http://www.cubesatkit.com/

CubeSat Kit™ Battery Module 2 (BM 2)

Hardware Revision: F3

Intelligent Protected Lithium Battery Module with SoC Reporting

Applications

- CubeSats, nanosatellites & small satellites
- Pumpkin MISC™ 3 3U CubeSats
- Pumpkin SUPERNOVA™ 6U/12U NanoSats

Features

- Topology:
  - 2S4P, 3S2P or 4S2P configurations using multiple 18650 Li-Ion cells
  - 8.4V, 12.6V or 16.8V battery busses
- Electrical:
  - > 10A output current
  - 84-168W peak power
  - 72-100Wh energy storage
- SWaP:
  - < 0.5U, < 700g, << 1W
- Environment:
  - Tested to NASA GEVS (14grms) levels
  - Satisfies JSC EP-WI-032 for use on ISS
  - Satisfies NASA flight safety program for use on ISS
- Features:
  - OC, OV, UV & OT 1st-level battery protection
  - 2nd-level battery protection via disconnect
  - Active cell balancing
  - Intelligent gas gauge to monitor and predict battery status, health/aging and capacity
  - Intelligent Charge Override (ICO™) to permit battery charging with active separation inhibit
  - SupMCU over I2C for commands & fully formatted telemetry
  - Status LED, debug terminal and versatile SYNC input/output
  - Dual, high-current interface connectors
  - Zero-current RBF & separation inhibits
  - 5-segment LED battery SoC and fault indicators
  - Integrated temperature sensors
  - Integrated battery heaters and heatsinks
  - Very low self-discharge rates
  - Trickle (0V) charging mode
  - Minimal self-discharge rate
  - Stackable & chainable

ORDERING INFORMATION

Pumpkin P/N 710-01640

Option Code	Configuration
/B00 (standard)	2S4P battery configuration
/B01	3S2P battery configuration
/B10	4S2P battery configuration

CAUTION

Electrostatic Sensitive Devices

Handle with Care

- CSK Bus Interface:
  - Battery positive & negative
  - **-RESET**, **OFF_VCC**, **SDA_SYS** & **SCL_SYS**
- 6-layer gold-plated blue-soldermask PCB with ground plane for enhanced signal integrity
- Supervisor MCU programmed with Pumpkin's space-proven Salvo™ RTOS & SCPI command interface
- Optional enhancements & configurations:
  - Compatible with many different 18650 cell chemistries
  - Battery Switch Module (BSM) with four switched smart outputs

CHANGELOG

Rev.	Date	Author	Comments
A	20160721	AEK	Initial release of hardware Rev A.
B	20161006	AEK	Updated for hardware Rev D.
C	20161021	AEK	Various updates, including mechanical drawings.
D	20161111	AEK	New rendering (reflects Rev G brackets, etc.) and new block diagram.
E	20170421	AEK	Updates to reflect Rev E PCBs and new firmware functions.
F	20170609	AEK	Updates re battery heaters. Added studio image and mass numbers from first production units.
G	20170725	AEK	Added table with mating connectors.
H	20190307	AEK	Added additional information on heaters, etc. Fixed the pin numbers on the 14-pin connectors. Updated connector names to the new system-wide numbering scheme.
I	20201003	AEK	Added cell balancing specs.
J	20220926	AEK	Updated various specifications, added MJ1 data, added more information on cell balancing and heater behavior. Reflects Rev F3 controller PCB specifications.

OVERVIEW

The Pumpkin Battery Module 2 (BM 2) provides energy storage, battery protection and comprehensive battery telemetry in the form of up to eight 18650 Li-Ion batteries arranged in a 2S4P, 3S2P or 4S2P configuration. BM 2 electronics provide battery inhibits, first- and second-level battery safeties (OV, UV, OC, OT, individual cell overvoltage, and others), a battery heater, and a “gas gauge” to provide up-to-date state-of-charge information on the batteries. The BM 2 can be charged and discharged by an appropriate charger or Electrical Power System (EPS) via its two identical connectors. Control and telemetry of the BM 2 is provided via SCPI over I2C through the BM 2’s SupMCU. The BM 2 connects to the bus via a dedicated high-current harness.

CONSTRUCTION

An aluminum core secures up to eight 18650 cells, battery heaters, and one or more temperature sensors together. With the 18650 cells clamped to the core, their end terminals are spot-welded together in an arrangement that is appropriate for the desired configuration (2S4P, 3S2P or 4S2P). A double-sided multi-level PCB houses all of the BM 2 electronics and connectors, and connects to the battery/cell terminals, as well as to the heater and temperature sensor(s). The PCB mounts to one side of the battery terminals. Non-conductive inserts and covers conceal all of the cell terminals, and expose the connectors and user interface. Aluminum surfaces are hard-anodized black for maximum emissivity.

MOUNTING

Optional external brackets are attached to the core in order to provide additional thermal mass, heat dissipation and mounting surfaces. Multiple mounting points are provided on the brackets, to enable various mounting orientations. The overall footprint (with brackets) is roughly 100x100x48mm, or 0.5U. The hole pattern in the brackets is designed to mate to SUPERNOVA Space Access Port (SAP) bolt hole patterns, for effective thermal coupling to a SUPERNOVA structure, and can be used in other applications. Via an optional kit, two BM 2s can be attached to each other to fit within 1U (100x100x100mm) of volume.

The BM 2 brackets have provisions for direct mounting to popular ADCS enclosures. Adapters can also be attached to the BM 2 brackets to establish a PC/104-style hole pattern. Mounting lugs on the brackets can also be used to mount a PCB to the top of the BM 2.

ARCHITECTURAL DESCRIPTION

Up to eight 18650 Li-Ion battery cells can be connected in 2S4P, 3S2P or 4S2P configurations. The resultant battery presents high-current ‘+’ and ‘-‘ terminals, as well as low-current sense/balance terminals in-between cells, to the electronic circuitry of the BM 2. The ‘+’ (high-side) and ‘-‘ (low-side) battery terminals pass through power MOSFETS that form an inhibit system with three independent control inputs. Post-inhibit, the ‘-‘ battery terminal passes through a low-value sense resistor that is sensed by the gas gauge circuitry to integrate current into and out of the battery.

The primary function of the remaining electronics is to monitor and protect the battery during charging and discharging, and to ensure proper operation of inhibits. High-level functionality in the form of a “gas gauge” that accurately measures charge into and out of the batteries and hence can accurately calculated the battery’s current state of charge (SoC) is also provided. A Pumpkin SupMCU provides the interface between the bus and the telemetry and control of the gas gauge and other BM 2 electronics. Micropower / nanopower circuitry is employed to ensure that the quiescent current draw of the BM 2 is small compared to the self-discharge rate of the batteries employed.

The monitor and protection circuitry controls a further set of three MOSFETs, associated with (independent) charging, discharging and trickle charging (for 0V charge conditions). The primary battery protections include:

- Cell over/undervoltage (OV/UV) protection – charging and discharging are inhibited when the cells are in an over- or under-voltage condition
- Overcurrent (OC) charge/discharge protection – charging and discharging beyond predefined charge and discharge limits is inhibited

- Overtemperature (OT) charge/discharge protection – charging and discharging are inhibited when the cell temperature exceeds a predefined limit

The secondary battery protections include:

- Fault in charge FET
- Fault in zero-volt charge FET
- Fault in discharge FET
- Detection of cell imbalance
- Cell overvoltage detection (independent of primary protection)

OPERATIONAL DESCRIPTION

When inhibited, the battery is disconnected from the BM 2's electronics and **V+** and **V-** terminals, and essentially zero current is drawn from the battery. In this state, the batteries are isolated from everything else, and the state of charge is subject only to the inherent self-discharge properties of the batteries.

Apart from its inhibits, the BM 2's electronics are powered either by the batteries themselves, or by external power. Therefore, whenever a source of external power (e.g., a battery charger) is connected to the BM 2, its electronics (SupMCU, battery gauge, etc.) are powered and enabled, regardless of the state of the batteries.[1] The BM 2's electronics are also active whenever no inhibits are active and the batteries are in a good state of charge. Telemetry is available via the SupMCU's SCPI interface over I2C whenever the BM 2's electronics are active.

Whenever the BM 2 electronics are active and the batteries are not inhibited, the protection circuitry independently controls the charge, discharge and trickle-charge MOSFETs. It controls currents in and out of the batteries, as well as maximum and minimum battery voltages, thereby implementing the OC, OV and UV protections, respectively. Battery temperatures are monitored by the protection circuitry as well, thereby providing OT protection.

An external Li-Ion battery charger can charge the batteries by connecting to the battery **V+** and **V-** terminals, and by not exceeding the OV and OC setpoints of the BM 2. Excessive voltages and/or currents at the **V+** and **V-** terminals, as well as too-high voltages on a per-cell basis, will result in the protection circuitry disabling the charge and/or trickle-charge MOSFETs. Excessive temperature in the battery pack will have similar results.

An external load can discharge the batteries by connecting to the **V+** and **V-** terminals, and by not exceeding the UV and OC setpoints of the BM 2. Excessive currents and/or too low a voltage at the **V+** and **V-** terminals, will result in the protection circuitry disabling the discharge MOSFETs.

All protection faults are automatically cleared once the fault condition is removed from the BM 2's **V+** and **V-** terminals (or the pack has cooled down, in an overtemperature fault condition).

N.B. Charge and discharge faults are independent of one another – for example, the BM 2 may not accept further charging, while still delivering full current to the load, in a case where charging resulted in a fault but discharging did not.

TYPICAL USAGE

Mechanically / structurally, the BM 2 should be mounted to a structure that provides a good thermal path and heatsink for the batteries, as charging and/or discharging them at high currents will create heat that must be removed from the batteries to avoid the potential for thermal runaway.

Electrically, the interface is entirely through the 14-pin connectors. Each 14-pin connector has the same pinout. The BM 2's **V-** terminal is connected to system ground, and its **V+** terminal is connected such that it can sink charge currents and source discharge currents. Additionally, if telemetry is desired, an I2C master can connect to the BM 2 via **SCL_SYS** and **SDA_SYS**.

[1] Note that in the case where external power is applied and the inhibits are active, the BM 2's telemetry will report that the batteries are not present.

In a simple, relatively low-power application, the entire connection to the BM 2 will be accomplished through one of the two 14-pin primary connectors. Both charging and discharging will occur through this single connector.

In more sophisticated applications that require higher power levels, the two identical 14-pin primary connectors enable a wide variety of useful configurations. For example, one connector can be used for relatively low-rate charging and discharging (as per the above example), while the second connector can be used for high-rate discharging. In this configuration, a high-power load is easily accommodated.

COMMAND & TELEMETRY INTERFACE

A Pumpkin SupMCU provides a command and telemetry interface to the BM 2, via SCPI over I2C. Commands and telemetry are both BM 2-specific and general to SupMCUs. Most of the telemetry is passed through the SupMCU from the gas gauge chip, and includes comprehensive information on the battery and cells, their state of charge, and overall system status.

The I2C address of the BM 2 is configured in software. Multiple BM 2s can be accommodated on a single I2C bus thusly.

DEBUGGING/PROGRAMMING INTERFACE

Three connectors are provided for SupMCU (re-)programming, a debug terminal to the SupMCU, and an SMBus interface. These are typically only used at the factory.

USER INTERFACE

A human user interface is provided in the form of a battery gauge with button and 5-segment LED, as well as an inhibit jumper and additional LEDs. The human UI functions are as follows:

Name	Color	Function
JP1	red	Install to inhibit BM 2. Must be removed before use
SW1	n/a	Press to display battery state of charge via LED bargraph
LED1	blue	Gas gauge bargraph (0-20%, LSB)
LED2		Gas gauge bargraph (21-40%)
LED3		Gas gauge bargraph (41-60%)
LED4		Gas gauge bargraph (61-80%)
LED5		Gas gauge bargraph (81-100%, MSB)
LED6	orange	Status LED for SupMCU. Blinks with a period of 3s during startup / bootloader phase. Thereafter, under software control.
LED7	red	Indicates when second-level cell overvoltage protection is active

18650 CELL COMPATIBILITY

The BM 2 is compatible with a wide range of 18650 cells. The standard cell is currently the LG INR18650 MJ1 cell (3500mAh), and alternate cells may be compatible – contact the factory for more information. The use of non-standard cells typically requires a reprogramming of the gas gauge portion of the BM 2's circuitry; please consult the factory.

ABSOLUTE MAXIMUM RATINGS

All voltages relative to **`V-`** or system **`GND`**.

Parameter	Conditions / Notes	Symbol	Value	Units
Operating temperature	Discharge	T_{OP_DSCHG}	-40 to +75	ºC
	Charge	T_{OP_CHG}	-40 to +50	
Voltage on **`–RESET`**, **`OFF_VCC`**, **`SCL_SYS`**, **`SDA_SYS`**, **`SMBC`** & **`SMBD`**, **`J213 (Clock)`**			-0.3 to +6.0	V
Voltage on **`V+`**			-0.3 to +20	V
Frequency of clock input on **`J213`**			60	MHz
Charge / discharge current[2]	Sinking (charging)		20	A
	Sourcing (discharging)		20	A

PHYSICAL CHARACTERISTICS

Parameter	Conditions / Notes	Symbol	Min	Typ	Max	Units
Mass	Eight 18650 cells, with optional SUPERNOVA-compatible heatsink / mounting brackets			692	710	g
	Eight 18650 cells, without SUPERNOVA-compatible heatsink / mounting brackets			542	560	g
Length	With SUPERNOVA-compatible heatsink / mounting bracket			100		mm
Width				100		mm
Height				48.4		mm
Pitch of 14-pin connector terminal	Horizontal or vertical distance to nearest terminal			2		mm
Material & surface finishes	Core structure and mounting brackets	AL6061-T6, hard-anodized, black				
	End covers	Ultem® thermoplastic				
	Fasteners	SST 316, passivated				
	Printed circuit boards (PCBs)	FR4, FR406 or similar				

[2] Module's programming may limit currents to lower values. Maximum current into or out of each 14-pin connector is 10A over full temperature range. Higher currents are available in alternate connector configurations or if/when a greater temperature rise in the connector is tolerable – consult factory for details.

SIMPLIFIED MECHANICAL LAYOUT – WITH OPTIONAL BRACKETS [3]

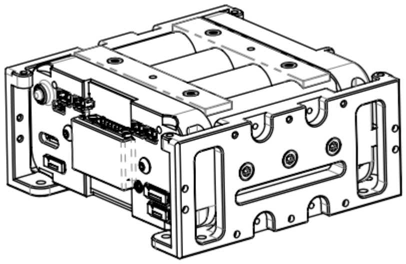


Figure 1: Perspective view

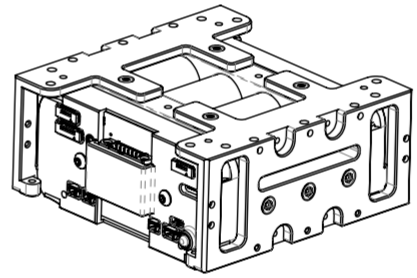


Figure 2: Perspective view (flipped)

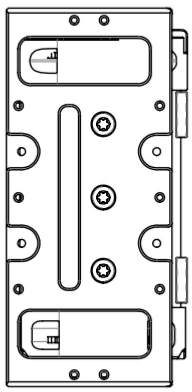


Figure 3: Side view

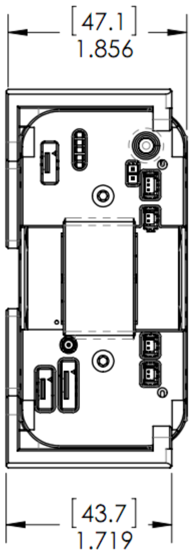


Figure 4: Front view

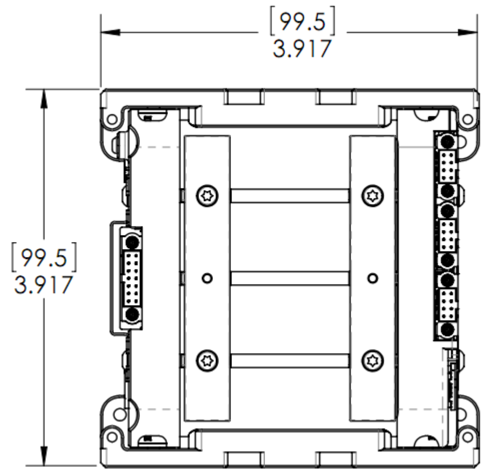


Figure 5: Top view[4]

[3] Dimensions in inches [mm].
[4] Shown with optional Battery Switch Module (BSM) on right side.

SIMPLIFIED MECHANICAL LAYOUT – MOUNTING HOLES WITH OPTIONAL BRACKETS

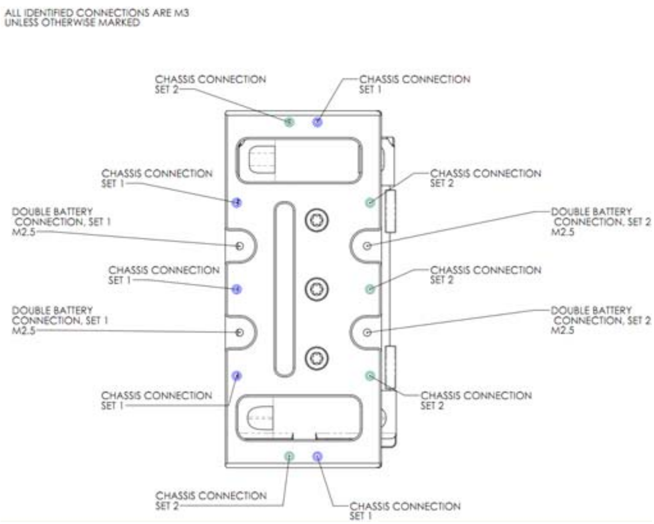


Figure 6: Mounting holes, side view

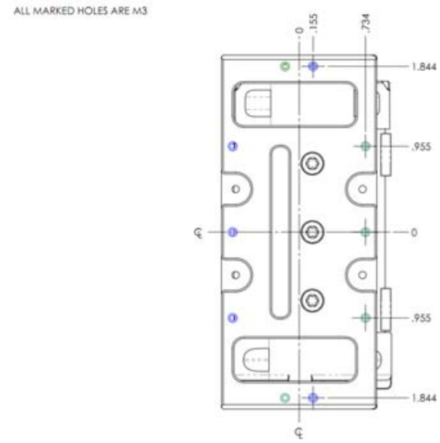


Figure 7: Mounting hole locations, side view

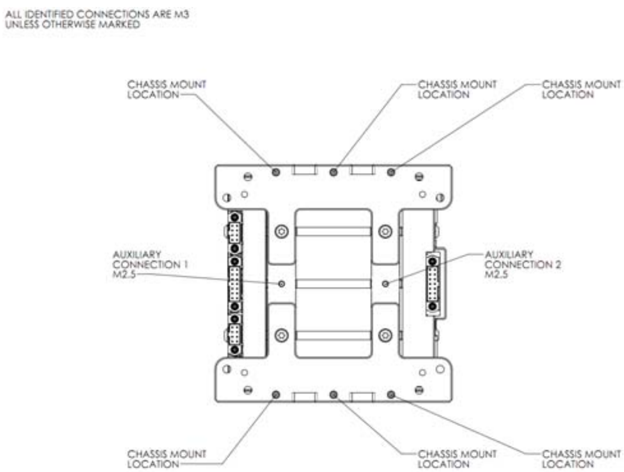


Figure 8: Mounting holes, bottom view

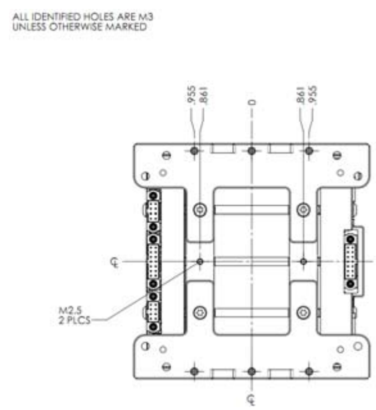


Figure 9: Mounting hole locations, bottom view

SIMPLIFIED MECHANICAL LAYOUT – WITHOUT BRACKETS

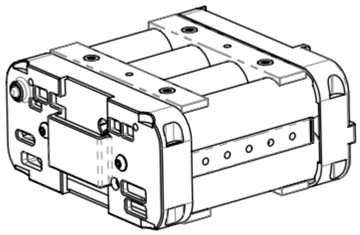


Figure 10: Perspective view

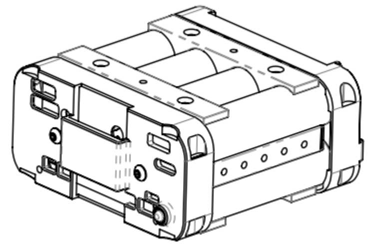


Figure 11: Perspective view (flipped)

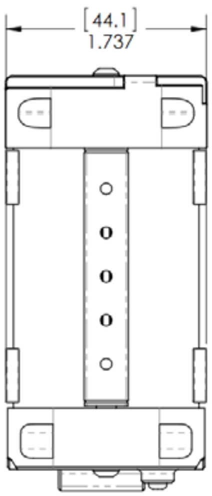


Figure 12: Side view

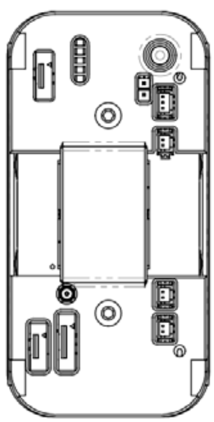


Figure 13: Front view

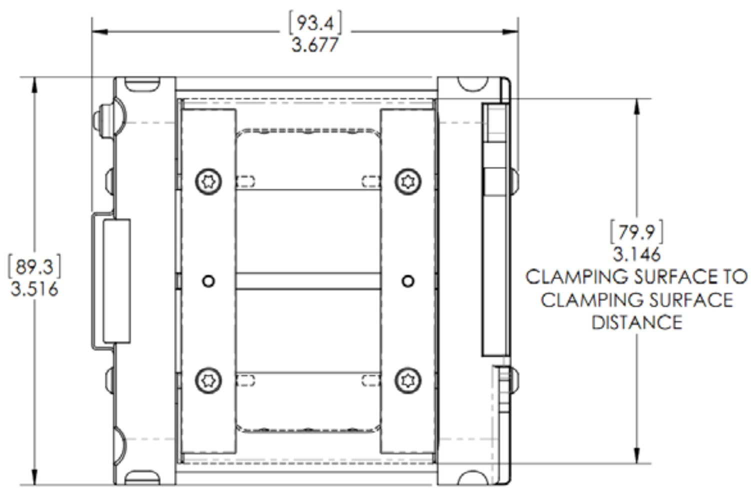


Figure 14: Top view

SIMPLIFIED MECHANICAL LAYOUT – MOUNTING HOLES WITHOUT BRACKETS

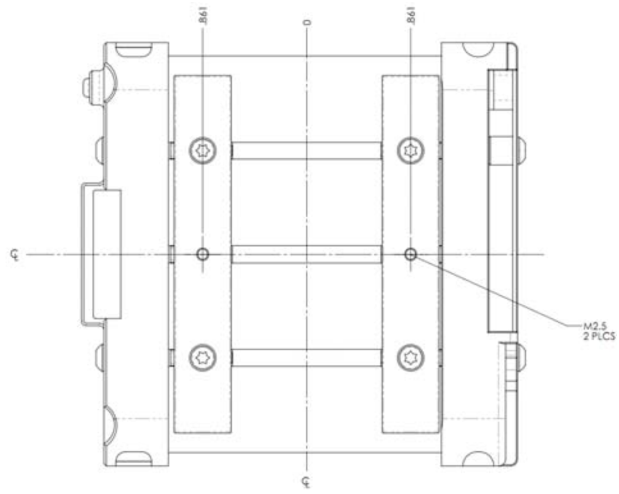


Figure 15: Mounting holes, side view

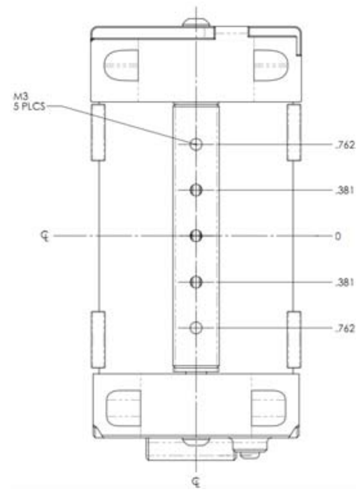


Figure 16: Mounting hole locations, side view

ELECTRICAL CHARACTERISTICS

(T = 25ºC, +5V bus = +5V unless otherwise noted)

Parameter	Conditions / Notes	Symbol	Min	Typ	Max	Units
Non-operating current draw	RBF and Sep switches inhibited	$I_{\_INHIBITED}$			3	µA
Operating power consumption	RBF and Sep switches not inhibited; no commands or telemetry active over I2C or SMB; all LEDs off	I_{OP_NORM}		20		mA
Sleep current	After processing SLEEP command	I_{OP_SLEEP}		2.5		mA
Shutdown current	In undervoltage condition	I_{OP_SHDN}		20		uA
Current per pin	**V+** or **V-** pin, charge or discharge, BM 2 initially at 25ºC	I_{PIN}			4	A
Battery charge voltage	2SNP configuration	$V_{CHG\_MAX\_2S}$			8.40	V
	3SNP configuration	$V_{CHG\_MAX\_3S}$			12.60	V
	4SNP configuration	$V_{CHG\_MAX\_4S}$			16.80	V
Cell voltage differences	2S4P / 3S2P / 4S2P — After balancing is complete	$V_{CELL\_\Delta\_BAL}$		<3	5	mV
Battery charge (sink) current	Through battery.[5] Current passes through all **V+** and **V-** pins of one or both 14-pin connectors.	I_{CHG_MAX}			6	A
Battery trickle-charge / 0V (source) current				TBD	TBD	mA
Battery discharge (source) current		I_{DSG_MAX}		10	15	A
Power consumed by battery heater	2S4P	P_{HEATER}		8		W
	3S2P			16		W
	4S2P			8		W
Number of cell temperature sensors	2S4P and 4S2P configurations			8		
Number of cell heaters	2S4P and 4S2P configurations			8		
Heater control temperature in automatic mode	Turn-off threshold	T_{HEATER_OFF}		7		ºC
	Turn-on threshold	T_{HEATER_ON}		5		ºC
Minimum built-in heater operating temperature	BM2 is shrouded in plastic inside a thermal convection chamber	Heater still cycling between on and off thresholds	-25			ºC
Supervisor MCU internal clock frequency	Base frequency, can be multiplied by onboard PLL	f_{CLK_MCU}		2x 7.3728		MHz
-RESET signal validity	**-RESET** driven by external source		0		0.5	V
Secondary-protection per-cell trip voltage				4.45		V

[5] Current limits are set for all batteries in aggregate; system cannot distinguish between currents in different strings of batteries.

18650 CELL CHARACTERISTICS[6] [7] [8]

Parameter	Conditions / Notes	Min	Typ	Max	Units
Manufacturer & model	The BM2 supports multiple different cell chemistries	LG INR18650 HG2 LG INR18650 MJ1			
United Nations battery compliance	UN transportation regulation test T1-T8	completed successfully on 2015-03-25 (HG2)			
IEC safety requirements	Report # BA-4786867568-A-1	completed successfully on 2015-03-31 (HG2)			
Chemistry		Li[NiMnCo]O2 (H-NMC) / Graphite + SiO (HG2)			
Capacity	@0.2C & 25C	3,000 (HG2) 3,500 (MJ1)			mAh
Remaining capacity after 500 cycles	Charge: 4A, 4.2V, 500mA cutoff @ 40ºC Discharge: 7.5A, 2.5V cutoff @ 40ºC		2,450 (HG2) 3400 (MJ1)		mAh
Self-discharge rate	SOC 100%, 4.185V		5.5		mV/month
	SOC 50%, 3.720V		2.0		mV/month
Internal resistance	DC		25		mΩ
	AC		15		mΩ
Nominal voltage			3.6		V
Standard charge	Constant current		0.5C		mA
	Constant voltage		4.2		V
	End condition (cutoff)		50		mA
Fast charge	Constant current		1-2C		mA
	Constant voltage		4.2		V
	End condition (cutoff)		100		mA
Charge voltage				4.20 +/-0.05	V
Charge current				6,000	mA
Standard discharge	Constant current		600		mA
	End voltage (cutoff)	2.5			V
Fast discharge	Constant current			10 - 20	A
	End voltage (cutoff)	2.5			V
Discharge current	For continuous discharge			10	A
Operating temperature (cell surface temperature)	Charge	0		+45	ºC
	Discharge	-20		+75	ºC
Storage temperature (for shipping state of 40% SOC)	1 month	-20		+60	ºC
	3 months	-20		+45	ºC
	12 months	-20		+20	ºC

[6] From manufacturer's datasheet PS-HG2-Rev0, dated 2015-01-28 and other LG test data. These are the characteristics for the 3000mAh HG2 cell, as supplied as one possible cell for the BM 2. Alternate cells can be supplied, some at additional cost. Test data for this cell can be found at http://www.batteryspace.com/techsupport/9989 Tech Info.pdf.
[7] C is defined to be the battery's nominal capacity, in mA. E.g. the MJ1's C is 3500mA.
[8] Cell/battery current, voltage and temperature settings are defined by the specific cell type, and are programmed into the BM2 at the factory based on the cell type. The table above indicates rough values. Precise values can be gleaned by reading gas gauge telemetry settings from the BM 2.

I2C CHARACTERISTICS

Parameter	Conditions / Notes		Min	Typ	Max	Units
I2C address	7-bit I2C address	default	0x5C			
		via debug terminal, command or custom firmware build, nonvolatile	0x08-0x77			
I2C clock speed					400	kHz
I2C pull-up resistors	No pull-up resistors are fitted to **SCL_SYS** or **SDA_SYS**			∞		Ω

SMB DEVICE CHARACTERISTICS

Parameter	Conditions / Notes	Value
SMBus compatibility	With Master Mode and packet error checking (PEC) options per the SBS specification	v1.1
Speed	Slave mode, SMBC 50% duty cycle	10-100kHz

MATING CONNECTORS

The mating connectors for the BM 2 shown below:

Ref.	Mating Connector Mfg.	P/N	Description	Notes
J201 (Sep)	Hirose	DF13-2S-1.25C	DF13 series 1.25mm pitch crimp receptacle connector	For 26-30AWG wire
J202 (RBF)		DF13-3S-1.25C		
J203	Pumpkin	n/a	BMC SMB Interface Adapter	Factory use only
J204	Pumpkin	710-00540	JFPC-PIC24 Programming Adapter	Factory use only
J205	Pumpkin	710-01001	USB Debugging Adapter	
J206	Harwin	M80-4801442	Datamate series 2mm pitch 2x7 rectangular receptacle connector	For 22AWG wire
J207				
JP1 (RBF)	generic	generic	0.100" pitch 2-pin shorting jumper block	BM 2 ships with red JP1 installed

PRIMARY CONNECTOR PIN DESCRIPTIONS

The primary connection to the BM 2 is via two identical 14-pin connectors **J206** & **J207**.[9] Each pin on **J206** is connected to the same pin on **J207**. These connectors provide a high-current charge/discharge path for the battery, as well as some control signals. Their pinout is shown below:

Name	Pin	I/O	Description
V+	1 2 3 4 5	–	Battery positive terminal. Post-inhibit and protection circuitry. Active when the BM 2's RBF and Sep inhibits are inactive. Charge, trickle-charge and discharge paths into and out of the battery are under the control of the BM 2's protection circuitry. Normally connected to the output(s) of battery charger(s) and the inputs of regulated and unregulated output stages of the connected system.
V-	8 9 10 11 12	–	Battery negative terminal. Post-inhibit circuitry. Active when Sep inhibit is inactive. Charge, trickle-charge and discharge paths have no effect on this terminal. Normally connected to the system ground of the connected system.
OFF_VCC	6	I	An active signal on this pin will disable **VCC_MCU** power to the supervisor MCU. Pull up to disable power to the BM 2's electronics.
-RESET	13	I	Input to reset supervisor controlling supervisor MCU. Pulled up to 3.3V. Pull down to reset the BM 2's electronics.
SDA_SYS	7	I/O	I2C data. To/from supervisor MCU (an I2C slave device) via a PCA9515A I2C isolator.
SCL_SYS	14	I	I2C clock. To supervisor MCU (an I2C slave device) via a PCA9515A I2C isolator.

Each pin is rated at up to 3A @ 25C. A pair of screw terminals is used to secure each connector in place.

Signal pins 11 through 14 are typically connected to the same-name signals on a CubeSat Kit bus. The I2C interface is used to communicate with the BM 2's SupMCU via SCPI. **–RESET** and **OFF_VCC** are used to ensure an orderly power-on, etc.

[9] Note that these connectors utilize a rather non-standard pin numbering scheme; it is distinctly different from neary all 2-row connectors, where one column has even pin numbers and the other has odd pin numbers.

IN-CIRCUIT DEBUGGING PIN DESCRIPTIONS

The debugging/ programming connector **`J204`** is is designed to mate to a Pumpkin JFPC-PIC24 Programming Adapter via a 6-terminal flexible printed circuit (cable). It is for factory use only.

Name	Pin	I/O	Description
	`J204.1`	–	Unused.
`PGEC`	**`J204.2`**	I/O	**`PGEC1`** – clock signal for in-circuit debugging.
`PGED`	**`J204.3`**	I/O	**`PGED1`** – data signal for in-circuit debugging.
`DGND`	**`J204.4`**	–	Digital ground.
`VCC`	**`J204.5`**	–	Supervisor MCU power.
`-MCLR`	**`J204.6`**	I	Supervisor MCU's reset.

DEBUGGING ADAPTER PIN DESCRIPTIONS

The Pumpkin USB Debugging Adapter-compatible debugging connector **`J205`** is implemented with a standard 4-pin Pumpkin USB Debug FPC connector. It is designed to mate to a Pumpkin USB Debugging Adapter via a 4-terminal flexible printed circuit (cable). The serial interface is configured as 115200,N,8,1. This interface can be used to field-upgrade the BM 2 SupMCU's firmware via the built-in bootloader.

The BM2 provides a user terminal via **`J205`**, with **`stdout`**-style output from internal BM firmware operations. A command-line interface (CLI) is also provided, supporting both SCPI commands and other commands (e.g., the ability to unlock and write new values to the NVM memory).

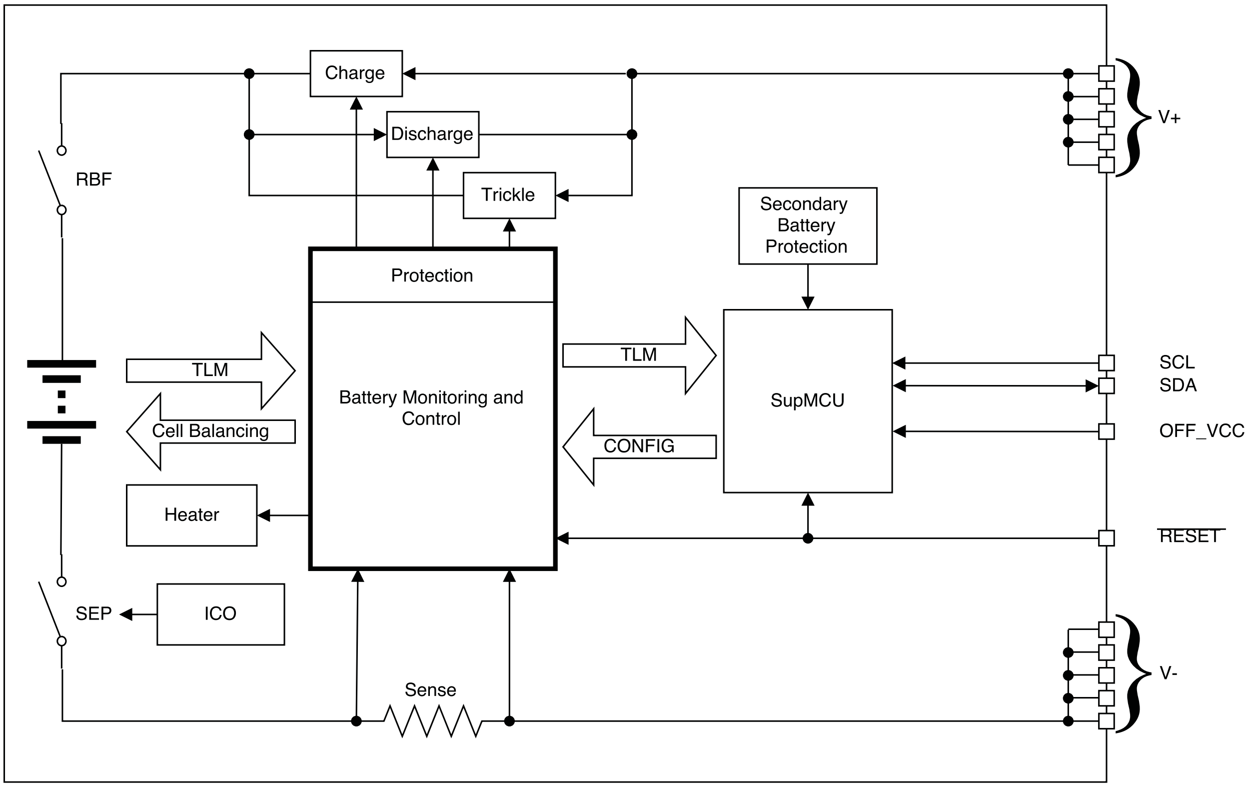
Name	Pin	I/O	Description
`VCC`	**`J205.1`**	–	Supervisor MCU power. When used with the BM 2, users must ensure that this voltage from the Pumpkin USB Debug Adapter is set to 3.3V, or disconnected (preferred).
`DGND`	**`J205.2`**	–	Digital ground.
`TXD`	**`J205.3`**	O	Asynchronous serial data out of the Supervisor MCU.
`RXD`	**`J205.4`**	I	Asynchronous serial data into the Supervisor MCU.

SMBus / EVM PIN DESCRIPTIONS

Connector **`J203`** is provided to enable a direct connection via System Management Bus (SMBus) to the battery fuel (gas) gauge chip in the BM 2. The connector is implemented with a 4-pin FPC connector. This interface is for factory use only.

Name	Pin	I/O	Description
`SMBC`	**`J203.1`**	I	SMBus clock.
`SMBD`	**`J203.2`**	I/O	SMBus data.
`DGND`	**`J203.3`**	–	Digital ground.
`SENSE`	**`J203.4`**	I	Monitored by the SupMCU. Pulled up to local VCC through >20kΩ. When connected to ground, indicates that a Pumpkin SMBus Interface Adapter is connected to **`J203`**.

BLOCK DIAGRAM



Battery Configurations

The BM 2 supports three different battery configurations, with different numbers of 18650 cells and overall battery voltages supported, as outlined below, when outfitted with HG2 (3000mAh) or MJ1 (3500mAh) cells:

Configuration	Total cells	Cells in series	Cells in parallel	Battery voltage (V)	Nominal Energy (Wh)	Nominal Power (W)[10]
2S4P (HG2)	8	2	4	6.0 - 8.4	86	84
2S4P (MJ1)					100	
3S2P (HG2)	6	3	2	9.0 - 12.6	65	126
3S2P (MJ1)					100	
4S2P (HG2)	8	4	2	12.0 - 16.8	86	168
4S2P (MJ1)					100	

BM 2 stored energy is a function of the number of 18650 cells, and the cell characteristics. BM 2 output current is fixed at roughly 10A (nominal) to match the maximum, full-temperature capability of the pins of a single connector. BM 2 available power is the product of output current and string voltage; therefore, configurations with more cells in series can deliver higher power. This limit can be raised in software, by end-user request.

N.B. Each cell choice and battery configuration must be configured at the factory, and cannot be changed in the field.

Battery Charging

The BM 2 is a standalone battery module – it does not include any charging circuitry, nor any regulated outputs. Charging, regulated output and (where appropriate) solar power conversion functionality must be implemented externally,[11] and connected appropriately to the BM 2. Typically, a charger implements a CC/CV/float charge algorithm with the relevant currents and voltages tailored to match the chemistry of the Lithium batteries employed in the BM 2.

To successfully charge the BM 2, the charge currents and voltages must not exceed the battery-specific upper bounds set by the BM 2. The voltage and current limits set by the BM 2 are true for all values of the battery's SoC, and may vary with temperature. The BM 2 will disconnect its batteries from the primary connector when a fault condition (e.g., UV) is experienced, independent of any external charger or EPS.

All that is required of a simple battery charger is to connect the charger to the BM 2's **V+** and **V-** terminals, and to implement its own charging algorithm. A more sophisticated charging scheme can communicate with the BM 2 during charging, to e.g. obtain the SoC of the battery and incorporate it into the charging algorithm (e.g. to maximize battery life).

Connecting the BM 2

A harness is used to connect the BM 2 (see Primary Connector Pin Descriptions) to the 104-pin CubeSat bus connector. A typical implementation utilizing one of the BM 2's 14-pin connectors to a CubeSat Kit is shown below. This implementation connects the BM 2 to the system's EPS, enabling both charging of the BM 2 batteries, as well as drawing power from the BM 2 to supply the EPS' regulated and unregulated outputs.

N.B. The V+ and V- signals of a harness should be twisted pairwise together (i.e., pins 1&2 together, pins 3&4 together, etc.) to minimize the magnetic fields that will develop due to the currents going into or out of the BM 2.

[10] At a cell voltage of 4.2V.
[11] Typically, in an integrated EPS that accepts power from solar arrays, provides regulated and unregulated outputs, and charges the battery.

BM 2 Signal Name	CubeSat Kit Bus Signal Name	CubeSat Kit Bus Pin	Description
`V+`	`S0`	`H2.33` `H2.34`	From/to EPS, for charging and discharging. For EPSes that connect to the battery positive terminal / call these two pins **`BAT_POS`**.
`V-`	`DGND`	`H2.29` `H2.30`	Battery ground.
	`VBATT`	`H2.45` `H2.46`	Typically provided (in current-limited form) by a connected EPS. *Do not connect directly to* ***`V+`****.*
`-RESET`	`-RESET`	`H1.29`	Control signals from CSK bus.
`OFF_VCC`	`OFF_VCC`	`H1.31`	
`SDA_SYS`	`SDA_SYS`	`H1.41`	Command & telemetry interface from/to CSK bus.
`SCL_SYS`	`SCL_SYS`	`H1.43`	

Note Pumpkin offers a Battery Bus Interface Module that presents a matching 14-pin connector and harness to connect the BM 2 to a typical CubeSat utilizing the 104-pin CSK bus connectors.

For applications that require greater unregulated battery currents than are provided via the EPS and the **`VBATT`** pins of the CSK bus connector, the BM 2's second 14-pin connector can be used to draw large currents.

Use with EPS

The BM 2 is compatible with a wide range of existing satellite EPSes, including Pumpkin's EPSM 1.

The various current and voltage limits associated with the cells in the BM 2 are set by the BM 2. Lower limits (e.g., a lower limit for the maximum charging current) should be set (if required) in the connected charger / EPS.

Battery charging and discharging is accomplished via an external EPS, with the EPS connected to the BM 2's **`V+`** and **`V-`** terminals (see above). All separation switch / inhibit functionality that controls battery power to connected loads must be implemented on the EPS; the inhibits on the BM 2 are intended for battery disconnect.

Module Inhibits

The BM 2 includes two independent system-level inhibits. Remove-Before-Flight (RBF) and Separation (Sep) switch functionality is available through these inhibits. These inhibits are independent of the battery-specific first- and second-level safety features of the BM 2's battery protection circuitry.

Each inhibit must be independently wired to a C/NO contact on an inhibit switch. Inhibits must not be connected to any common ground, nor to each other.

The system inhibits override all other battery protection and monitoring circuits. When either inhibit is active, the battery is isolated from all other circuitry and hence the BM 2's own active circuits are powered down.[12]

Each inhibit is activated by shorting two pins of its associated connector together; this is typically done by an external SPST switch or equivalent. Each inhibit controls the gates of power MOSFETs, and little to no current flows within the inhibit circuits. When an inhibit connector is left unpopulated or unconnected, the corresponding inhibit function is inactive, and the associated MOSFET switch is closed and in the conducting state when no battery faults are present. When the pins on an inhibit connector are connected together, the corresponding MOSFET is disabled and no current flows through it. The RBF connector is implemented via a 3-pin Hirose DF13-series header, and the Sep connector is implemented via a 2-pin Hirose DF13-series headers.

Name	Connector	Function	Description
RBF	**`J202`** pins 1&2	RBF Inhibit	High-side switch to isolate battery positive. Must be removed before use. Pin 3 is not used.
`JP1`	**`JP1`** pins 1&2		In parallel with **`J202`**; used to manually inhibit RBF. Must be removed before use.
Sep	**`J201`** pins 1&2	Separation Inhibit	Low-side switch to isolate battery negative.

[12] The BM 2's Intelligent Charge Override (ICO) enables battery charging when the RBF is uninhibited and the Sep is inhibited.

The BM 2 is completely disabled – with essentially zero current draw from its batteries – when either the RBF or Sep inhibit is active. Therefore, for long-term storage, one or more inhibits should be activated. The **JP1** two-pin removable jumper-style inhibit is suggested for this application.

All applications that require RBF functionality should implement it via the BM 2's RBF inhibit.

Applications must implement one separation switch with the BM 2's Sep inhibit; leaving the Sep inhibit unconnected will result in the BM 2 "going live" as soon as the RBF inhibit is removed.

The BM 2 utilizes an intelligent charger override (ICO) to permit charging of its batteries whenever the RBF inhibit is inactive, irrespective of the status of the BM 2's Sep inhibit. This permits safe and predictable charging of the BM 2 whenever the system's RBF pin is removed, including when a nanosatellite that employs the BM 2 is fully integrated into its deployer.

To better understand the interaction of the BM 2's RBF and Sep inhibits, and those of an EPS with solar panel inputs and one or more typical serial inhibits that are ANDed together, consult the table below.

<table>
<tr><th>Config.</th><th>BM 2 RBF</th><th>BM 2 Sep</th><th>EPS Sep(s)</th><th>BM 2</th><th>Loads</th></tr>
<tr><td>1</td><td rowspan="4">inhibited</td><td rowspan="2">inhibited</td><td>inhibited</td><td rowspan="4">Cannot charge or discharge; asleep</td><td>Cannot draw any power</td></tr>
<tr><td>2</td><td>uninhibited</td><td>Can draw power from solar panels</td></tr>
<tr><td>3</td><td rowspan="2">uninhibited</td><td>inhibited</td><td>Cannot draw any power</td></tr>
<tr><td>4</td><td>uninhibited</td><td>Can draw power from solar panels</td></tr>
<tr><td>5</td><td rowspan="4">uninhibited</td><td rowspan="2">inhibited</td><td>inhibited</td><td rowspan="2">Cannot discharge; awake and can charge via ICO</td><td>Cannot draw any power</td></tr>
<tr><td>6</td><td>uninhibited</td><td>Can draw power from solar panels</td></tr>
<tr><td>7</td><td rowspan="2">uninhibited</td><td>inhibited</td><td rowspan="2">Can charge and discharge, awake</td><td>Cannot draw any power</td></tr>
<tr><td>8</td><td>uninhibited</td><td>Can draw power from solar panels or batteries</td></tr>
</table>

Table 1: Truth table for BM 2 and typical EPS inhibits

Configuration 1 is the storage configuration, with all RBF and Separation inhibits present. Configuration 5 is the configuration where the nanosatellite is fully integrated into its deployer, with RBF removed but all Separation inhibits active. Configuration 8 is the fully deployed configuration with RBF and Separation inhibits inactive.

Use in Manned Space Flight Applications

The RBF and Sep inhibits of the BM 2 are arranged in a manner that satisfies the requirements set forth by NanoRacks® (NR) for use on the ISS.[13] In particular, the requirements 1) through 7) of Section 5.1 Electrical System Design are met by:

- The BM 2's design
- Connecting an external RBF switch to the BM 2's **J202** RBF inhibit connector as the RBF switch (not shown in the NR diagram)
- Connecting an external separation / disconnect switch to the BM 2's **J201** Sep inhibit connector as separation switch **D3**
- Connecting two independent external separation / disconnect switches to an EPS or other off-module system that implements the **D1** and **D2** switches prescribed by NanoRacks

When active, the BM 2's RBF and Sep inhibits ensure that the battery is fully isolated from all loads. With the RBF inhibit inactive, the prescribed ground-referenced "ground charge circuit" can be applied to the BM 2's V+ and V- terminals to charge its batteries without energizing any loads or the flight computer; in this situation the off-module **D1** and **D2** disconnects must be open (i.e., inhibited) to prevent loads from being energized. Discharging of the batteries is suppressed as long as the **J201** Sep inhibit (**D3**) is active. The SoC of the battery being charged in this situation can be monitored externally via the current into the battery and the voltage at the battery terminals.

The choice and location of physical switches and the requisite harnesses to be used as RBF and Sep switches in conjunction with the BM2 is left to the end-user. Switches are typically implemented as high-

[13] See NRCSD-ICD, NanoRacks document NR-SRD-029 v0.36, available online.

reliability rocker/lever switches (with the C and NO terminals) or via pushbutton SPST switches, all connected to the inhibits of the BM 2.

Fault Handling

The BM 2's active circuitry protects the BM 2's batteries through the actions of the gas gauge / first-level battery protection. The SupMCU monitors this protection for faults, and autonomously attempts to clear all first-level faults reported by the gas gauge / first-level battery protection, five seconds after the fault is registered. A persistent fault condition will result in the SupMCU continually attempting to clear the fault(s). The SupMCU cannot override a fault condition. Faults are typically cleared through the action of the external battery charger (e.g., a UV fault is cleared by the external charger successfully raising the battery past the BM 2's UV threshold).

Second-Level Battery Protection

The BM 2 incorporates an additional, independent second-level battery safety mechanism. These electronics constantly monitor the cell voltages of all of the cells in the battery. If/when an overvoltage condition is detected on a cell, in addition to the main circuitry disconnecting the charge, discharge and/or trickle-charge MOSFETs, the second-level protection illuminates a red LED and discharges the battery pack through a 75Ω power resistor. This 2-4W discharge is intended to gradually reduce the affected cell voltage(s) while the cell overvoltage condition exists. Once the cell overvoltage condition is removed, the second-level protection is automatically removed as well and the MOSFETs are reenabled.

Cell Balancing

The BM 2 automatically balances individual cell voltages during charging nearing the end-of-charge, and maintains the overall cell balance to a predetermined maximum cell voltage difference. As the per-cell balancing current is relatively modest (approximately C/100), balancing will only be active and will only have an appreciable effect when the cells are nearly "at rest" when charging, i.e. when they are near their final charging voltage. The balancing can be left in automatic mode, or can be forced on or off, all via command. Balancing automatically ends when a cell's imbalance relative to the other cells drops below a preprogrammed threshold, and will resume automatically if it exceeds that threshold.

Battery Heater

Each cell is individually wrapped with a conformal Kapton heater, and the majority are instrumented with a thermistor for temperature telemetry. The individual heaters combine to form a parallel combination of resistive heaters that are driven by the battery's **V+** and **V-** terminals. Two heater controllers are present: one in the protection circuitry, and one in the SupMCU; the heater is driven by the OR of these two heater controllers.

The heater is enabled when the battery temperatures nears freezing (0ºC) by crossing through the turn-on threshold temperature. The heater will remain on until the battery temperature increases enough to cross through the turn-off temperature threshold.

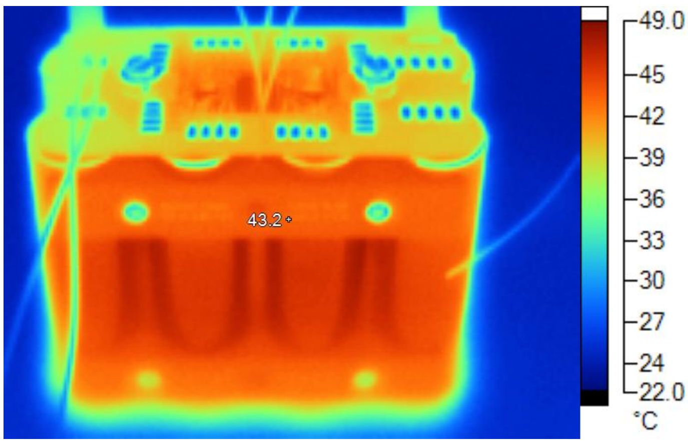


Figure 17: IR view of BM 2 core with battery heater enabled

The power for the heater will be drawn from the battery directly, or from external power when it is of sufficient strength. This means that the batteries can heat themselves even in the absence of any external (charging) power. When drawing power from the cells themselves, the heater will be disabled if/when the cell undervoltage limit is reached.

The heater controller has commands to turn it on, to turn it off, or to allow it to run in an automatic mode (the default). This controller can be used, for example, to enable the battery heaters at a temperature above the heater turn-on threshold.

As part of its battery safety protocol, the BM 2 will prevent any cell charging that is attempted when the cells are too cold. Users should analyze their on-orbit conditions to establish whether the built-in heaters in automatic mode are adequate to maintain a minimum battery temperature suitable for charging, while in eclipse conditions. In exceptionally cold-biased situations, it may be necessary to manually enable the heaters "early" at a temperature above the built-in automatic heater threshold temperatures, to ensure that the cells are already at a temperature compatible with charging when coming out of eclipse.

Battery SoC Indicator

The BM 2 includes a 5-LED bargraph and pushbutton switch to provide an immediate means of discerning the state-of-charge (SoC) of its batteries, from 0 to 100% in 20% steps.

Whenever the BM 2 is active, pushing the battery test button will result in the LED bargraph illuminating with up to 5 LEDs for roughly 5s. Additionally, the LED bargraph is automatically on when the batteries are charging. The bargraph can also be activated via a SCPI command to the BM 2.

The LED bargraph blinks the “highest” LED when charging.

The battery test indicator is especially useful for ascertaining the status of a standalone battery pack, e.g., one that is in long-term storage. The SoC is also available as telemetry from the battery.

N.B. The battery test indicator works only when none of the system inhibits are active.

Reset Behavior

The BM 2 has its own dedicated power-on-reset (POR) controller. The BM 2’s **-RESET** input takes into account potential signal loading of unpowered external devices connected to the CubeSat’s **-RESET** signal, and permits resetting of the BM 2 only by powered external devices.

All of the BM 2’s computing electronics are held in reset when its RBF inhibit is active.

System power-up with a charged battery is nearly instantaneous.

Telemetry

The BM 2 provides a wide range of telemetry via its gas gauge chip. For example, a user can query the BM 2 for the battery voltage, current and temperature, as well as the state-of-charge, and the expected runtime to empty given the battery’s current conditions. Telemetry is acquired by making SCPI telemetry request commands to the BM 2’s SupMCU. The gas gauge’s telemetry indices start at 0x00 and go to 0x7F. Additional BM2-specific telemetry points for subsystems other than the gas gauge begin at 0x80. See the Pumpkin SupMCU firmware reference manual for more information.

Figure 18 and **Figure 19** below illustrate just some of the telemetry items and cell-specific parameters that are programmed into the BM 2's gas gauge. [14]

In **Figure 18**, we see that cell 4 is a bit out of balance with cells 1-3; the BM 2's automatic cell balancing will take care of this. We also see that this 4S2P MJ1 pack is at 21.75 ºC and at 87% SoC, is drawing a charging current of 255mA as it nears the end-of-charge, and the pack voltage is at 16.401V.

Figure 19 shows the first-level safety settings for the MJ1 cells. There are many temperature ranges (e.g., Low Temperature (LT), Standard Temperature (ST), High Temperature (HT)) and other operational domains that apply to different battery conditions, and each has its own limits. These are all programmed into the BM 2 at the (Pumpkin) factory, and should never be changed by the user. N.B. Pumpkin does *not* provide customer support in interpreting gas gauge settings.

[14] The screens shown are via an application that pulls this data from the SMBus connector **J203**. Customers will normally access this through the BM 2's I2C telemetry interface.

Nearly all of this data is available as telemetry when querying the BM 2.

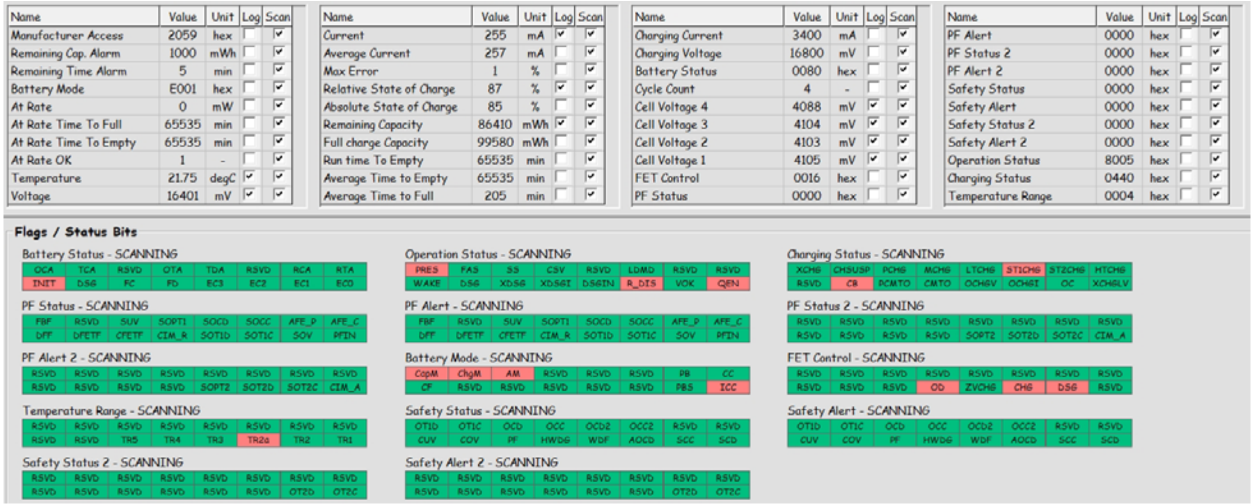


Figure 18: Example of real-time telemetry available from BM2's gas gauge (MJ1 cells)

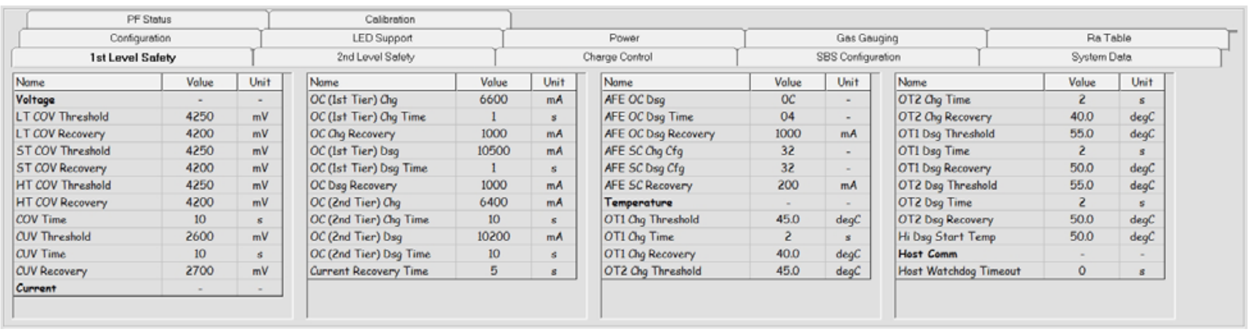


Figure 19: One of many pages of cell-specific parameters programmed into the gas gauge (MJ1 cells)

Fielding multiple BM 2s

Some structures have mounting provisions (e.g., Pumpkin's SUPERNOVA) for multiple BM 2s. In high-power applications, consideration should be given towards distributing the BM 2s for best possible utilization of the structure's thermal mass.

When multiple BM 2s are present, it is advisable to populate all of the primary connector's signals so that each BM2 can charge and discharge at high rates, and so that commands and telemetry are available for each BM 2. Unique I2C addresses should be applied to each BM 2.

Connections from a typical CubeSat-class bus to multiple BM 2s can be accomplished with serial (i.e., chained) harnesses to the primary connectors, or via parallel / independent harnesses to the primary connectors.

Chaining for added Capacity or Power

When a battery charger is present, multiple BM 2s using the same battery topology (e.g., 4S2P) and identical battery types can be connected in parallel, with the use of a suitable connector.

WARNING: Parallel connections between BM 2 modules should only be made when all of the BM 2s are at the same SoC at have the same open-circuit battery voltage on their **V+** terminals.

Parallel-connected BM 2s provide an integer multiplication of the power and energy of a single BM 2; however, since the wiring harnesses current is limited from a practical standpoint, only harness topologies that connect BM 2s in parallel permit an increase in usable power over a single BM 2. In a seriallyconnected topology, only the last BM 2 in the chain has an available 14-pin connector to connect to the load(s), and the currents (and hence, power) delivered to the load are limited to that of a single BM 2.

A battery charger that is at or near its limit in the rate at which it can charge a single BM 2, will see the charge rate for multiple BM 2s reduced by the number of BM 2s connected to the charger.

External Oscillator into SupMCU[15]

The BM 2's SupMCU operates with an internal 7.37MHz oscillator. For applications that wish to synchronize the SupMCU's clock with an external source, the SupMCU can be configured to run from an externally-provided oscillator applied to its **`J213`** MMCX connector.

If the external oscillator signal fails, the SupMCU will automatically switchover to its internal 7.37MHz oscillator.

If/when providing an external oscillator at a frequency other than 7.37MHz, the SupMCU must be commanded with the new operating frequency, so that it can reconfigure peripherals that are dependent on particular clock speeds (e.g., UARTs).

Other clocks present on the BM 2 (e.g. those associated with MOSFET-drive charge pumps and the onboard switching regulator) run independent of the SupMCU's clock.

The external oscillator in function is disabled when the oscillator out function is selected.

External Oscillator out of SupMCU[16]

The BM 2 can output an oscillator signal on its **`J213`** MMCX connector. This signal can be used to synchronize to other SupMCUs, or to derive information re the BM 2's SupMCU operation.

The oscillator output is the SupMCU's internal clock, divided by a commandable power-of-2. This oscillator output can be enabled, disabled and the resultant frequency changed via SCPI commands.

The oscillator out function is disabled when the external oscillator in function is selected.

[15] Future software enhancement.
[16] Future software enhancement.

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PUMPKIN™ INCORPORATED

744 Naples Street
San Francisco, CA 94112 USA
tel: (415) 584-6360
fax: (415) 585-7948

web: http://www.pumpkininc.com/
email: info@pumpkininc.com

web: http://www.cubesatkit.com/
email: info@cubesatkit.com

