ABENGOA

ESA Contract: 4000129433/19/NL/HK

Active Battery Management

Final Presentation

29.06.2023

Agenda

1 **Objective of the Activity**

2 **Task 1**

- Literature study and Identification of missions and their specific scenarios that would benefit from active battery management functionality

3 **Task 2**

- Definition of functions and requirements of a space battery management system

4 **Task 3**

- Detailed design of the battery management system

5 **Task 4**

- Development and Production of a BMS subsystem breadboard at TRL3

6 **Task 5**

- Breadboard characterization and test

7 **Task 6**

- System study, further development needs, costs, risks and trade-off

Overview

Active Management System

Objective:

- Literature study of state of the art battery management systems in space applications or terrestrial BMS suitable for space application. Identification of mission and their specific scenarios that would benefit from an advanced active battery management functionality through a BMS.
- Definition and consolidation of function list for battery management system.
- Identification of data handling interfaces for monitoring and signal processing requirements to support functions. The required changes in respect to conventional spacecraft power system design shall be elaborated and described.
- Identification of possible power system interfaces and architectures with additional needed hardware to support the functions.
- Assessment of operation of a battery management system in a space environment and identification of specific constraints.
- Experimental verification of the most promising concept(s) by a downscaled breadboard
- Feasibility study of active battery management system in space mission and identification of future steps.

At the end of the activity the agency expects to have the technology at TRL 3 for the selected mission scenario

Schedule:

1. **KOM** 29/01/2020
2. **TRR** 15/07/2021
3. **Battery integration Completed** 30/06/2022
4. **Life Test completed** 13/12/2022
5. **Final Presentation** 29/06/2023

2 Task 1

State of the Art and advantages of BMS in different space missions

Task 1

State of the Art and advantages of BMS in different space missions

Objective:

Literature study and Identification of missions and their specific scenarios that would benefit from active battery management functionality

Battery Management System Benefits

- To increase safety and reliability of battery systems.
- To protect individual cells and battery systems from damage.
- To improve battery energy usage efficiency.
- To prolong battery lifetime

Battery Management System Functionalities

- Measurement and diagnostics functionality.
  - Measurements variables: Voltage, current and temperature
  - Auxiliary variables related with the battery state. Sate of Charge (SOC), State of Health (SOH), State of Function (SOF), etc.
- Safety management: Security circuits allow to disconnect the battery from the application when a security hazard is presented by a static or electro-
- Balancing: The balancing system is responsible of maximizing the life and improving the battery performance.
- Thermal Management Systems.
- Charger control interconnectivity.
- Data acquisition, processing and data storage.
- Communication with other devices and Interaction with the human

Task 1

Terrestrial BMS Architecture

BMS Architecture Components

BMS subsystems are classified in three different tiers:

- ☐ Cell monitoring unit (**CMU**): Lowest level, one attached to each cell, measures cell voltage, and temperature on cell level and provides cell-level balancing.
- ☐ Module management unit (**MMU**): Middle level manages and controls a group of CMUs and therefore cells (usually between 8 and 12 cells), groups them into a module, and provides intercell balancing functions.
- ☐ Pack management unit (**PMU**): Highest level manages and controls the MMUs, communicates with external systems, measures pack-wide parameters such as pack current and voltage, and controls pack safety devices.

Centralized BMS

All subsystems (CMU, MMU and PMU) are combined into a single entity directly connected to battery cells:

- ☐ Simple and Compact
- ☐ Difficult to Scale-up
- ☐ Poor isolation requirements (low voltage batteries)
- ☐ Optimized for batteries with small number of cells (i.e., Electric bicycles)

Modular and Master-Slave BMS

Several MMUs connected close to the battery cells. MMUs transfers cell parameters and measurements to the PMU.

- ☐ Good flexibility
- ☐ Good Scalability
- ☐ Medium Complexity
- ☐ Aimed for batteries with high number of cells (i.e., Electric Vehicle)

Distributed BMS

Several PMUs that supervise their own set of cells or supercells (MMUs). Connect with each other and works autonomously or under other PMUs control.

- ☐ Excellent flexibility
- ☐ Good Scalability
- ☐ Complex and Expensive
- ☐ Aimed for batteries composed by multiple battery packs (i.e., large Energy Storage Systems)

Task 1

Terrestrial BMS Technologies

SoC Estimation

Technique	Field of application	Advantages	Drawbacks
Discharge test	Used for capacity determination at the beginning of life	Easy and accurate; independent of SOH	Offline, time intensive, modifies the battery state, loss of energy
Coulomb counting	All battery systems, most applications	Accurate if enough re-calibration points are available and with good current measurements	Sensitive to parasite reactions; needs regular recalibration points. A Coulomb counter cannot measure internal discharging as no net current flows through the battery terminals.
OCV	Lead, Lithium, Zn/Br	Online, cheap, OCV prediction	Needs long rest time (current = 0)
Linear model	Lead Photovoltaic	Online, easy	Needs reference data for fitting parameters
Impedance spectroscopy	All systems	Gives information on SOH and quality	Temperature sensitive, cost intensive
D.C. Internal resistance	Lead, NiCd	Gives information on SOH; possibility of online measurements	Good accuracy, but only for a short time interval
Artificial Neural Networks	All battery systems	Online	Needs training data of a similar battery, expensive to implement
Fuzzy logic	All battery systems	Online	Ask a lot of memory in real-word application
Kalman filters	All battery systems, PV, dynamic application	Online Dynamic	Difficult to implement the filtering algorithm that considers all features as e.g. nonnormalities and nonlinearities

Cell Balancing Methods

Method		Speed	Size/ weight	Cost	Control complexity	Efficiency
Passive	Charge limiting	Very slow	Very small	Very cheap	Very simple	Poor
	Shunt resistors fixed	Very slow	Very small	Very cheap	Very Simple	Very Poor
	Shunt resistors switched	Slow	Small	Cheap	Simple	Poor
Active	Switched capacitor	Slow	Small	Cheap	Medium	Very good
	Fly-back converters	Medium	Very large	Very expensive	Complex	Good
	Buck-boost converters	Fast	Small	Medium	Complex	Very good
	Full-bridge converters	Very fast	Large	Very expensive	Large	Very good
	Lossless balancing	Very fast	Medium to large	Expensive to very expensive	Medium, Large	Very good excellent

Cell Balancing Algorithms

- ☐ VOC based requires some computing to manage undesired effects at high current or high state of charge.
- ☐ SoC based: Independent from impedance variations but must rely on trusted SoC estimations

Task 1

Space BMS Technologies Efforts & Heritage

Space BMS Technologies

Description	Mission	Reference	Estimated improvements	Validated model against S/C data
Switched capacitor (flying capacitor switching) – uses only 1 capacitor to remove & reuse the charges continuously, non-dissipative threshold-based Cell dispersion < 10 mV	GEO	Prakash et al 2016 [29]	low hardware (1 one switching capacitor) – less mass & volume low power dissipation → thermal dissipation simplified fast model convergence	unknown
Electrochemical Impedance Spectroscopy with square wave excitation	Non-specific	Carbonnier et al 2019 [24]	Increase on-board diagnostic capabilities	Practical measurements provided but not mission model
SOC estimation	LEO	Baccari et al 2019 [25]	Avoid estimation techniques Reduces computational burden	Battery model validated with HW experiments
Constant current/constant voltage (CC/CV) algorithm	LEO	Mostacciuolo et al 2019 [26]	Reduces system losses by increasing calculations burden.	Algorithm validated against tasks & environmental conditions for a LEO mission
Deep belief network (DBN), a type of neural network	Non-specific	Li et al 2019 [27]	Improves resolution in SOC calculation by increasing calculations burden	Not simulated against mission
Buck& boost converters	LEO	Ibrahim et al 2019 [28]	Non dissipative method for balancing	Simulation Tested with mission data
Kalman filter	LEO	Aissa et al 2019 [19]	Improves resolution in SOC calculation by increasing calculations burden	Simulation Tested with mission data
Kalman filter & Neural networks	LEO	Ananda et al 2018 [17]	Improves resolution in SOC calculation by increasing calculations burden	Simulation Tested with mission data
Resonant forward converters	Not specified	Rishivathsala et al 2018 [18]	Non dissipative method for balancing	Not tested with mission data
Machine learning	Scientific (XMM-Newton)	De Canto et al 2018 [21]	Could be integrated into mission planning tool making the BMS fully autonomous during eclipses, useful for missions requiring heaters permanently on during eclipses	Used mission data for 100 eclipses: 80% to train the algorithm and 20% to predict

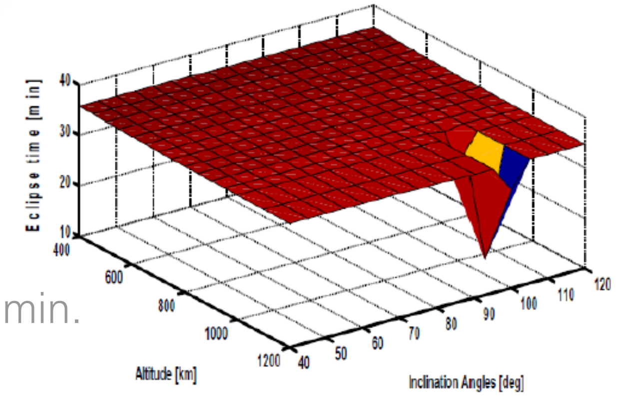
Space heritage

- Low maturity and limited examples compared with terrestrial applications
- Few examples of active BMS systems in flight.
- Key requirement for spacecraft (safety and reliability) leads towards dissipative/passive and simple active BMS configurations.
- Most of reported literature is based on theorical studies
- Literature does not describe in detail the few flight examples

Task 1

Orbit Analysis (I)

LEO Orbit Analysis



Characteristics

- ❑ Continuous Cycling in the order of 100min.
- ❑ Eclipse Time quite constant
- ❑ Sunlight period depends on altitude

Altitude	Eclipse	Sunlight	Period	Nº Cycles / year
400km	35.5 min	56.5min	92min	5688
800km	34.5 min	65.5min	100min	5221
1200km	34 min	75 min	109min	4814

Effects of LEO missions on Batteries

- ❑ Charge rate is increased to store enough energy during sunlight period, it accelerate cells unbalance.
- ❑ Fast and continuous cycling with no resting periods for the Battery makes difficult to estimate SoC.

Benefits of a BMS

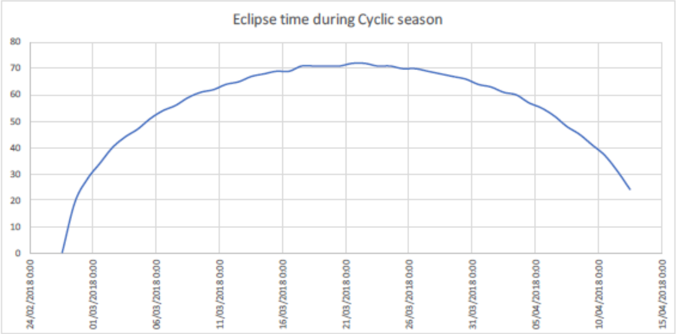
- ❑ Early detection of Potential battery failures
- ❑ Better estimation of SoC and SoH by including enhanced monitoring and algorithms
- ❑ Fast Cell balancing operations can reduce cell degradation

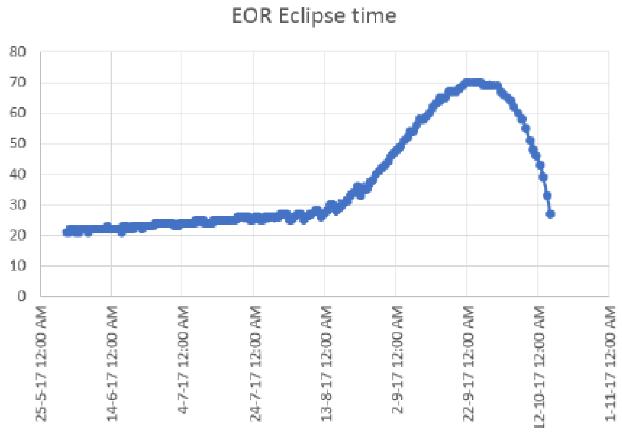
GEO Orbit Analysis

Characteristics (based on Eutelsat172B orbit analysis)

- ❑ Transfer Orbit phase (Electric Orbit Rising) with hundred of cycles AND
- ❑ Once in GEO, 2 Long sunlight periods of around 135 days each
- ❑ Once in GEO 2 Short cycling periods (equinoxes) of 45 days each, where the satellite is submitted to one eclipse per day of maximum 75min.

Period	Beginning of EOR	Medium EOR	End of EOR
Eclipse Time	20 min	27 min	As GEO (20 to 70 during 45 days around equinox)
Sunlight Time	650min	1050 min	As GEO


Eclipse time during Cyclic season


EOR Eclipse time

Effects of GEO missions on Batteries

- ❑ The limited number of charge and discharge cycles reduces the imbalance of the cells (90 cycles per year)
- ❑ Long resting periods during sunlight and cycling seasons allows good SoC estimations.
- ❑ DoD is higher to support the large eclipse periods close to the equinoxes. The charging rate is kept low as the sunlight after eclipse is nearly 23h.

Benefits of a BMS

- ❑ Early detection of Potential battery failures
- ❑ Slow Cell balancing operations can reduce cell degradation

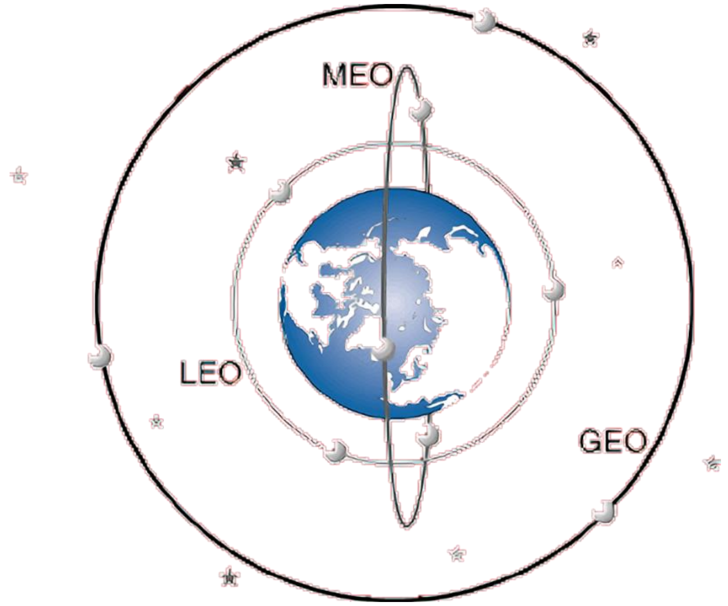
Orbit Analysis (II)

Trade Off and selection of a mission scenario

Mission	Technical Benefits	Challenges to reach a space product
GEO	BMS improves battery lifetime and reliability by adding enhanced cell monitoring, battery isolation & passivation resources. Cell balancing can be managed by simpler passive (resistor based) or slow active (switched capacitor) techniques. Low imbalance effect is expected after EOR and cyclic periods.	Cell monitoring shall be designed as proximity electronics to be hosted in a reduced volume using available space qualified parts. HW for isolation / passivation of the string shall be included as string/battery level Balancing HW shall be included in the proximity of other electronic components, based on available space qualified parts
LEO	BMS improves battery lifetime and reliability by adding enhanced cell monitoring, Coulomb counting for better SoC calculation, improved mission control to better estimate charge current and battery isolation & passivation resources. Cell balancing will be managed by complex fast active (converter based) techniques. Relevant imbalance effects are expected and shall be mitigated on real time using both sunlight and eclipse periods.	Cell monitoring shall be designed as proximity electronics to be hosted in a reduced volume using available space qualified parts. Computing and memory capabilities shall be enhanced to allow Coulomb counting algorithms. HW for isolation / passivation of the string shall be included as string/battery level Balancing HW will require dedicated development to migrate fast active techniques meeting efficiency, mass and size requirements.

Selection:

- ✓ The low Earth orbit (LEO) scenario has been selected to serve as baseline for the rest of the activity, since it is the one in which the implementation of an active battery management system will bring most benefits.



Task 1

Task 1 Outcomes

Terrestrial BMS State of the Art Analysis

Terrestrial BMS Architecture

- Centrilized BMS
- Modular Master-Slave BMS ✓
- Distributed BMS ✓

Terrestrial BMS Technologies

- SOC estimation
  - Discharge Test
  - Coulomb Counting ✓
  - OCV ✓
  - Linear Model
  - Impedance Spectroscopy
  - DC Internal Resistance
  - Artificial Neural Networks
  - Fuzzy Logic
  - Kalman filters
- Balancing Methods
  - Passive Methods
    - Charge limiting
    - Fixed Shunt R
    - Switched Shunt R
  - Active
    - Switched Capacitors
    - Flyback Converter
    - Buck-Boost Converter ✓
    - Full-bridge Converter
    - Lossless Balancing
- Balancing Algorithms
  - Cell V based ✓
  - Cell SoC based

BMS Selected Technologies

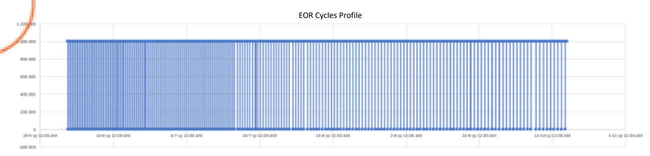
- Optimized for LEO Orbit
- SOC Estimation by Enhanced Coulomb Counting with Observer that corrects error by partial OCV compensation
- Balancing Method Active with Buck-Boost Converter based on Cell V monitoring

Task 2

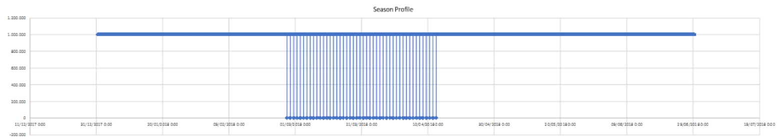
Space BMS State of the Art and Missions Analysis

Mission Orbit Analysis

✓ LEO Battery use



GEO Battery use



Space BMS Technologies

Efforts & Heritage

- Balancing Methods
  - Passive Methods
    - Charge limiting
    - Fixed Shunt R
  - Active
    - Switched Capacitors
    - Buck-Boost Converter
    - Resonant Converters
- SOC estimation
  - OCV
  - Impedance Spectroscopy
  - Artificial Neural Networks
  - Kalman filters
  - Machine Learning
- Balancing Algorithms
  - Cell V based

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3 Task 2

Definition of functions and requirements of a space battery management system

Task 2

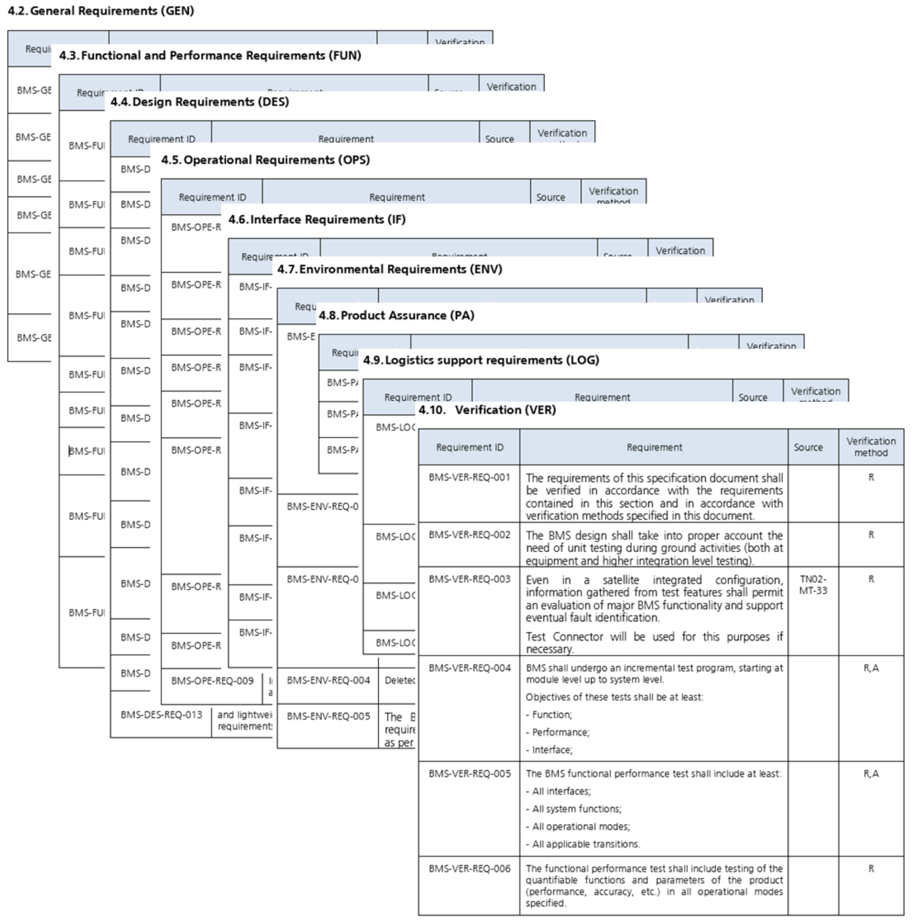
Definition of functions and requirements of a space battery management system

Objective:

Definition of functions and requirements for the selected mission scenario

Trade-off Potential architectures for the selected mission type and select the most promising architecture addressing BMS integration (in battery vs. PCDU; all or some functions) and Evaluate the impact on current spacecraft architectures

Requirements Specification



4.2. General Requirements (GEN)

4.3. Functional and Performance Requirements (FUN)

4.4. Design Requirements (DES)

4.5. Operational Requirements (OPS)

4.6. Interface Requirements (IF)

4.7. Environmental Requirements (ENV)

4.8. Product Assurance (PA)

4.9. Logistics support requirements (LOG)

4.10. Verification (VER)

Requirement ID	Requirement	Source	Verification method
BMS-VER-REQ-001	The requirements of this specification document shall be verified in accordance with the requirements contained in this section and in accordance with verification methods specified in this document.		R
BMS-VER-REQ-002	The BMS design shall take into proper account the need of unit testing during ground activities (both at equipment and higher integration level testing).		R
BMS-VER-REQ-003	Even in a satellite integrated configuration, information gathered from test features shall permit an evaluation of major BMS functionality and support eventual fault identification. Test Connector will be used for this purposes if necessary.	TN02-MT-33	R
BMS-VER-REQ-004	BMS shall undergo an incremental test program, starting at module level up to system level. Objectives of these tests shall be at least: - Function; - Performance; - Interface;		R,A
BMS-VER-REQ-005	The BMS functional performance test shall include at least: - All interfaces; - All system functions; - All operational modes; - All applicable transitions.		R,A
BMS-VER-REQ-006	The functional performance test shall include testing of the quantifiable functions and parameters of the product (performance, accuracy, etc.) in all operational modes specified.		R

Requirement Specification

Definition of the requirements for the BMS to be installed in Low Earth Orbit (LEO) satellites, as well as the impact / requirements imposed in the rest of equipment comprising the power subsystem: PCDU and Battery

Requirement Classification

- ☐ General Requirements
- ☐ Functional and Performance Requirements
- ☐ Operational Requirements
- ☐ Interface Requirements
- ☐ Environmental Requirements
- ☐ Product Assurance Requirements
- ☐ Logistic Support Requirements
- ☐ Verification Requirements

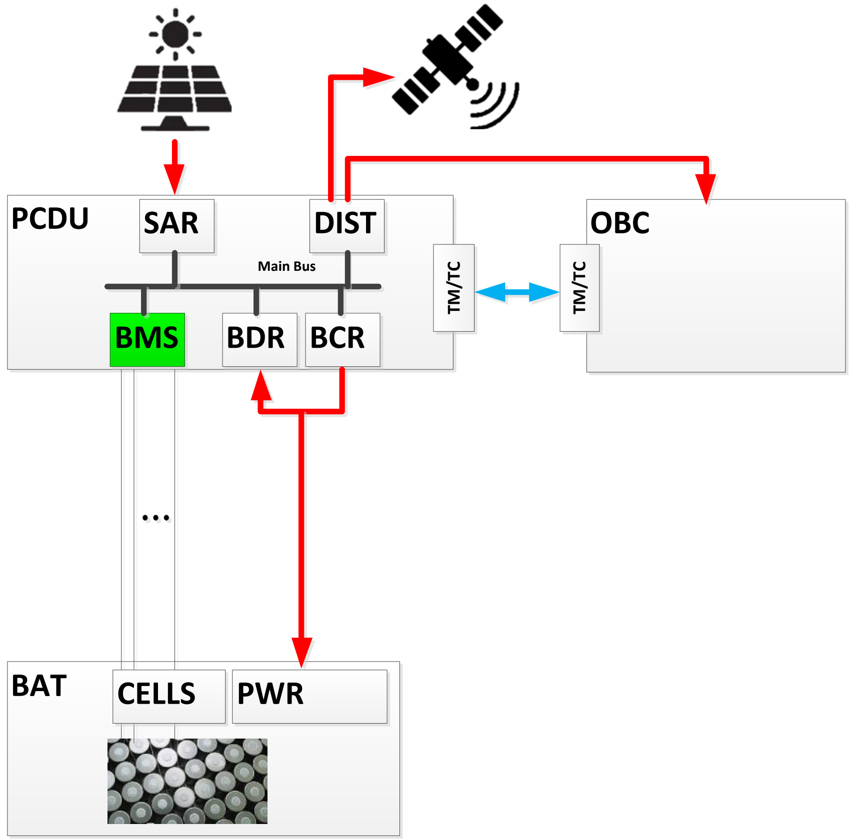
Task 2

BMS Architectures Trade-off & Selection (I)

Potential Architectures Overview

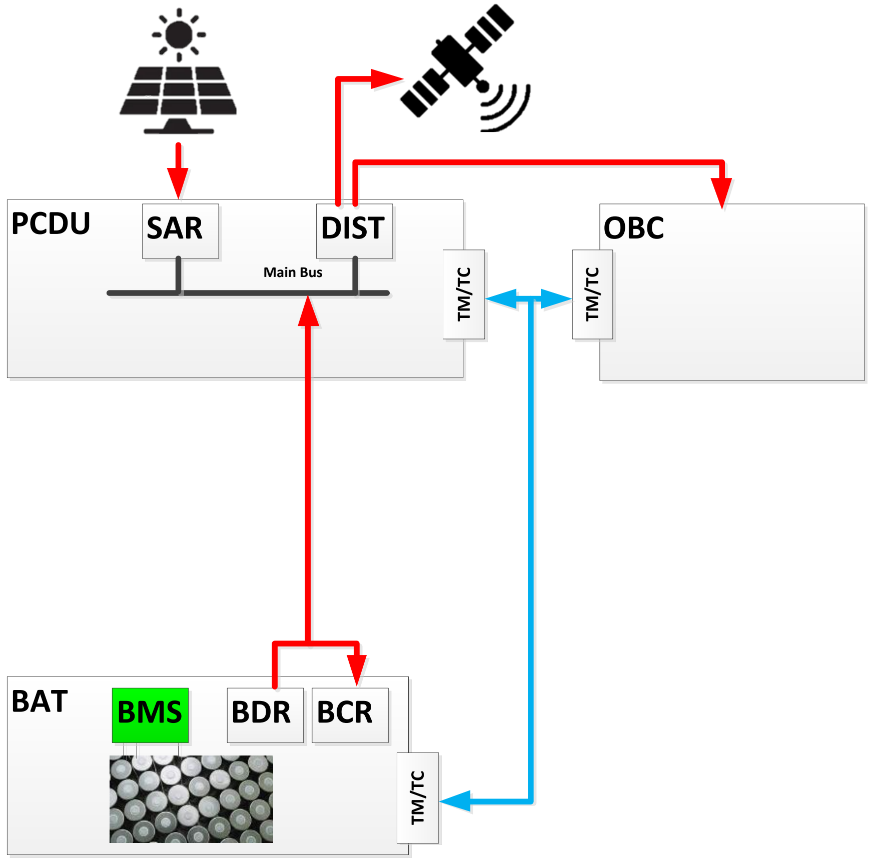
Terrestrial Architectures analyzed in TN-01 are used to propose different potential implementations of a BMS for space.

BMS Function hosted in PCDU



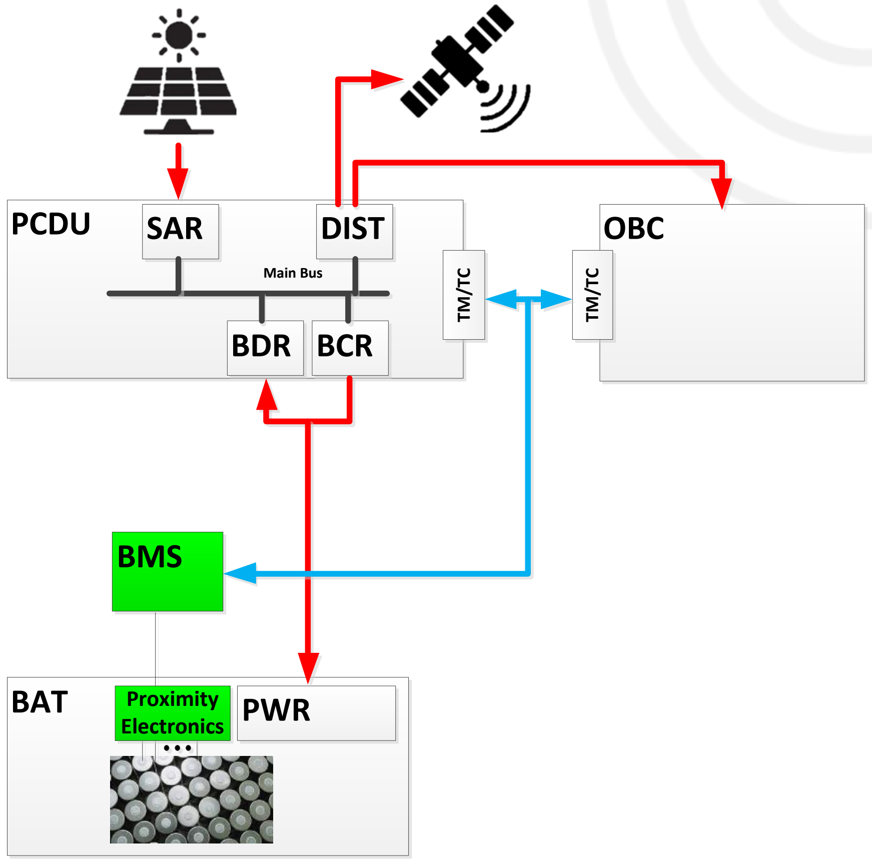
- ❑ PCDU hosts BCR, BDR and BMS functions
- ❑ Battery Pack provide standard harness to connect Battery Power line to BCR/BDR and also additional harness to reach each one of the battery cells to the BMS for monitoring and Balancing purposes.

BMS Function hosted in Battery



- ❑ Battery Pack Host BCR, BDR and BMS functionalities
- ❑ Battery Pack provide harness only to connect SAR and Main Bus to PCDU

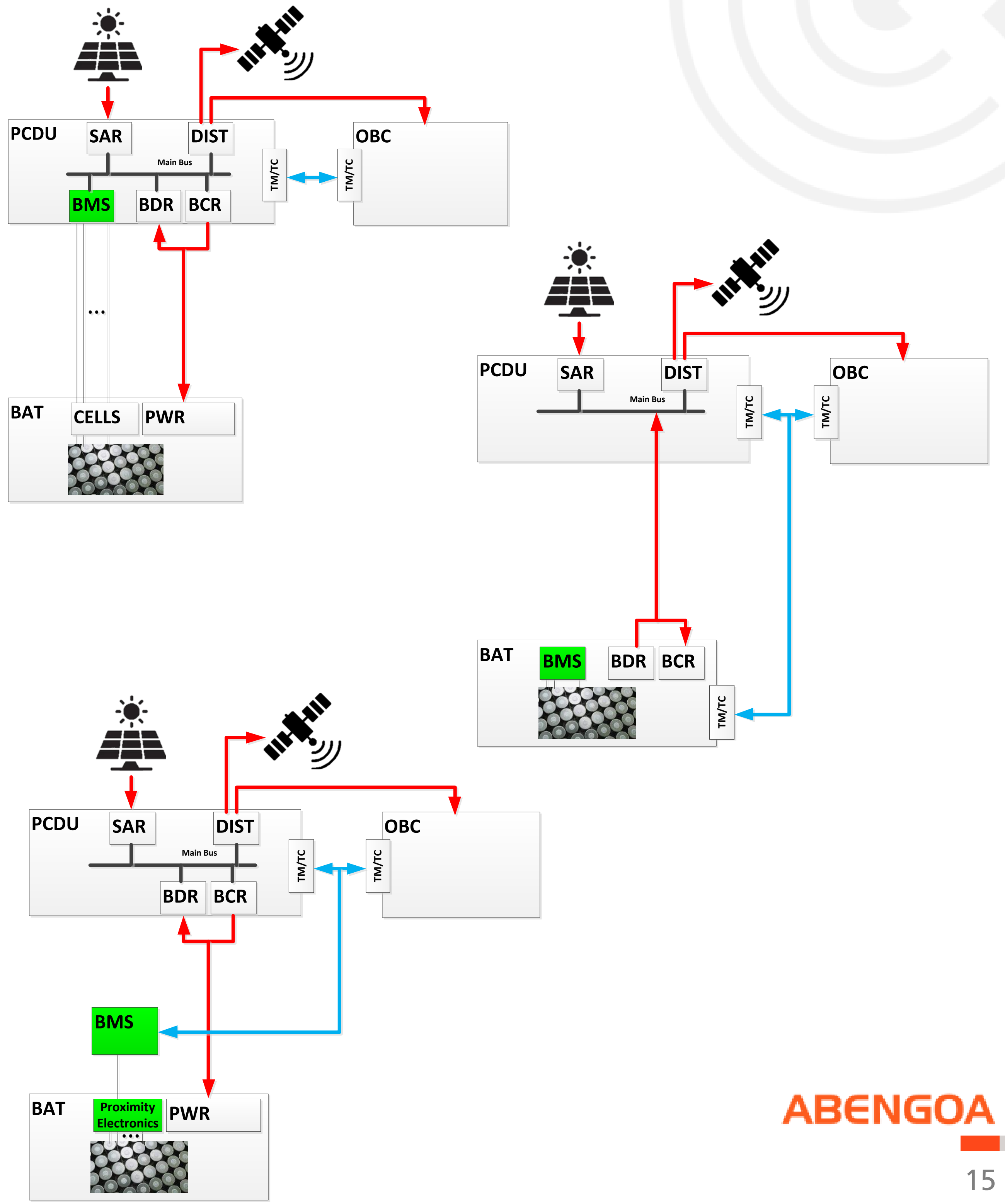
BMS Function Distributed



- ❑ PCDU hosts BCR and BDR functions
- ❑ Battery includes Proximity Electronics for cell monitoring and support to balancing function
- ❑ A new unit (BMS) include all computing, balancing and interface functions of the BMS
- ❑ Battery Pack provides standard harness to connect Battery Power line to BCR / BDR and additional reduced harness to connect BMS to Proximity Electronics

BMS Architectures Trade-off & Selection (II)

Architecture	Impact on Battery	Impact on PCDU	Impact on EPS
BMS hosted in PCDU	High: - Lot of Internal Harness for hundreds of signals. - Several new IF Connectors - Mass and Size relevant increment - Safety Constrains (double isolation)	Medium - New modules required for computing and memory capabilities - New modules required for Balancing Driving and Signal monitoring - Several new connectors that impacts in ICDs, Mass and Size	Medium - New harness for hundreds of signals among PCDU and Battery
BMS hosted in Battery	Very High - New Technologies on Battery (regulators, computing, TMTC) - Extra internal harness - High impact in Mass, Size and dissipation.	High - BCR/BDR regulators in Battery shall work together with SAR and Distribution Regulators. This would require intermediate power buses definition.	Low - New RT for 1553 bus for the BMS - Small size harness added for 1553 and Discrete.
BMS Distributed	Medium - Inclusion of Auxiliary Proximity Electronics - Reduced amount of internal harness - New small connector needed for BMS IF.	Very Low - Some new TMTC commands for 1553	Low - New RT for 1553 bus for the BMS - Small size harness added for 1553 and Discrete. - New unit (BMS) close to Battery

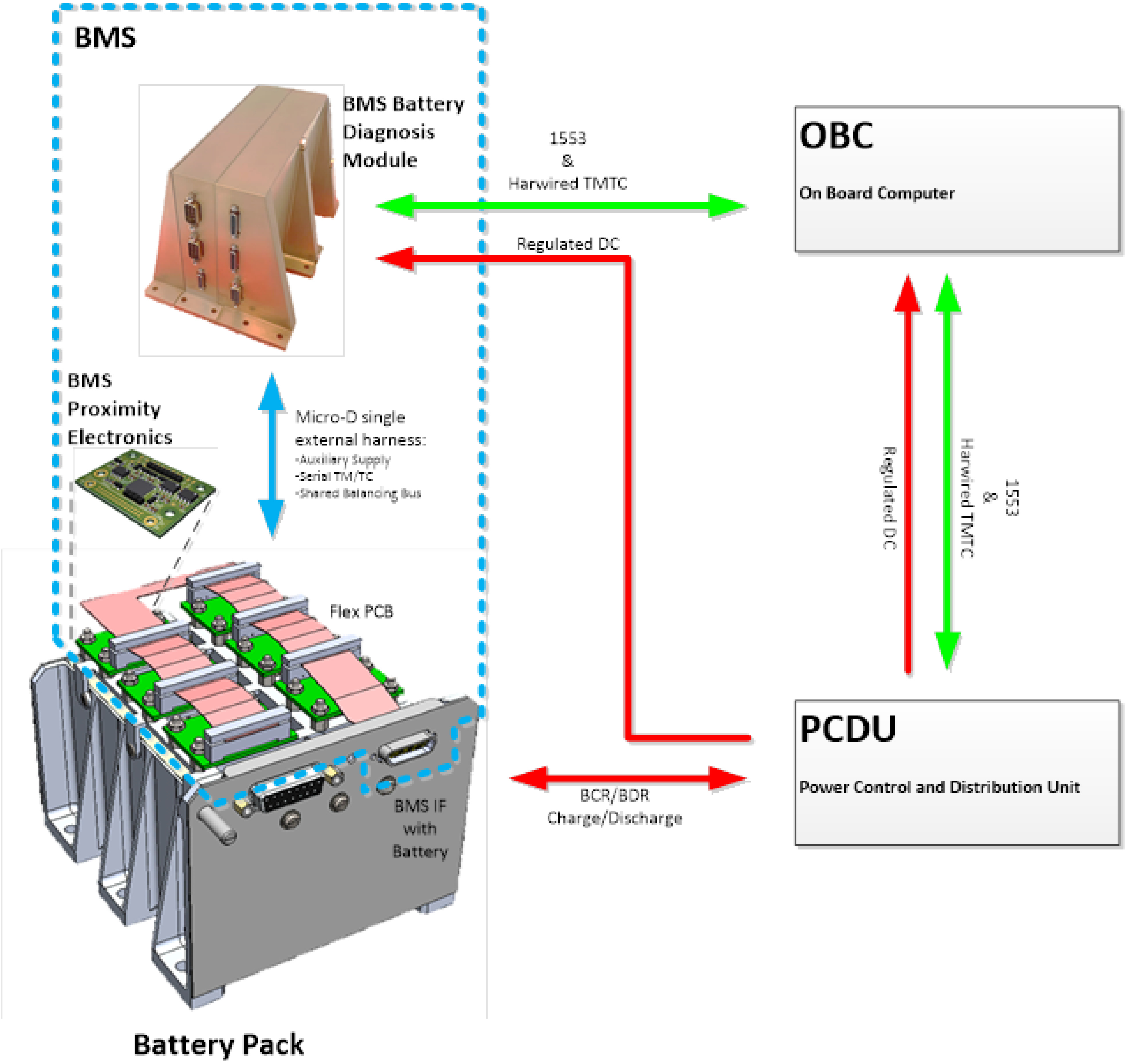


Task 2

BMS Architectures Trade-off & Selection (III)

BMS Distributed Architecture Selected

- ✓ Medium Impact on the Battery
- ✓ Very Low Impact on the PCDU
- ✓ Low impact on the EPS.



Task 2

Task 2 Outcomes

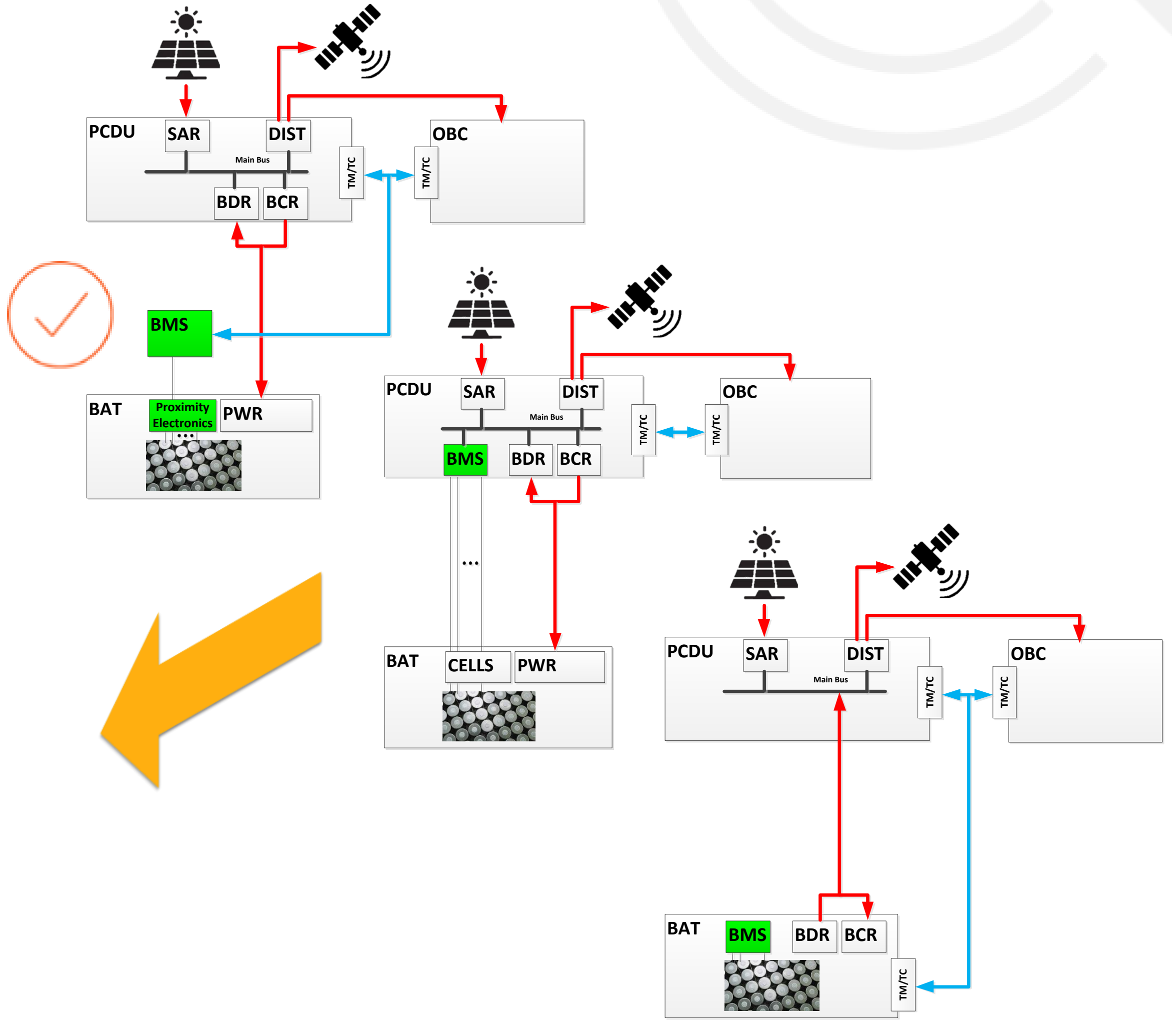
BMS Requirements

BMS Selected Technologies

- Optimized for LEO Orbit
- SOC Estimation by Enhanced Coulomb Counting with Observer that corrects error by partial OCV compensation
- Balancing Method Active with Buck-Boost Converter based on Cell V monitoring

TN-01

BMS Arquitecture for Space



- BMS Distributed Architecture equivalent to a Terrestrial Distributed + Modular Master-Slave Architecture
- Requirement Specification Definition

TN-02

Task 3

BMS Down-scaled BB

4 Task 3

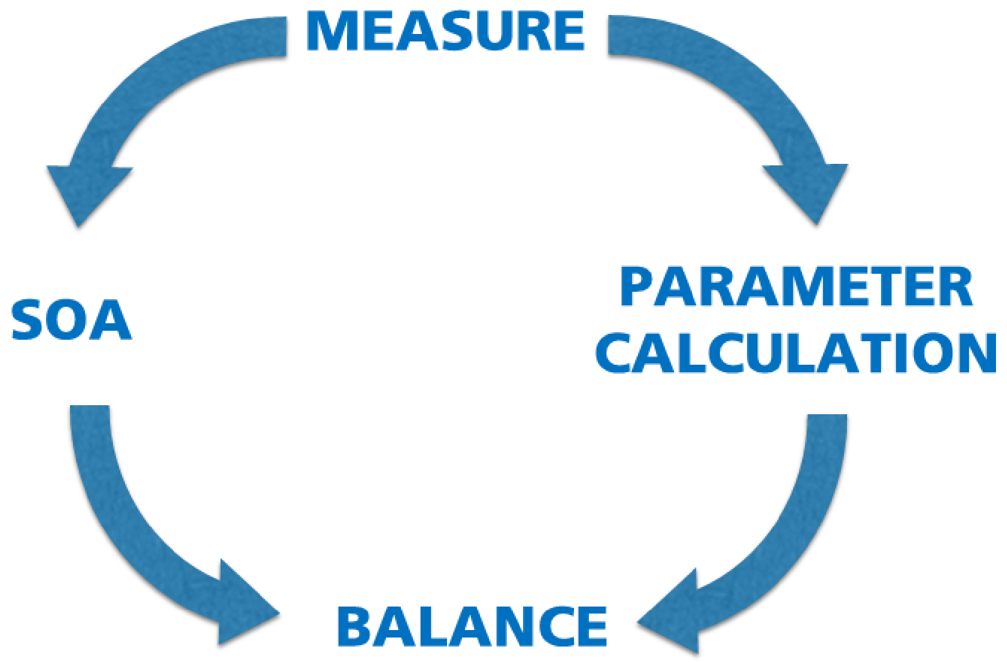
Detailed Design of a BMS Subsystem

Task 3

BMS Capabilities

The System must be capable of :

- Measure the voltage of each cell, the current that passes through it at each moment and its temperature.
- Obtention of the state of charge (SoC), the state of health (SoH) and retained capacity.
- Calculate internal parameters of each cell
- Balance the cells if needed accurately balancing the cells during periods of battery use
- Prevent possible failures by defining a Safe Operating Area (SOA)



MEASURE

PARAMETER CALCULATION

BALANCE

SOA

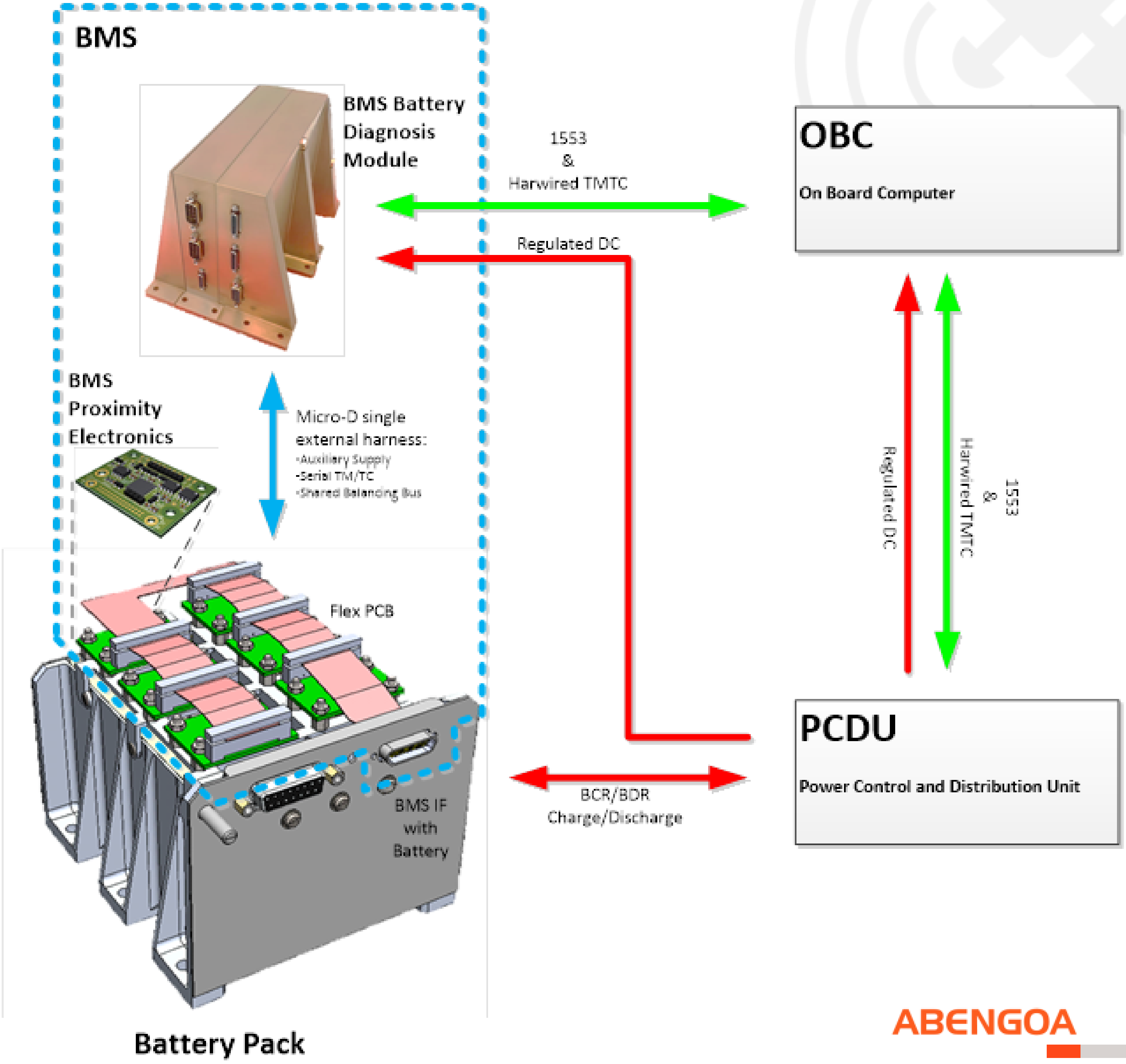
Task 3

BMS HW Implementation

BMS implementation

- ❑ PEU is a small PCB that are assembled on top of battery for:
  - ✓ Monitoring of the battery voltage, current and temperature
  - ✓ Connect cells for balancing

- ❑ BDU is a separated unit with electronics inside to:
  - ✓ SoC and Soh Calculation
  - ✓ Cell selection for balancing
  - ✓ SOA monitoring
  - ✓ Power supply generation for PEUs
  - ✓ TM/TC to OBC



Task 3

Cell Parameters

Parameter obtention

The state of charge SoC of the batteries is given by the voltage in open circuit VOC after a long period of rest.

To properly balance, it is necessary to calculate the SoC from the voltage and current measured during operation.

The internal parameters of a cell are R, Ro and C, and these parameter define the behaviour of the cell under excitations

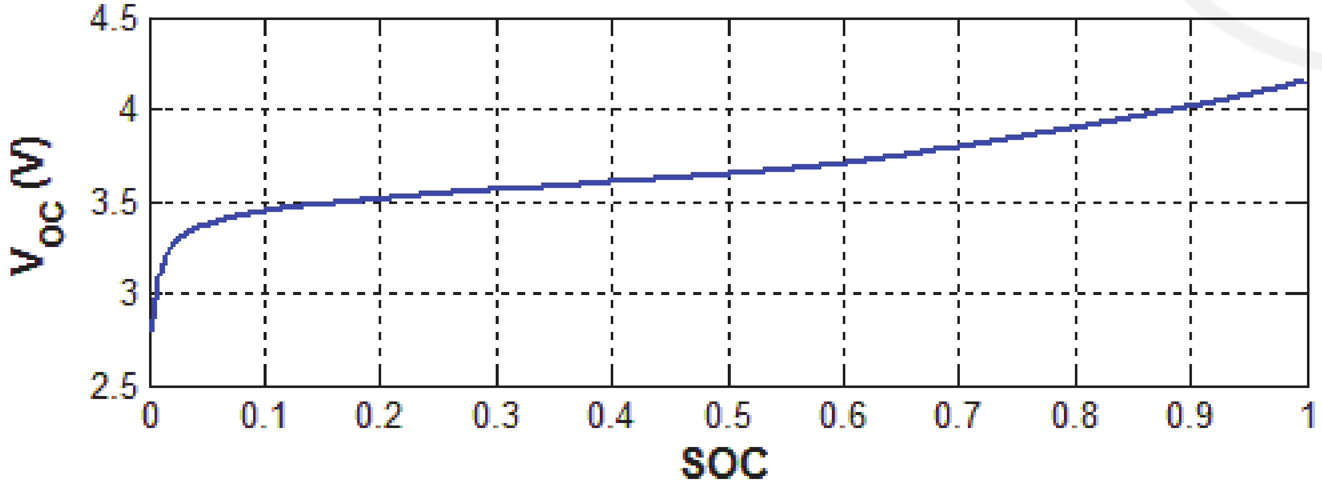
Steps to develop the method to calculate parameters:

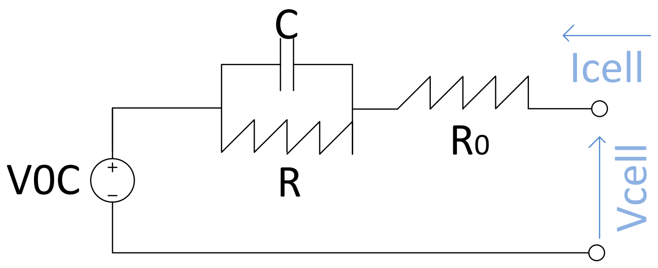
- Obtention of electrochemical equivalent
- Validation of the model by mathematical SW
- Obtention of state-space equations of the model
- Solve the state-space equations
- Translate the solving method to BDU microcontroller

By measuring the excitation of the cell and its reaction it is possible to obtain the parameters by using the developed mathematical method

The obtained parameters are used to calculate SoC and VOC, and the evolution in time of these parameter are used to calculate the SoH

The implementation of the SoC and SoH calculation is first checked by simulation and then transferred to the final hardware





Task 3

SoC, Q and SoH

SoC Calculation

The SoC is calculated at BDU every time a new data comes from PEU

This calculation is based on coulomb counting, with the correction of the cell model

The capacity of the battery Q is calculated by SoC differences during operation.

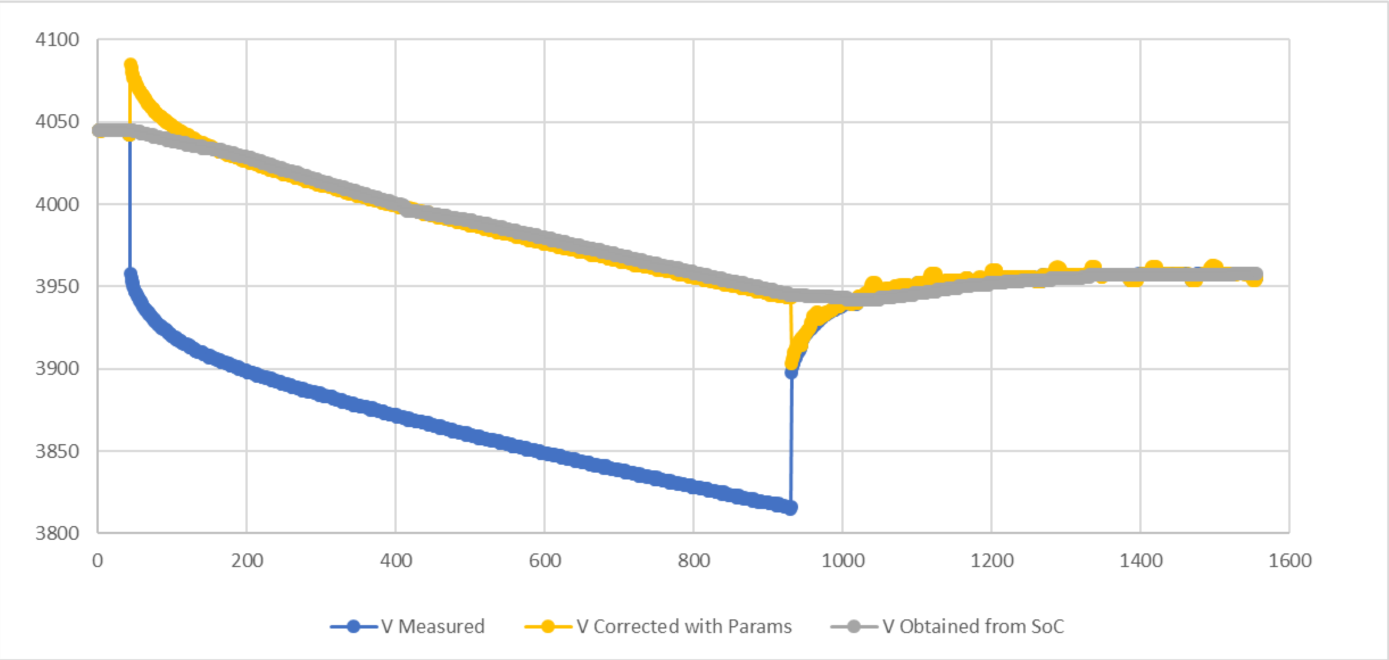
If a long enough resting period is detected, Q is recalibrated to increase the accuracy of the calculations

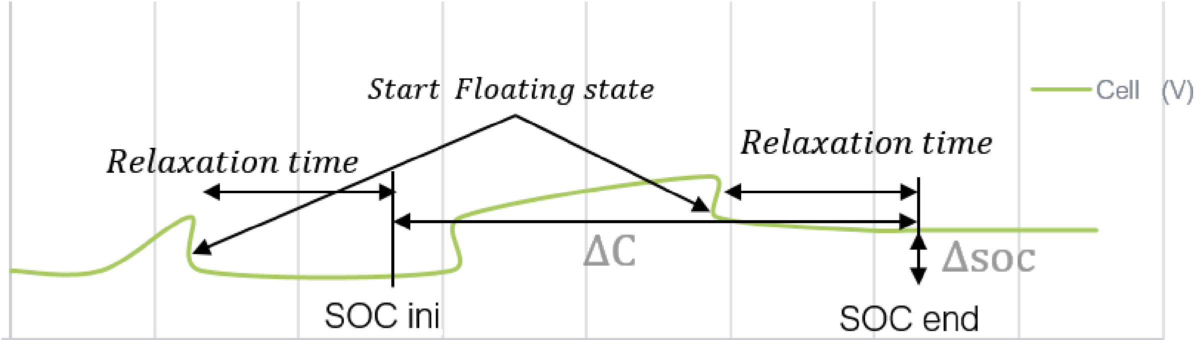
With the correction, the SOC remains accurate even during transition or long periods of cycling without relaxation, but during relaxation times, the model correction section of the equation is working, and correcting drifts.

SOH calculation for a single cell is obtained in 2 different ways:

- Using the change in internal resistance compared with BoL and EoL values provided by cell manufacturer / mission
- Using the change in retained capacity compared with BoL and EoL (typically 60%) values provided by cell manufacturer .

$$SOC_{j,i} = \mu \int \frac{i_j(t)dt}{Q_{j,i}} + Model\ Correction\ Cell_{i,j}$$





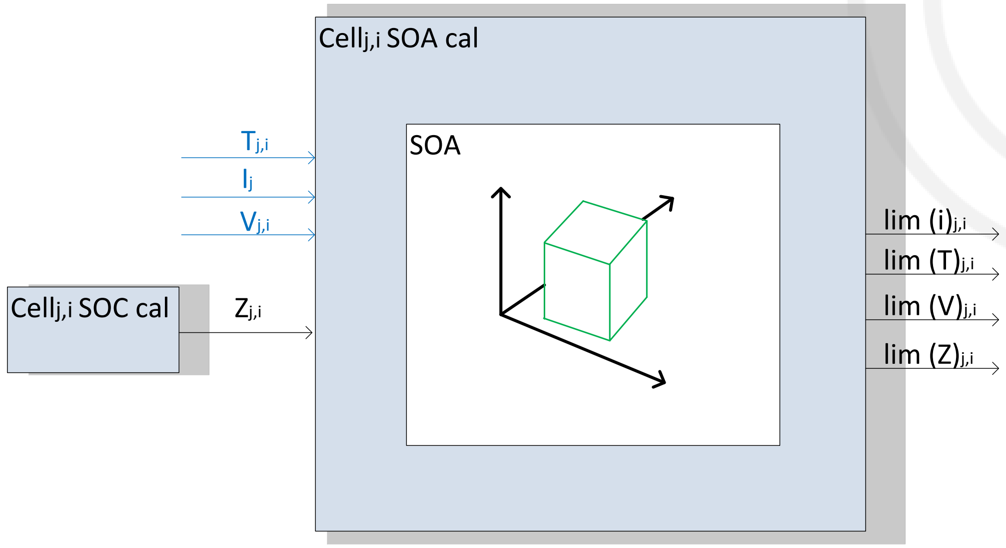
Task 3

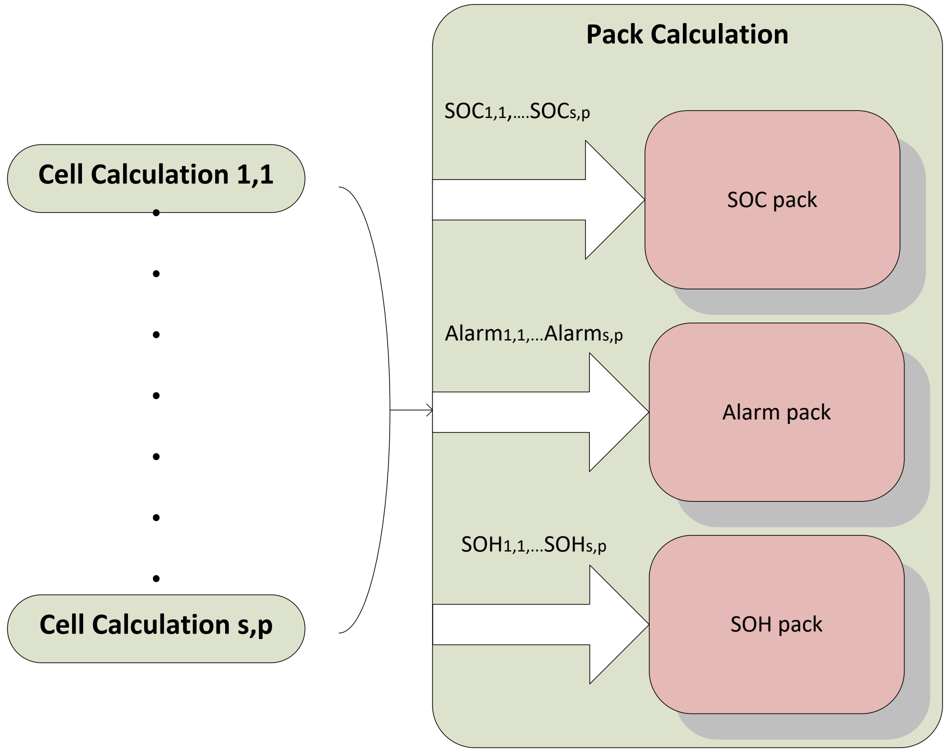
SOA

SOA supervision

- Safe Operating Area (SOA) module evaluates the voltage, current and temperature.
- Register events and inform to On board computer
- Evaluate charging and discharging speeds and maximum levels

- BMS calculate the parameters of each cell but also estimate the whole battery parameters using cells data.



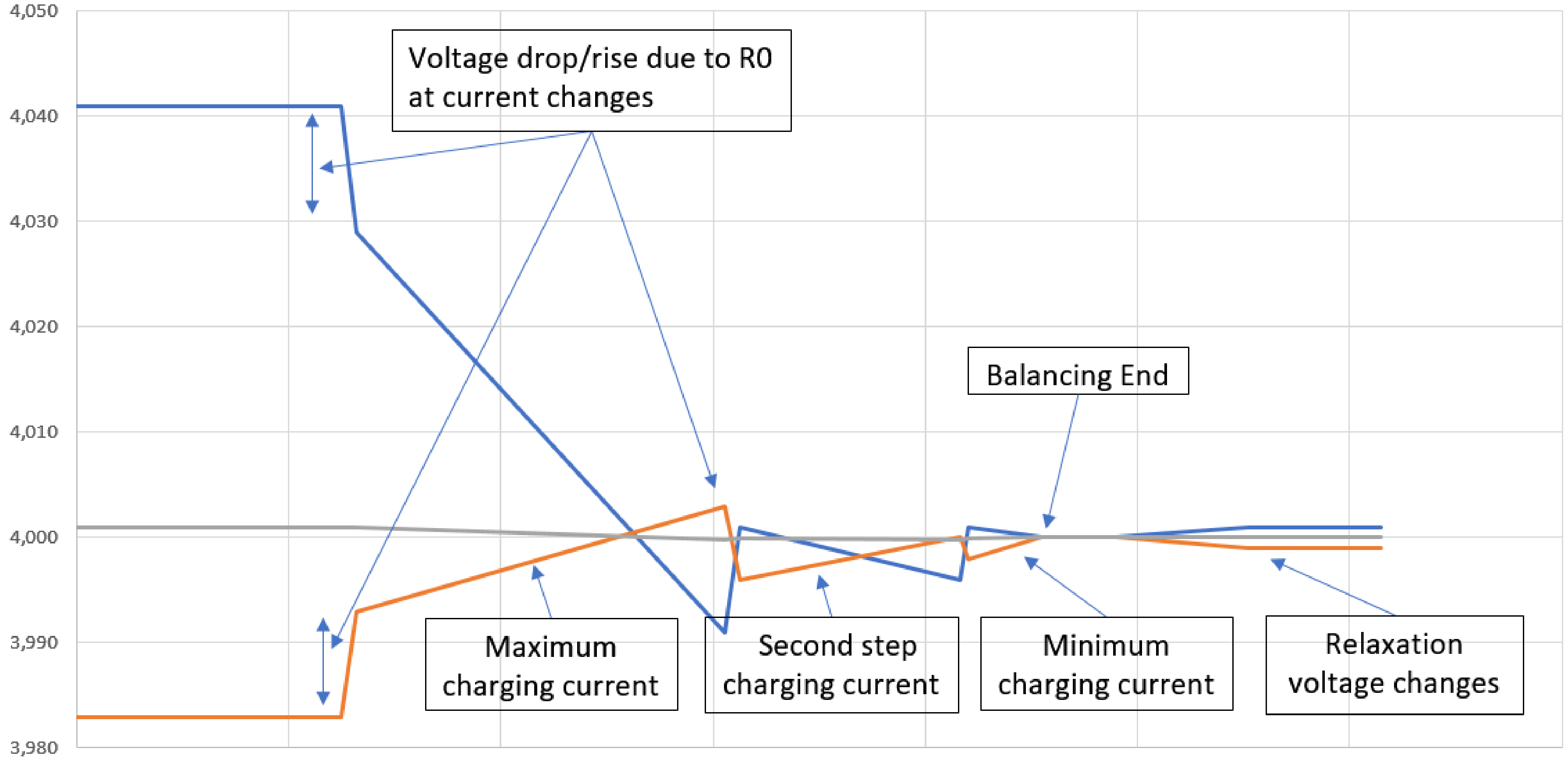


Task 3

Balancing

Balancing process

- ☐ 2 Balancing methods implemented through Buck-Boost converter:
  - ➢ Pack to Cell
  - ➢ Cell to Cell
- ☐ BDU selects the most charged and the most discharged cells.
  - ➢ If the most discharged is much below from the average value, then perform a Pack-to-Cell balancing.
  - ➢ If the Pack-to-Cell is not required and the difference between the most charged and the most discharged exceeds the configured limits, then performs Cell-to-Cell balancing.
- ☐ The system implements protections to not over-discharge or overload any cell above or below the average.
- ☐ Once all the cells have the same voltage, the balancing is stopped.



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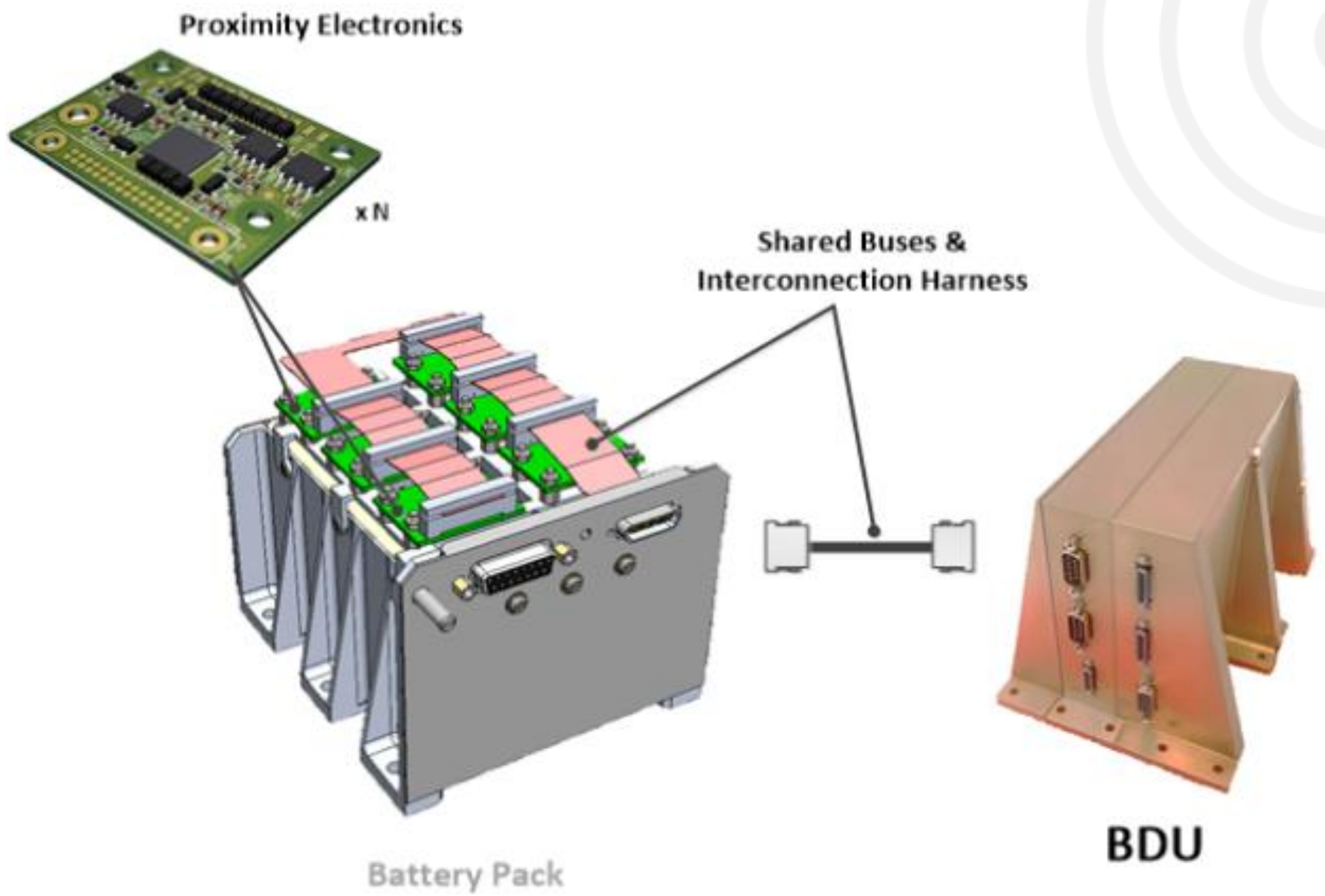
Task 3

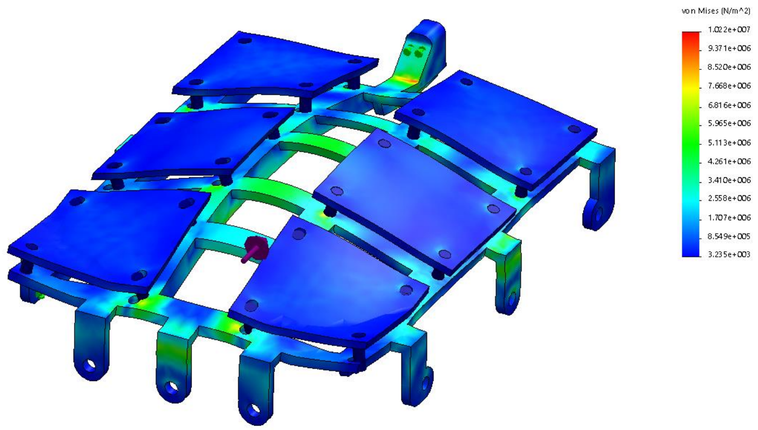
PEU HW Design

PEU is designed for:

- ✓ PCB fits in the top of 4 18650 size cells, its size is 27x36 mm
- ✓ Acquire voltage and temperature of 4 cells, and the current of the string
- ✓ Connect cells for balancing process
- ✓ Identify and acquire sets of valid data for parameter calculation
- ✓ Communicate with BDU
- ✓ Designed for robustness and minimum weight impact at the battery pack

- ☐ Connection of all PEUs is made by a rigid-flex PCB
- ☐ To attach the electronics to the battery pack it is designed an aluminum plate were PEUs are placed on the top of the battery pack





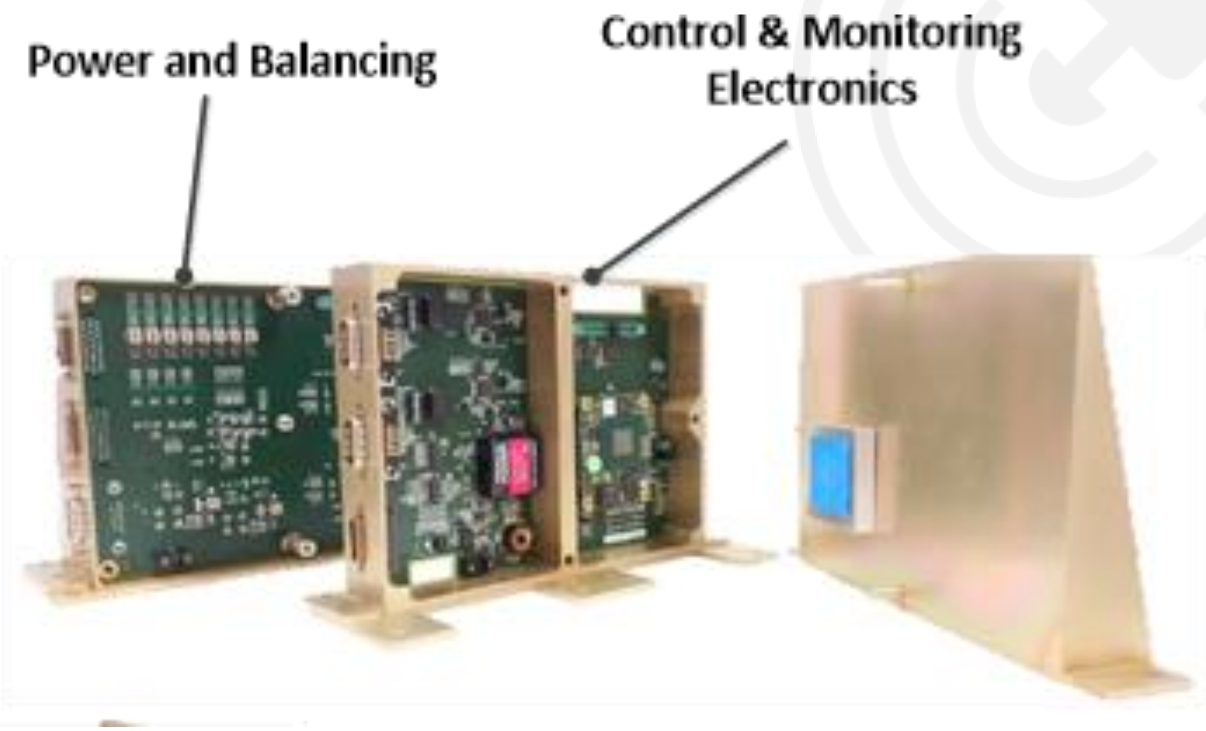
Task 3

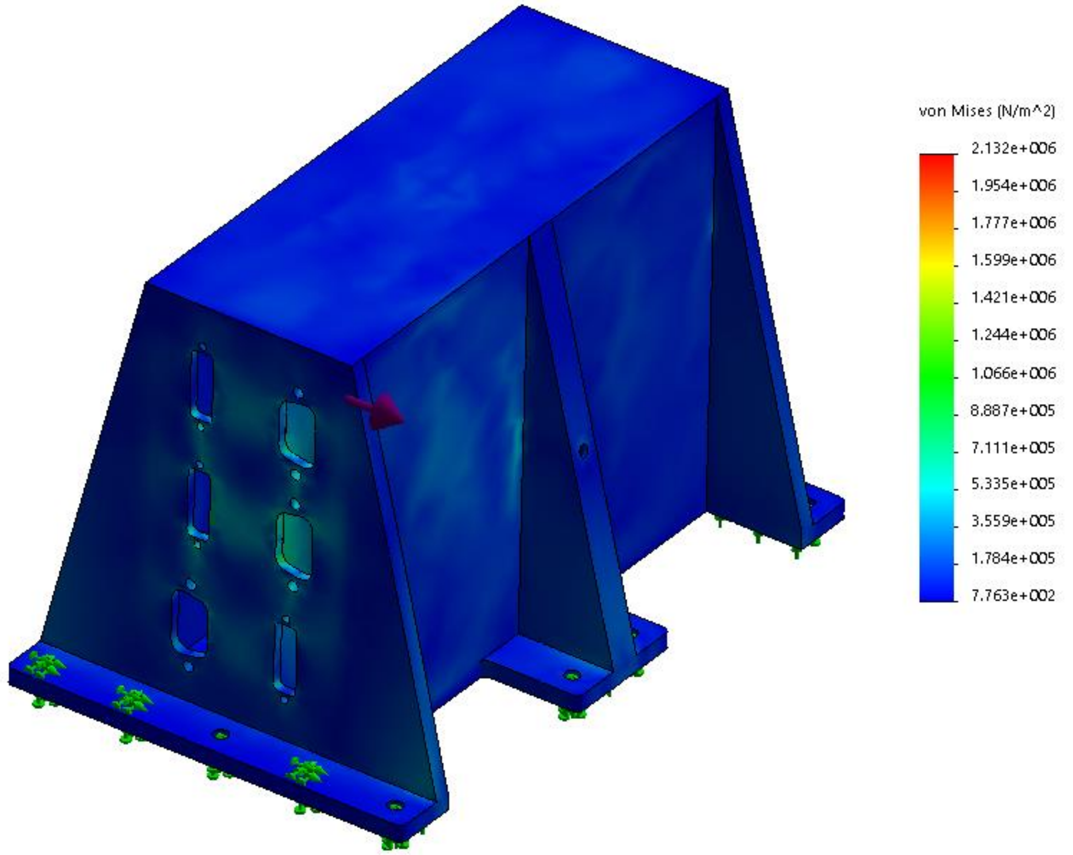
BDU HW Design

BDU is composed by a power and balancing board and control and monitoring board.

- ✓ Designed for Light weight and robustness
- ✓ Communication with the OBC by 1553 and HWC
- ✓ Power Supply to PEU
- ✓ Parameter calculation SoC, SoH, Q
- ✓ Supervision of SOA
- ✓ Balancing process management (decisions, execution and supervision)
- ✓ Protection and isolation

❑ The metallic case is designed to meet with space grade thermo-mechanical environment (high vibration and cooling paths for ICs)



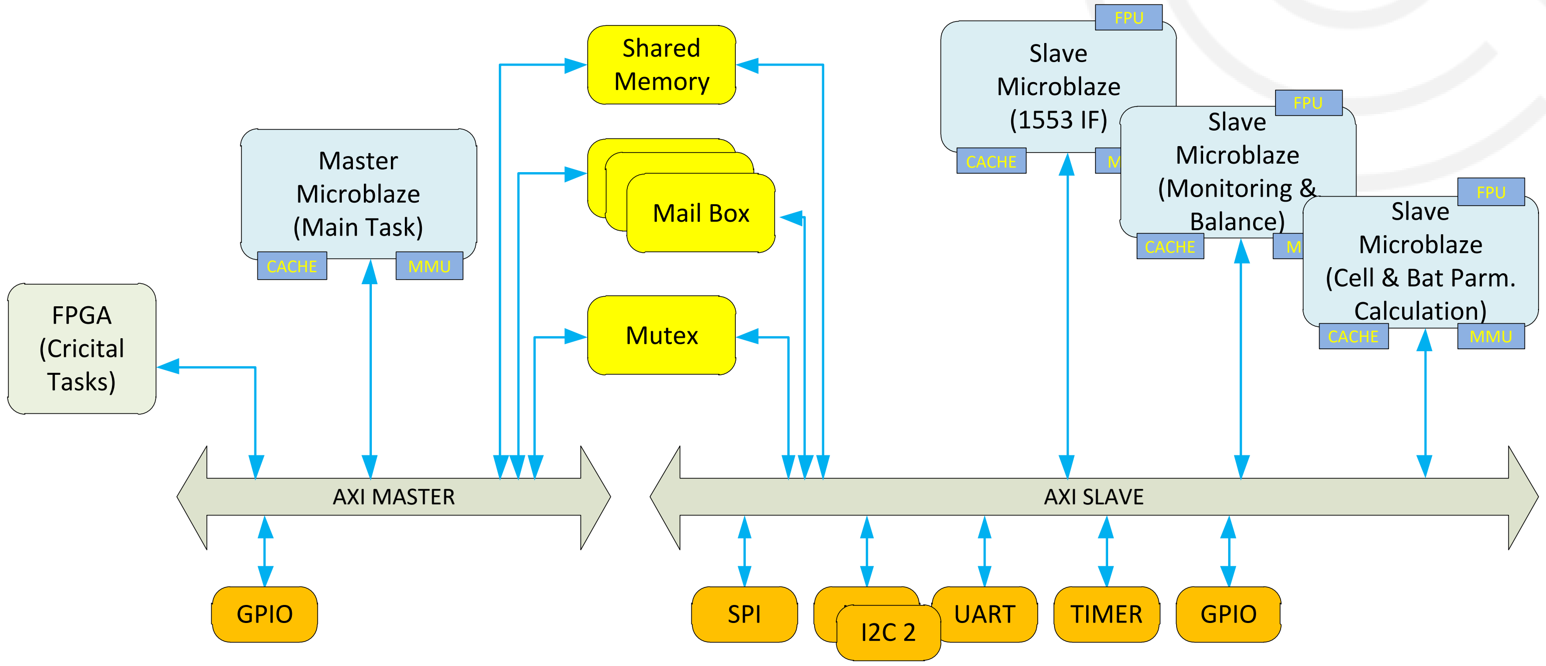


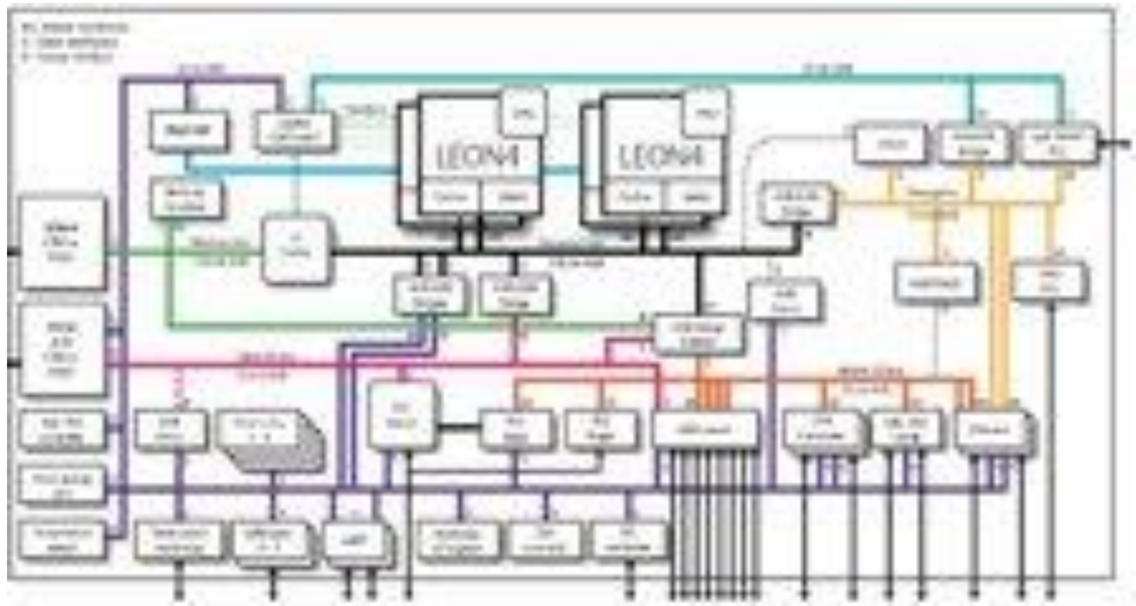
BDU Architecture Design

The BDU is designed with a future space grade implementation in mind.

- It has a performance similar to a space grade microprocessor LEON 4
- It has dedicated processors to critical tasks and an exclusive processor for parameter calculation.
- Space standards were also used for the interface of the BMS with the OBC
  - Hardwired Commands ECSS-E-ST-50-14C.
  - Mil-Std-1553B standard, following ECSS-E-ST-50-13C

	DMIPS/MHz	CoreMark/MHz	FPU	MMU	Cache (Kb)
LEON 4	1,7	2,1	✓	✓	256 - 1024*
ARM Cortex M3	1,25 - 1,89*	Up to 3,3	✓	×	0 - 1024*
MicroBlaze v11	1,1 1,4*	1,3 - 2,2*	✓	✓	0 - 128*
OpenRISC 1200	1	1,34	✓	✓	0 - 128*
*Depending on Configuration					


Shared Memory
Master Microblaze (Main Task)
CACHE
MMU
Mail Box
Mutex
FPGA (Cricital Tasks)
Slave Microblaze (1553 IF)
FPU
CACHE
Slave Microblaze (Monitoring & Balance)
FPU
CACHE
Slave Microblaze (Cell & Bat Parm. Calculation)
FPU
CACHE
MMU
AXI MASTER
AXI SLAVE
GPIO
SPI
I2C 2
UART
TIMER
GPIO

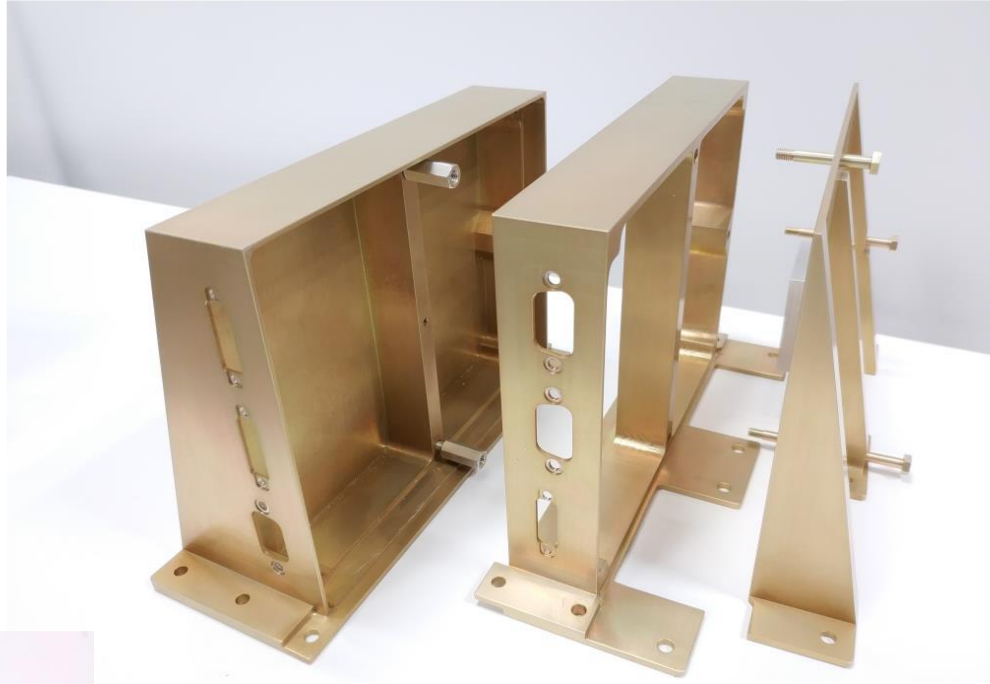


5 Task 4

Production of a BMS subsystem Bread Board at TRL-3

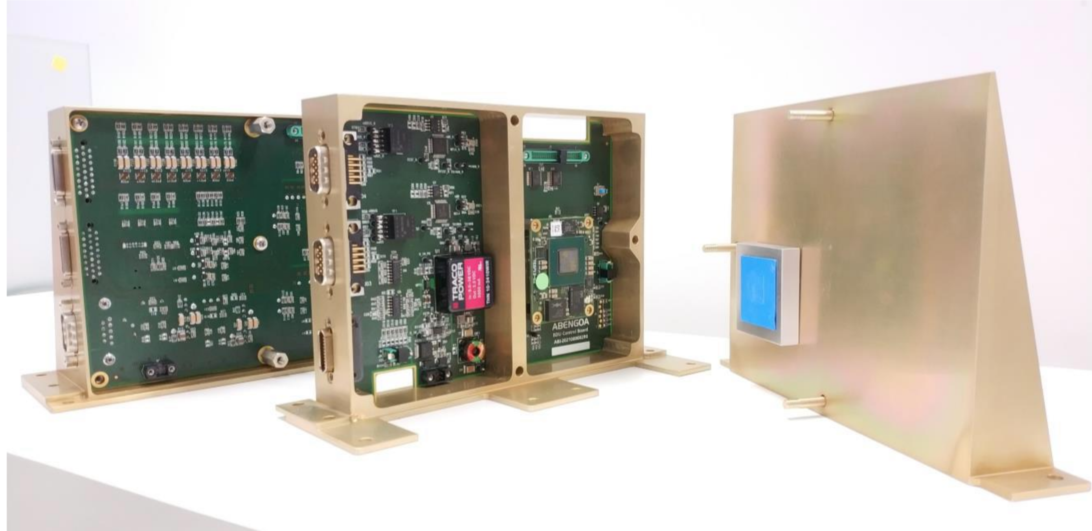
Task 4

Manufacturing of BDU



Hardware for BDU:

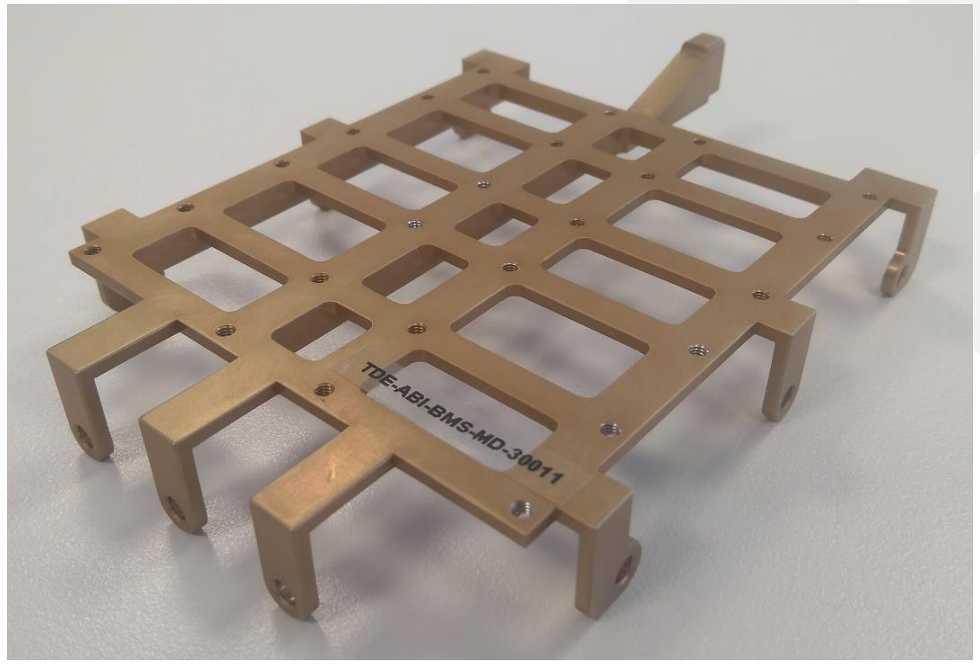
- The electronic boards of BDU are installed inside an enclosure comprised of 3 parts:
  - Stiffener 1 to allocate the Power & Balancing electronic board
  - Stiffener 2 to allocate the Control & Monitoring electronic board
  - A lateral cover



- Overall the interface of BDU is the following:
  - Mechanical interface consists of the following parameters:
    - Dimensions: (194 x 125 x 126) mm
    - Weight: 1420 g (mechanical parts)
    - 14 M4 screws are available for fastening to the structure
  - Electrical interface consists of 6 connectors:
    - HWC: interface with S/C OBC to be used for hardwired commands
    - PEU: interface with PEU
    - POWER IN: interface for power input
    - 1553: 2 interfaces (nominal & redundant) for 1553 functionalities
    - DEBUG: a connector used for tests and debugging tasks.

Task 4

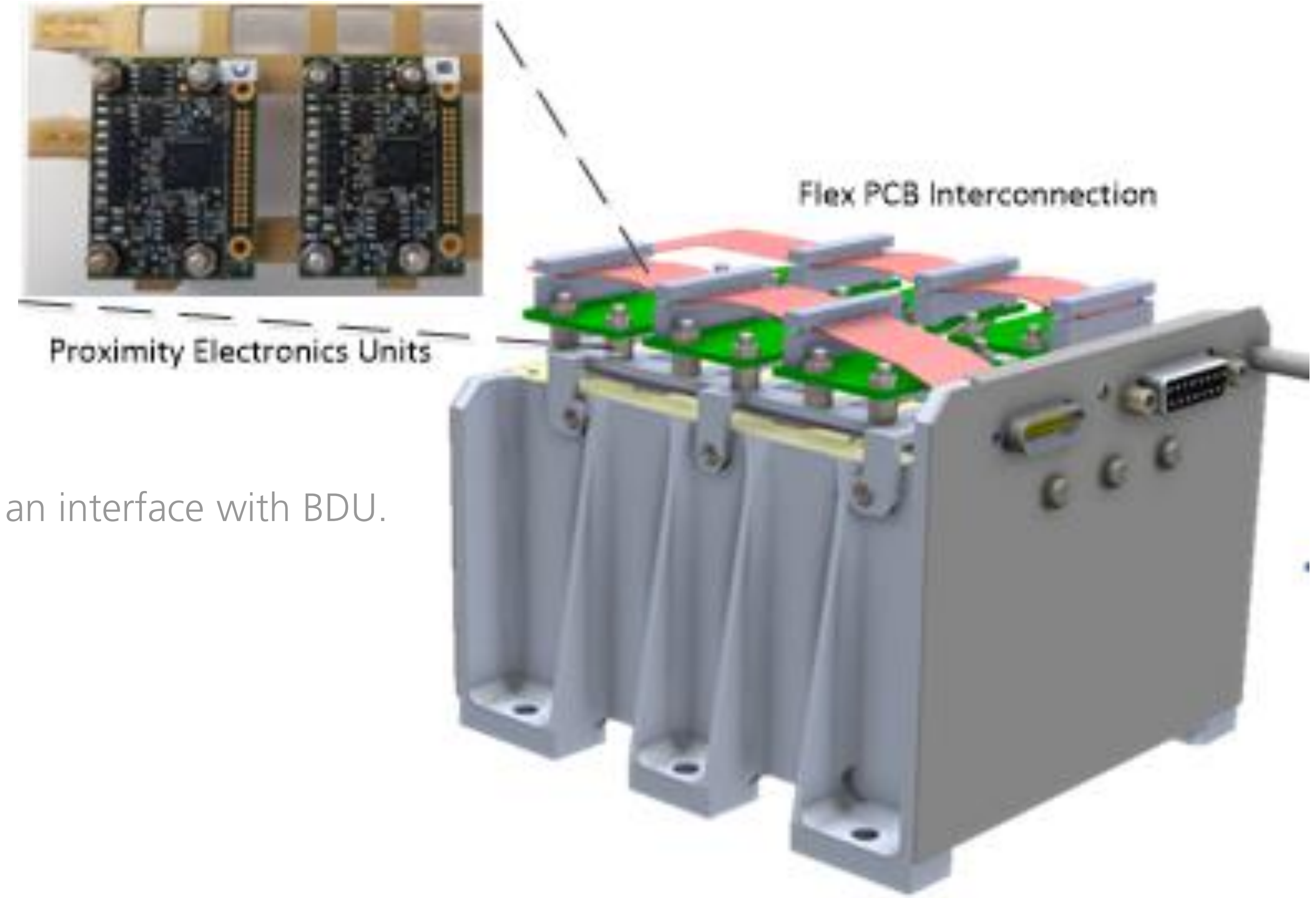
Manufacturing of PEU



Hardware for PEU:

- ➢ The electronic boards of PEU require a mounting plate for their integration with the battery:
  - ➢ The mounting plate is screwed directly to the battery enclosure
  - ➢ 6 PEU electronic boards are mounted on this plate
  - ➢ A Flex PCB is connected to and mounted on the PEU boards on the PEU connectors.

- ➢ Overall the interface of PEU is the following:
  - ➢ Mechanical interface consists of the following parameters:
    - ➢ Dimensions: (125 x 90 x 23.5) mm
    - ➢ Weight: 90 g (mechanical part)
    - ➢ 10 fixing points are available for fastening to the structure
  - ➢ Electrical interface consists of 1 connector:
    - ➢ This connector is placed on the flex PCB, which interconnects all 6 PEU boards, and is an interface with BDU.



6 Task 5

Bread Board Characterization & Test

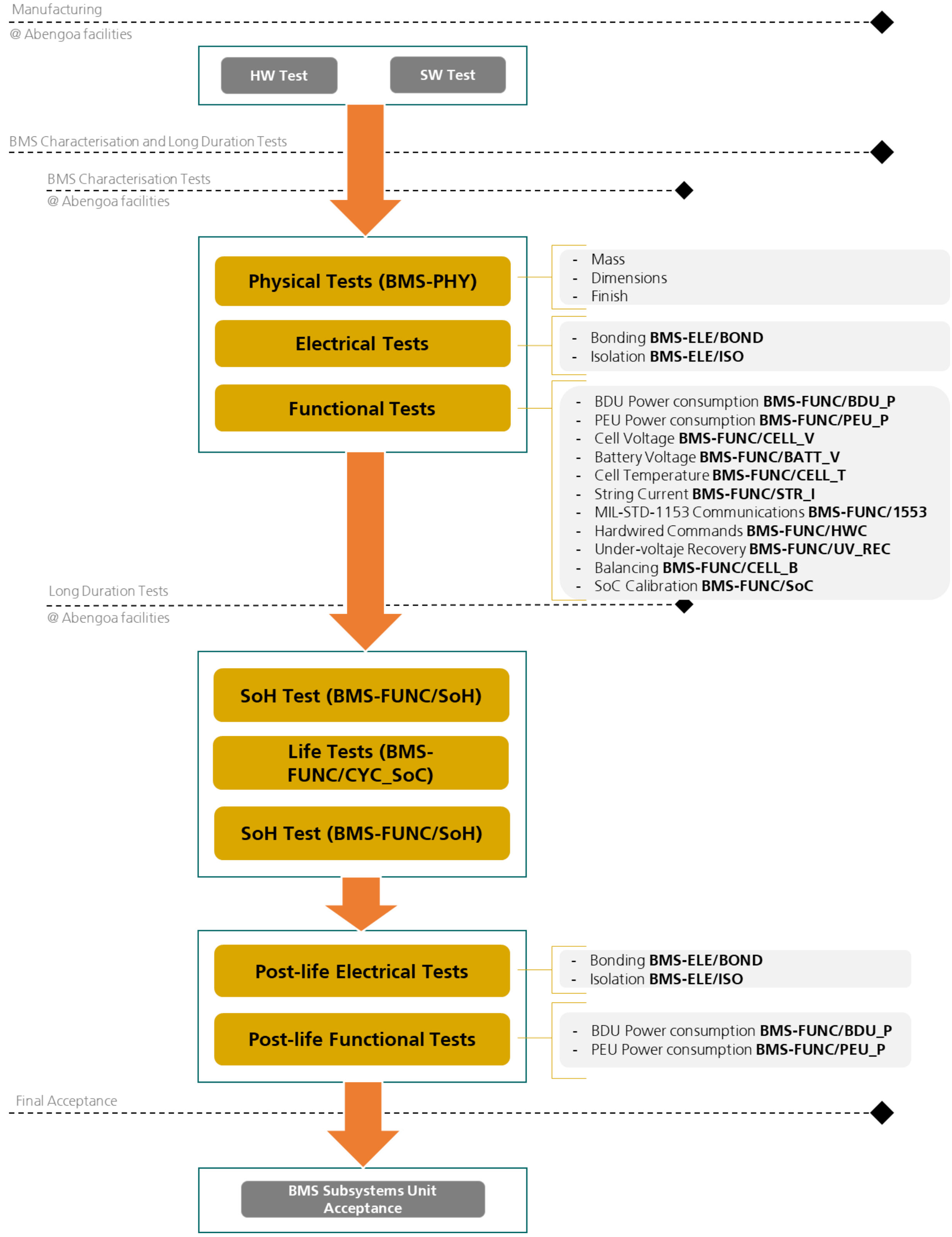
Task 5

Characterisation and Life Test Report of BMS subsystems

Test Procedures

This tests verifies the accomplishing of requirement and characterize the behavior of the system:

- ☐ HW Verification
  - ✓ Sort of test, with the aim to check manufacturing process and assure safety integration of the BMS, as PEU, connectors or unit box
- ☐ SW Verification
  - ✓ Tests performed during SW and FPGA development by means of tests cases as well as all unitary tests to check each low level function.
  - ✓ To check the correct integration between HW and SW, all SW tests are validated also at system level after the integration
- ☐ System Characterization
  - ✓ Inspection, electrical and functional tests carried out on the integrated BMS Unit with the aim to check manufacturing process and assure safety integration
- ☐ Long Duration Tests (Life Tests)
  - ✓ Validation of the functionality of the system



Manufacturing
@ Abengoa facilities

HW Test
SW Test

BMS Characterisation and Long Duration Tests

BMS Characterisation Tests
@ Abengoa facilities

Physical Tests (BMS-PHY)
- Mass
- Dimensions
- Finish

Electrical Tests
- Bonding **BMS-ELE/BOND**
- Isolation **BMS-ELE/ISO**

Functional Tests
- BDU Power consumption **BMS-FUNC/BDU_P**
- PEU Power consumption **BMS-FUNC/PEU_P**
- Cell Voltage **BMS-FUNC/CELL_V**
- Battery Voltage **BMS-FUNC/BATT_V**
- Cell Temperature **BMS-FUNC/CELL_T**
- String Current **BMS-FUNC/STR_I**
- MIL-STD-1153 Communications **BMS-FUNC/1553**
- Hardwired Commands **BMS-FUNC/HWC**
- Under-voltaje Recovery **BMS-FUNC/UV_REC**
- Balancing **BMS-FUNC/CELL_B**
- SoC Calibration **BMS-FUNC/SoC**

Long Duration Tests
@ Abengoa facilities

SoH Test (BMS-FUNC/SoH)

Life Tests (BMS-FUNC/CYC_SoC)

SoH Test (BMS-FUNC/SoH)

Post-life Electrical Tests
- Bonding **BMS-ELE/BOND**
- Isolation **BMS-ELE/ISO**

Post-life Functional Tests
- BDU Power consumption **BMS-FUNC/BDU_P**
- PEU Power consumption **BMS-FUNC/PEU_P**

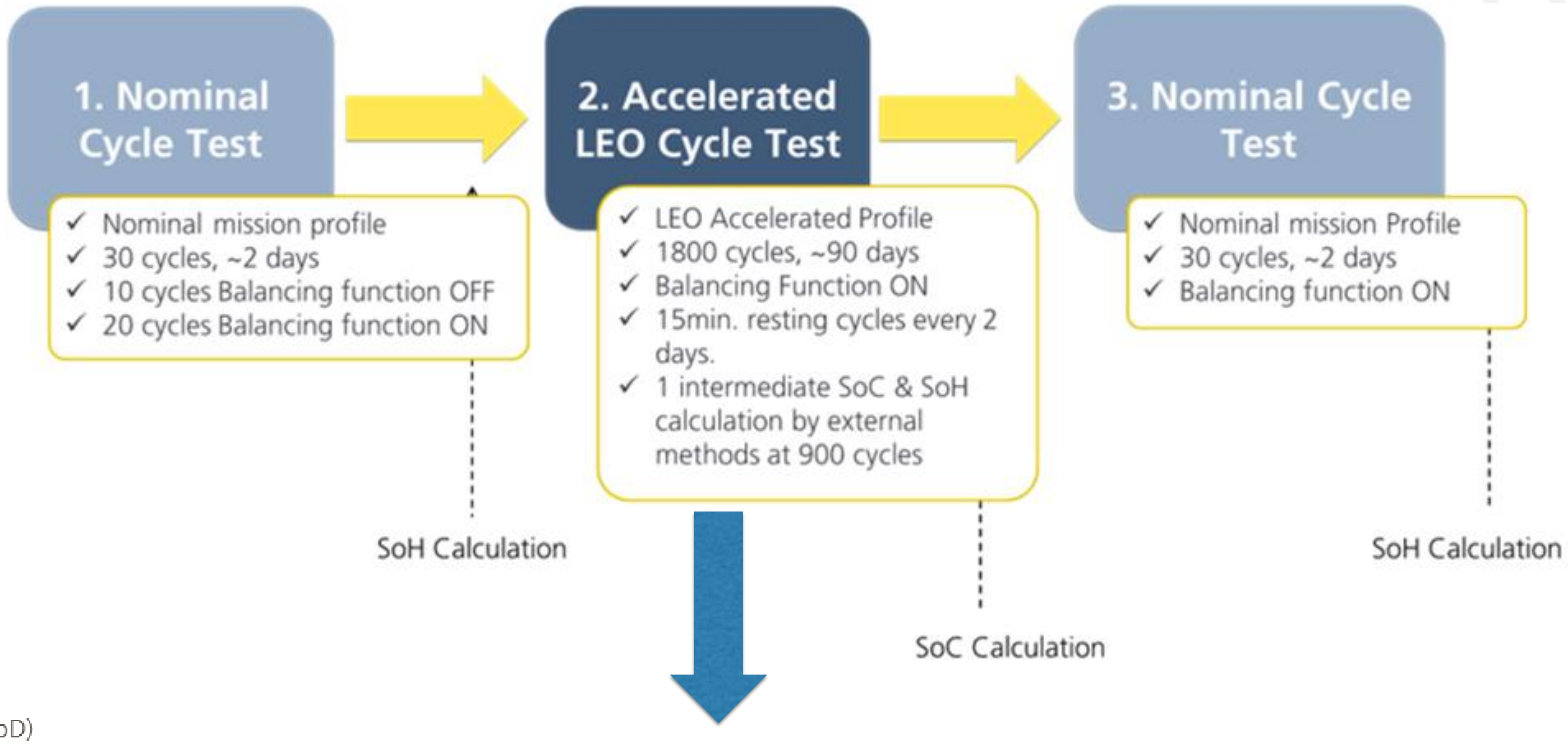
Final Acceptance

BMS Subsystems Unit Acceptance

Characterisation and Life Test Report of BMS subsystems

Life Cycles Test

- ✓ 30 nominal cycles
- ✓ 1800 accelerated LEO cycles
- ✓ 30 nominal cycles



1. Nominal Cycle Test

- ✓ Nominal mission profile
- ✓ 30 cycles, ~2 days
- ✓ 10 cycles Balancing function OFF
- ✓ 20 cycles Balancing function ON

SoH Calculation

2. Accelerated LEO Cycle Test

- ✓ LEO Accelerated Profile
- ✓ 1800 cycles, ~90 days
- ✓ Balancing Function ON
- ✓ 15min. resting cycles every 2 days.
- ✓ 1 intermediate SoC & SoH calculation by external methods at 900 cycles

SoC Calculation

3. Nominal Cycle Test

- ✓ Nominal mission Profile
- ✓ 30 cycles, ~2 days
- ✓ Balancing function ON

SoH Calculation

✓ Battery test condition: 10% DoD (considering 7.2 Ah = 100% DoD)

✓ Cycles: 30 (~2 days)

✓ Charge (CC-CV)

- Constant voltage at 32.8V and máximum current limited to 1.66 A (0.23C)
- Charge time: 69 min

✓ Discharge

- With average current discharge of 0.79 A (0.11C) and máximum current dispersion of 0.144 A (0.02C)
- Discharge time: 32.3 min

✓ Balancing functionality disabled
✓ No rest between charge and discharge steps

✓ Battery test condition: 20% DoD (considering 7.2 Ah = 100% DoD)

✓ Cycles: 1800 cycles with a total duration of~90 days

✓ Charge (CC-CV)

- Charge CC-CV, with constant voltage at 32.8V and maximum current limited to 3.6A (C/2).
- Charge time: 48 min

✓ Discharge

- Average current discharge at 3.6 (C/2). Maximum current dispersion will be 0.29A (0.04C).
- Discharge time: 24 min

✓ Balancing functionality enable
✓ 15 mins of rest every 2 days for data collect

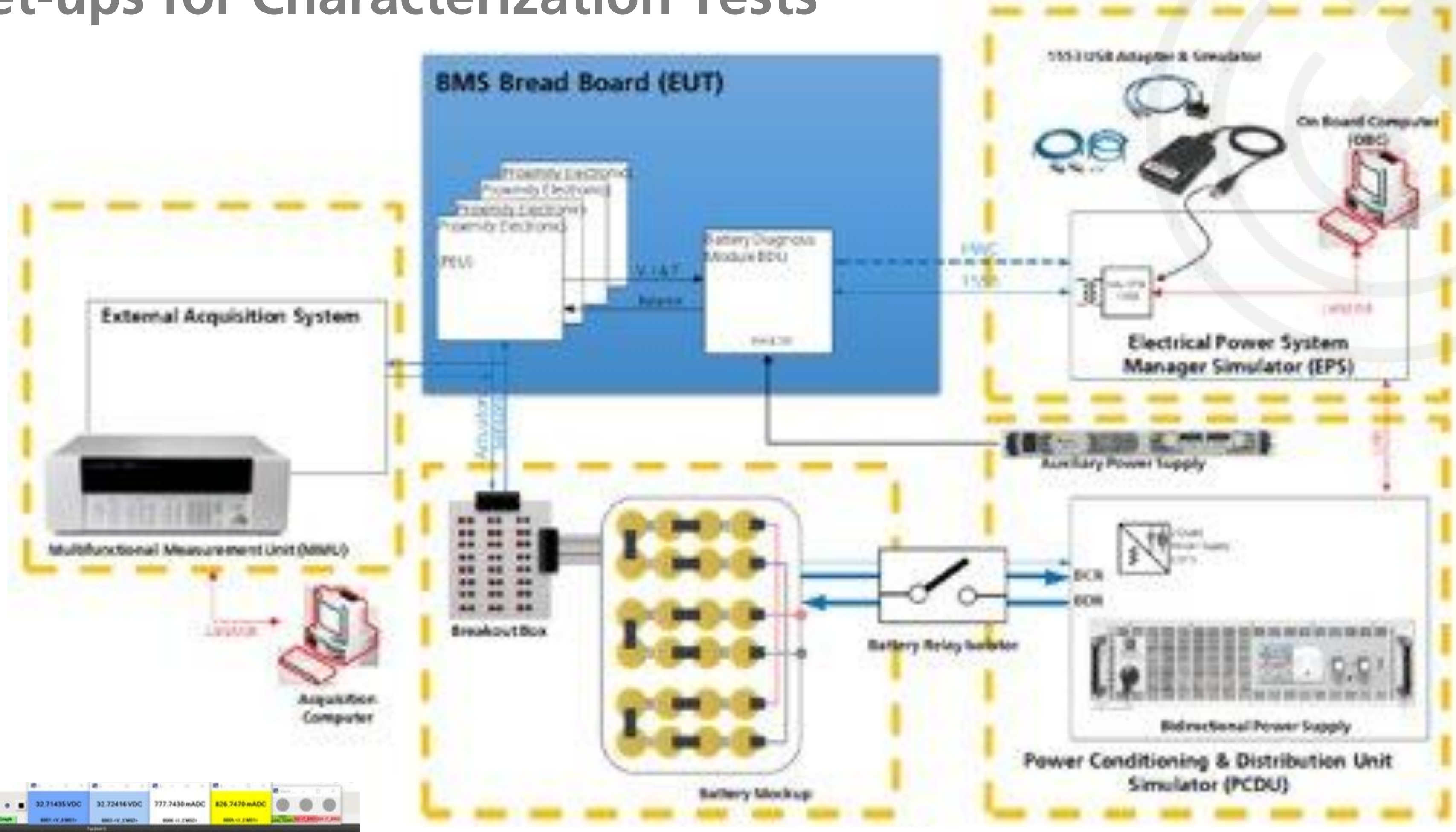
TN-05

Test Set-ups for Characterization Tests

Characterization Test Set-up

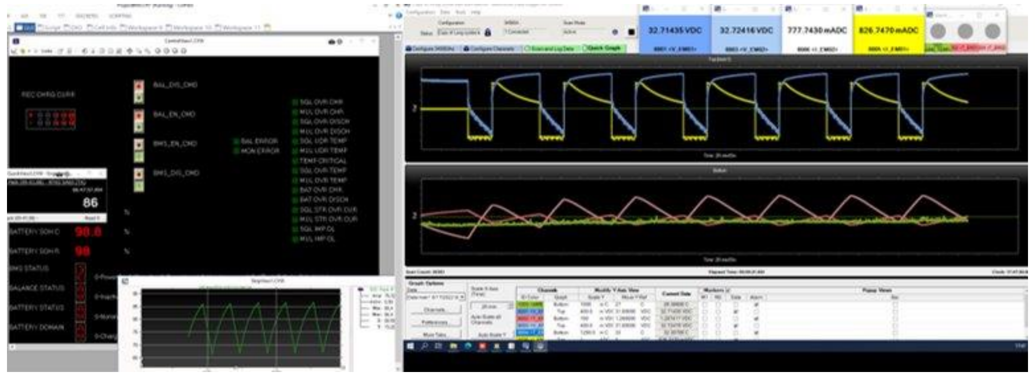
Battery Mockup substitutes the real Battery Pack for having a versatile Test Bench to:

- Replace a Cell to inject / monitory electric parameter at PEU level
- Provide Test points and Straps for Voltage & Current acquisition with dedicated instrumentation (oscilloscope, multimeters) or stimulus injection (AWG / Power Supply)
- Connection to an Automated Acquisition system to acquire full Battery parameters with a period n the order of 1 second (24V, 4I, 25 Temp)



Test setup for the following Tests

- ✓ BMS-BDU Power Consumption Test
- ✓ BMS-PEU Power Consumption Test
- ✓ BMS Cell Voltage Monitoring Test
- ✓ BMS Battery Voltage Monitoring Test
- ✓ BMS Cell Temperature Monitoring Test
- ✓ BMS Current Flow Through Battery String Monitoring Test
- ✓ BMS MIL-STD-1553B Communication Protocol Test
- ✓ BMS Hardwired Commands Test
- ✓ BMS ShutDown or Under-voltage Recovery Test
- ✓ BMS Cell Balancing Functional Test



Task 5

Test Set-ups Long Life Tests

Functional & Life Tests Set-up

- ❑ Test Setup Equipment
  - ➢ PDCU Simulators, 2 units
    - One for Downscaled BB Battery with BMS (EM01)
    - One for Reference Battery (EM02)
  - ➢ Auxiliary Power supply for feeding BMS
  - ➢ OBC Sim (1553 & HWC simulator)
  - ➢ Interconnection Jigs
  - ➢ 2 Battery Packs
    - One for Downscaled BB Battery with BMS (EM01)
    - One acting as Reference Battery (EM02)

Test setup for the following Tests:

Functional Tests
BMS SoC Calibration Test
Long Duration Tests
BMS Charge/Discharge Cycles & SoC Estimation Performance Test
BMS SoH Estimation Performance Test

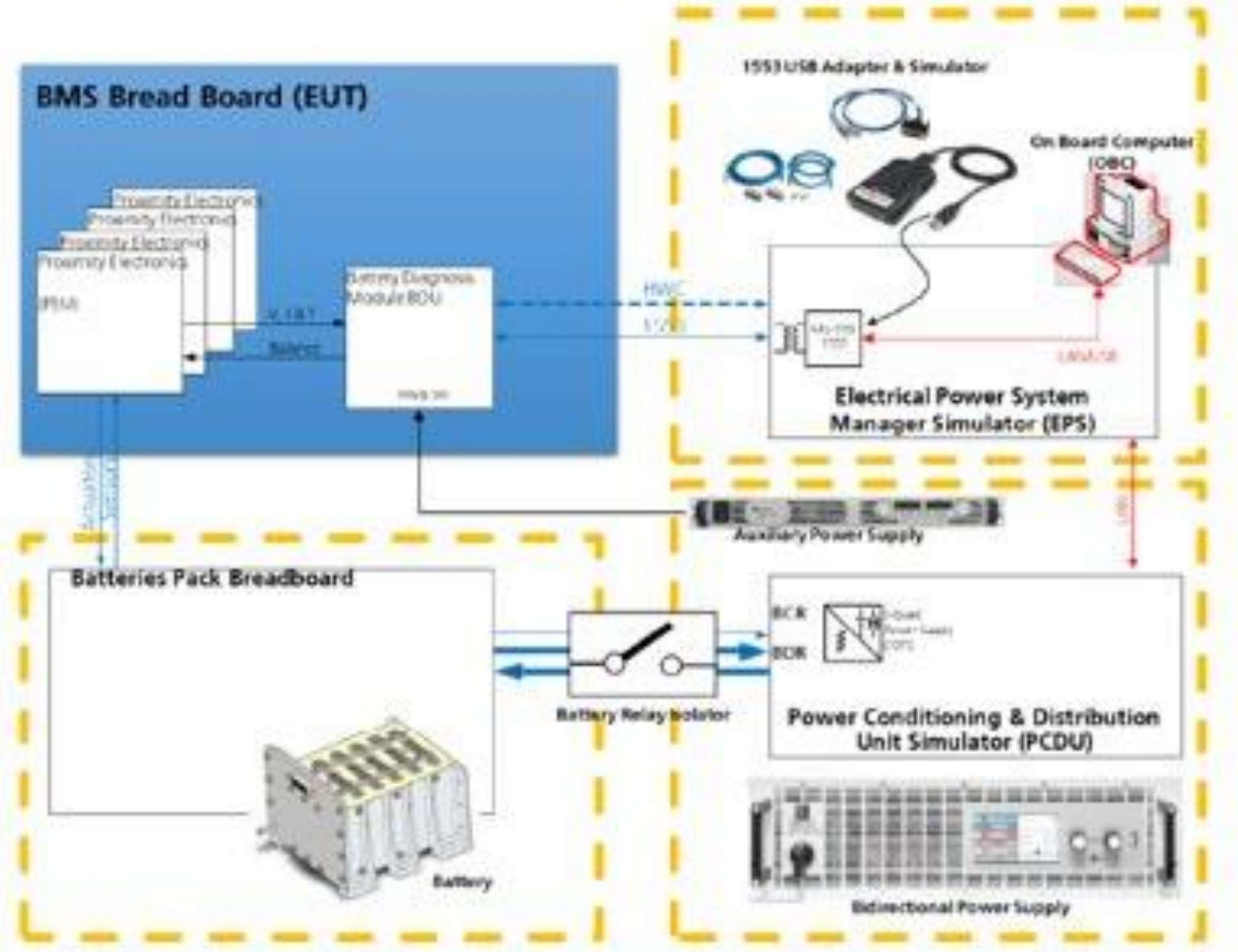


Figure 3 Test Setup for Long Duration Tests (Section 1: Battery & BMS)

Autonomous Battery Test Setup

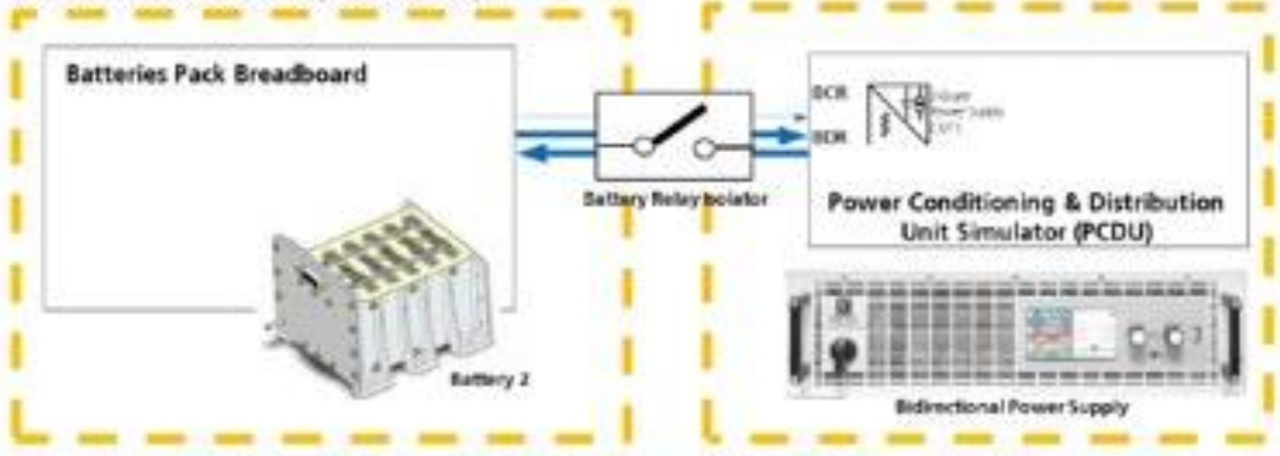
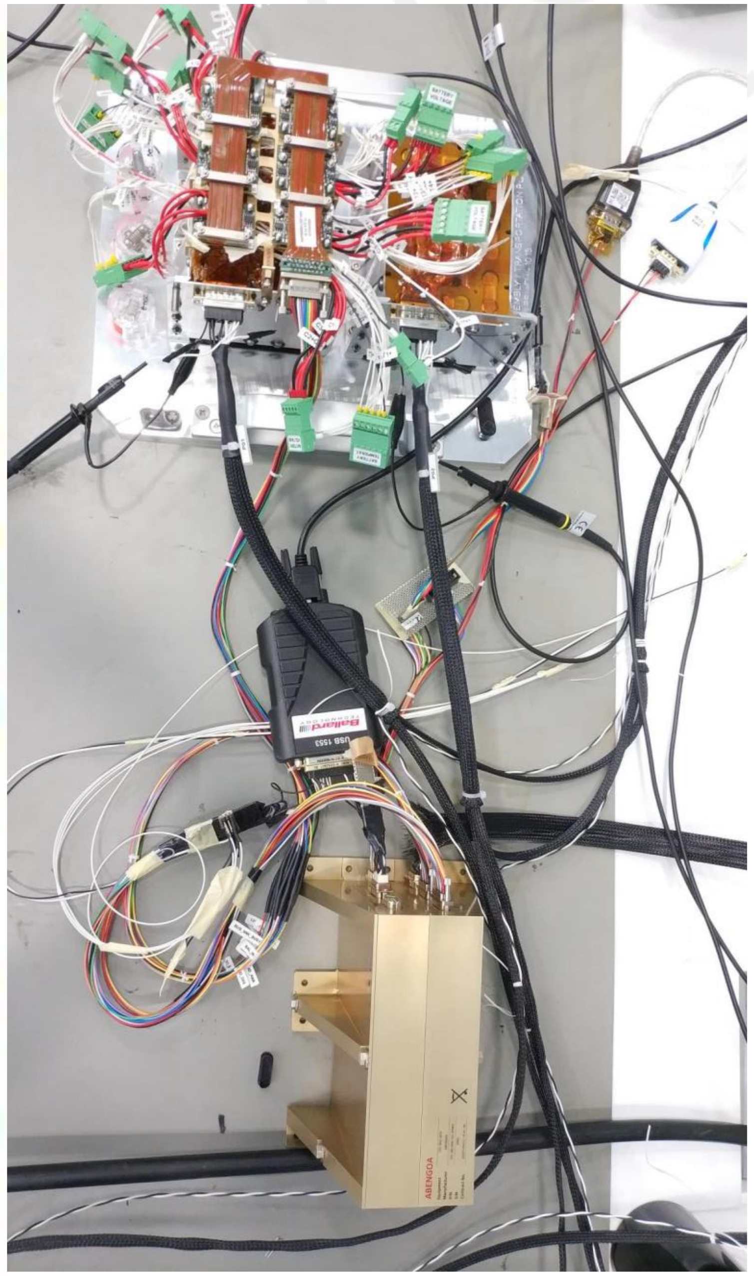


Figure 4 Test Setup for Long Duration Tests (Section 2: Autonomous Battery)

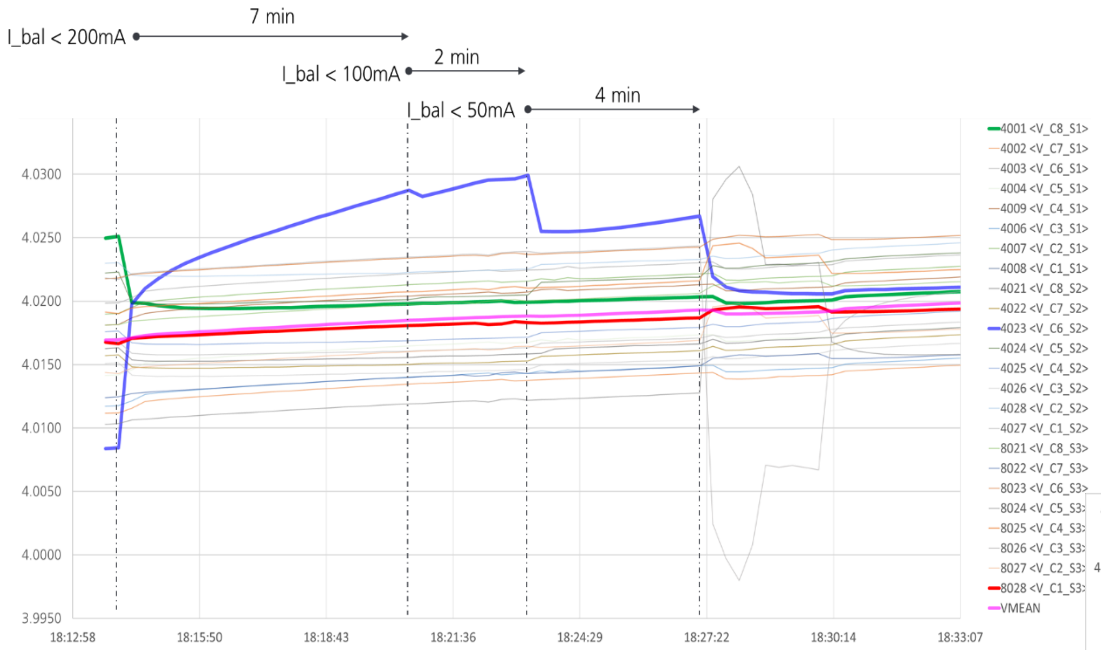


Task 5

Characterization Tests

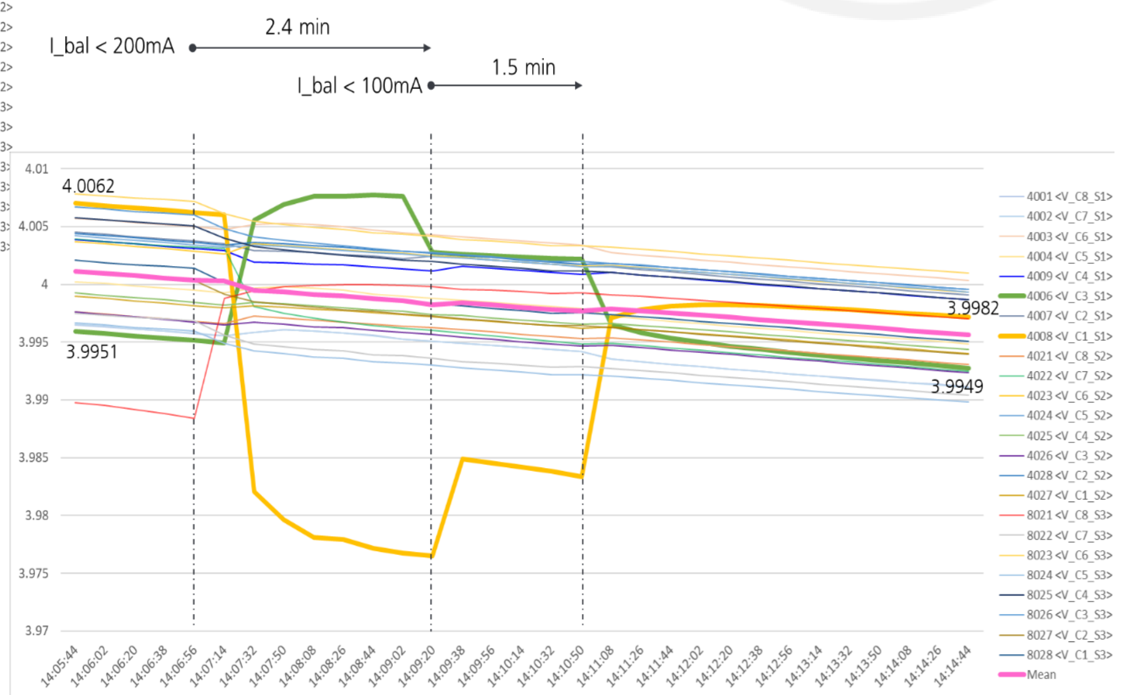
Balancing process

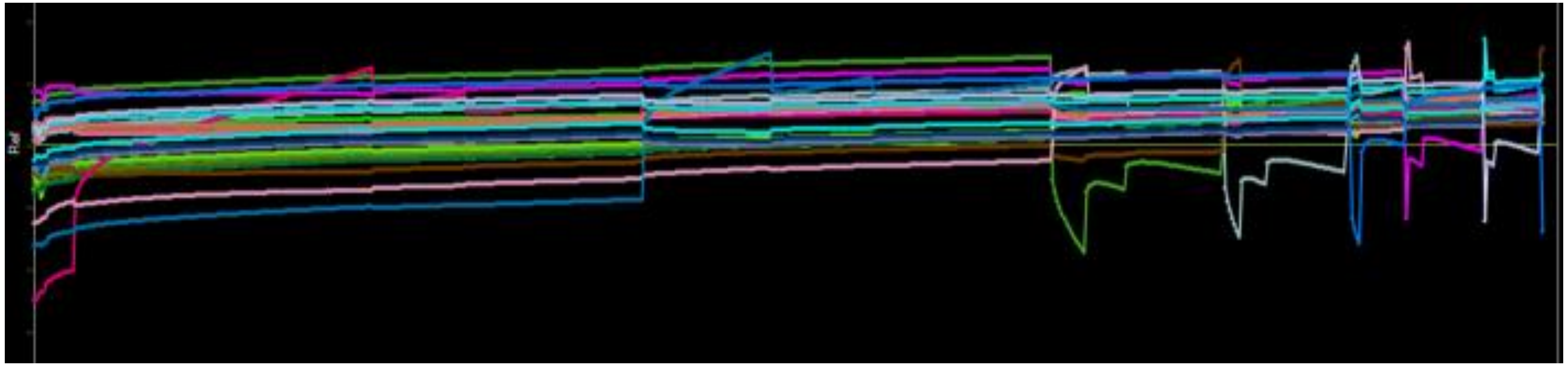
- ☐ During functional test, the performance of the balancing process was tested
  - Pack-to- Cell
  - Cell-to-Cell
- ☐ The system also was tested with high imbalanced cells to verify the functionality and the final status of the cells after balancing process



Pack-to-Cell

Cell-to-Cell

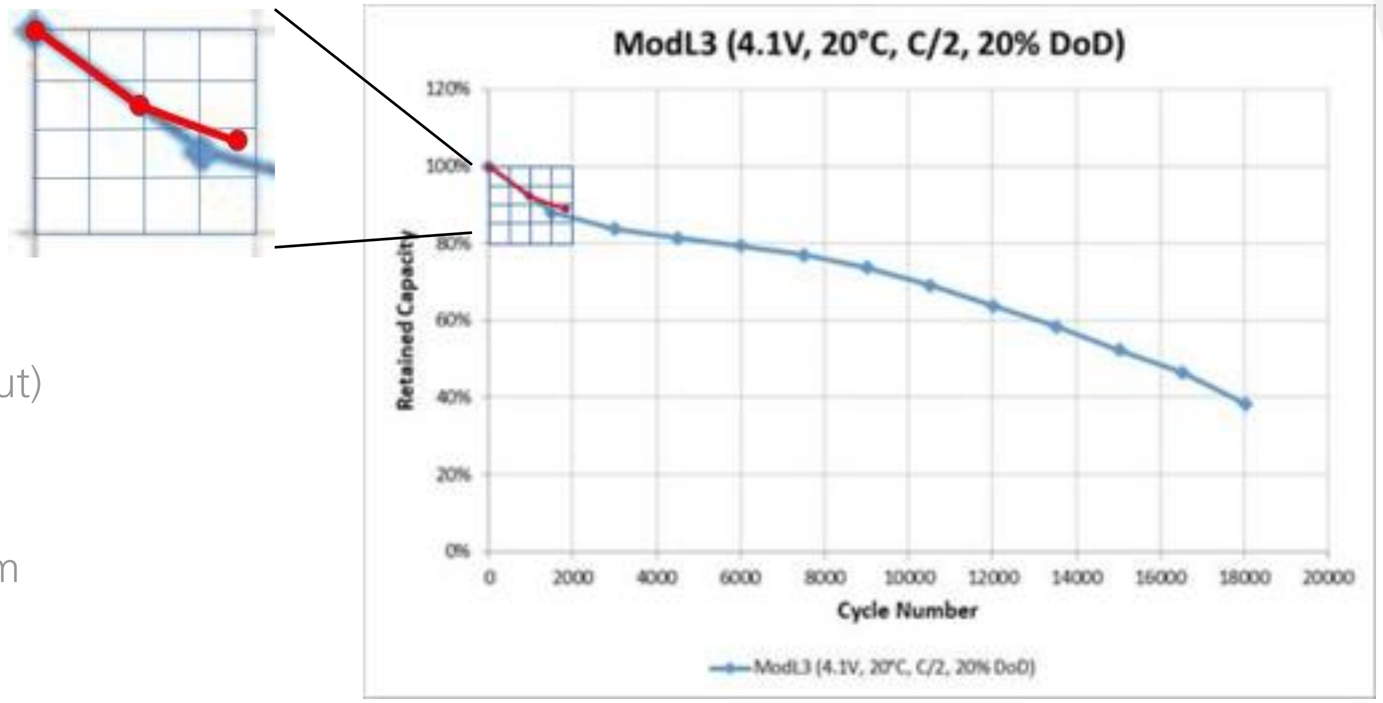


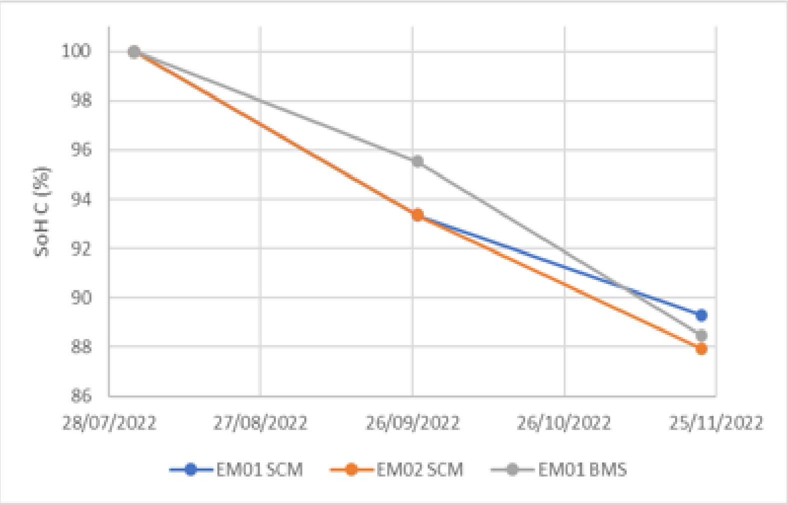


Long Duration Test Results

SoH C

- ❑ The battery is losing capacity over the cycles
  - ➢ The retained capacity obtained by SCM method show a higher degradation in the SoHC values of the Battery without BMS with respect to the Battery with BMS (89.3% With BMS; 87,9% Without)
  - ➢ The calculated SOH by BMS have an error during long live cycles because the lack of low current periods, as explained in previous meetings. But during SCM test, the current is C/10 and the Q seem to be well calculated, during the last SCM test the calculation was 88,5%, that is very close to SCM results.
  - ➢ Comparing the results with similar cycle characteristics of a battery from same manufacturer also shows the differences in degradation.





SOH C BMS calculated

Cycles	SOH C (%)
	EM01
0	100
900	95.53
1800	88.48

SOH C from external method

Cycles	Capacity (Ah)		SOH C (%)	
	EM01	EM02	EM01	EM02
0	6.219	6.243	100	100
900	5.806	5.828	93.36	93.35
1800	5.553	5.491	89.29	87.95

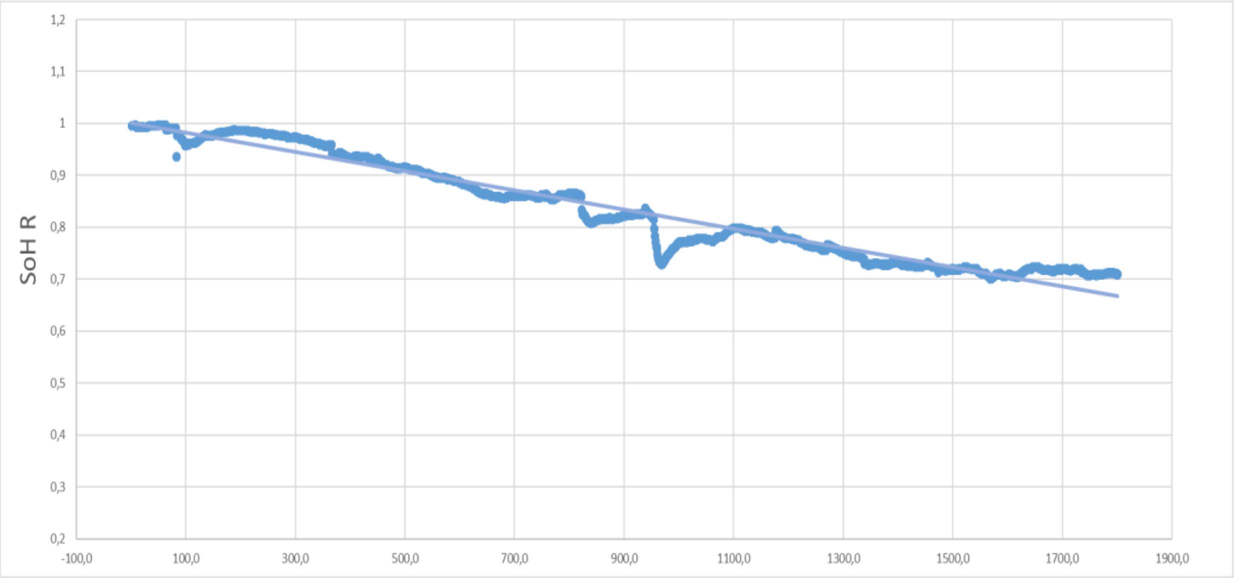
Task 5

Long Duration Test Results

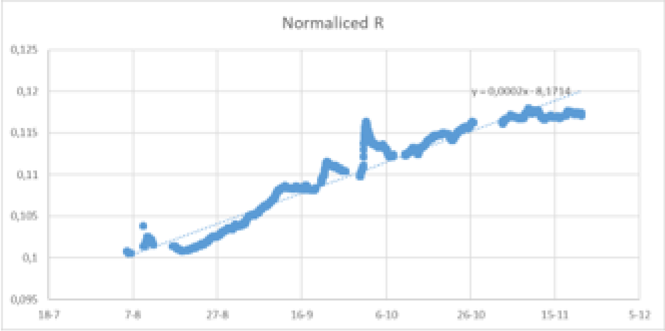
SoH R

- ☐ The internal resistance of the battery is increasing over the cycles
  - ➢ Comparing the results with similar cycle characteristics of a battery from same manufacturer also shows the differences in degradation

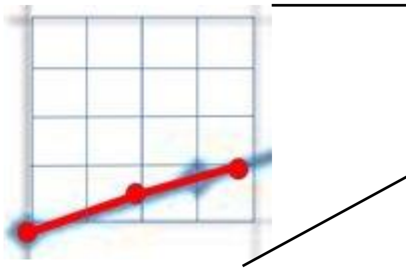
SOH R BMS calculated

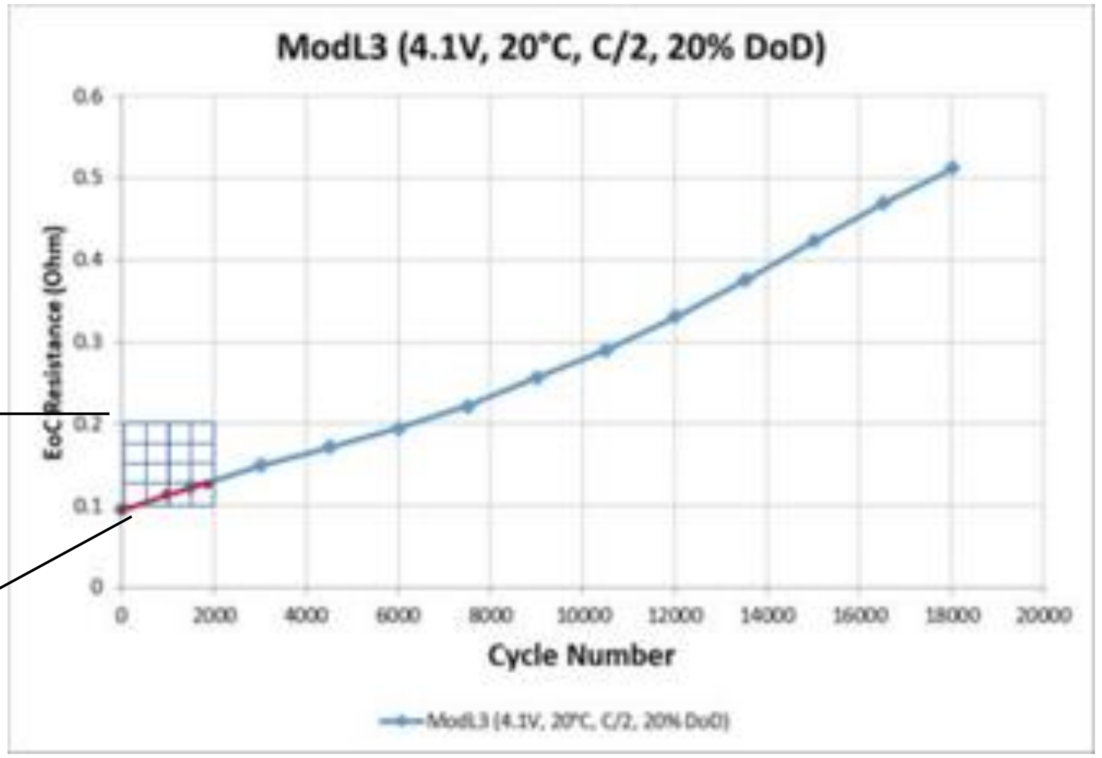


SOH R Normaliced



Cycles	R Normaliced
0	1
900	0,111
1800	0,118



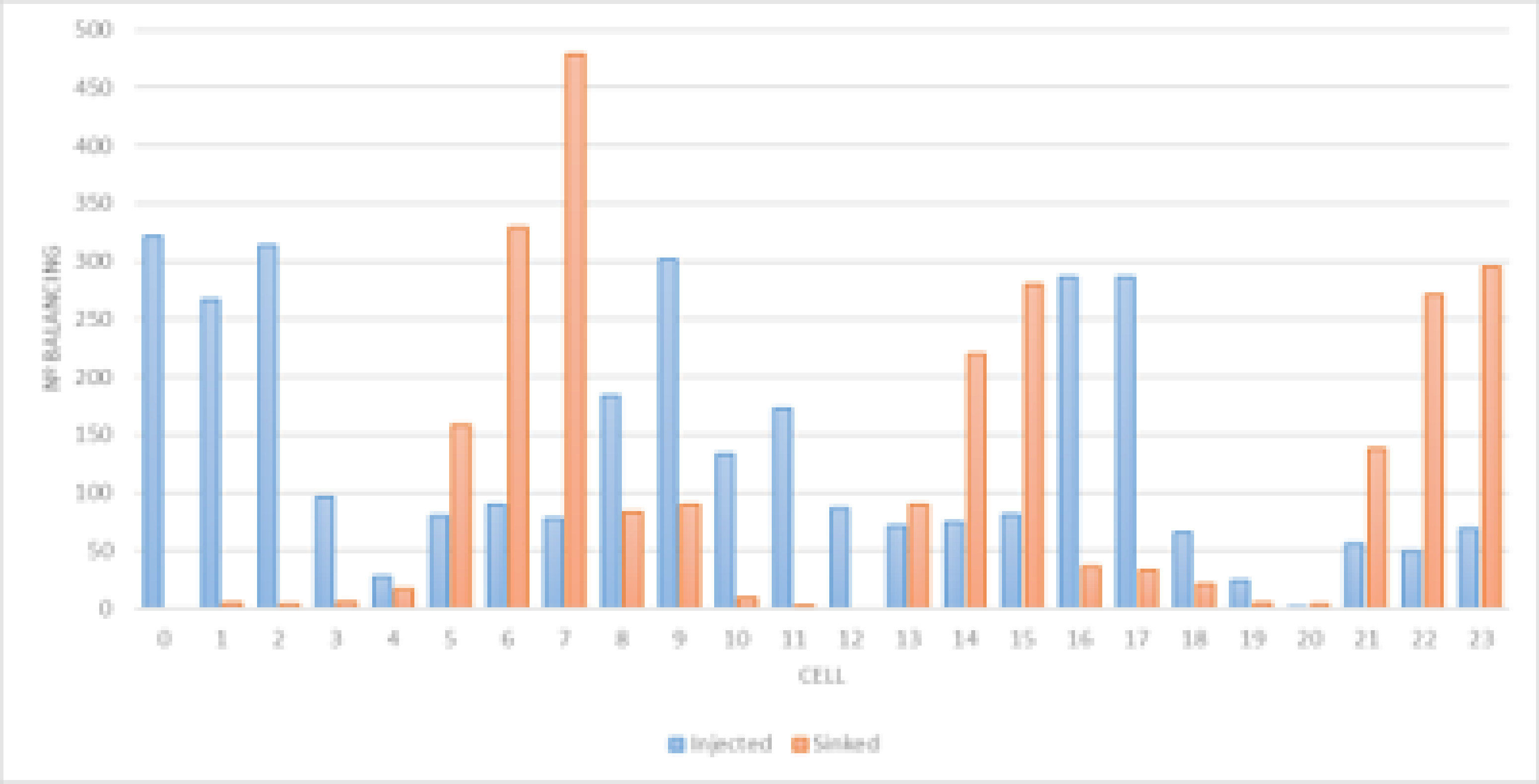


Task 5

Long Duration Test Results

Balancing statistics

- ☐ Along the long duration tests, more than 3216 balancing process has been executed.
- ☐ C2C have been performed 80% of the times



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7 Task 6

System Study, further development needs and trade-off

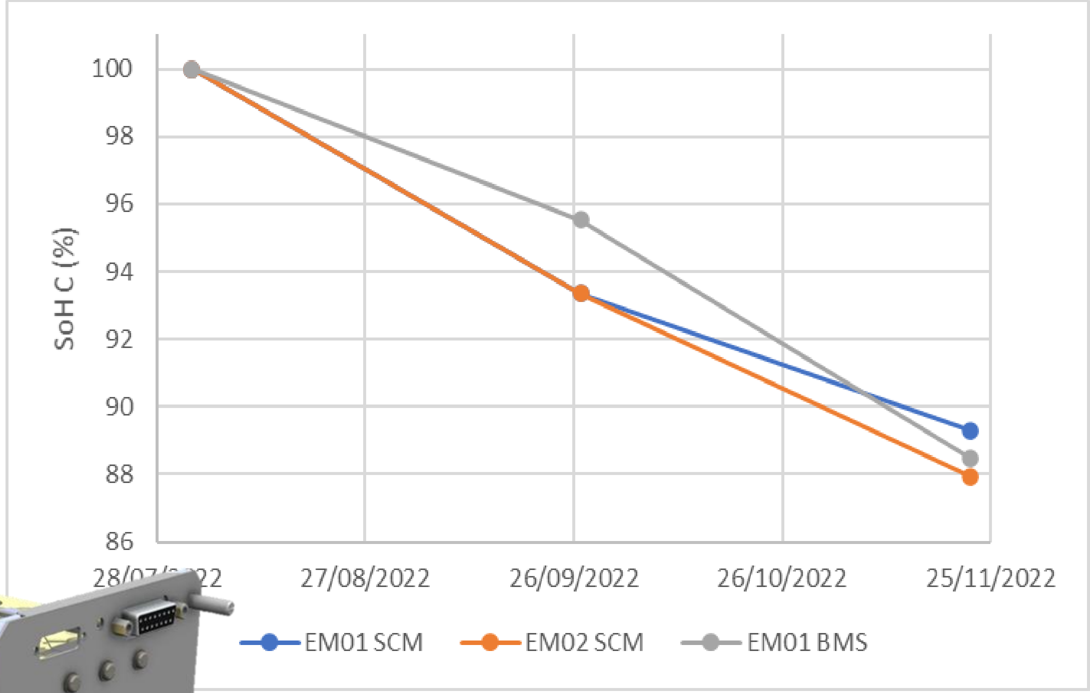
Task 6

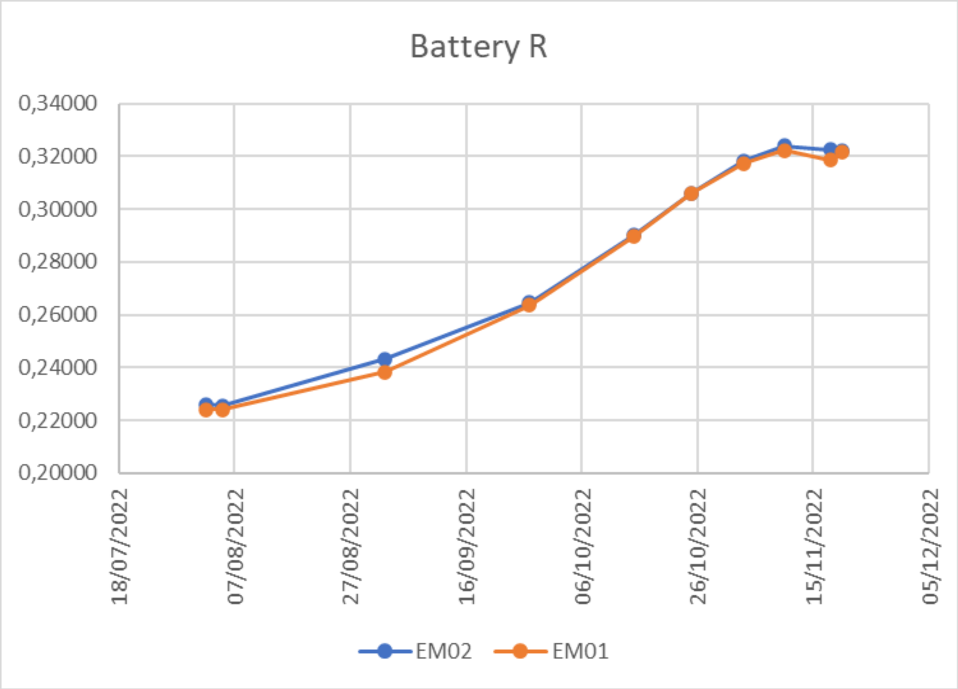
Comparison of the performance to the system without BMS

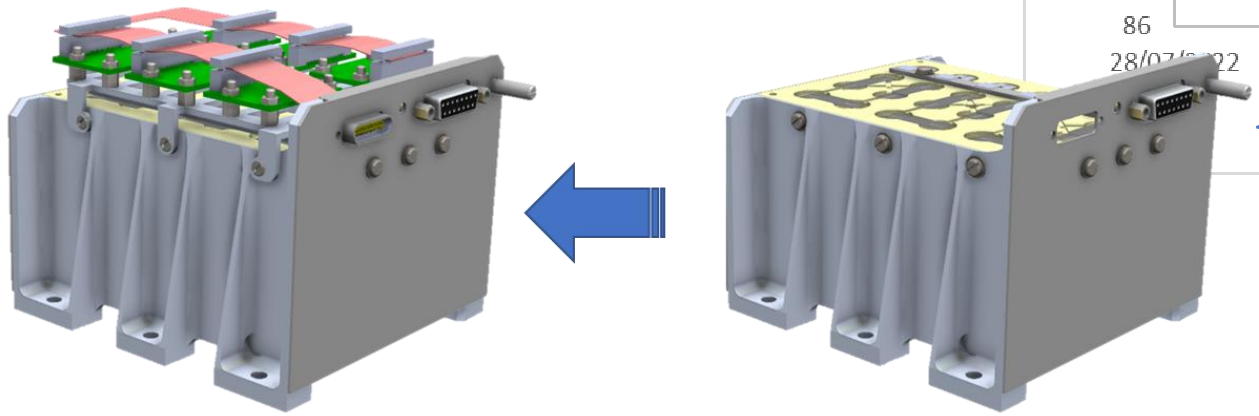
Parameter	EM01 (with BMS)	EM02
Initial Capacity Fade (Ah)	6.219	6.243
Final Capacity Fade (Ah)	5.553	5.491
Initial Capacity Fade (SoH C%)	100	100
Final Capacity Fade (SoH C%)	89.29	87.95
Initial Resistance (Ω)	0.2241	0.2260
Final Resistance (Ω)	0.3216	0.3220
Initial Resistance (SoH R%)	100	100
Final Resistance (SoH R%)	89.12	89.39

Performances of the BMS

- ➢ EM01 (with BMS) vs EM02 results
  - ✓ Slightly Better response of EM01 (with BMS) with lower Capacity Fade after 1800 accelerated cyles
  - ☐ Similar Resistance increment after 1800 accelerated cycles in EM01 and EM02
- ➢ Test Coverage:
  - ➢ 1800 accelerated cycles show a trend in retained capacity that anticipate the benefits of the BMS but it would be necessary to extend the cycles to rate better the positive impact of the BMS at end of life of the Battery







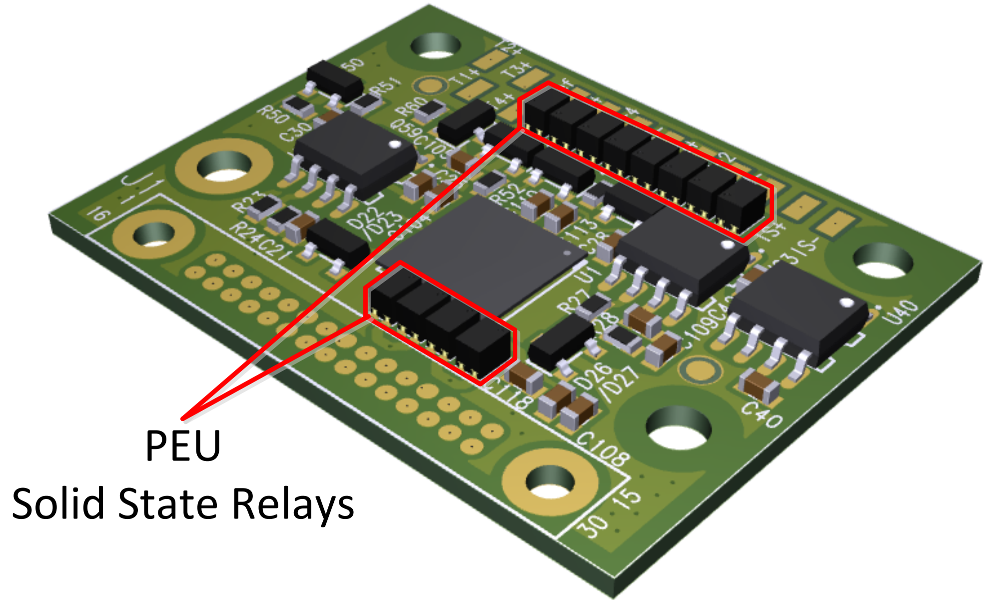
EM01 EM02

Task 6

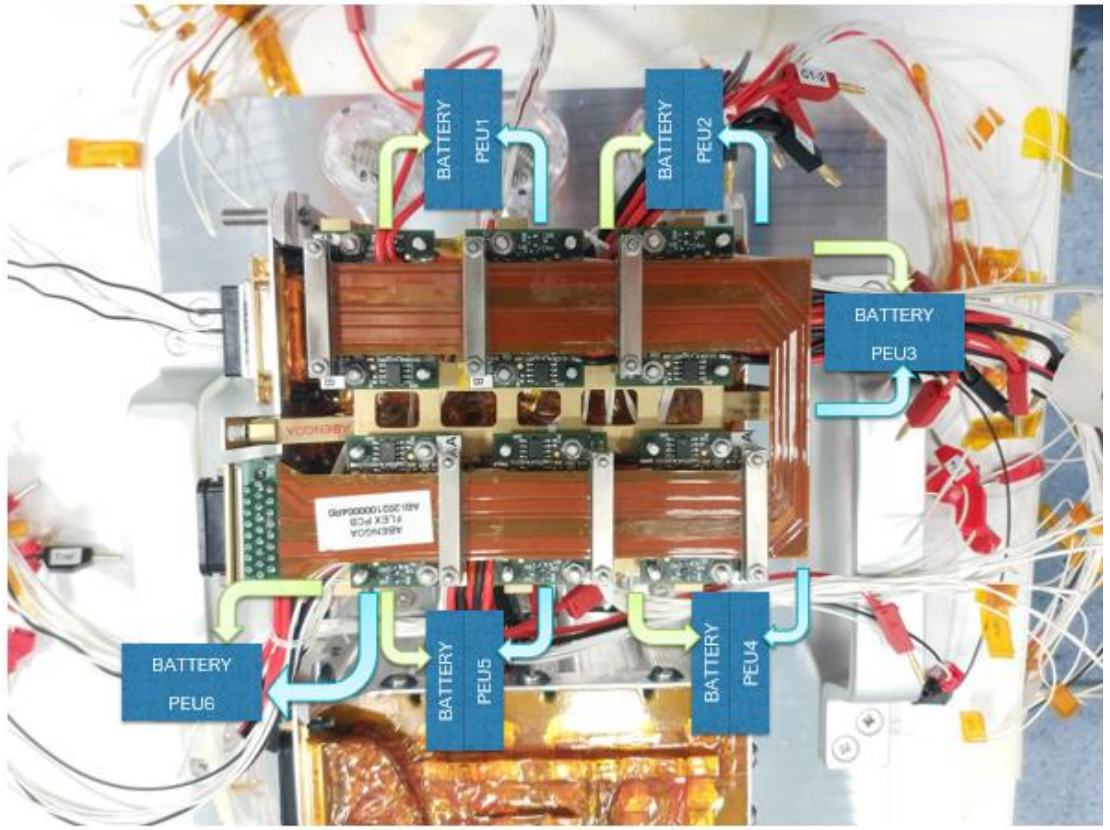
Necessary Improvements

Following Necessary Improvements has been identified

- DC-DC Converter efficiency improvement
- SSRs improvement for better reliability and Space Grade availability
- Proximity Electronics Interface with Battery



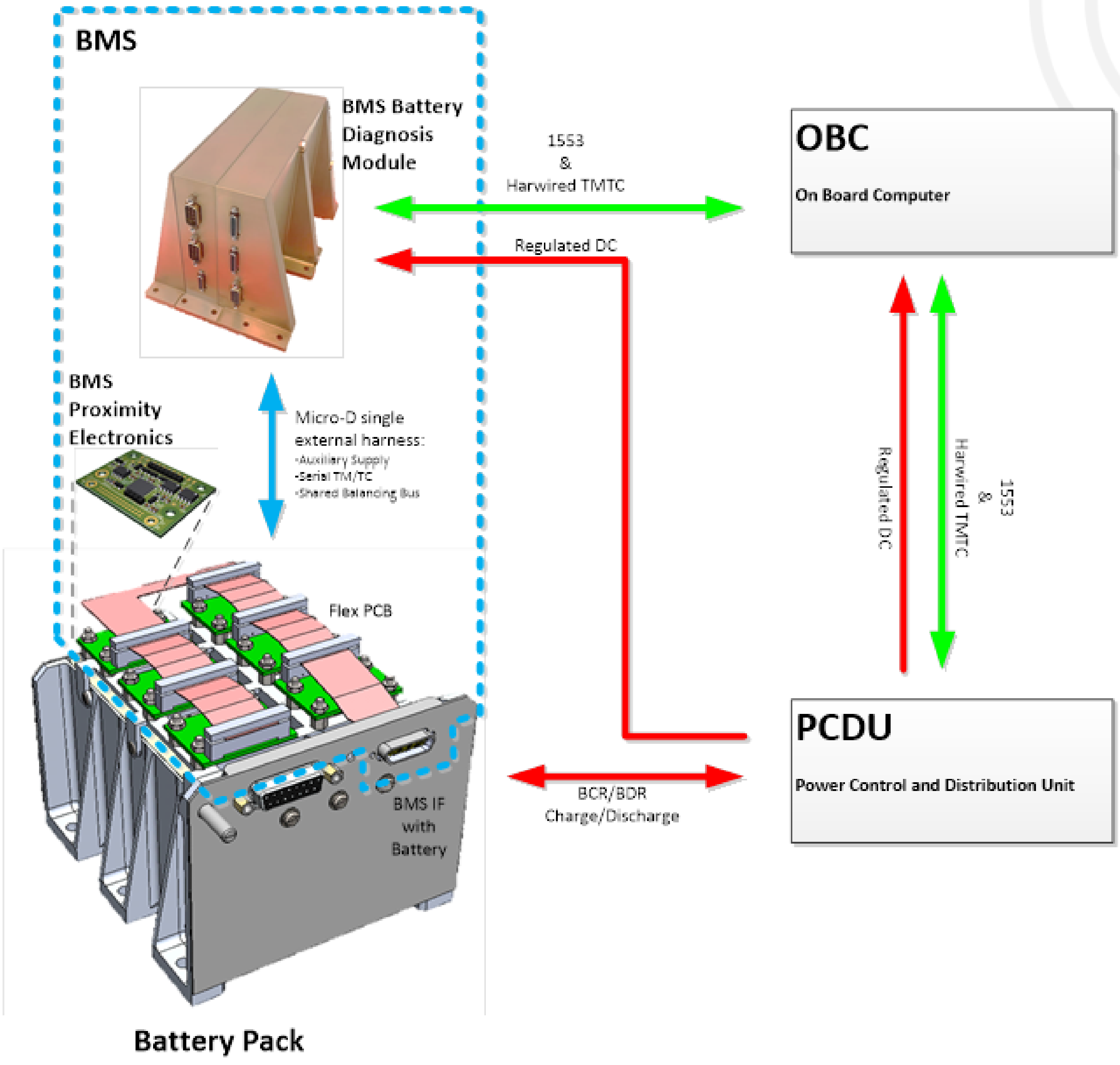
PEU
Solid State Relays



Trade-off with BMS architectures assessed in Task 2

The advantages of the selected architecture anticipated during Task 2 have been confirmed with some remarks during the activity

- ✓ Medium Impact on the Battery
  - ☐ Remark: Interface PEU – Battery shall be improved to mitigate potential risks during AIV phases
- ✓ Very Low Impact on the PCDU
  - ☐ Remark: If mission current steps does not meet with levels required for the proper performance of the Algorithms, the PCDU could have to implement "dummy" current steps to stimulate parameter estimation algorithms
- ✓ Low impact on the EPS
  - ☐ Remark: Depending on the Chemistry of the Cell and the mission orbit profile, it could be necessary to schedule some "maintenance" period (7 min) for resting the battery and allow SoC algorithm recalibration.

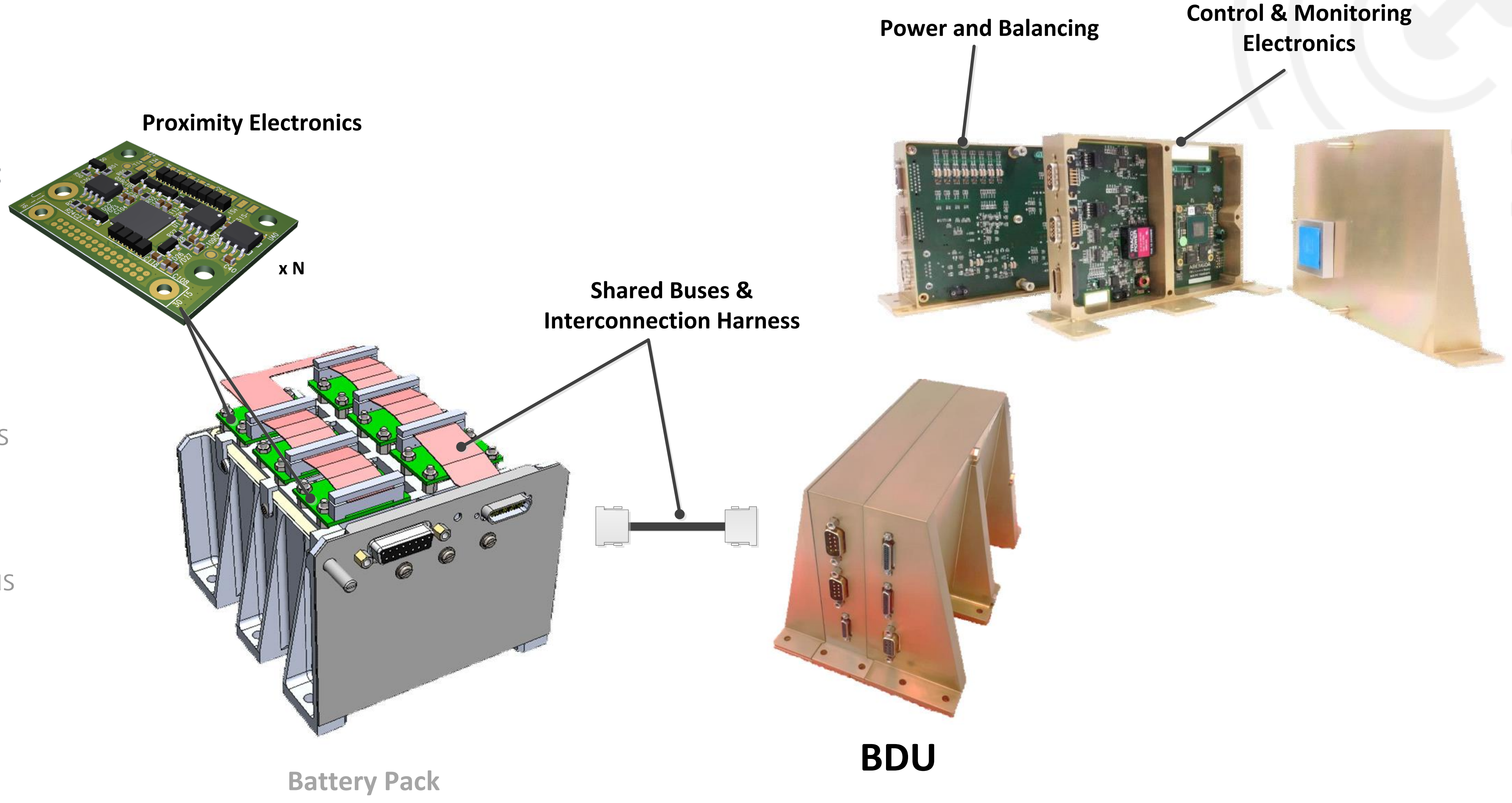


Task 6

Assessment of the system reliability and possible approaches to increase it

Downscaled BB design anticipate potential improvements to increase the reliability of the system:

- Fail Safe PEU Design
  - Hard mass and size requirements
  - Directly connected to Cells
- Shared Bus Redundancy
  - Advantages if hot redundancy is selected in terms of parallel balancing process now available
- BDU electronics redundancy
  - Power and Balancing board to support shared bus redundancy
  - Control and Monitoring board to cover more tradicional functions. Primary and Sencondary supplies, Processors
- Inclusion of cell safety devices will increase the reliability of the EPS
  - SSR to Bypass cells
  - Relays to Isolate Strings

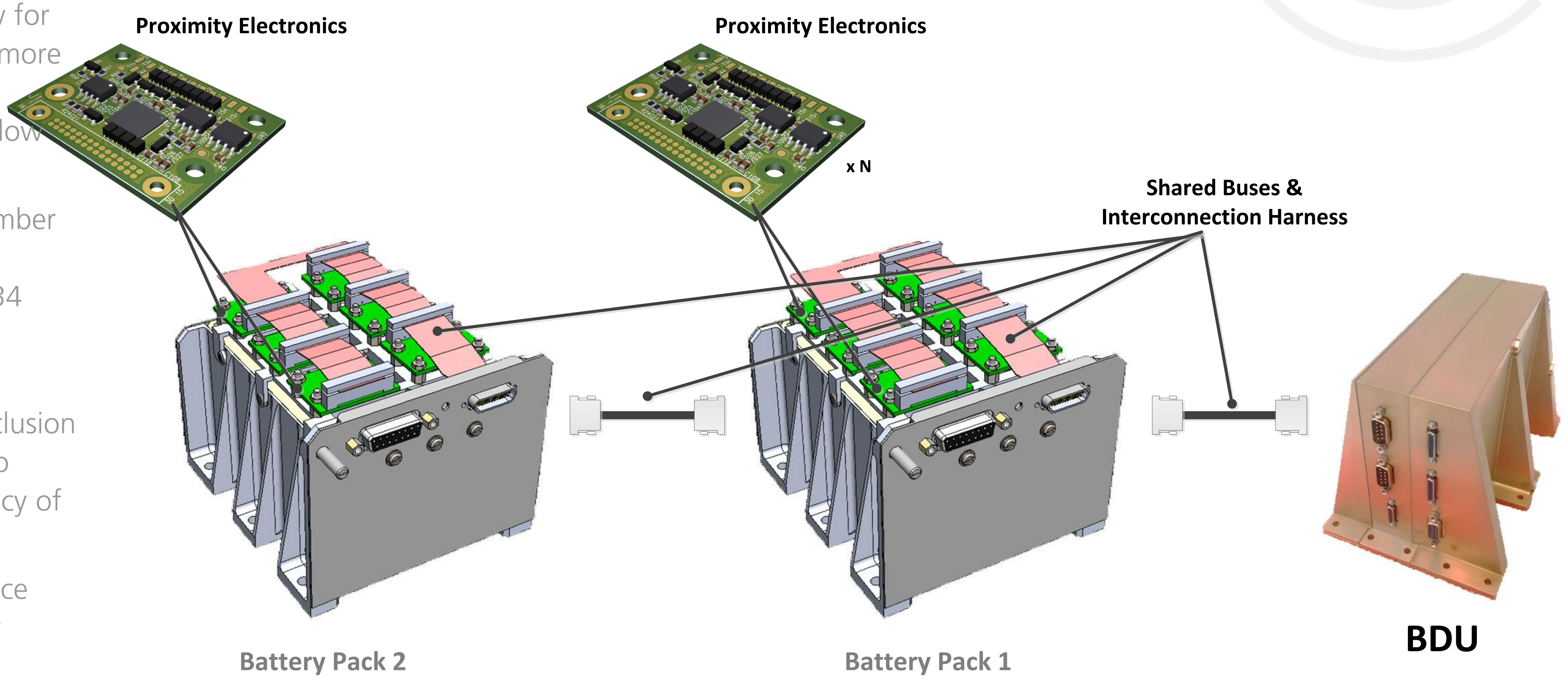


Task 6

Possibility to scale up the system to the needed number of cells for a full-size power system

BMS Growth capacity limitations

- Orbit definition in terms of available time window for Balancing processes. Faster windows will require more iterations of shared balancing buses to parallelize balancing process. Current LEO orbit definition allow up to 40 cells per bus
- BDU-PEU communications baud rate limit the number of cells that can be managed by a single communication bus. Current design allow up to 34 cells per bus
- Processor Use. With current design 24 cells are managed by an FPGA at 42% occupancy. The inclusion of other 24 cells will increase the occupancy up to 57%. Further increment will decrease the efficiency of the Processor.
- Battery Voltage affect to accuracy of the PEUs since CMRR Amplifiers works good up to 100V. Higher voltages will reduce the accuracy that can be compensated by medium-complexity calibration process (or auto-zero technics during the measurement)



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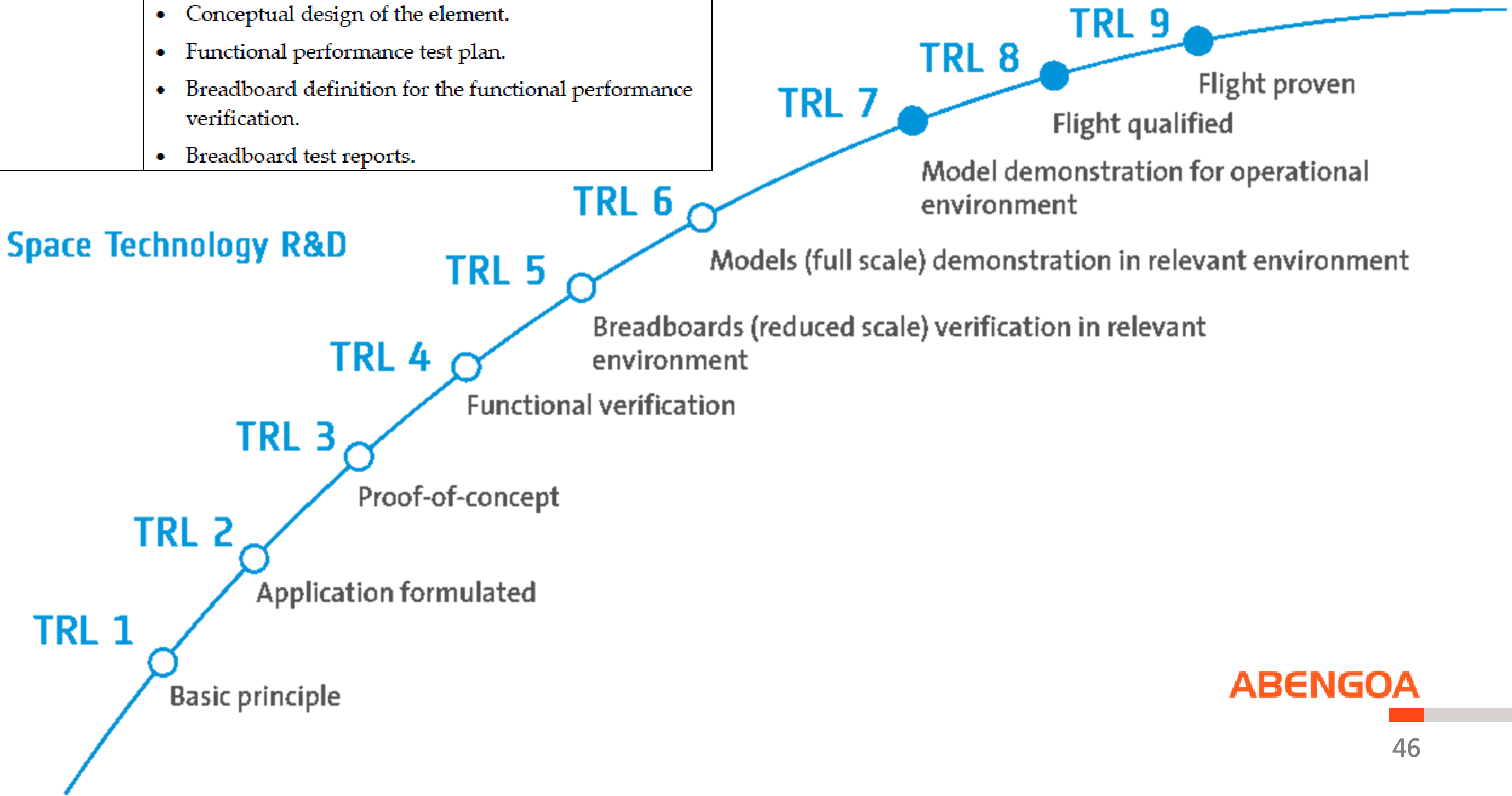
Task 6

End of TRL Assessment

Initial TRL	Planned TRL as activity outcome	Actual TRL at end of activity
2	3	4

TRL 4: Component and/or breadboard functional verification in laboratory environment	Element functional performance is demonstrated by breadboard testing in laboratory environment.	• Preliminary performance requirements (can target several missions) with definition of functional performance requirements. • Conceptual design of the element. • Functional performance test plan. • Breadboard definition for the functional performance verification. • Breadboard test reports.

- ✓ At the end of Task 5, the downscaled BB of the BMS has demonstrated its functionality based on the test results obtained in the laboratory test campaign.
- ✓ Also, Long life accelerated tests has set downscaled BB of the BMS in a relevant environment connected to a representative EM of a space battery and to a PCDU simulator.
- ✓ At the end of Long Life test, promising trend in the retained capacity of the EM equipped with BMS has been observed, anticipating the benefits of a Active BMS for Space applications.


Space Technology R&D

TRL 1
Basic principle

TRL 2
Application formulated

TRL 3
Proof-of-concept

TRL 4
Functional verification

TRL 5
Breadboards (reduced scale) verification in relevant environment

TRL 6
Models (full scale) demonstration in relevant environment

TRL 7
Model demonstration for operational environment

TRL 8
Flight qualified

TRL 9
Flight proven

8 Questions?

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Innovative Solutions
for a **sustainable development**

Thank you

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