larger energy density and lower internal resistance. The capacity could be varied by changing cell thickness and 6600 mAh cells were chosen. To get sufficient capacity for the Formula Student vehicle, two 6600 mAh cells would be in parallel, resulting in 13200 mAh.

This gave the final configuration of 144 cells in series and 2 parallel. The resulting battery would have the following features:

- Voltage: 144 cells in series * 3,7 Volts=532.8 volts nominal and maximum of 144*4.2 Volts=604.8 Volts. Voltage is limited by charging to 600 volts allowed by the rules (1).

- Maximum Continuous discharge: 2 cells parallel * 99 Amps * 532.8 volts = 105 kW. Power limited by inverters to allowed 80kW maximum.

- Capacity: 532.8 Volts * 2 cells parallel * 6.6 Ah = 7.0 kWh

4 Container Design

The requirements for the battery container were providing protection to the cells and the electrical equipment and adequate attachment to the vehicle. It should also provide electrical insulation from high voltage components for safe usage and servicing of the vehicle. The container is described in the Formula Student rules (1) being manufactured from aluminum, but equivalent material has been allowed, if suitable properties have been defined by testing and datasheets.

4.1 Container Requirements

The battery container must meet the following basic requirements according to the Formula Student (1) rules:

- Material must be fire retardant according to the UL94V-0 standard
- Has a protective frame structure around it pictured in Figure 3.
- The bottom of the container is required to have equivalent strength of 3.2 mm thick aluminium or 1.25 mm steel. Other parts of the container need to have equivalent strength of 2.3 mm thick aluminium or 0.9 mm steel.
- Mounting of the container and the cells of the container need to be designed to withstand 40g acceleration in longitudinal or lateral directions and 20g in vertical direction.

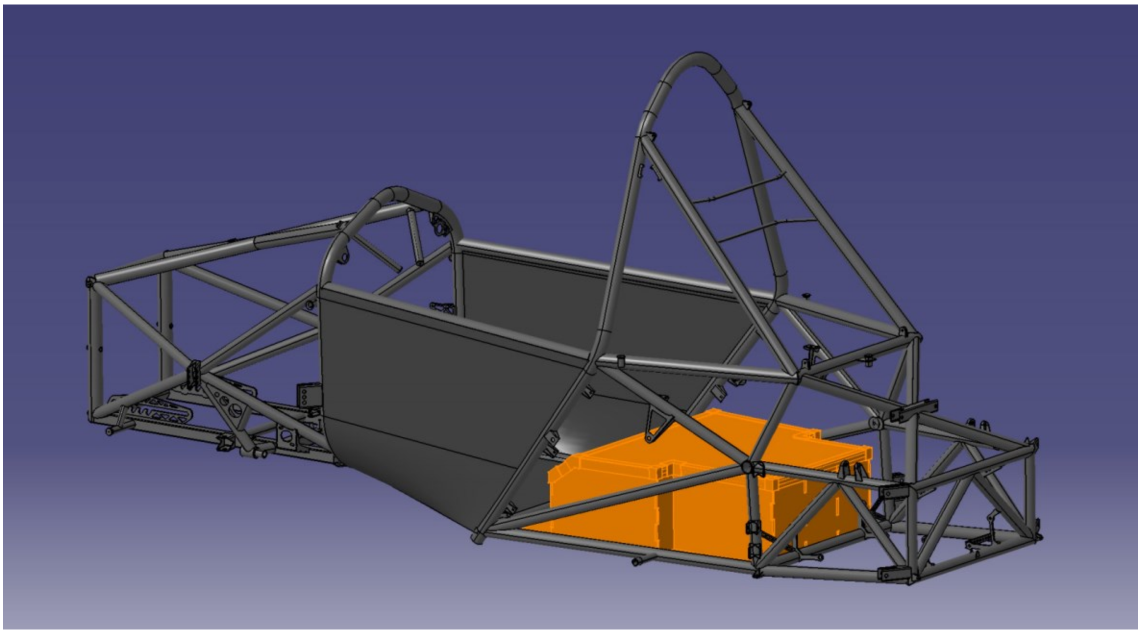

Figure 3. Battery container is positioned in the vehicle within a protective structure.

4.2 Container Serviceability and Electrical Safety

Working with large batteries has a risk of breaking parts, if something unexpected happens because cells are always live and capable of supplying huge currents. One of the design goals of the container and the parts inside was to make possible that all electronic parts could be lifted away from the container and live cells for servicing. By making components easily removable from the container working safety is improved. It also allows better serviceability of the parts in difficult positions.

4.3 Material Selection

After testing with multitude of composite sandwich structures the following were used in the final container parts:

Container Bottom Panel

6 Layers, 0° reference longitudinal axis (x-axis of the car)
- Layer 1: 175g/m2 twill aramid fiber (0°)
- Layer 2: 400g/m2 biax +/- 45° carbon fiber (0°)
- Layer 3: 400g/m2 biax +/- 45° carbon fiber (0°)
- Layer 4: 3mm Gurit pvc 60 foam core (0°)
- Layer 5: 400g/m2 biax +/- 45° carbon fiber (0°)
- Layer 6: 600g/m2 twill carbon fiber (0°)

Internal Walls, External Walls and Lid

5 layers, 0° reference longitudinal axis (x-axis of the car)
- Layer 1: 175 g/m2 twill aramid fiber (0°)
- Layer 2: 600g/m2 twill carbon fiber (0°)
- Layer 3: 3mm Gurit pvc 60 foam core (0°)
- Layer 4: 600g/m2 twill carbon fiber (0°)
- Layer 5: 175 g/m2 twill aramid fiber (0°)

In principle, sandwich structure works so that the two heavy carbon fiber layers give the material structural integrity. Better bending strength and torsional stiffness is achieved by separating two skins with 3 mm PVC foam.
Carbon fiber is electrically conductive. Container safety was improved by making the outermost layers of the material from aramid fiber which is a good electrical insulator. It also naturally provides some additional strength to the material.

4.3.1 Material Tests

Equivalency of composite materials to the required material were proved by testing the material with 3-point bending (Figure 7) and perimeter shear tests (Figure 8).

4.3.1.1 Three Point Bending Test

Three-point bending test is applying a load with 50 mm diameter tube to a composite panel which is supported from two pieces at least 400 mm apart. The test panel is 275 mm x 500 mm.

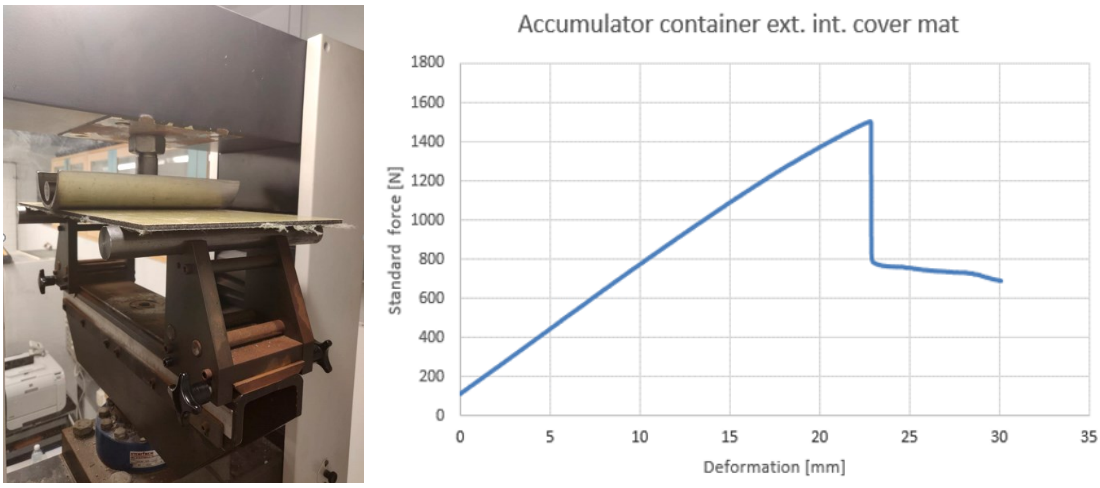

Figure 4. Three-point bending test bench showing composite panel failure point data.

4.3.1.2 Perimeter Shear Test

Perimeter shear test consists of measuring the force to punch 25 mm diameter flat punch through a flat laminate sample. It is supported from beneath except 32 mm hole aligned co-axially with the punch. The test pieces were 100 mm x 100 mm.

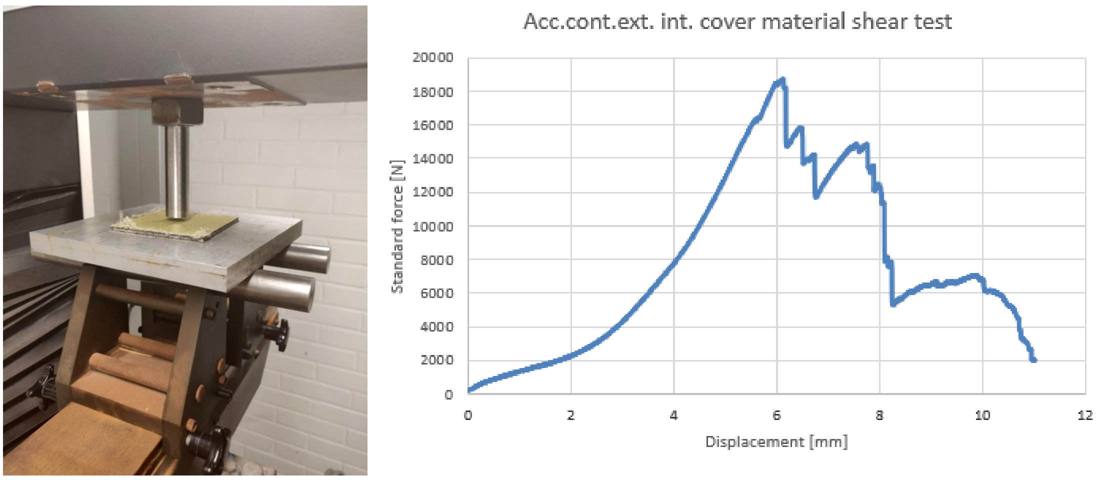

Figure 5. Perimeter shear test bench showing composite panel penetration data.

4.3.2 UL94V-0 Flammability Standard

To proof fire retardancy of the materials UL94V-0 standard tests were carried out to the test pieces. UL94V-0 requires the test piece burning to stop within 10 seconds on a vertical specimen and does not allow any flaming particles to drip from the material.

Before testing 5 test specimens were conditioned 48 hours in 23 degrees Celsius and 50% relative humidity. Another 5 specimens were conditioned 7 days at 70 degrees Celsius.

Figure 6. UL94V-0 Burning test with Bunsen burner and battery container material.

4.4 Computer-aided Engineering

All parts of the battery were designed by using CATIA software. The battery assembly included 1075 parts which gives a good implication how complex design a high voltage battery is. Creating technical drawings and manufacturing files from the CAD model made it possible to outsource and manufacture the parts in multiple places simultaneously. The manufacturing methods included machining, composite work, 3D printing and waterjet cutting. Overall, CAE enabled a faster manufacturing process and improved quality and accuracy of the parts.

4.5 Manufacturing

The battery container was manufactured from fiber composite material. The manufacturing method used was making larger composite panels of sandwich structure and waterjet cutting them to the required parts (Figure 7).

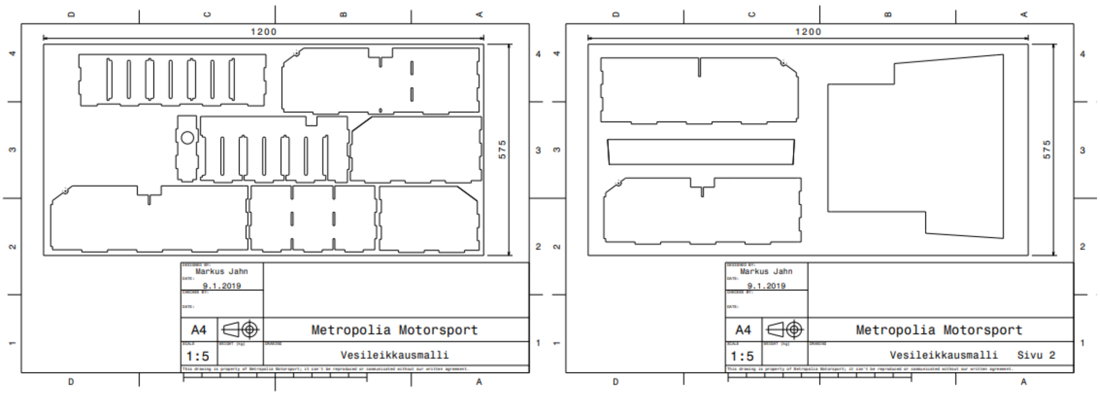

Figure 7. Technical drawings of composite plates for waterjet cutting instructions.

The parts where then bonded together by gluing them with 2-component epoxy. Using a structure where parts interlocked to each other and using slots and steps highly accurate manufacturing tolerances were achieved.?? Accuracy of less than 1 mm was easily achieved with these working methods allowing for good implementation of the original CAD design(Figure 7 and 8).

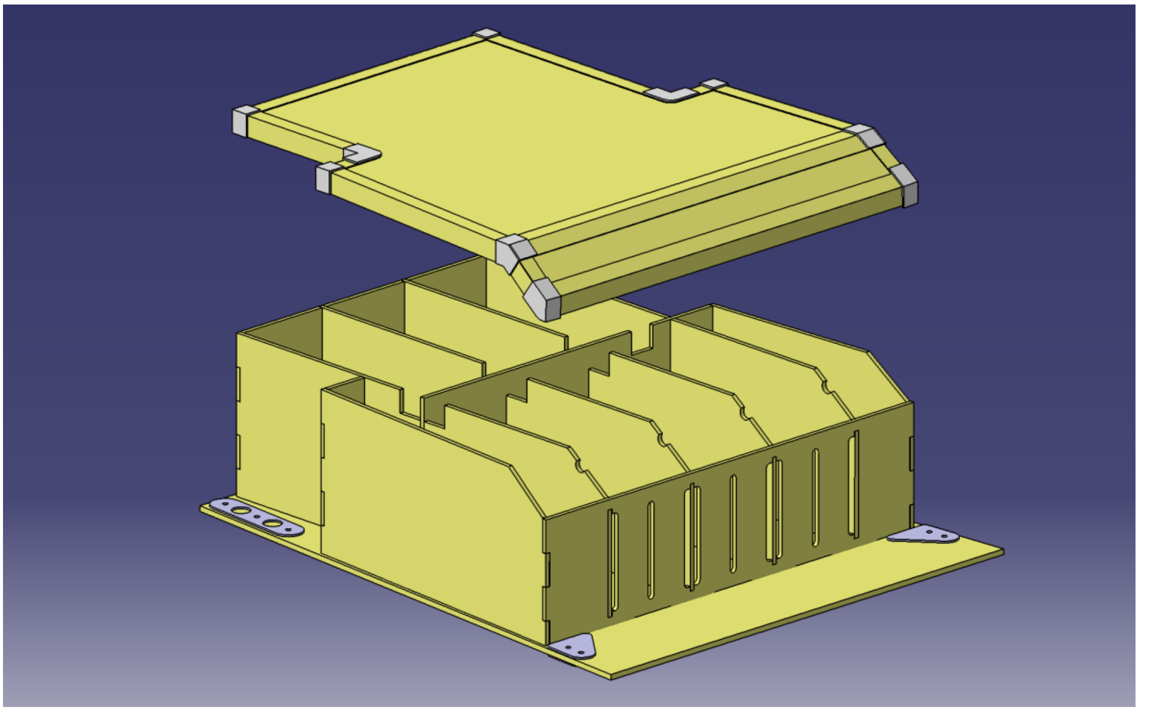

Figure 8. Battery container is manufactured from composite sandwich plates waterjet cut and bonded together.

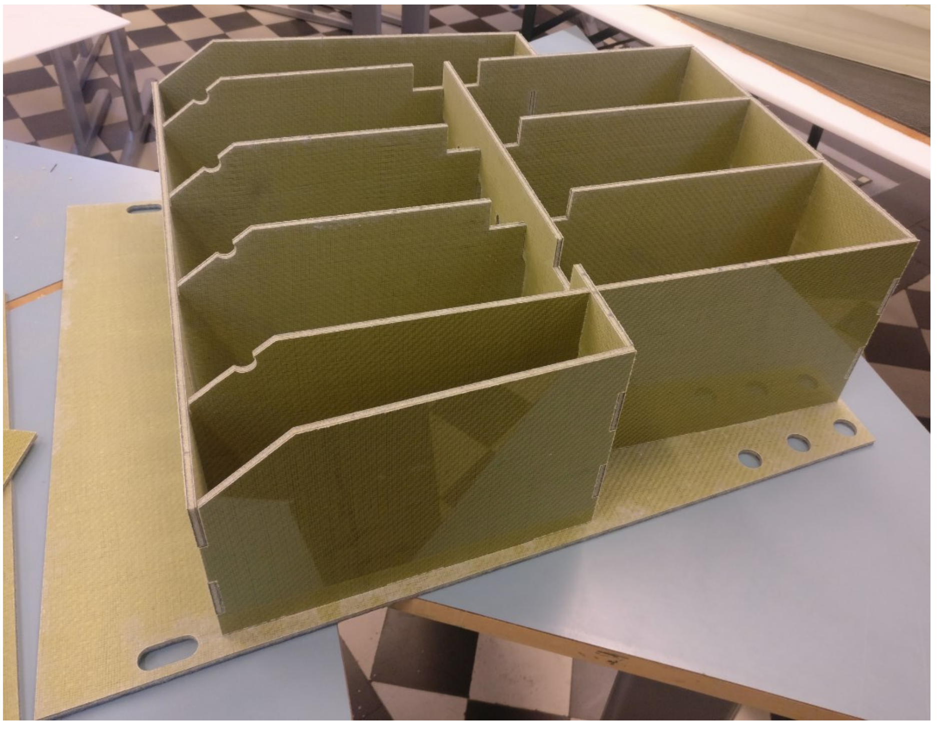

Figure 9. Test fitting the composite parts before final assembly with epoxy.

5 Cell Segment

The Formula Student rules (1) require the battery to be divided into segments with maximum voltage of 120 Volts and have maximum energy of 6 megajoules.

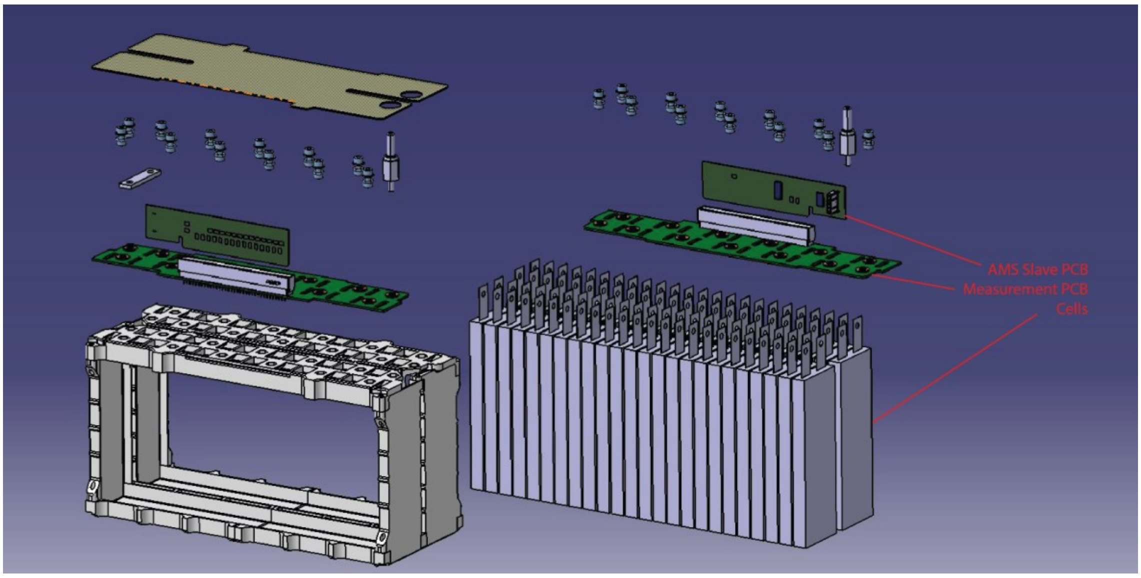

Figure 10. CATIA design of Cell Segment and components required.

5.1 Segment Size

Suitable size for one segment was decided to be 24 cells in parallel and 2 in series. Maximum voltage from 24 cells in series is 4.2 Volts*24=100.8 Volts per segment. Maximum energy per segment is 100.8 Volts* 13.2 Ah=1331 Wh which is equivalent 4.79 megajoules. Both of these are within the requirements of the rules (1).

5.2 Maintenance Plugs

To achieve the required 144 cell pairs in series six of these segments were connected in series. These segments had to be connected electrically with maintenance plugs which could be separated without tools. Whenever working with the battery the first procedure is always first to remove the maintenance plugs and drop voltage to a safe level. This is a good practice for working with any kind of high voltage battery as lowering the voltage highly reduces the danger in case electric shock is passed through a person. Removing maintenance plugs also removes voltage from the output terminals of the battery.

5.3 Cell Compression

In general it has been found that pouch cells give slightly more capacity when a slight even pressure is applied to the cells. This happens because closer the anode and cathode are to each other more effectively they operate. To achieve this a cell pack for each segment were tightly wrapped with glass fiber tape. Taping also helps to keep the cells in place and provides protection.

5.4 3D Printed Cages

Cell packs for segments were then installed in 3D-printed cages (Figure 11). The cage provided additional support and it was needed to keep air gaps from cooling when segments were installed inside the container. The cage also provided attachments for the cell tab connections and the BMS circuit boards.

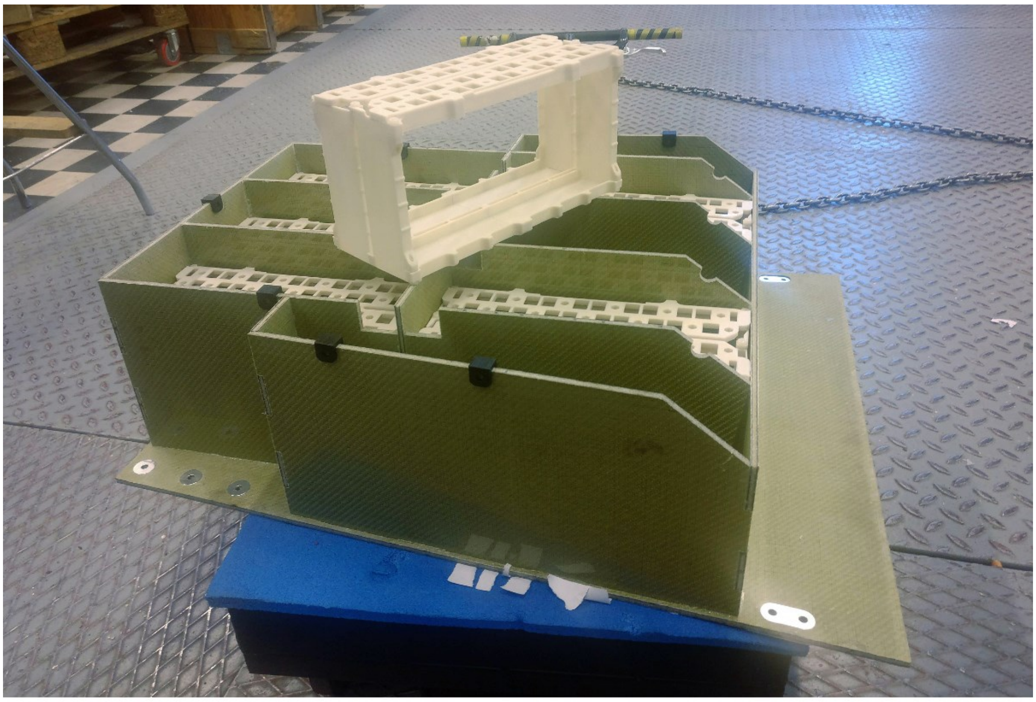

Figure 11. 3D-printed segment cages test fitted to composite parts of the container.

5.5 Measurement Boards and BMS

The Formula student rules (1) require voltages of all the 144 series connected cell pairs to be monitored by BMS. It also demands that at least 30% of cells temperatures should be measured from negative cell tab. The voltage and the temperature connections to BMS could be done by separate wires but already early in the design a decision was made to manufacture circuit boards to take care of these connections providing a cleaner and better working solution. As each BMS board was only able to handle 12 cell connections it and the measuring board were doubled on each segment.

As a negative side in the design could be mentioned that if there is a faulty connection, it will be harder to trace and fix than on individual wires that could be changed more easily. Now it will require disconnecting thirteen live cell connections to change the connecting circuit board.

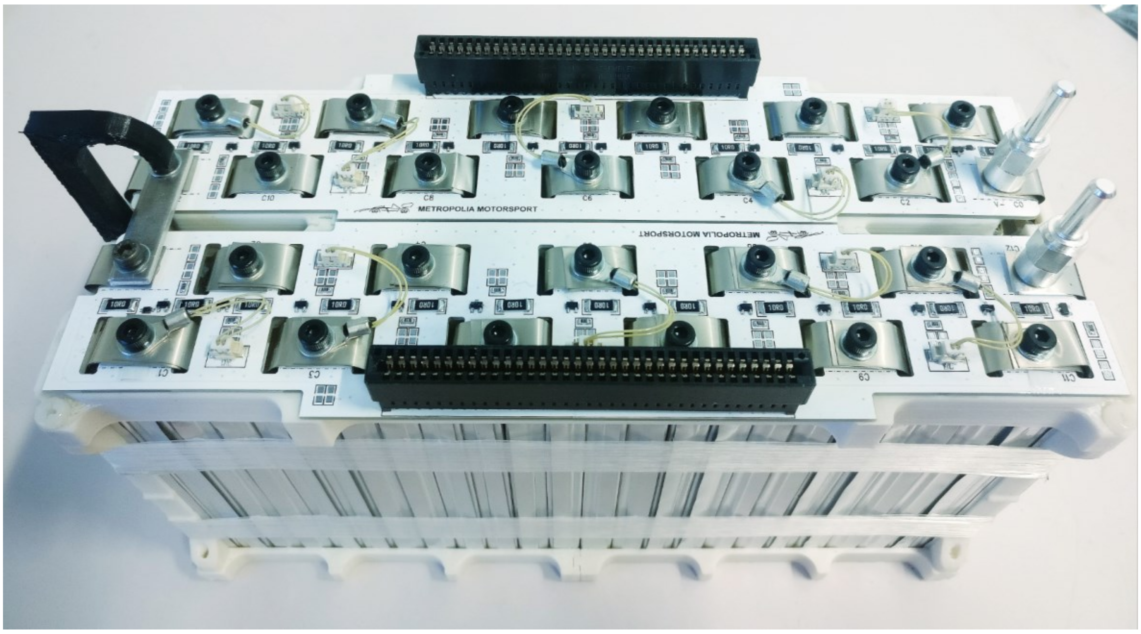

Figure 12. Measurement PCB with connectors ready for BMS installation, 26 live cell tab connections and 10 wired temperature sensors in place.

Passive cell balancing is also included in the measuring board adding resistors and MOSFETs to the board. As this increased the number of traces needed, the PCBs were changed to 4-layer versions to have enough space for everything needed.

5.5.1 PCB Trace Fusible Links

The Formula Student Rules (1) require cell measurements to be protected by fuses or fusible link wire. As that would have required a huge amount of fuses Metropolia Motorsport decided to use the PCB traces as a fuse. One extra measurement PCB was tested so that all the voltage measurement traces were burned, and amperage required was logged down. It was found that traces needed maximum 5 Amps before they melted, and each cell pair was capable of 200A continuous current.

6 Cooling

Air cooling was used to allow cooling the system to be as light as possible. The specifications of the fans in the previous vehicles were used as a base for selecting suitable fans for the cooling. Three fans selected can move 8.3 m^3 air per minute. Inside the container segments of the battery the battery segments are separated by 3d printed plastic cages leaving 8mm cooling ducts between the cells to push the air through the battery (Figure 13).

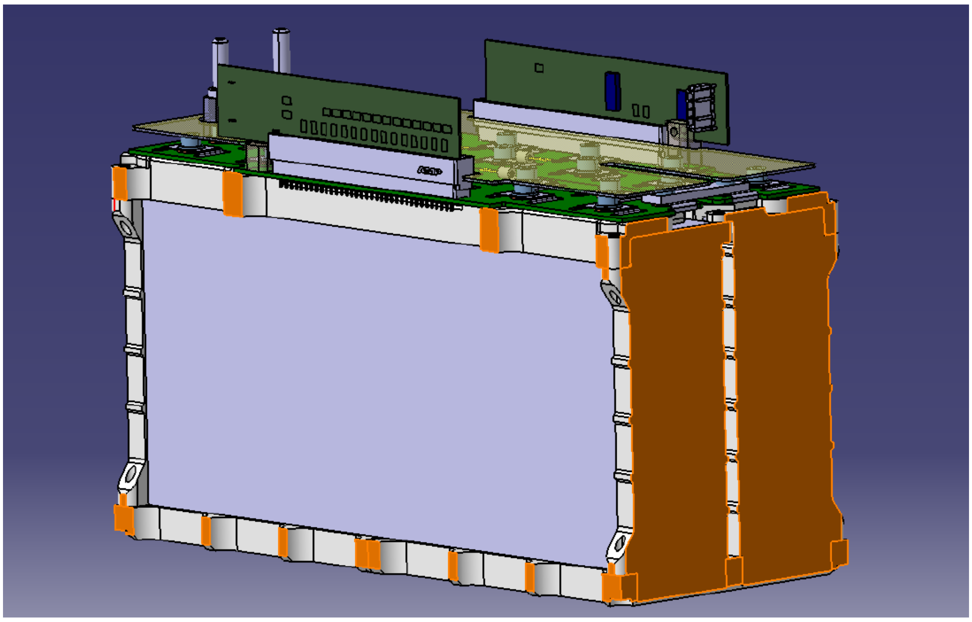

Figure 13. Orange areas marking cage contact areas to composite container leaving air gaps for cooling.

The fans operate in push through way to make the container over pressurized helping in keeping the water and dust out of the battery. Incoming air goes through a filter fabric which keeps debris out of the battery. Exhaust for the cooling air is from a gap on the top cover of the container to prevent moisture from the rear of the vehicle getting into the container (Figure 14).

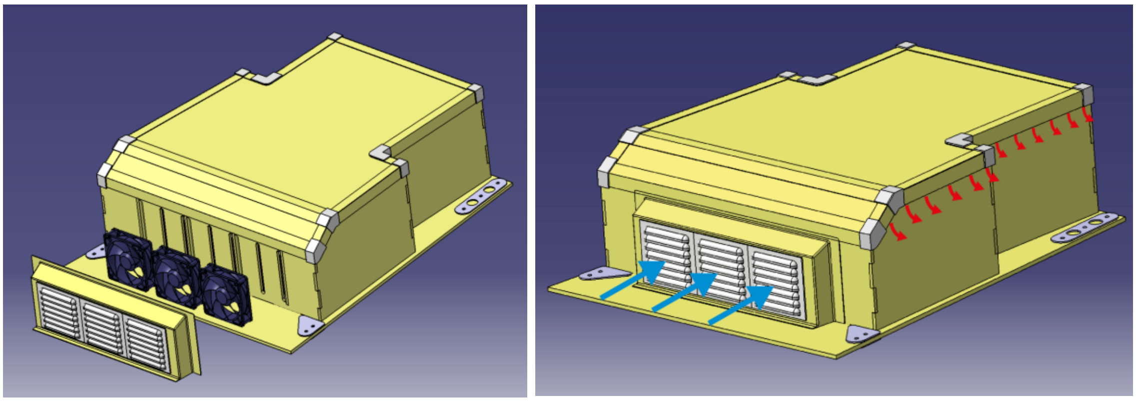

Figure 14. Cooling is arranged with three fans taking air from front of battery and pushing it out from under the lid.

During the test days with the car battery temperatures were logged to get whole image how it operates. Battery has 60 temperature sensors so a good coverage of the different positions in the battery was achieved (Figure 15). It was found out that the segments where cells are in direct contact with each other warm up like a one solid piece which is warmer in the middle than in the edges. It also seems that the composite material was able to transfer some of the heat and helped cooling the cells through container walls.

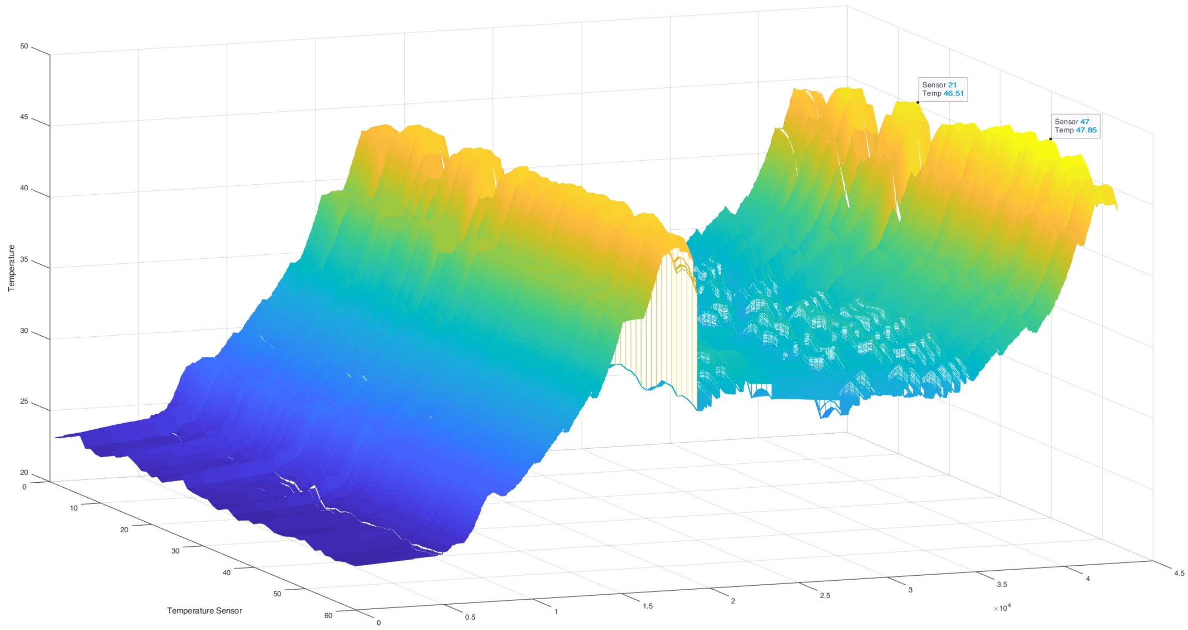

Figure 15. 3D Graph of logged temperatures during a test day. Temperature sensors 1-30 are front segments and 31-60 on the rear cells. Quite high temperatures were reached on purpose to see the maximum capability of the cooling(see Appendix 2).

The warmest parts of the battery were in the middle of three rear segments. There air cooling was not as effective because air had warmed up cooling the front segments and air needed to make an extra turn to escape through the lid gap. During testing while heavily stressing of the car battery achieved approximately 50 degree temperatures when the Formula Student rules (1) allowed maximum temperature of 60 degrees.

7 High Current Path

Maximum current battery needs to theoretically be able to provide can be calculated by dividing Formula Student power limit of 80 kW with allowed battery minimum voltage:

80000W/(3.0 Volts*144)=185 Amps

Referring to this all parts in high current path of the vehicle are rated to handle 200 Amperes and at least 600 Volt DC.

7.1 Cell Tab Connections

The cell tab connections were made with bolted connections pressing the two cell tab pairs together. Simultaneously the bolt presses connection against the copper insert soldered to measuring PCB and provides cell connection to BMS. A Ring connector type temperature sensor(Figure 16) can be added to each connection where needed.

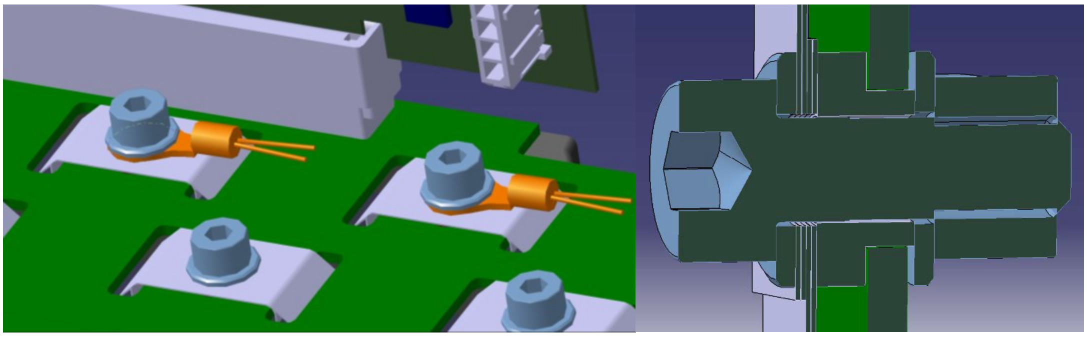

Figure 16. Cell tab connections and temperature sensors (orange).

7.2 Maintenance Plugs and Segment Connections

The maintenance plugs can be removed by lifting them from the battery terminals. Exceptionally small 200 Amp rated connectors were found to keep connections light and compact. These Methode PowerBuds (3) can provide the 200 Amp required current rating for only 5.7 mm terminal size with extremely low resistances. PowerBuds are press fitted to aluminium busbars to provide connections between segments that can be easily lifted off for servicing the battery. The container lid keeps the connectors in place when attached.

The goal of designing the high current path inside the container was done by trying to minimize its length. This resulted in half of the cell segments being 180 degrees turned to allow the maintenance tabs be shorter and more compact (Figure 17).

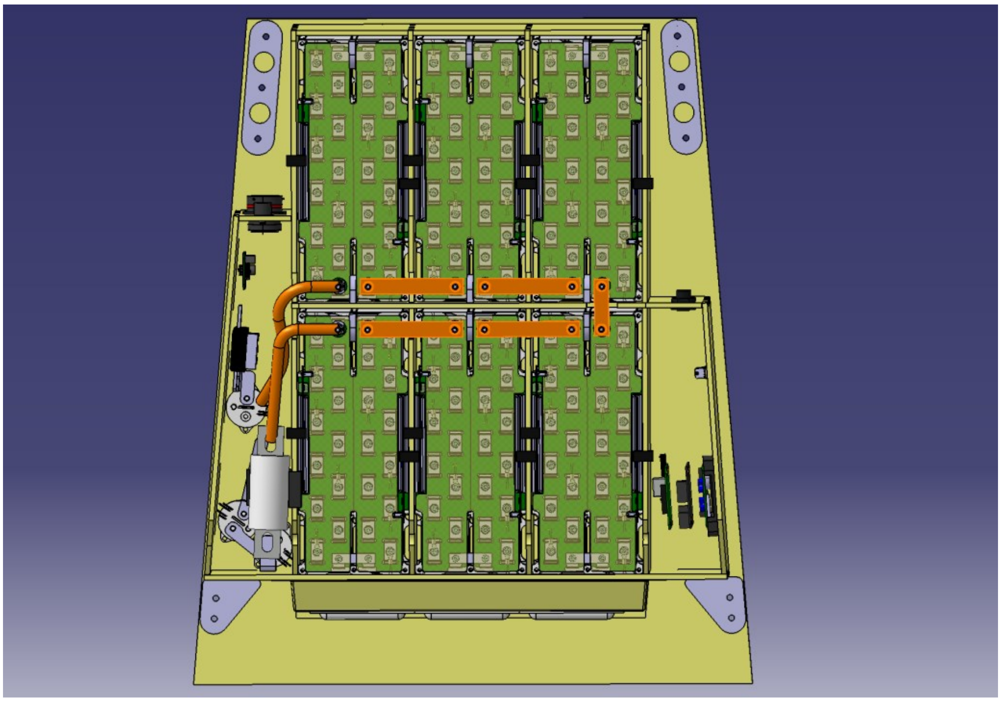

Figure 17. Maintenance tab connections marked with orange.

7.3 Fusing

The main function of a fuse is to be the weakest link in the high current path. Fusing will then interrupt the circuit if long term overcurrent is present or short circuit situation occurs.

7.3.1 Fuse Melting Current

Battery main fusing was done with one 125A fuse L70QS125 (4) with 700VDC rating. Despite using 125A rated fuse datasheet gives it 100 second melting time using 300 A current. The Formula Student car is only capable of using 150A for less than 2 seconds in normal use. The selected fuse is sufficient of handling the currents needed.

7.3.2 Interrupt Rating

Fuse interrupt rating indicates what the maximum current is that the fuse can safely interrupt at rated voltage. Safe operation requires that there is no explosion or body rupture, and circuit is cleared. During a fault or short circuit condition fuse may temporarily receive high currents from the battery.

Maximum available current from the battery was needed for the calculation. The internal resistance of the battery according to the manufacturer is 1.5 mΩ per cell.

(144 cells in series * 1.5 mΩ)/2 cells parallel = 108 mΩ

Maximum available current from the battery is 600Volts / 0.108 Ω= 5555 A

Fuse interrupt rating is 50kA which means that it is well within the limits and protection will trip in less than a millisecond.

7.4 Busbars and Thermal Stress Calculation

Aluminium busbars were favored in designing internal high current conductors between the components. They were lighter and more compact than using copper wiring for everything. The busbars were designed in CAD software and laser cut allowing lower tolerances of the parts. Electrically it was needed to know that the busbars were conductive enough to not melt before the main fuse tripped in short circuit situation. The selected fuse had I^2t rating of 2208 A^2s. The busbar had to meet the following requirement to operate correctly:

$$I^2t(Fuse) \leq k^2S^2(Busbar)$$

Here k is a constant based on volumetric heat capacity of the conductor and S is the cross-sectional area of the busbar.

The battery bus bars are of aluminium and they are covered with polyolefin heat shrink material with better temperature characteristics than common PVC cable insulation. To simplify the calculation k value of 66 for aluminium cable with PVC insulation according to IEC 60364-5-54 standard was used. This gave the following minimum cross-sectional area:

$$S = \frac{\sqrt{5555^2\ A \times 0.001\ s}}{66} = 2.66\ mm^2$$

The smallest busbar used in the battery has a cross-sectional area of 3mm x 10mm = 30 mm^2

7.4.1 Busbar Resistance

Calculation of resistances on all the busbars was carried out to see the importance in total resistance of high current path. The vehicle had a total of 1 meter of aluminium busbars. For calculation the cross-section of 10mm x 3mm = 0.00003 m^2 and resistivity of 2.8x10^{-8} ohms per meter was used. The total resistance of all the busbars in the vehicle were:

$$2.8 * \frac{10^{-8}\Omega}{m} * \frac{1\ m}{0.00003\ m^2} = 1m\Omega$$

The formula above shows that the resistance of the busbars is quite a small figure compared for example to the battery internal resistance of 108 mΩ or a single bolted connection resistance which normally exceeds 1 mΩ. Busbar resistance can be described a negligible amount of resistance in the high current path.

7.5 Cabling

Radaflex 25 mm^2 Cables were chosen by current rating to sufficient 200 A use. The Copper cable is quite heavy. To keep the weight penalty at minimal routing was designed with the shortest possible cable length.

7.6 Connectors

Connector selection was done according to the same 200A current rating. The main connector on the battery is Deutch Autosport HD series one which has probably the smallest pins rated for 200 A use.

8 Active Safety Features

The Formula Student rules require the high voltage battery to be equipped with quite many safety systems to ensure safe use of the battery and monitoring of possible failures.

8.1 Shutdown Circuit

Safety systems are all connected as one LV circuit called shutdown circuit (Figure 18). When all safety systems are ready for operation, in other words, shutdown circuit switches and relays are in a closed position, the vehicle´s main AIR+, AIR- and precharge -contactors have power and high voltage can be used on the vehicle. If any of the safety systems opens the circuit it will always result in high voltage battery being insulated from the rest of the vehicle by opening the main contactors. Some systems are also required to latch leaving shutdown circuit open not allowing return normal operation despite the fault disappearing.

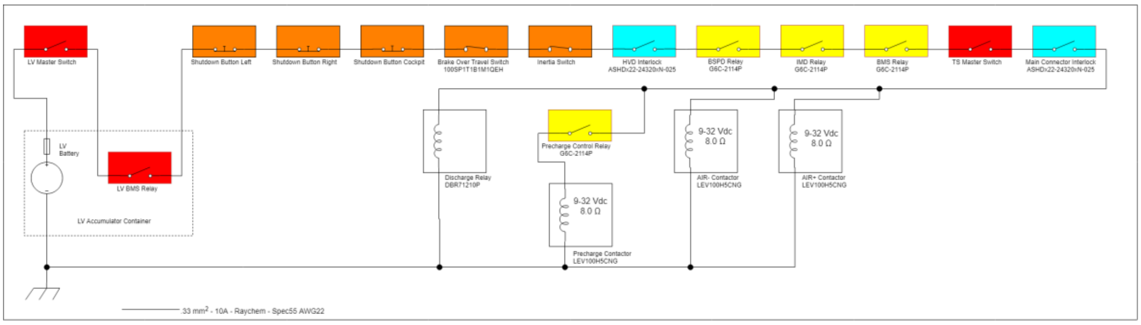

Figure 18. Shutdown circuit including controlling car main contactors(See Appendix 3).

8.2 Connector Interlocks

All removable high voltage cables have interlock which opens the main contactors in case the connector is removed or not properly installed (Figure 19). Interlocks are part of the shutdown circuit, so if any of the cables is not attached, the shutdown circuit remains open.

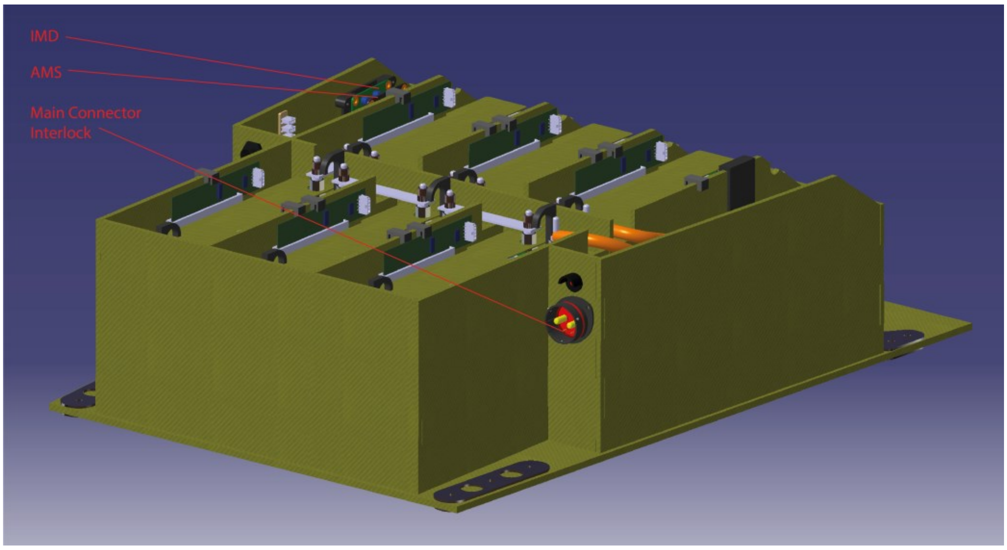

Figure 19. Shutdown circuit elements in battery container.

8.3 BMS

One of the most important safety devices in any lipo battery is the battery monitoring system. Metropolia Motorsport has developed during several years their own BMS system based on LTC 6811 Battery monitoring chips. This system operates using master-slave configuration. It has one master PCB, which has 12 slave boards.

8.3.1 Slave Board Funtions

Slave boards are used to measure 12 slaves x 12 voltages = 144 cell voltages covering all the cell pairs in the battery. The slaves also measure 12 x 5 = 60 temperatures from different positions of the battery. Data from the slaves to the master are sent along twisted pair cable IsoSPI differential signal, which can achieve good error tolerance as noise imparted onto wiring is nearly identical. The slave boards also control resistors used to discharge individual cell pairs during balancing of the battery.

8.3.2 Master Board Functions

BMS master is connected to all the slaves, CAN network and Relay situated in the shutdown circuit. The slaves will transform information of all voltages and temperatures to the master. The master will then determine if all the values are within allowed limits mentioned in Figure 20.

Allowed limits for battery cells	
Voltage Min	3.0 Volts
Voltage Max	4.2 Volts
Temperature Max	60 °C

Figure 20. Voltage and temperature limits used by BMS to allow battery being operated.

The BMS master controls the BMS relay which is part of the shutdown circuit. This allows BMS to open the battery main contactors in case the battery is operating outside safety limits.

8.4 Insulation Monitoring Device

To keep the vehicle safe for users, active insulation measurement is always present when the vehicle has low voltage on. This is achieved using Bender IR155-3204 insulation monitoring device (5) which is defined to open the main contactors if a resistance of less than 300 kiloohms is measured between positive or negative terminals HV battery outputs to low voltage negative potential connected to vehicle frame. To assure that insulation measurement covers all the vehicle parts where electric shock is possible, all conductive materials of the vehicle are connected low voltage ground.

In the dash of the vehicle there is an indicator led which informs the driver that an insulation hazard is present. By rules (1) if it illuminates driver must leave the vehicle within 5 seconds.

8.5 High Voltage Present Indicators

8.5.1 Accumulator Indicator Light

According to the rules (1) an indicator light or voltage meter must be next to main battery connection to show if the connector has over 50 volts present. This indicator is powered directly from high voltage in the connector and does not need any external power. The indicator circuit naturally needs to be able to withstand maximum voltage of the battery constantly without breaking. Metropolia Motorsport had two designs to achieve this. The first one used current limiting diodes and resistors to drop the high voltage and resistors to drop voltage for the led. The second one had a switching voltage regulator which was able to drop the voltage. The regulator version was implemented because it allowed the led to be brighter when voltage was close to the required 50 Volts requirement.

8.5.2 Tractive System Active Light and Ready to Drive Sound

Whenever the main contactors are closed, and high voltage is present outside the battery housing there is a blinking red light on the highest point of the vehicle. The light can be seen from all directions to let anybody around the car to know that high voltage is on. When only low voltage is on the light turns green. Also, another indicator is on the dash of the vehicle to inform the driver.

TSAL is also connected to auxiliary contacts on the main contactors to indicate if a contactor fails and a dangerous situation occurs. This will help to discover a situation where one of the contactors has failed, but other contactor still removes the high voltage from the circuit.

9 Precharge & Discharge

9.1 Precharge Requirement

Inverters usually have some capacitance in DC bus. This capacitance would be enough to burn 125 ampere main fuse if the main contactors would be just closed. So, it is required that the capacitance needs to be charged to 90% of the battery voltage under 5 seconds through a 680 ohm resistor before connecting both main contactors (AIR) of the vehicle.

To achieve this a third contactor to control a resistor bypassing main positive contactor is added as in Figure 21. Voltage is measured on both sides of the main positive AIRs to check that 90% of battery voltage is reached before closing the second contactor. For extra safety here is also a timed delay of three seconds before it is possible to close the second relay.

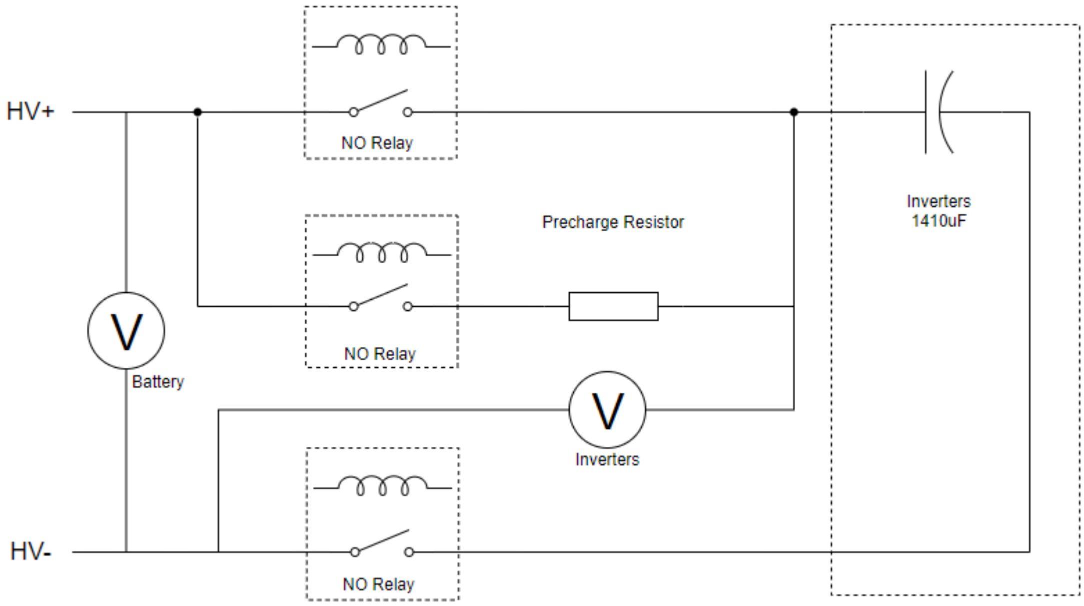

Figure 21. Precharge circuit diagram.

9.2 Discharge

To prevent the possibility of having high voltage present anywhere in the vehicle when the battery is disconnected by AIRs a discharge resistor has been added to Formula Student vehicles. It is controlled by a NC relay which has its coil side on the end of shutdown circuit, and it is connects HV+ and HV- through a resistor to discharge the inverter capacitance (Figure 22). This circuit will be closed when the main contactors are not closed. In other words, high voltage is not present outside the battery container.

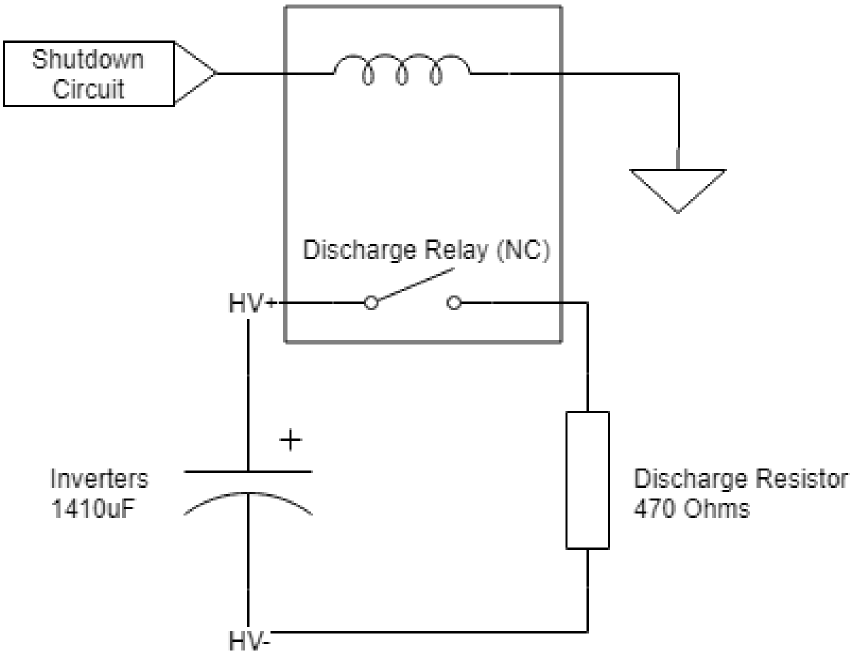

Figure 22. Discharge circuit diagram.

10 Charging

Battery is charged with two Brusa NLG513 chargers. They are connected in series to achieve the charging voltage of 600 V when maximum voltage for each charger individually is 520V. Charging is controlled by BMS, the charger and Metropolia Motorsport´s own software communicating through 1 Mbit/s CAN bus.

BMS is also operational during charging. It is capable of opening AIRs and isolating charger from the battery if voltage or temperature limits are exceeded. Also insulation measurement is active during charging and all the conductive parts of the battery and the charger are grounded together, so IMD can open AIRs, if it sees a connection between high voltage and low voltage ground.

Maximum possible charge current of the cells would be 13.2 Ah x 5C = 66 A. Charging operates in commonly used CC-CV manner. In constant current phase current is limited to 12 A. After charging voltage reaches maximum 600 Volt upper limit charger starts dropping current keeping the constant voltage at 600. Full charge from empty battery to full requires 1 hour and 20minutes.

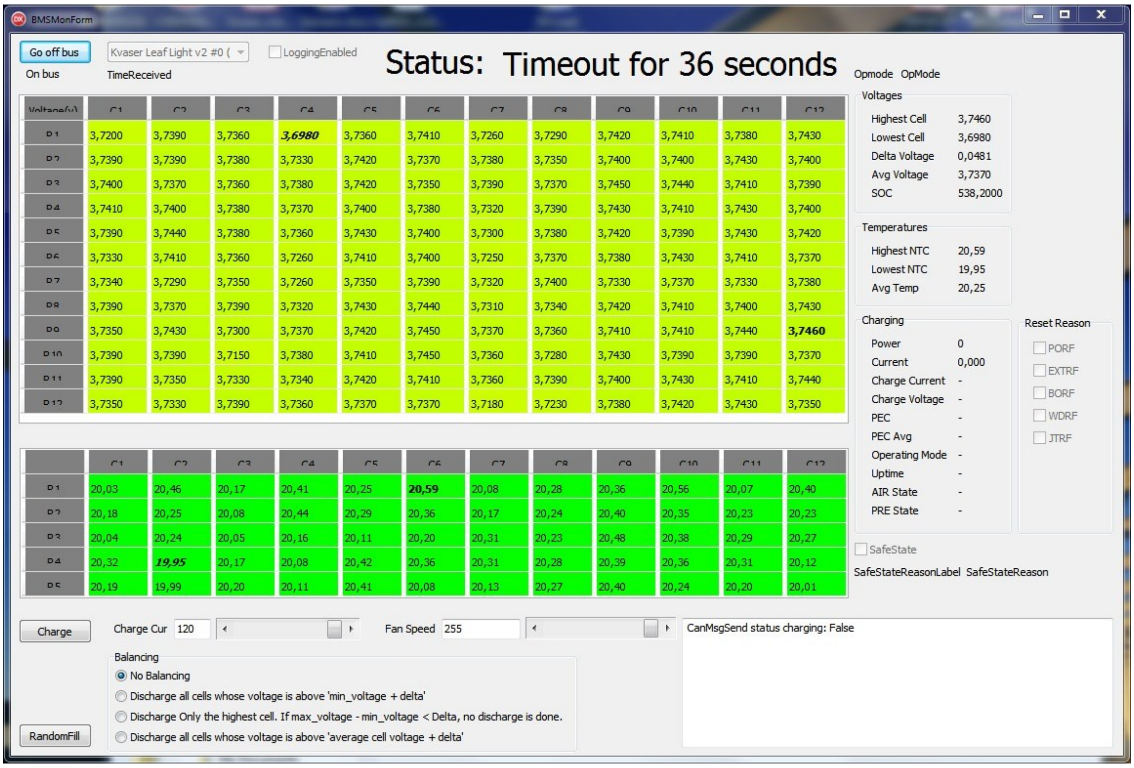

Figure 23. Monitoring cells and temperature sensors online during charging and controlling options for charging.

During charging all 144 cell voltages and 60 temperature measurements can be monitored. It is possible to find the weaker cells when looking at the charging data and comparing them to the driving data. Damaged or otherwise worse cells have lower capacity and higher internal resistance. This shows as having slightly higher voltage during charging and lower voltage during discharging compared to other cells.

11 Measuring Battery Performance

A huge amount of data from the actual vehicle was collected and analysed for evaluating the final concept. The battery design was used in competitions two years by Metropolia Motorsport. There are logged power measurement from competition events and more detailed battery management logs of cell voltages and temperature data.

Battery voltages have been logged while driving the vehicle with AIM Solo 2 DL Can bus data logger which logs battery voltages from BMS and IVT-MOD (6) current measurement system (figure 24), logging frequency being 100 Hz.

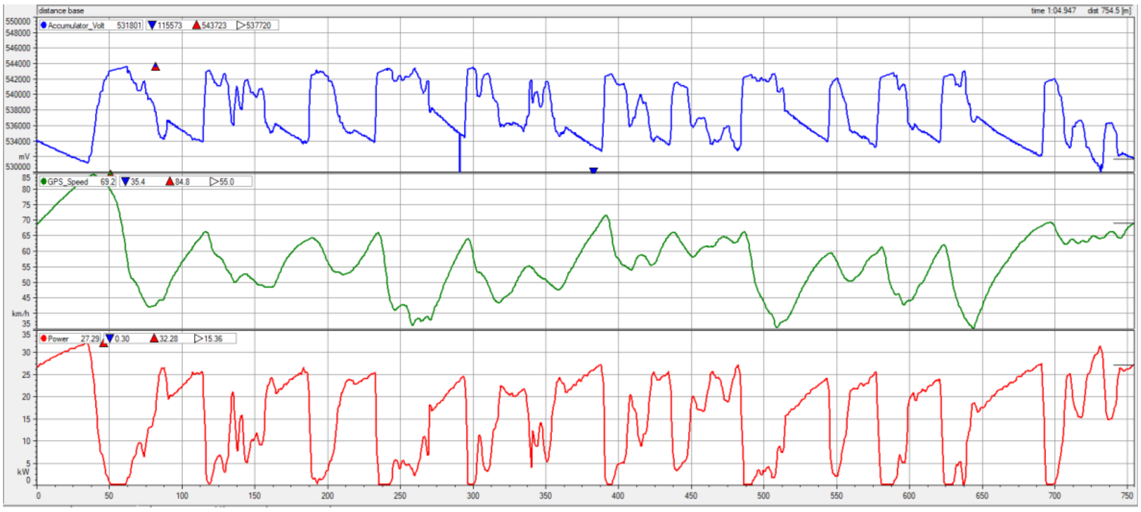

Figure 24. AIM Solo 2 DL data showing how speed(green) and power(red) are related in Formula Student vehicle. At the same time battery voltage (blue) drops always in relation to power output from battery.

In addition BMS stores more voltage data to a SD card with 5Hz frequency and this data were imported to Matlab and converted to 3D graphs. These graphs provide simplified overall coverage of the behavior of the battery during longer driving and still can show individual cell information (Figure 25).

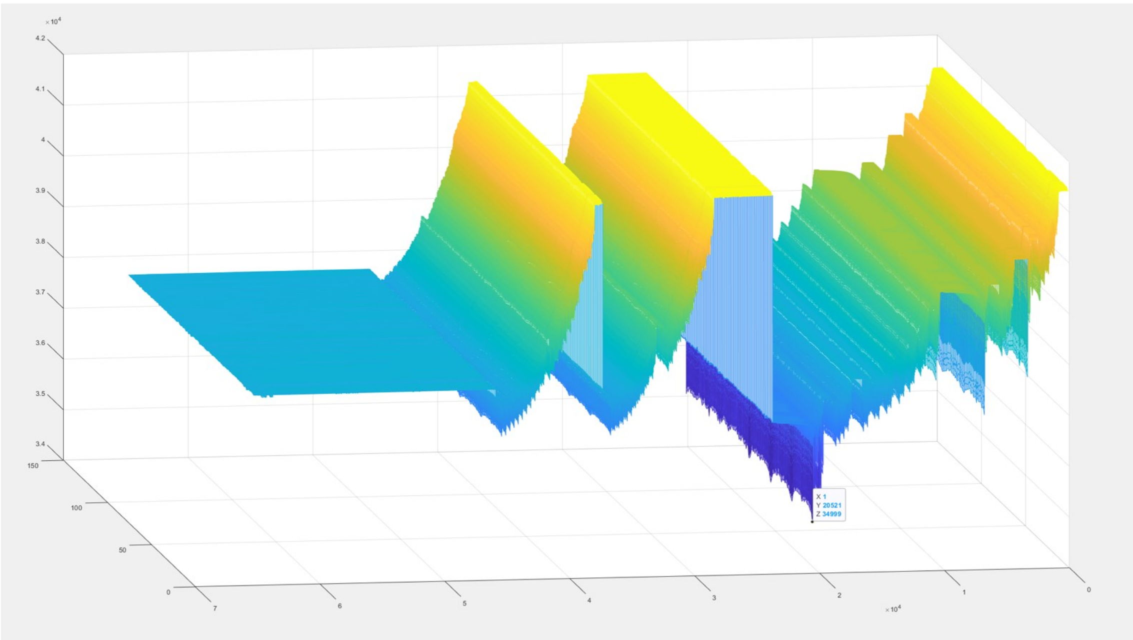

Figure 25. 3D graph from Matlab showing voltages of battery during a test day. Despite starting from balanced state cells have small differences when they warm differently and battery approaches empty state.

IVT-MOD (6) also provides data of energy consumed. This was used to determine the real capacity of the battery. In average the actual battery capacity has remained around 5.6-5.8 kWh of energy instead of the theoretical 7 kWh.

12 Conclusions

As a conclusion of the design process, manufacturing and two years of competition use the battery fulfills all the requirements defined in the beginning of the project. Comparing to previous design the following improvements have been achieved:

- Mass of the battery is 7 kilograms lighter.
- Center of gravity has been lowered 70 mm.
- Capacity is 10% larger
- Voltage drop with full 80 kW load has decreased from 50-60 Volts to around 30-40 Volts. This is partly because capacity change.

In the next generation of battery the focus should be in refining details and improving manufacturing processes to achieve higher quality. Making new evolutions of this concept should be preferred instead of starting to design a new one from the beginning as a replacement.

References

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Melasta Cell Information

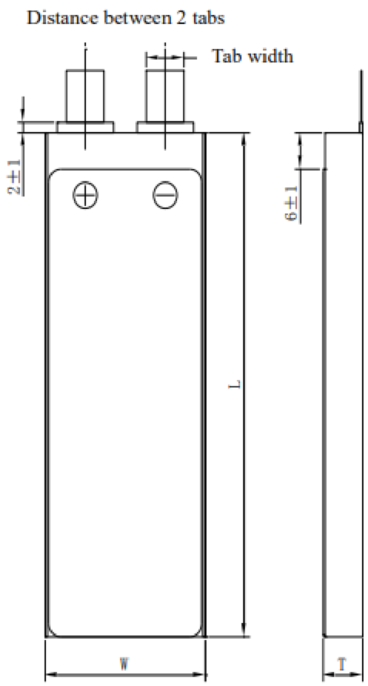
General information of selected Melasta cell.

2. 型号 MODEL

SLPBB042126 6600mAh 15C 3.7V

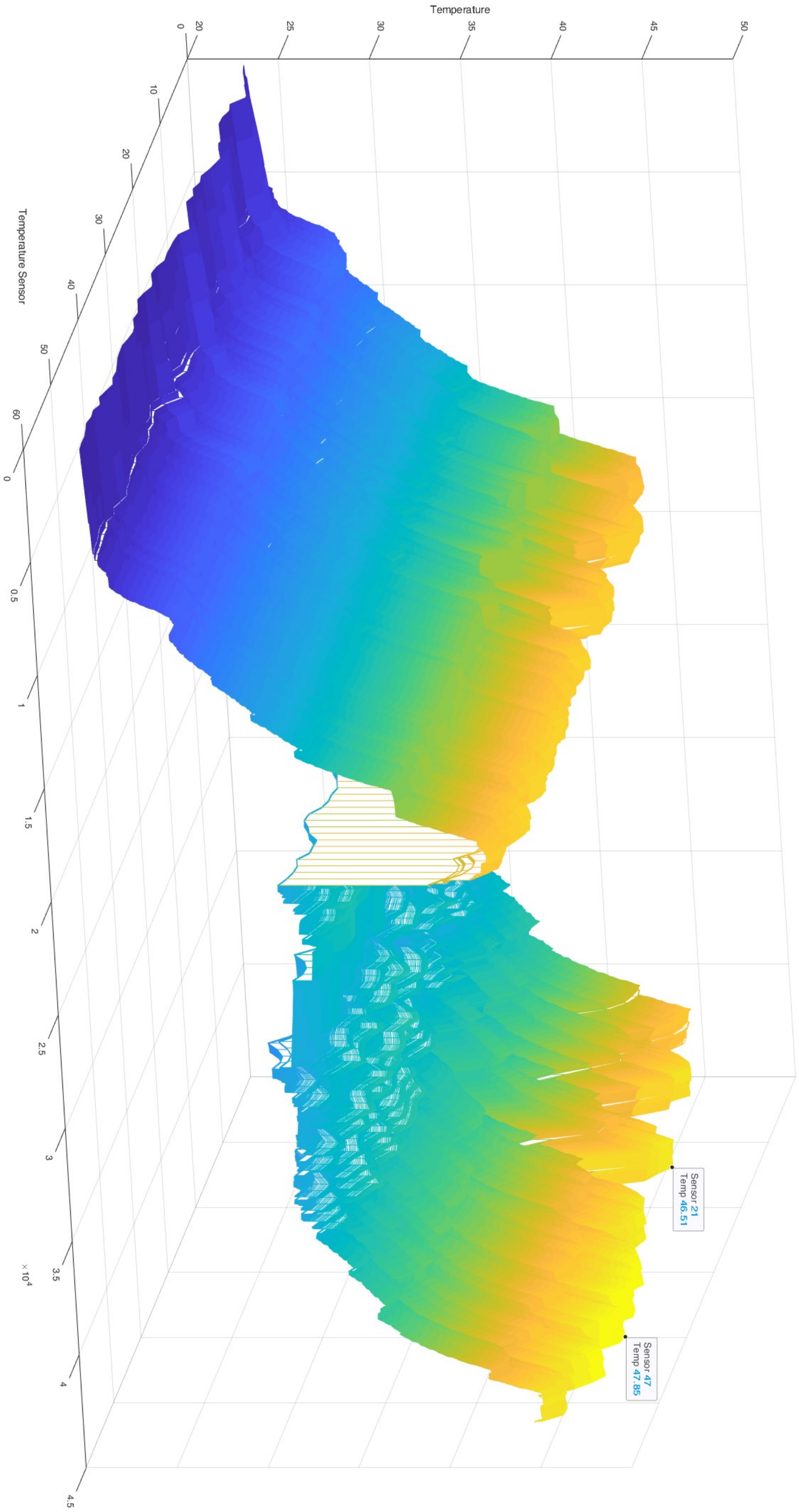
3. 产品规格 SPECIFICATION

单颗电池规格 Specifications of single cell



◆电芯正极材料 Cell Cathode Materials		$LiCoO_2$
◆标称容量 Typical Capacity①		6.6Ah
◆标称电压 Nominal Voltage		3.7V
◆ 充电条件 Charge Condition	最大可持续充电电流 Max. Continuous Charge Current	13.2A
	峰值充电电流 Peak Charge Current	26.4A (≤1sec)
	充电截止电压 Charging Cut-off Voltage	4.2V±0.03V
◆ 放电条件 Discharge Condition	Max Continuous Discharge Current	99A
	Peak Discharge Current	132A (≤5sec)
	Discharging Cut-off Voltage	3.0V
◆交流内阻 AC Impedance(mOHM)		<1.5
◆循环寿命【充电:1.0C,放电:15C】 Cycle Life【CHA:1.0C,DCH:15C】		>100cycles
◆使用温度 Operating Temp.	充电 Charge	0℃~45℃
	放电 Discharge	-20℃~60℃
◆ 电芯尺寸 Cell Dimensions	厚度 Thickness(T)	10.2±0.3mm
	宽度 Width(W)	42±0.5mm
	长度 Length(L)	127.5±0.5mm
	极耳间距 Distance Between Tabs	21±1mm
◆ 极耳尺寸 Dimensions of Cell tabs	极耳宽度 Tab Width	12mm
	极耳厚度 Tab Thickness	0.2mm
	极耳长度 Tab Length	Max 30mm
◆重量 Weight(g)		126±3.0
①标称容量：0.5CmA,4.2V~3.0V@23℃±2℃ Typical Capacity:0.5CmA,4.2V~3.0V@23℃±2℃		

Battery temperatures measured from 60 sensors inside showing a total test day.



Shutdown Circuit Diagram showing all the safety measures able to open the circuit and disable high voltage outside the battery.