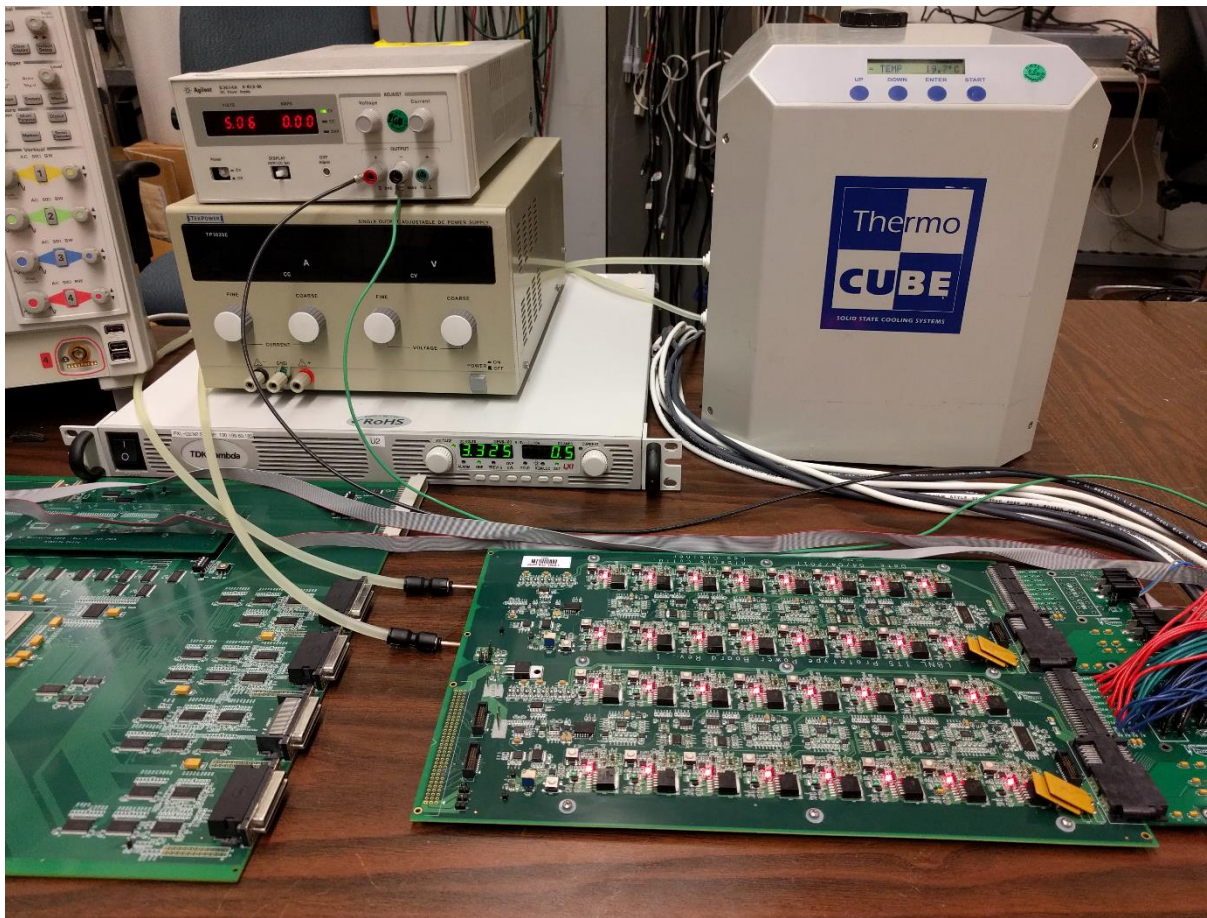# ALICE ITS POWER SYSTEM
32-CHANNEL VERSION

OPERATION MANUAL v1.6

This manual is meant for use with prototype production power board v1.1 (labelled v1) and v1.2 (labelled v1.1)

LAWRENCE BERKELEY NATIONAL LABORATORY - NUCLEAR SCIENCE DIVISION

1 CONTENTS

ALICE ITS POWER SYSTEM – 32-CHANNEL VERSION – OPERATION MANUAL

ALICE ITS POWER SYSTEM – 32-CHANNEL VERSION – OPERATION MANUAL

2 HISTORY

12/6/2017 – A. Collu - Released first draft of the Operation Manual (v1.0)

3/7/2017 – A. Collu – Added section on how to assemble the power system, reviewed breakout board section, applied minor corrections (v1.1)

14/7/2017 – A. Collu – Added table containing trace resistances (v1.2)

14/09/2017 – L. Greiner – Added section on stand-alone cooling system installation and operation (v1.3)

3/7/2018 – A. Collu – Fixed wrong cross references and reformatted section 10 on the stand-alone cooling system (v1.4)

4/9/2018 – A. Collu – Modified sequence of commands to configure the ADCs to increase conversion rate (v1.5)

12/10/2018 – A. Collu – Fixed typo found in the command to read out the ADC channels (v1.6)

3 INTRODUCTION

This manual provides the specifications of the ALICE ITS power system – 32-channel version, a description of its functionalities and guidelines to its operation.

The ALICE power system is composed of a power board where a basic set of functionalities is implemented and of two breakout boards that serve as physical adapters to connect the power board to up to 16 sensor modules.

This system can generate 32 nominally 1.8V power supply voltages - one analog supply voltage and one digital supply voltage per module - each providing drive strength up to 3A, and 16 additional negative voltages with low current strength that can be used to bias the sensor modules.

The main features of the power generation system, addressable via standard I2C interfaces (see specifications in section 6.2.3), are summarized below:

- Individual enabling of supply and bias voltages
- Individual adjustment of supply voltages
- Adjustment of bias voltages on a power unit (8-channel basis)
- Over-current protection circuits with adjustable thresholds on each supply voltage
- Over-temperature protection circuits with manually adjustable thresholds for each 16-channel power unit.
- Monitoring features (voltage / current / temperature)

In order to dissipate the heat generated during normal operation, the main power board is equipped with a heat exchanger (true only for endurance tests/stave testing power boards) which needs to be connected to a liquid based cooling system (see Section 10 or information on how to cool the power board). Due to their low dissipated power, individual module testing power boards do not need to use an external cooling system. For this reason these power boards will not come with a heat exchanger.

It is intended that this power system be used in conjunction with the MOSAIC readout board developed by Bari for the testing of modules/staves for the ALICE ITS Upgrade.

The latest version of this manual can be found at:

https://twiki.cern.ch/twiki/pub/ALICE/Documentation/2018_10_12_ITS_power_system_V16_32-channel_operation_manual.docx

Other functionalities added to the board with the purpose of testing alternative system configurations (e.g. control over VME bus) will not be described in this manual.

4 Content of the package

The power system comes in a package that contains the following items* (

):
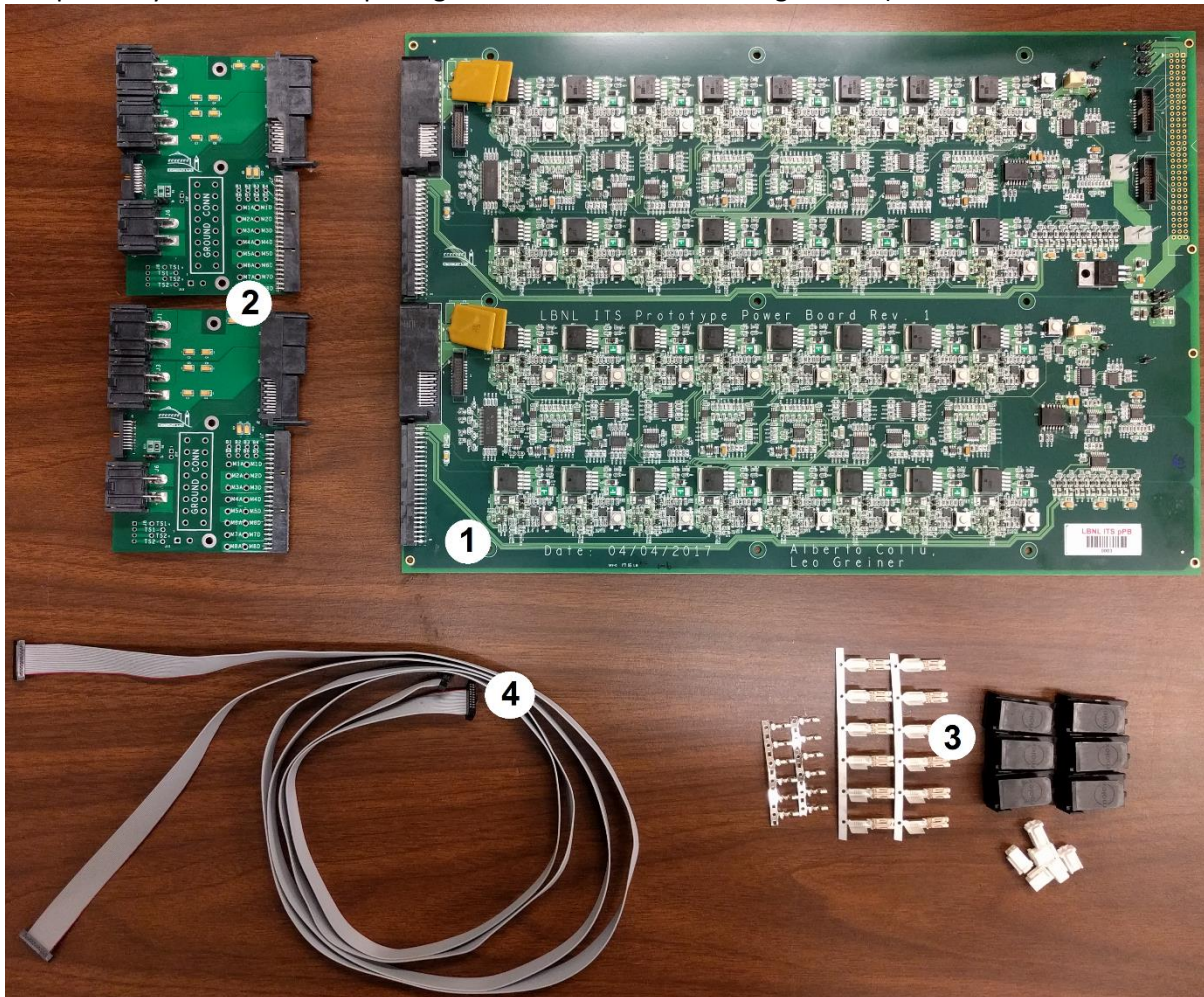
1) 1 x Power Board (VME 6U x 340mm) with a heat exchanger on its back**

2) 2 x Breakout Board (7cm x 103.5cm)

3) mating connectors, pins and jumpers (items and item quantity may differ from shown)

4) 2 x 20-pin ribbon cable SAMTEC FFSD-10-D-40.00-01-N cable (length ~1m)

5) 1 x liquid cooling system (will be delivered to endurance tests/stave testing sites, not shown in the picture)
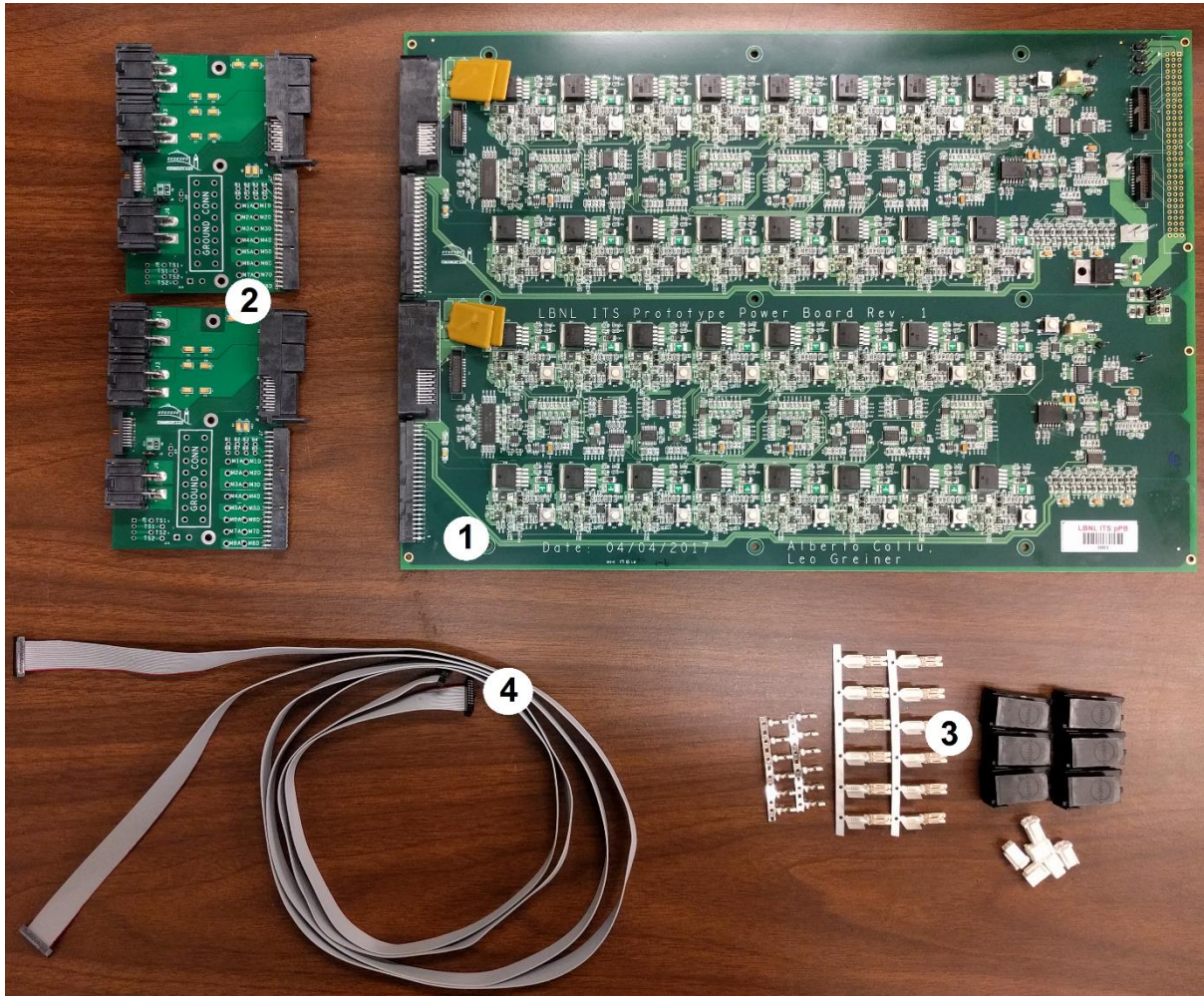
Figure 1: Content of the package (quantity for each part may be different than shown)

*Quantity for some of the items may exceed minimum required.

**Please note that this version of the power board will not fit a 1 unit VME slot of the specified dimensions (thickness is not compatible with 1 unit size). Heat exchanger may not be provided (e.g. single module testing power boards).

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5 POWER BOARD

The power board (Figure 2) consists of two fully independent and functionally identical half boards or Power Units (PU). Each power unit is split into two polyfuse-protected power domains referenced to a common ground plane. Jumpers on the power board allow for different powering/grounding configurations. The input power may be provided to each domain either from the front of the power board via a breakout board or from the rear side of the power board via a VME connector (only possible for single module testing power boards, see section 7.1).

Each power unit contains a set of 16 positive voltage regulators powered at 3.3V (R* in Figure 2, 8 per power domain) which are used to generate digital and analog supply voltages to the modules. One negative voltage regulator (NR1 in Figure 2) plus a set of 8 FET switches per power unit generate 8 additional low-current voltages to bias up to 8 sensor modules.

All the functionalities implemented on the power board can be accessed via I2C interfaces (the two power units have independent interfaces). A set of push buttons (SW* in Figure 2) allows each supply channel to be enabled manually for test purposes.

A heat exchanger, positioned on the back of the board (not shown), may be connected to an external cooling system (see Section …). The temperature of each power unit can be monitored (see Subsection 9.8) using a PT100 temperature sensor (T in figure).
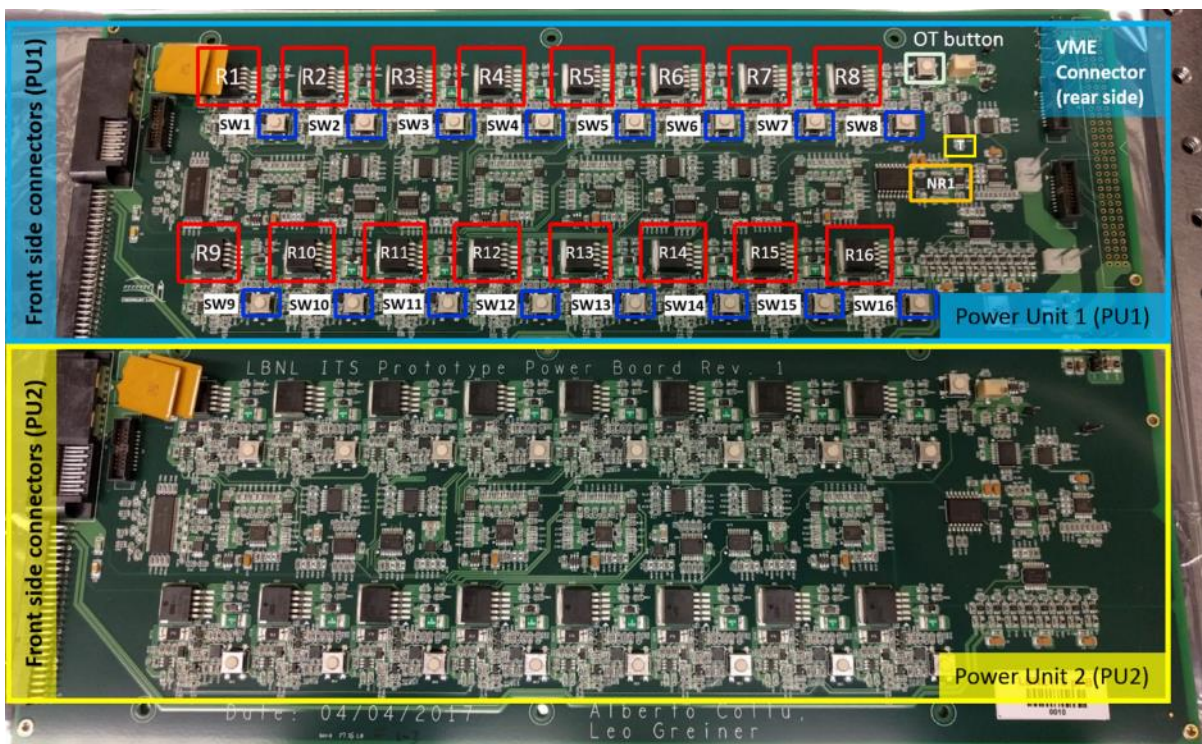

Figure 2: Power Board

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A total of 66 LEDs indicate the status of various parts of the board and can help identifying possible issues (See Table 1 for power unit 1 and Table 2 for power unit 2), in particular:

1) A red LED near each regulator is used to indicate the occurrence of an overcurrent condition. When this happens, the corresponding channel is automatically switched off. At board power on all these red LEDs are turned on indicating that all supply voltages are grounded.

2) A green LED located near each regulator is used to indicate that the corresponding channel is enabled and working properly. Since its brightness grows with the magnitude of the output voltage, it may not be visible for low output voltage values (below 1.8V). Green LED and red LED belonging to the same channel cannot be simultaneously on. The happening of such condition is an indication that the board is not working properly.

3) A red LED located on the right (back) side of each power unit is used to indicate the occurrence of an over-temperature condition (temperature threshold is set to 70°C by default). When this happens all the supply channels of that power unit are disabled simultaneously. To recover from an over-temperature condition it is necessary that the OT button located on the rear side of the power unit is pressed (works only if power unit temperature is below threshold). Alternatively, the power unit can be power cycled.

Table 1: Description of Power Unit 1 status LEDs

LED ID	Description
D35	Module 1 analog voltage is enabled
D1	Module 1 analog voltage is disabled (at power up and after overcurrent)
D36	Module 1 digital voltage is enabled
D3	Module 1 digital voltage is disabled (at power up and after overcurrent)
D37	Module 2 analog voltage is enabled
D5	Module 2 analog voltage is disabled (at power up and after overcurrent)
D38	Module 2 digital voltage is enabled
D4	Module 2 digital voltage is disabled (at power up and after overcurrent)
D39	Module 3 analog voltage is enabled
D9	Module 3 analog voltage is disabled (at power up and after overcurrent)
D40	Module 3 digital voltage is enabled
D6	Module 3 digital voltage is disabled (at power up and after overcurrent)
D41	Module 4 analog voltage is enabled
D8	Module 4 analog voltage is disabled (at power up and after overcurrent)
D42	Module 4 digital voltage is enabled
D7	Module 4 digital voltage is disabled (at power up and after overcurrent)
D43	Module 5 analog voltage is enabled
D13	Module 5 analog voltage is disabled (at power up and after overcurrent)
D44	Module 5 digital voltage is enabled
D10	Module 5 digital voltage is disabled (at power up and after overcurrent)
D45	Module 6 analog voltage is enabled
D12	Module 6 analog voltage is disabled (at power up and after overcurrent)

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LED ID	Description
D46	Module 6 digital voltage is enabled
D11	Module 6 digital voltage is disabled (at power up and after overcurrent)
D47	Module 7 analog voltage is enabled
D17	Module 7 analog voltage is disabled (at power up and after overcurrent)
D48	Module 7 digital voltage is enabled
D14	Module 7 digital voltage is disabled (at power up and after overcurrent)
D49	Module 8 analog voltage is enabled
D16	Module 8 analog voltage is disabled (at power up and after overcurrent)
D50	Module 8 digital voltage is enabled
D15	Module 8 digital voltage is disabled (at power up and after overcurrent)
D2	Power Unit 1 over-temperature condition has occurred

Table 2: Description of Power Unit 2 status LEDs

LED ID	Description
D51	Module 1 analog voltage is enabled
D21	Module 1 analog voltage is disabled (at power up and after overcurrent)
D52	Module 1 digital voltage is enabled
D18	Module 1 digital voltage is disabled (at power up and after overcurrent)
D53	Module 2 analog voltage is enabled
D20	Module 2 analog voltage is disabled (at power up and after overcurrent)
D54	Module 2 digital voltage is enabled
D19	Module 2 digital voltage is disabled (at power up and after overcurrent)
D55	Module 3 analog voltage is enabled
D25	Module 3 analog voltage is disabled (at power up and after overcurrent)
D56	Module 3 digital voltage is enabled
D22	Module 3 digital voltage is disabled (at power up and after overcurrent)
D57	Module 4 analog voltage is enabled
D24	Module 4 analog voltage is disabled (at power up and after overcurrent)
D58	Module 4 digital voltage is enabled
D23	Module 4 digital voltage is disabled (at power up and after overcurrent)
D59	Module 5 analog voltage is enabled
D29	Module 5 analog voltage is disabled (at power up and after overcurrent)
D60	Module 5 digital voltage is enabled
D26	Module 5 digital voltage is disabled (at power up and after overcurrent)
D61	Module 6 analog voltage is enabled
D28	Module 6 analog voltage is disabled (at power up and after overcurrent)
D62	Module 6 digital voltage is enabled
D27	Module 6 digital voltage is disabled (at power up and after overcurrent)
D63	Module 7 analog voltage is enabled
D33	Module 7 analog voltage is disabled (at power up and after overcurrent)
D64	Module 7 digital voltage is enabled
D30	Module 7 digital voltage is disabled (at power up and after overcurrent)
D65	Module 8 analog voltage is enabled
D32	Module 8 analog voltage is disabled (at power up and after overcurrent)
D66	Module 8 digital voltage is enabled
D31	Module 8 digital voltage is disabled (at power up and after overcurrent)
D14	Power Unit 2 over-temperature condition has occurred

6 BREAKOUT BOARD

6.1 GENERAL DESCRIPTION

The breakout board (Figure 3) is an interface board that connects to a power unit on the power board. It has the following main purposes:

1) Provide power to the two positive power domains of a power unit

2) Provide power to the bias section of a power unit

3) Provide a physical interface between an external readout system and a power unit (connector J4, Samtec SHF-110-01-L-D-RA type). Note that the MOSAIC board is not compatible with the pinout of this connector on the breakout board and will need to be connected directly to dedicated connectors on the power board (J72 on power unit 1 and J75 on power unit 2).

4) Provide a physical interface between the power unit and the sensor modules. In particular it allows for the soldering of wires that bring power/bias to the modules.

On the top side of the breakout board (Figure 3), 3 MOLEX 172043-0202 connectors (J1, J3 and J6) are placed which bring 2 nominally 3.3V voltages (3.3V input power for domain 1 and 2) and a nominally -5V voltage to generate the bias voltages for the modules.
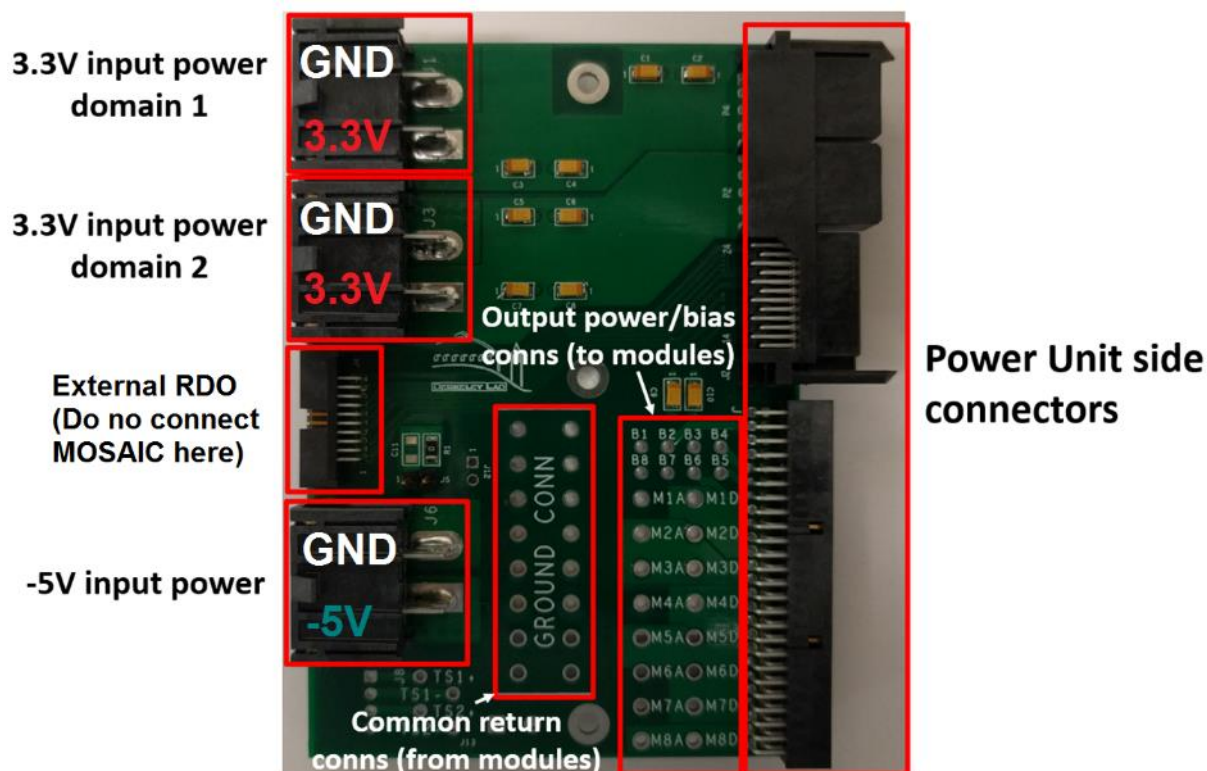

Figure 3: Detailed picture of the top side of the breakout board

A Samtec SHF-110-01-L-D-RA connector is also placed on top of the board that allows the power unit to interface to an external readout system (not intended for use with MOSAIC, only with RUv1).

On the bottom of the breakout board, underneath the input power connectors, 3 MOLEX 53426-0210 connectors are located that are used to for attaching the sense wires that go to the 3.3V and -5V power supplies. In this way, the voltage at each power input of the breakout board can be kept constant regardless of current consumption.
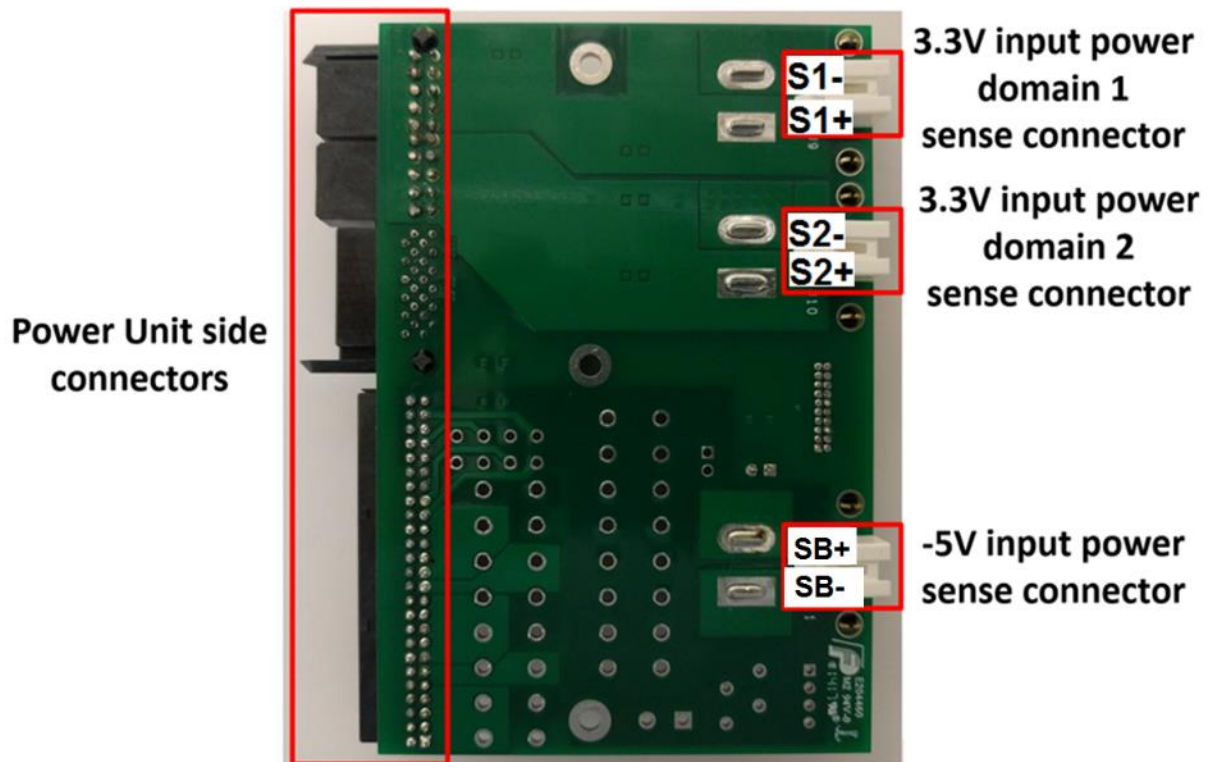
Figure 4: Detailed picture of the bottom side of the breakout board

Cables for powering the power board (3.3V and -5V) are not provided. However pins and mating connectors are provided for all the input connectors (See section 7 for details on how to build these cables). Table 4 gives recommendations for wire sizes to use for input power and sense wires.

Table 3: Recommended wire sizes for input power/sense cables

Description	Wire AWG (Section [mm^2])
3.3V (power and return)	10 (5.26)
-5V (power and return)	10 (5.26)
sense wires for 3.3V	22 (0.326)
sense wires for -5V	22 (0.326)

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A total of 16 power, 16 return and 8 bias connections (M*A, M*D, GROUND CONN, B*) allow for the soldering of wires to interface to up to 8 sensor modules (see recommendations for max wire sizes for the various connections in Table 4.

Table 4: Wire connection points on the Breakout Board, description and maximum wire size

Label	Description	Wire Min AWG (Max Section [mm^2])
M1A	Analog voltage for Module 1	16 (1.31)
M1D	Digital voltage for Module 1	16 (1.31)
M2A	Analog voltage for Module 2	16 (1.31)
M2D	Digital voltage for Module 2	16 (1.31)
M3A	Analog voltage for Module 3	16 (1.31)
M3D	Digital voltage for Module 3	16 (1.31)
M4A	Analog voltage for Module 4	16 (1.31)
M4D	Digital voltage for Module 4	16 (1.31)
M5A	Analog voltage for Module 5	16 (1.31)
M5D	Digital voltage for Module 5	16 (1.31)
M6A	Analog voltage for Module 6	16 (1.31)
M6D	Digital voltage for Module 6	16 (1.31)
M7A	Analog voltage for Module 7	16 (1.31)
M7D	Digital voltage for Module 7	16 (1.31)
M8A	Analog voltage for Module 8	16 (1.31)
M8D	Digital voltage for Module 8	16 (1.31)
B1	Bias voltage for Module 1	20 (0.518)
B2	Bias voltage for Module 2	20 (0.518)
B3	Bias voltage for Module 3	20 (0.518)
B4	Bias voltage for Module 4	20 (0.518)
B5	Bias voltage for Module 5	20 (0.518)
B6	Bias voltage for Module 6	20 (0.518)
B7	Bias voltage for Module 7	20 (0.518)
B8	Bias voltage for Module 8	20 (0.518)

6.2 ELECTRICAL AND TIMING CHARACTERISTICS

This section provided the voltage specifications, current ratings, pinout and timing characteristics of the breakout board interfaces.

6.2.1 Power in connectors (3.3V) - Pin characteristics

Table 5: Pin functions and recommended operating conditions for 3.3V connectors* (applies to J1, J3 on breakout board)

Pin Number	Description	Recommended Operating Conditions	
		Min	**Max**
1	+3.3V	+3.3V	+3.6V
2	GND	-	-

*For best performance it is suggested that sense wires be used on each 3.3V power domain

Table 6: Current ratings for 3.3V connectors

Current	Description	Max
I₁	+3.3V sourcing current	10A (protected by PTC fuse on power board)
I₂	GND sinking current	30A (Unprotected)

Table 7: Pin functions for 3.3V sense connectors (applies to J9 and J10 on breakout board)

Pin Number	Description
1	+ sense
2	- sense

6.2.2 Power in connector (-5V) - Pin characteristics

Table 8: Pin functions and recommended operating conditions for -5V connectors (applies to J1 and J3 on breakout board)

Pin Number	Description	Recommended Operating Conditions	
		Min	**Max**
1	-5V	-4.5V	-5.5V
2	GND	-	-

Table 9: Current ratings for -5V connector

Current	Description	Max
I₁	-5V sinking current	1.1A (protected by PTC fuse on power board)
I₂	GND sourcing current	30A (Unprotected)

Table 10: Pin functions for -5V sense connector (applies to J11)

Pin Number	Description
1	- sense
2	+ sense

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Table 11: Pin functions (applies to J4 on breakout board)

Pin Num	I2C ch	Name	Description	Type	Direction
1	Main	SDA1_WRITE_N[1]	I2C data in line	Differential (N)	Input
2	Main	SDA1_WRITE_P[1]	I2C data in line	Differential (P)	Input
3	Main	SCL1_WRITE_N[1]	I2C clock in line	Differential (N)	Input
4	Main	SCL1_WRITE_P[1]	I2C clock in line	Differential (P)	Input
5	-	GND[2]	External ground	-	-
6	-	GND[2]	External ground	-	-
7	Main	SCL1_READ_N[1]	I2C clock out line	Differential (N)	Output
8	Main	SCL1_READ_P[1]	I2C clock out line	Differential (P)	Output
9	Main	SDA1_READ_N[1]	I2C data out line	Differential (N)	Output
10	Main	SDA1_READ_P[1]	I2C data out line	Differential (P)	Output
11	Aux	SDA1_AUX_WRITE_N[1]	I2C data in line	Differential (N)	Input
12	Aux	SDA1_AUX_WRITE_P[1]	I2C data in line	Differential (P)	Input
13	Aux	SCL1_AUX_WRITE_N[1]	I2C clock in line	Differential (N)	Input
14	Aux	SCL1_AUX_WRITE_P[1]	I2C clock in line	Differential (P)	Input
15	-	GND[2]	External ground	-	-
16	-	GND[2]	External ground	-	-
17	Aux	SCL1_AUX_READ_N[1]	I2C clock out line	Differential (N)	Output
18	Aux	SCL1_AUX_READ_P[1]	I2C clock out line	Differential (P)	Output
19	Aux	SDA1_AUX_READ_N[1]	I2C data out line	Differential (N)	Output
20	Aux	SDA1_AUX_READ_P[1]	I2C data out line	Differential (P)	Output

Note 1: The SDA and SCL bidirectional data line of the I2C protocol are split into two mono-directional lines (SDA*_READ and SCL*_WRITE).

Note 2: Pin 5, 6, 15 and 16 (all shorted together on the breakout board) must be connected to an external ground reference if AC or DC ground coupling via the breakout board is required. In such case a jumper must be placed on header J5 on the breakout board and values of capacitor C11 and resistor R1 on the breakout board may need to be reviewed to optimize coupling characteristics.

Table 12: Recommended operating conditions for differential input pins

Voltage level	Description	Min	Max
$|\Delta V_{IN}|$	Magnitude of differential input voltage	0.050V	+3.3V
V_{ABS-IN}	Absolute voltage at any differential input pin	-1.4V	+3.8V
$|\Delta V_{HYST}|$	Differential input voltage hysteresis	0V	+0.025V

Table 13: Specifications for differential output pins

Voltage level	Description	Min	Max
$|\Delta V_{OUT}|$	Magnitude of the differential output voltage	+0.48V	+0.65V
$V_{ABS-OUT}$	Absolute voltage at any differential output pin	GND	+2V

Table 14: Timing characteristics breakout board I2C interfaces (specified for signals SDA1_*_P and SCL1_*_P of "main" I2C interface, equivalent specifications for type N signals and for "aux" interface)

Name	Description	Min	Max
f_{SCL}	I2C clock frequency	-	100kHz
t_1	Bus-Free Time between Stop and Start	4.7us	-
t_2	SCL1_WRITE_P Hold time for start and repeated start	4us	-
t_3	Low period of SCL1_WRITE_P	4.7us	-
t_4	High period of SCL1_WRITE_P	4.0us	-
t_5	SCL1_WRITE_P setup time for stop	4us	-
t_6	SDA1_WRITE_P hold time	0	-
t_7	SDA1_WRITE_P setup time (also setup time for repeated start)	250ns	-
t_8	SDA1_WRITE_P and SCL1_WRITE_P rise time	-	1us
t_9	SDA1_WRITE_P and SCL1_WRITE_P fall time	-	300ns
t_{10}	SCL1_WRITE_P fall to SDA1_READ_P output (clock-to-output)		3.45us
t_{11}	SCL1_WRITE_P rise to SCL1_READ_P low (clock stretching)	0	1us

Note1: Differential input data signals (SCL1_READ and SDA1_WRITE) must be actively driven high in the high state.

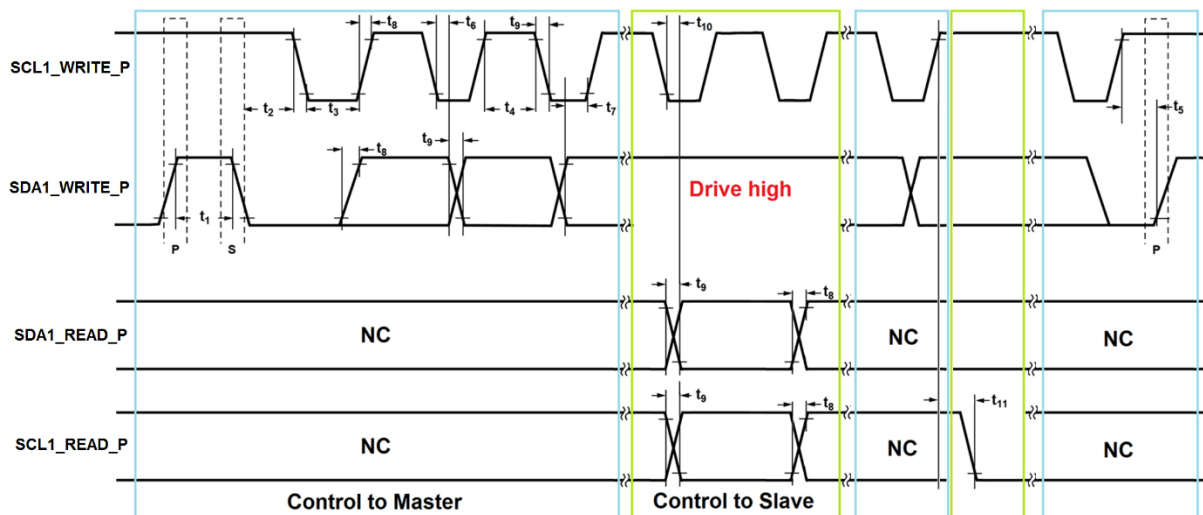Figure 5: Timing diagram for SCL1_*_P and SDA1_*_P lines (S = Start condition, P = Stop condition)

7 ASSEMBLING THE POWER SYSTEM

7.1 SINGLE MODULE TESTING SETUP

Single module testing stations will need to operate only two nominally 1.8V supply channels (1 digital and 1 analog voltage) and one bias channel on power unit 1. No cooling is required for this configuration. The connection scheme to external power supplies and configuration of the jumpers on the power board depends on whether a 6U is used as main source of power for the power board or if a standard power supply is used for this purpose. The following sections describe how to assemble the system in the two configurations.

7.1.1 Powering the power board using a power supply (default configuration)

Figure 6 shows how to configure the power for single module testing when a 6U VME crate is not available (wire size shown in the picture may be different than required, picture is meant for representation only). Sensing is not required if input power wire sizes are as specified in section 6.1. The following material is required:

- Two power supplies (5V/3A for the 3.3V and 5V/0.5A for the -5V, not provided)
- 1 x Breakout Board
- 2 x black connector (2-pin Molex 172672-2002 type)
- 4 x pins for the black connectors (Molex 171825-0100 type)
- 1 x readout cable (20-pin Samtec FFSD-10-D-40.00-01-N) for the connection to MOSAIC
- 2 x 0.2" jumper
- 4 x 1m-long wires for the input power to the power board (not provided)
- 5 x 1m-long wires (specs to be agreed with characterisation group) for output power and bias voltages to the modules (not provided)
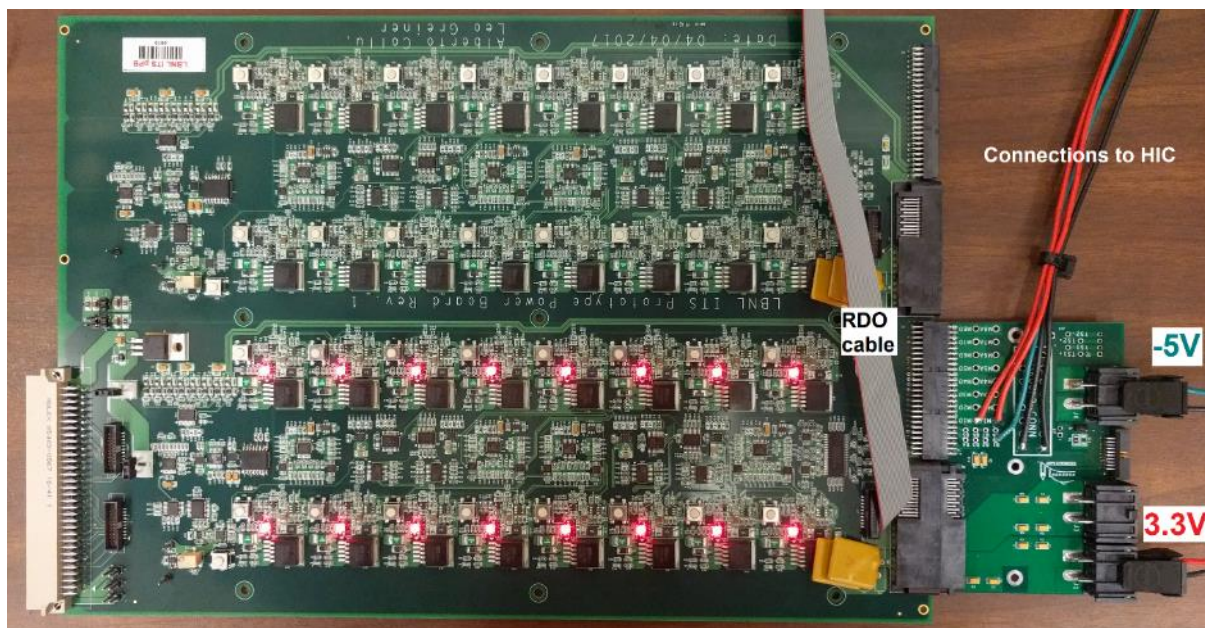

Figure 6: Power board connections for single module testing without a VME crate

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The user will be required to:

1) Build two power cables (one for the 3.3V voltage and one for the -5V voltage)
2) Solder 5 wires (for power to modules) on a breakout board (3 wires on M1A, M1D, B1 and 2 wires on "GROUND CONNS")
3) Load a 0.2" jumper on header J70 and another 0.2" jumper on header J71 (see Figure 7)
4) Connect the readout cable from MOSAIC to connector J72 on power unit 1
5) Connect each power cable to the corresponding power supply as shown in Figure 8. It is not required that the "+" side of the power supply for the -5V is shorted to the "-" side of the power supply for the 3.3V, since this connection is established by the breakout board.
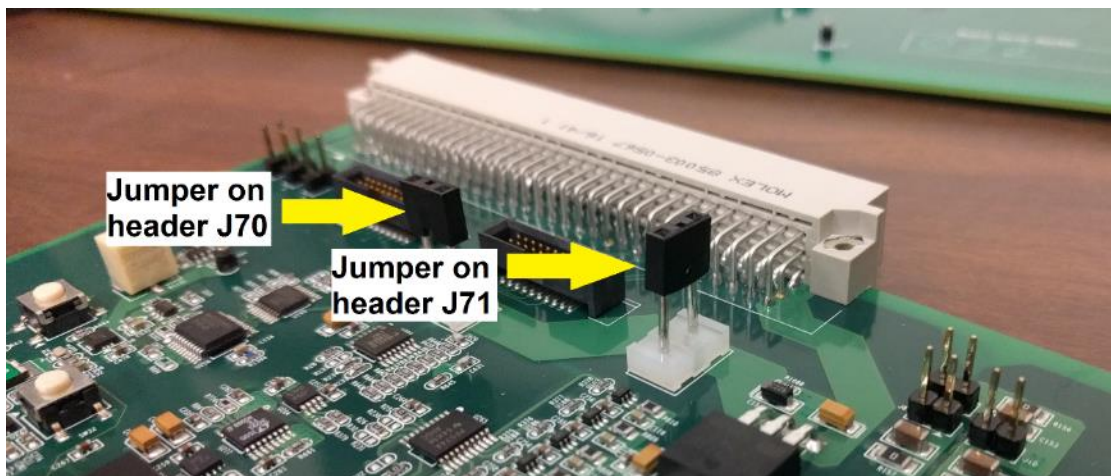

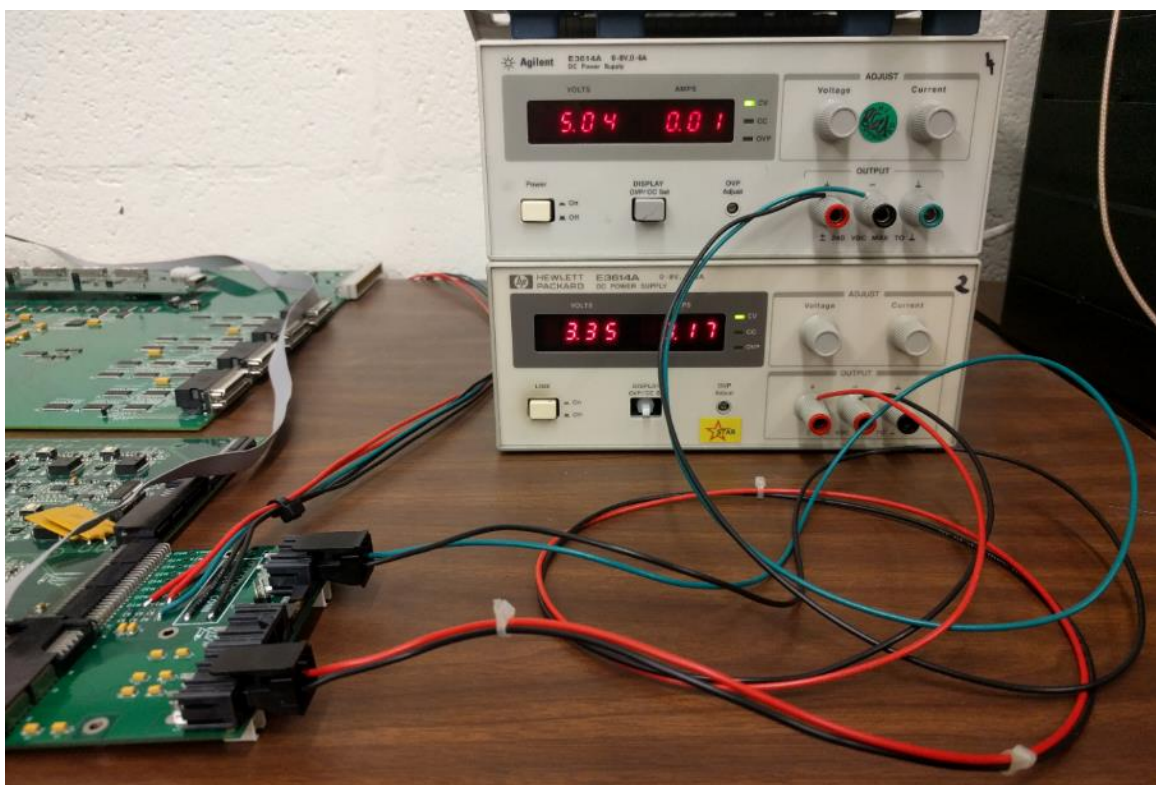**Figure 7: Power board jumper configuration without a 6U VME crate (single module testing only)**

Figure 8: Power supply connections to the breakout board - No VME crate configuration (single module testing only)

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7.1.2 Powering via a VME crate (requires front panel mechanics – not yet available)

Figure 9 shows how to configure the power for single module testing when a 6U VME crate is available (wire size shown in the picture may be different than required, this is meant for representation only). Sensing is not required if the size of the input power wires is as specified in section 6.1. The following material is required:

- 6U VME crate (3 or more slots must be available) and one power supply (5V/0.5A), not provided
- 1 x Breakout Board
- 1 x black connector (2-pin Molex 172672-2002 type)
- 2 x pins for the two black connector (Molex 171825-0100 type)
- 1 x readout cable (Samtec FFSD-10-D-40.00-01-N) for the connection to the MOSAIC board
- 2 x 0.2" jumper
- 1 x 0.1" jumper
- 2 x 1m-long wires for the input power to the power board (not provided)
- 5 x 1m-long wires (?) for output power and bias voltages to the modules (not provided)
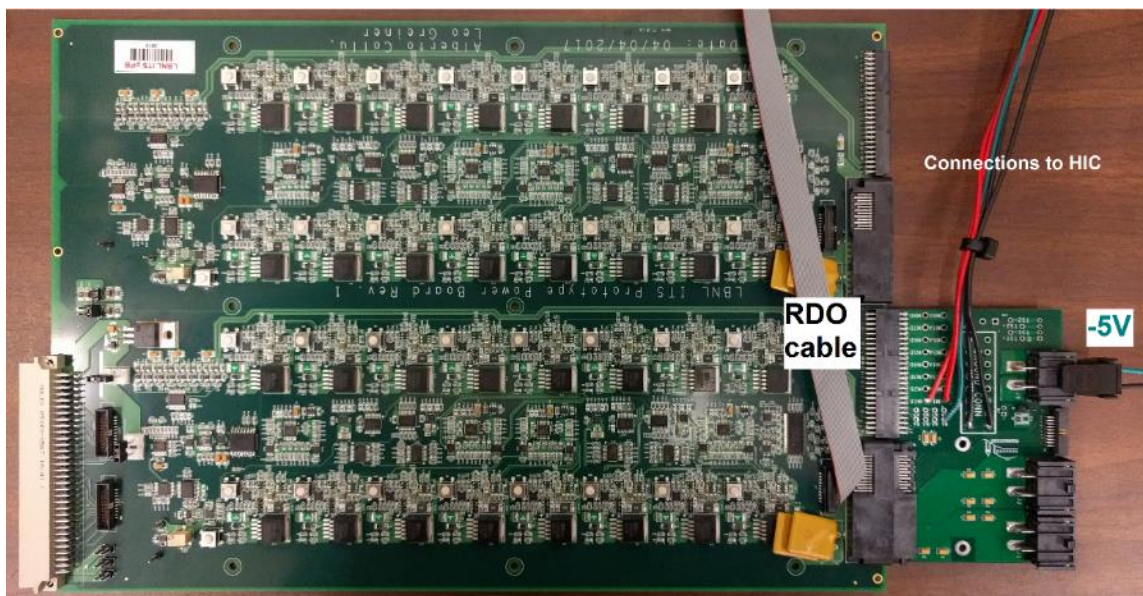
Figure 9: Power board connections for single module testing with a VME crate

The user will be required to:

1) Build a power cable for the -5V voltage
2) Solder 5 wires (for power to modules) on a breakout board (3 wires on M1A, M1D, B1 and 2 wires on "GROUND CONN")
3) Load a 0.2" jumper on header J70 and another 0.2" jumper on header J71 (see Figure 10)
4) Load a 0.1" jumper on header (see Figure 10)
5) Connect the readout cable from MOSAIC to connector J72
6) Plug the power board in the VME crate and connect the power cable to the power supply that provides the -5V (Figure 11). It is not required that the "+" side (black cable) of this power supply be connected to the ground of the VME crate, since this connection is established by the power board if jumper J8 is in place.

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Figure 10: Power board jumper configuration with VME (single module testing only)

Figure 11: Power board powered via a VME crate (not a 6U crate, picture is for representation only).

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7.2 ENDURANCE TESTS/STAVE TESTING RECOMMENDED SETUP

Multiple module testing stations (endurance tests or stave testing stations) will need to operate up to 14 channels per power unit. These stations require the use of active cooling as shown in Figure 12 and sense wires (not shown in Figure 12). VME crates cannot be used to provide power to the board. The following material is required (per power unit):

- Two power supplies (see specifications in the next sections, not provided)
- 1 x Breakout Board
- 3 x black connector (2-pin Molex 172672-2002 type)
- 6 x pin for the three black connectors (Molex 171825-0100 type)
- 1 x white connector (2-pin Molex 51103-0200 type)
- 2 x pins for white connector (Molex 50351-8000 type)
- 1 x readout cable (Samtec FFSD-10-D-40.00-01-N) for the connection to the MOSAIC board
- 6 x 1m-long wires for the input power (not provided)
- 2 x 1m-long wires for the sense connections to the 3.3V input voltage (not provided)
- Up to 35 x 1m-long wires (?) for output power and bias voltages to each module (not provided and not shown in the picture)
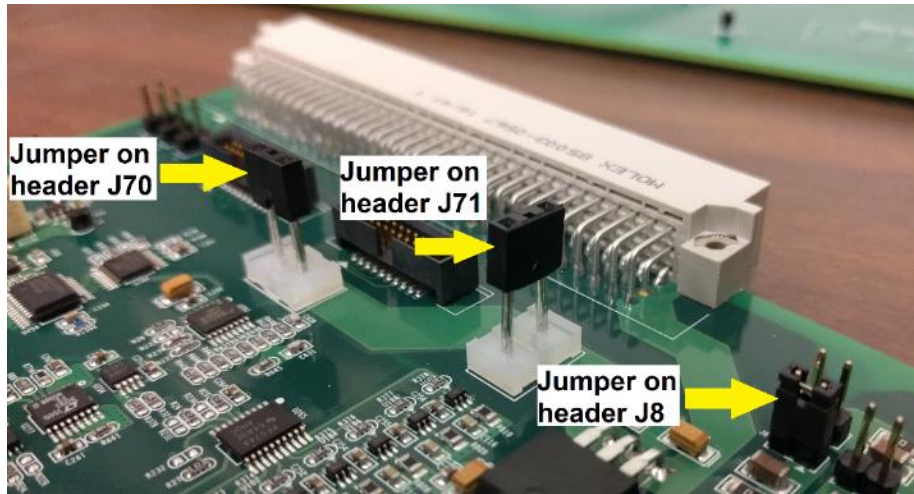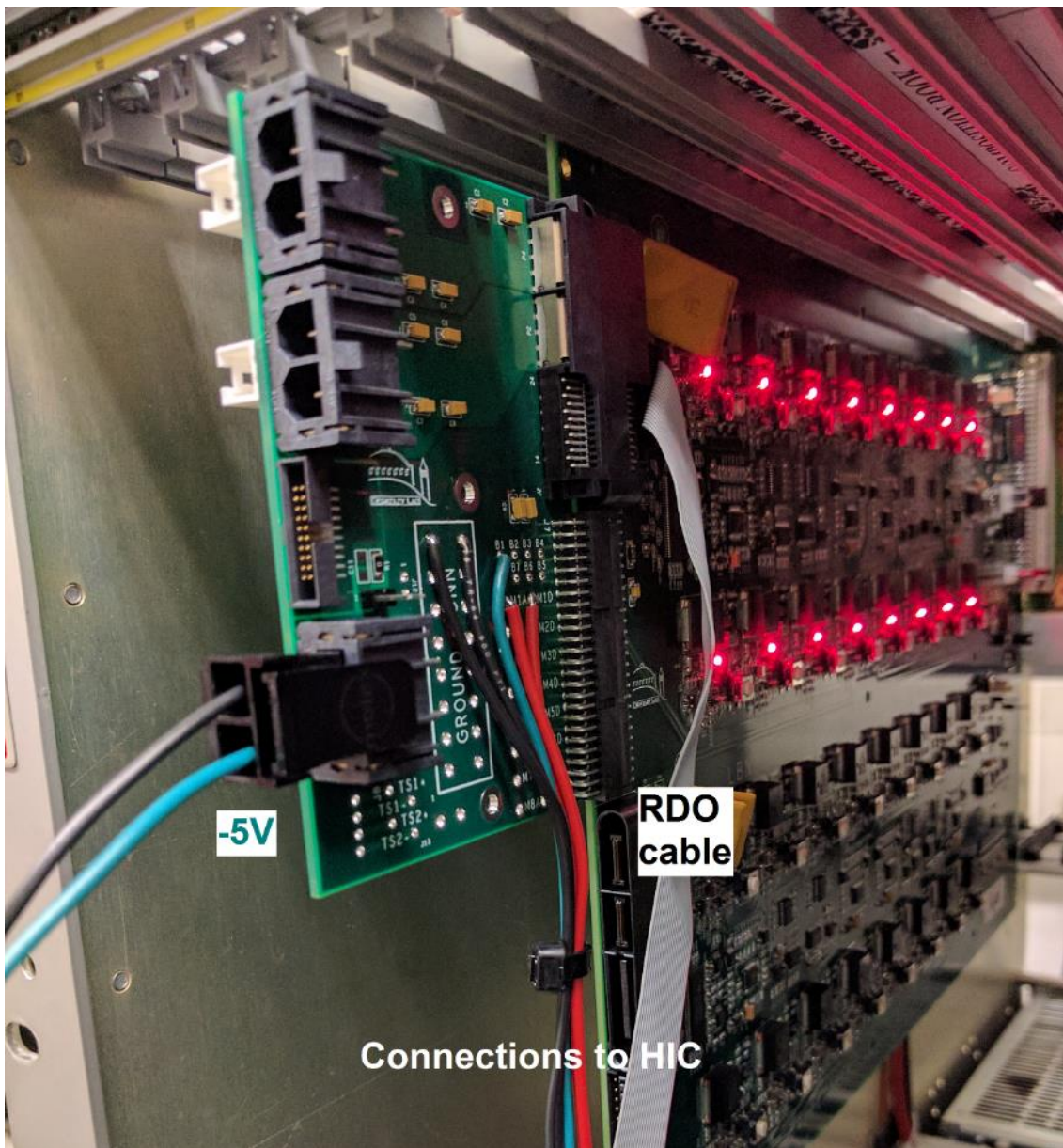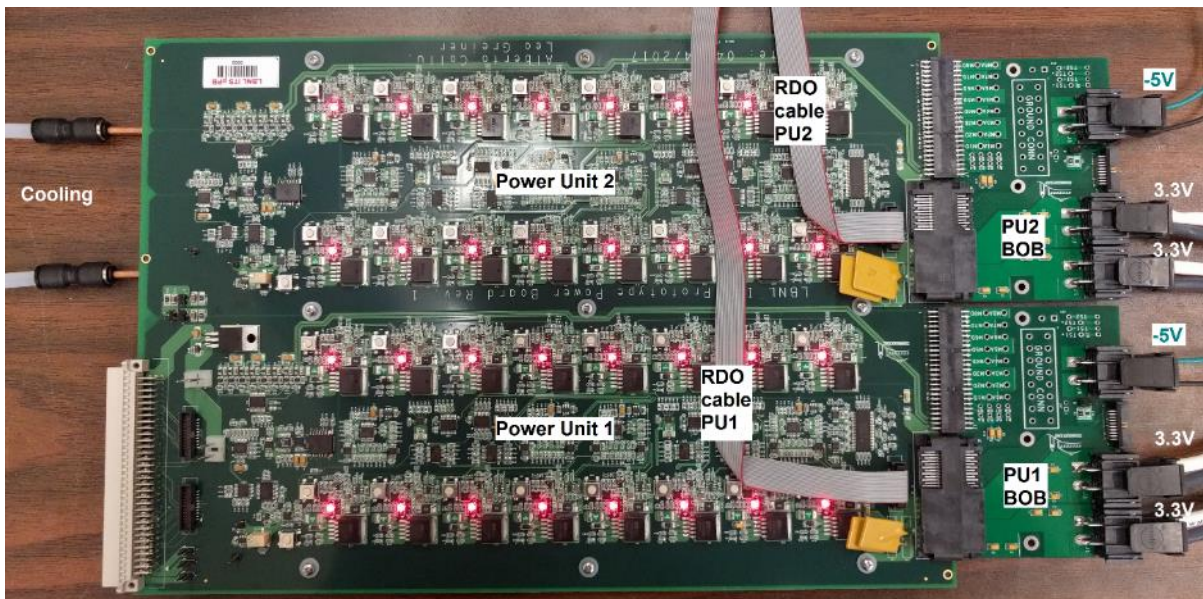

Figure 12: Endurance tests/stave testing power board configuration. Wire connections to modules not shown for simplicity.

The user will be required to (per power board):

1) Build 6 power cables (1 for the -5V and 2 for the 3.3V per power unit)
2) Build 2 sense cables (1 for the 3.3V per power unit)
3) Solder up to 35 wires on each breakout board (see next section for recommended configurations)
4) Make sure that no jumpers are present on the power board
5) Connect the readout cables from MOSAIC to connectors J72 (on power unit 1) and connector J75 (on power unit 2)

6) Connect each power and sense cable to the corresponding power supply (see Figure 13 for the scheme of connection and Figure 14 for an implementation):
   a) Connect two 3.3V power cables on each breakout board (a power supply will provide 3.3V to both breakout board domains)
   b) Connect a sense cable to the sense connector for 3.3V power domain 1 on each breakout board (see section 6.1 for pin polarity).
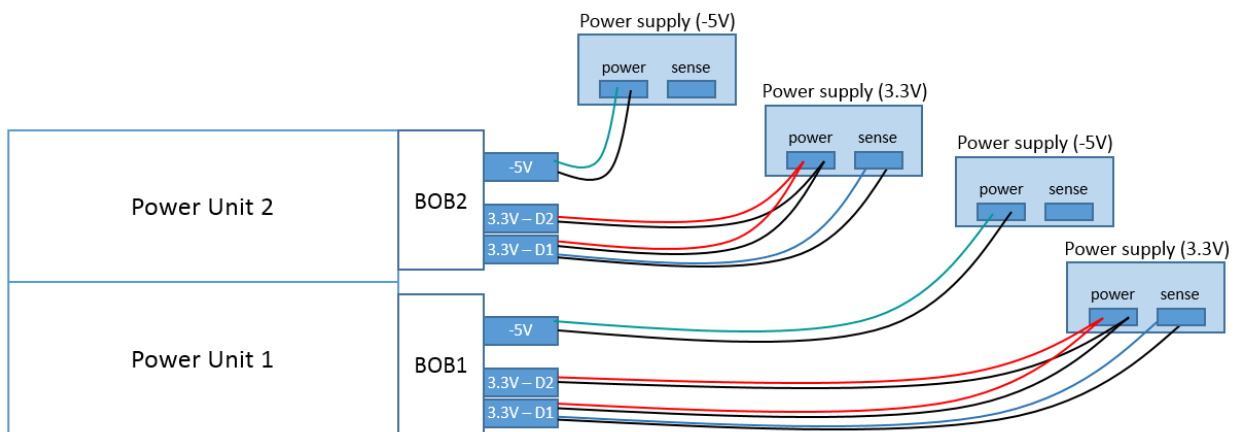

Figure 13: Configuration for power/sense wires at the input of the breakout boards
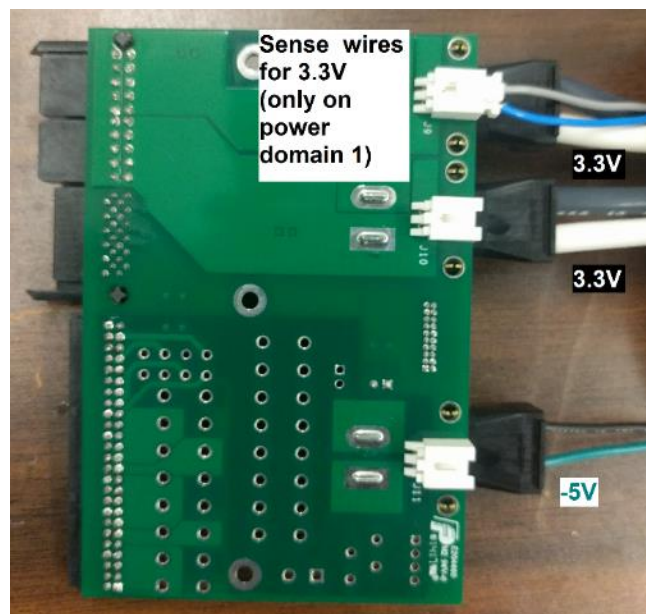

Figure 14: power unit sense wire configuration for endurance tests/stave testing

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Endurance tests: output power/bias connections

Endurance tests require 10 modules to be powered at the same time. The 3.3V input voltages to a power unit can be provided by the same power source (suggested power supply: 5V/10A with sense connection). An additional power supply per power unit is required for the input voltage to the bias circuitry (5V/1A). To minimize offsets and avoid overvoltage it is required that each power unit power 5 modules. In each power unit 3 modules may be powered via power domain 1 and 2 modules via power domain 2. This leads to the powering scheme represented in Table 15 for power and bias connections (for the ground connections, 10 wires per breakout board need to be soldered in the "GROUND CONN" island).

Table 15: Module connection scheme for endurance tests

Breakout Board #	Wire Connection Label on Breakout Board	Connections to modules
1	M1A	Module 1 Analog connection
	M1D	Module 1 Digital connection
	B1	Module 1 Bias connection
	M2A	Module 2 Analog connection
	M2D	Module 2 Digital connection
	B2	Module 2 Bias connection
	M3A	Module 3 Analog connection
	M3D	Module 3 Digital connection
	B3	Module 3 Bias connection
	M5A	Module 4 Analog connection
	M5D	Module 4 Digital connection
	B5	Module 4 Bias connection
	M6A	Module 5 Analog connection
	M6D	Module 5 Digital connection
	B6	Module 5 Bias connection
2	M1A	Module 6 Analog connection
	M1D	Module 6 Digital connection
	B1	Module 6 Bias connection
	M2A	Module 7 Analog connection
	M2D	Module 7 Digital connection
	B2	Module 7 Bias connection
	M3A	Module 8 Analog connection
	M3D	Module 8 Digital connection
	B3	Module 8 Bias connection
	M5A	Module 9 Analog connection
	M5D	Module 9 Digital connection
	B5	Module 9 Bias connection
	M6A	Module 10 Analog connection
	M6D	Module 10 Digital connection
	B6	Module 10 Bias connection

7.2.1 Stave testing: output power/bias connections

Stave testing requires up to 14 modules to be powered at the same time. The 3.3V voltages to a power unit can be provided by the same power source (suggested power supply: 5V/15A with sense connection). An additional power supply per power unit is required for the input voltage to the bias circuitry (5V/1A). To minimize offsets and avoid overvoltage it is suggested that each power unit power a half stave (7 modules in an outer layer half stave). In each power unit, 4 half stave modules may be powered via power domain 1 and 3 half stave modules via power domain 2. This leads to the scheme represented in Table 16 for power and bias connections (14 ground connections per breakout board need to be soldered in the ""GROUND CONN" island).

Table 16: Module connection scheme for stave testing

Breakout Board #	Wire Connection Label on Breakout Board	Half stave/module connections
1	M1A	HS1/Mod1 Analog connection
	M1D	HS1/Mod1 Digital connection
	B1	HS1/Mod1 Bias connection
	M2A	HS1/Mod2 Analog connection
	M2D	HS1/Mod2 Digital connection
	B2	HS1/Mod2 Bias connection
	M3A	HS1/Mod3 Analog connection
	M3D	HS1/Mod3 Digital connection
	B3	HS1/Mod3 Bias connection
	M4A	HS1/Mod4 Analog connection
	M4D	HS1/Mod4 Digital connection
	B4	HS1/Mod4 Bias connection
	M5A	HS1/Mod5 Analog connection
	M5D	HS1/Mod5 Digital connection
	B5	HS1/Mod5 Bias connection
	M6A	HS1/Mod6 Analog connection
	M6D	HS1/Mod6 Digital connection
	B6	HS1/Mod6 Bias connection
	M7A	HS1/Mod7 Analog connection
	M7D	HS1/Mod7 Digital connection
	B7	HS1/Mod7 Bias connection
2	M1A	HS2/Mod1 Analog connection
	M1D	HS2/Mod1 Digital connection
	B1	HS2/Mod1 Bias connection
	M2A	HS2/Mod2 Analog connection
	M2D	HS2/Mod2 Digital connection
	B2	HS2/Mod2 Bias connection
	M3A	HS2/Mod3 Analog connection
	M3D	HS2/Mod3 Digital connection
	B3	HS2/Mod3 Bias connection
	M4A	HS2/Mod4 Analog connection
	M4D	HS2/Mod4 Digital connection
	B4	HS2/Mod4 Bias connection
	M5A	HS2/Mod5 Analog connection
	M5D	HS2/Mod5 Digital connection
	B5	HS2/Mod5 Bias connection
	M6A	HS2/Mod6 Analog connection
	M6D	HS2/Mod6 Digital connection
	B6	HS2/Mod6 Bias connection
	M7A	HS2/Mod7 Analog connection
	M7D	HS2/Mod7 Digital connection
	B7	HS2/Mod7 Bias connection

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8 I2C TRANSACTIONS

As mentioned previously, each power unit is equipped with a Samtec SHF-110-01-L-D-SM connector that allows it to interface to an external readout system. This connector carries the signals for two I2C interfaces with data (SDA) and clock (SCL) lines implemented as separate (mono-directional) read and write channels (SDA_WRITE and SDA_READ, see Paragraph 6.2.3 for electrical specifications). The following lines illustrate how transactions are performed through one of these interfaces.

Each transaction is always initiated by the external board and can be of three types represented Figure 15, Figure 16 and Figure 17 (write, read and read with repeated start). Each x-bit field represented in any table or figure in the following sections is intended to be transmitted/received with the most significant bit going out/coming in first.
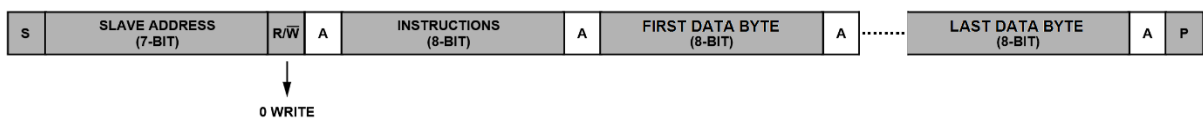
Figure 15: I2C write transaction (Grey = control to Master, White = control to Slave, S = Start, A = ACK, P = Stop)

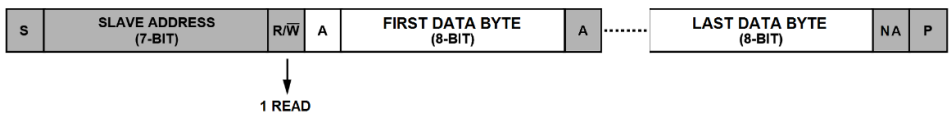**Figure 16: I2C read transaction (Grey = control to Master, White = control to Slave, NA = NOT ACK)**
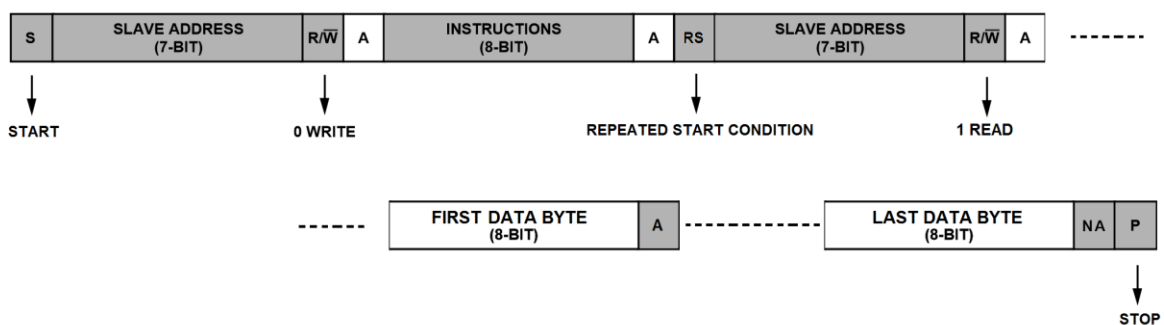

Figure 17: I2C read transaction with repeated start (Grey = control to Master, White = control to Slave, RS = rep start)

The following sections describe the I2C transactions that are required to operate a power unit. Commands are for power unit 1 but equivalent commands may be used for power unit 2.

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9 OPERATING THE SYSTEM

9.1 SETTING A TEMPERATURE THRESHOLD

An over-temperature mechanism is implemented in the system that switches off power to the regulators in case the temperature of the heat exchanger exceeds a default threshold of 70°C.

Upon power on of the board this mechanism is disabled. In order to enable it is necessary to bias the on-board temperature sensor performing an I2C write transaction to the "I2C main interface" of the target power unit as shown in Table 17 (start, acknowledge and stop bits are not reported).

Table 17: Write transaction to bias the temperature sensor used by the over-temperature circuit (all values are binary)

Trans type	Slave address + R/W bit		Instruction 1	Instruction 2	Data byte
write	0101000	0	00000001	10000000	1100001[FREQ]

The 1-bit FREQ field must be set high if the frequency of the mains power system is 50Hz, zero otherwise.

The default threshold may be modified by acting on trimmer R1135 (R1136 on power unit2, see Figure 18). This causes the voltage on test point J4 and J3 respectively to change. Press SW34 switch (SW27 in power unit 2) to reset the over-temperature protection circuit at the end of the procedure. Make sure that D2 red LED is off (D34 in power unit 2).
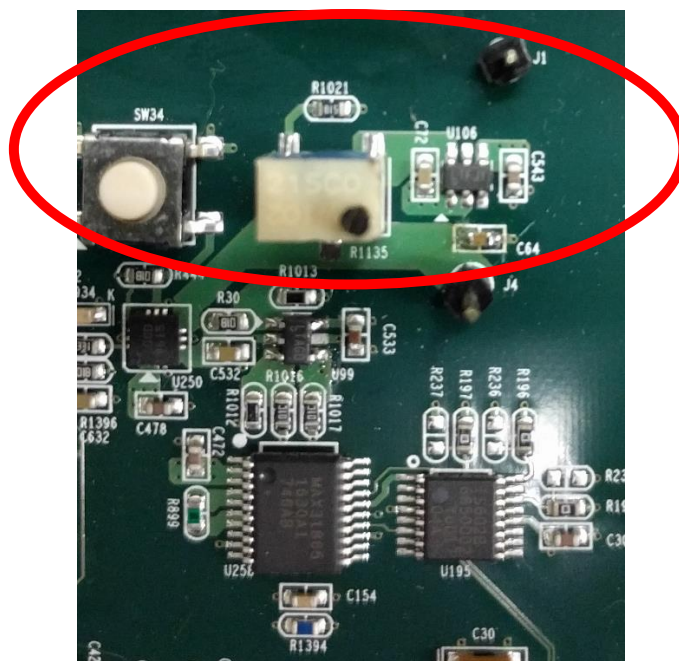
Figure 18: Trimmer and test point used to set the threshold for the over-temperature protection circuit. The switch is used to reset the circuit after the occurrence of an over-temperature condition

9.2 SETTING THE CURRENT THRESHOLDS

Each 1.8V power supply channel is protected by an independent over-current circuit with a default threshold of 1.5A for the digital channels and 250mA for the analog channels. The 16 default current thresholds may be modified via I2C using four on-board 12-bit DAC IC. Each of these DAC IC controls the thresholds for 4 supply channels. Table 18 describes a generic I2C transaction to the "I2C main interface" to set the threshold of a given channel (or group of channels).

Table 18: Single transaction used to set one or all current threshold for the over-current circuits (all values are binary)

Trans type	Slave address + R/W bit		Instruction	Data byte 1	Data byte 2
write	[SL_ADDR]	0	0011[TH_ID]	$[I_{th}^{DIG}$_H]	$[I_{th}^{DIG}$_L]xxxx

The 7-bit field SL_ADDR is the full slave address of one of the DAC IC on the power unit. The 4-bit field TH_ID represents the identification number of the DAC channel on the selected DAC IC. See Table 19 for details about the possible combinations of SL_ADDR and TH_ID.

The 8-bit and 4-bit fields (I_{th}^{DIG}_H and I_{th}^{DIG}_L) in Table 18 are the most and least significant part of the digital value (I_{th}^{DIG}) of the current threshold (I_{th}). This value has to be derived from the following formula:

$$I_{th}^{DIG} = 410 + \frac{3685}{3A} I_{th}$$

Table 19: List of the values for SL_ADDR and TH_ID field and related functions

SL_ADDR	TH_ID	Function
0x52	0000	Set threshold for Module 1 analog voltage (CH1)
	0001	Set threshold for Module 1 digital voltage (CH2)
	0010	Set threshold for Module 2 analog voltage (CH3)
	0011	Set threshold for Module 2 digital voltage (CH4)
	1111	Broadcast: set thresholds for CH1-4
0x60	0000	Set threshold for Module 3 analog voltage (CH5)
	0001	Set threshold for Module 3 digital voltage (CH6)
	0010	Set threshold for Module 4 analog voltage (CH7)
	0011	Set threshold for Module 4 digital voltage (CH8)
	1111	Broadcast: set thresholds for CH5-8
0x70	0000	Set threshold for Module 5 analog voltage (CH9)
	0001	Set threshold for Module 5 digital voltage (CH10)
	0010	Set threshold for Module 6 analog voltage (CH11)
	0011	Set threshold for Module 6 digital voltage (CH12)
	1111	Broadcast: set thresholds for CH9-12
0x72	0000	Set threshold for Module 7 analog voltage (CH13)
	0001	Set threshold for Module 7 digital voltage (CH14)
	0010	Set threshold for Module 8 analog voltage (CH15)
	0011	Set threshold for Module 8 digital voltage (CH16)
	1111	Broadcast: set thresholds for CH13-16

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9.3 ADJUSTING THE OUTPUT VOLTAGES

As mentioned previously, this system allows the nominally 1.8V output voltages to be adjusted in the range ~1.5-2.7V (it is however important to not exceed 2.5V, such voltages are indeed out of the ADC dynamic range, see section 9.7). The exact range for the voltages varies from channel to channel due to the non-negligible tolerance on the end-to-end resistance of the 8-bit digital potentiometers used to bias the circuit.

This output voltage adjustment feature can be used to compensate for voltage drops across the power and return paths that connect the power system to the modules, and allow them to operate with power within the operational 1.62V-1.98V range. An I2C transaction to the digital potentiometers via the "I2C main interface" is required to set the voltage to each supply channel on a power unit (see Table 20).

Table 20: Single transaction used to adjust the voltage of the regulators (all values are binary)

Trans type	Slave address + R/W bit		Instruction	Data byte
write	[SL_ADDR]	0	000000[V_ID]	R_{out}^{DIG}

The 7-bit field SL_ADDR is the full slave address of one of the DAC IC on the power unit. 2-bit field V_ID is used to select one of the four 1.8V channels. See Table 21 for details about the possible combinations of SL_ADDR and TH_ID.

The 8-bit R_{out}^{DIG} field is the digital value of the output resistance of the selected digital potentiometer channel. Its value has to be calculated using the following formula (valid in the range 1.49V-2.72):

$$R_{out}^{DIG} = \frac{V_{out}}{0.00486} - 306$$

where V_{out} is the output voltage of the targeted channel. Due to the tolerance on the end-to-end resistance of the digital potentiometers this formula is affected by 20% error maximum (the on-board ADC channels can be used to calibrate the output voltage settings or other precision methods can be used according to the datasheet of AD5254 digital potentiometer)

Table 21: List of the possible values for field V_ID

SL_ADDR	V_ID	Function
0x2C	00	Set threshold for Module 1 analog voltage (CH1)
	01	Set threshold for Module 1 digital voltage (CH2)
	10	Set threshold for Module 2 analog voltage (CH3)
	11	Set threshold for Module 2 digital voltage (CH4)
0x2D	00	Set threshold for Module 3 analog voltage (CH5)
	01	Set threshold for Module 3 digital voltage (CH6)
	10	Set threshold for Module 4 analog voltage (CH7)

	11	Set threshold for Module 4 digital voltage (CH8)
	00	Set threshold for Module 5 analog voltage (CH9)
0x2E	01	Set threshold for Module 5 digital voltage (CH10)
	10	Set threshold for Module 6 analog voltage (CH11)
	11	Set threshold for Module 6 digital voltage (CH12)
	00	Set threshold for Module 7 analog voltage (CH13)
0x2F	01	Set threshold for Module 7 digital voltage (CH14)
	10	Set threshold for Module 8 analog voltage (CH15)
	11	Set threshold for Module 8 digital voltage (CH16)

Once a digital potentiometer has been set, the selected value can be stored permanently inside the digital potentiometer itself so that it is automatically recalled any time the system is powered on. This can be done performing the transaction described in Table 22.

Table 22: Single transaction used to set the non-volatile memory of a digital potentiometer (all values are binary)

Trans type	Slave address + R/W bit		Instruction
write	[SL_ADDR]	0	100100[V_ID]

The values stored in the digital potentiometers can be recalled at any time using the transaction described in Table 23.

Table 23: Single transaction used to recall a value from the non-volatile memory of a digital potentiometer (all values are binary)

Trans type	Slave address + R/W bit		Instruction
write	[SL_ADDR]	0	000100[V_ID]

9.4 SETTING THE BIAS VOLTAGES

Each power unit embeds 8 additional low-current channels that can be used to bias up to 8 sensor modules. These bias circuits include a negative voltage regulator controlled by an 8-bit digital potentiometer - which generates a common voltage for the 8 low-current channels (range from GND to -4.5V) – and 8 FET double switches that provide either a solid connection to ground or to the adjustable voltage coming from the negative voltage regulator. This section describes how to set the output voltage of the regulator performing an I2C transaction to the digital potentiometer via the "I2C main interface" (see Table 24). For details on how to drive the double switches to switch between ground and the negative voltage refer to section 9.5.

Table 24: Single transaction used to set the bias voltage for the substrates of the sensors (all values are binary)

Trans type	Slave address + R/W bit		Instruction	Data byte
write	0101001	0	00010001	R_{bias}^{DIG}

The 8-bit R_{bias}^{DIG} field is the digital value of the bias voltage to be applied to the sensors. This value has to be chosen using the following equation

$$V_{bias} = -\frac{5}{125} R_{bias}^{DIG}$$

The bias voltage may saturate around and above R_{bias}^{DIG} values of 125 depending on the end-to-end resistance of the digital potentiometer (25% tolerance). Once the digital potentiometer has been set, the selected value can be stored permanently inside the digital potentiometer itself so that it is automatically recalled any time the system is powered on. This can be done performing the transaction described in Table 25.

Table 25: Single transaction used to set the non-volatile memory of the digital potentiometer (all values are binary)

Trans type	Slave address + R/W bit		Instruction	Data byte
write	0101001	0	01010001	xxxxxxxx

Furthermore the value stored in the digital potentiometer can be recalled at any time according to the procedure at Table 26.

Table 26: Single transaction used to recall the value written in the non-volatile memory of the digital potentiometer

Trans type	Slave address + R/W bit		Instruction	Data byte
write	0101001	0	01100001	xxxxxxxx

9.5 ENABLING SUPPLY AND BIAS CHANNELS

Once the current thresholds and all the voltages are set, it is possible to switch on the output channels of the power unit using two on-board open drain IO expanders each driving 8 supply channels. A generic transaction to access these IO expanders via the "I2C aux interface" is shown in Table 27.

Table 27: Single transaction used to activate the supply outputs on a power unit (all values are binary)

Trans type	Slave address + R/W bit		Data byte
write	[SL_ADDR]	0	[IO_EN]

The 7-bit field SL_ADDR is the full slave address of one of the two IO expander IC on the power unit. The 8-bit field IO_EN is used to enable or disable up to 8 supply channels per digital potentiometer IC. See Table 28 for details about the possible combinations of SL_ADDR and IO_EN.

Table 28: IO_EN field bits state and functions for supply voltages IO expanders

SL_ADDR	IO_EN bits	Description
0x38	0	Enable Module 1 analog – CH1
	1	Enable Module 1 digital – CH2
	2	Enable Module 2 analog – CH3
	3	Enable Module 2 digital – CH4
	4	Enable Module 3 analog – CH5
	5	Enable Module 3 digital – CH6
	6	Enable Module 4 analog – CH7
	7	Enable Module 4 digital – CH8
0x39	0	Enable Module 5 analog – CH9
	1	Enable Module 5 digital – CH10
	2	Enable Module 6 analog – CH11
	3	Enable Module 6 digital – CH12
	4	Enable Module 7 analog – CH13
	5	Enable Module 7 digital – CH14
	6	Enable Module 8 analog – CH15
	7	Enable Module 8 digital – CH16

In order to enable a 1.8V channel, the corresponding bit has will be set high. The red LED that signals an overcurrent condition (on at board power on) will switch off and the channel green LED will switch on (since its brightness depends on the output voltage of the channel it may not be visible). The channel will stay enabled until an overcurrent condition occurs. However it can be switched off following one of the two procedures:

1) Triggering the over-current protection circuit. The current threshold for the channel is lowered below the current drawn by the channel (can be set to 0x000). This will trigger the over-current protection circuit (the green LED will be switched off and the red LED will be switched back on).

2) Disabling the regulator. The corresponding bit in the IO_EN string is lowered. The green LED will be switched off but the red LED will not be switched on (no overcurrent condition has occurred).

As already mentioned, each of the bias outputs can be either grounded or tied to a specific negative voltage level adjustable in the range from GND to -4.5V. In order to switch between the two voltage levels it is necessary to perform a write transaction to an IO expander via the "I2C main interface" as shown in Table 29.

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Table 29: Single transaction used to activate the supply outputs on a power unit (all values are binary)

Trans type	Slave address + R/W bit		Data byte
write	0111000	0	[IO_EN]

The 8-bit field IO_EN must be set according to Table 30 to either ground the bias channels or set them to a negative voltage.

Table 30: IO_EN field bits state and functions for bias IO expander

SL_ADDR	IO_EN bits	State	
		high (default @ poweron)	low
0x38	0	Bias channel 1 is grounded	Bias channel 1 set to adjustable voltage
	1	Bias channel 2 is grounded	Bias channel 2 set to adjustable voltage
	2	Bias channel 3 is grounded	Bias channel 3 set to adjustable voltage
	3	Bias channel 4 is grounded	Bias channel 4 set to adjustable voltage
	4	Bias channel 5 is grounded	Bias channel 5 set to adjustable voltage
	5	Bias channel 6 is grounded	Bias channel 6 set to adjustable voltage
	6	Bias channel 7 is grounded	Bias channel 7 set to adjustable voltage
	7	Bias channel 8 is grounded	Bias channel 8 set to adjustable voltage

It has to be noticed that there is no LED that indicates whether the bias voltage is at a voltage lower than ground.

The system allows one to monitor the voltage at the output of the negative voltage regulator and the total current drawn by all the FET switches (refer to section 9.7 for more details on this monitoring feature).

9.6 CHECKING REMOTELY THE STATUS OF THE POWER OUTPUTS

During operation of the power system one of the following events may occur:

1) The system is automatically switched off due to an over-temperature condition. D2 LED (D34 LED in the case of power unit 2) will turn on and the downstream circuitry, which includes the 16 1.8V channels (but not the bias circuit) will be switched off together with any other LEDs.

2) One or more 1.8V channels are switched off due to the occurrence of over-current conditions. In such case the green LEDs that correspond to the channels where the over-current conditions occurred will be switched off and the corresponding red LEDs will be switched on.

Either condition can be remotely identified by performing read transactions to the IO expanders previously used to enable the power/bias channels. Perform a read transaction to the IO expanders

as shown in Table 31 via the "I2C main interface" for reading the status of the bias channels and via the "I2C aux interface" for reading the status of the supply channels.

Trans type	Slave address + R/W bit		Data byte
read	[SL_ADDR]	1	[IO_STAT]

The 8-bit IO_STAT field contains the status of the power/bias channels (see Table 32). Since it is unlikely that an over-current condition occurs simultaneously in 16 power channels, if all the 16 power channels are found to be disabled, this may be due to an over-temperature condition.

Table 32: IO_STAT field bits state and functions for supply/bias voltages IO expanders

SL_ADDR	IO_STAT bits	Status	
		Low	High
0x38 (I2C aux channel)	0	Module 1 analog – CH1 disabled	Module 1 analog – CH1 enabled
	1	Module 1 digital – CH2 disabled	Module 1 digital – CH2 enabled
	2	Module 2 analog – CH3 disabled	Module 2 analog – CH3 enabled
	3	Module 2 digital – CH4 disabled	Module 2 digital – CH4 enabled
	4	Module 3 analog – CH5 disabled	Module 3 analog – CH5 enabled
	5	Module 3 digital – CH6 disabled	Module 3 digital – CH6 enabled
	6	Module 4 analog – CH7 disabled	Module 4 analog – CH7 enabled
	7	Module 4 digital – CH8 disabled	Module 4 digital – CH8 enabled
0x39 (I2C aux channel)	0	Module 5 analog – CH9 disabled	Module 5 analog – CH9 enabled
	1	Module 5 digital – CH10 disabled	Module 5 digital – CH10 enabled
	2	Module 6 analog – CH11 disabled	Module 6 analog – CH11 enabled
	3	Module 6 digital – CH12 disabled	Module 6 digital – CH12 enabled
	4	Module 7 analog – CH13 disabled	Module 7 analog – CH13 enabled
	5	Module 7 digital – CH14 disabled	Module 7 digital – CH14 enabled
	6	Module 8 analog – CH15 disabled	Module 8 analog – CH15 enabled
	7	Module 8 digital – CH16 disabled	Module 8 digital – CH16 enabled
0x38 (I2C main channel)	0	Module 1 bias – CH1 adj voltage	Module 1 bias – CH1 grounded
	1	Module 2 bias – CH2 adj voltage	Module 2 bias – CH2 grounded
	2	Module 3 bias – CH3 adj voltage	Module 3 bias – CH3 grounded
	3	Module 4 bias – CH4 adj voltage	Module 4 bias – CH4 grounded
	4	Module 5 bias – CH5 adj voltage	Module 5 bias – CH5 grounded
	5	Module 6 bias – CH6 adj voltage	Module 6 bias – CH6 grounded
	6	Module 7 bias – CH7 adj voltage	Module 7 bias – CH7 grounded
	7	Module 8 bias – CH8 adj voltage	Module 8 bias – CH8 grounded

9.7 MONITORING THE OUTPUT VOLTAGES AND CURRENTS

An important functionality of each power unit is the possibility to monitor all the generated power/bias voltages and the corresponding currents using a total of 5 8-channel ADC IC. This feature can be used during operation both to check the overall status of the system, e.g. protection status and/or spot malfunctioning, and as feedback mechanism to finely adjust the output voltages of the power supply channels.

Each ADC IC needs to be configured before its use. This can be done performing four write transactions to its configuration/conversion registers via the "I2C main interface" as shown in Table 33

Table 33: Write transaction used to set the advanced configuration register of an ADC IC

Trans type	Sl addr + R/W		Instruction	Data byte
write	[SL_ADDR]	0	00000000	00000000
write	[SL_ADDR]	0	00000111	00000001
write	[SL_ADDR]	0	00001011	00000010
write	[SL_ADDR]	0	00000000	00000001

The 7-bit field SL_ADDR is the address of the target ADC IC (see Table 34 for a list of the various slave addresses).

Table 34: List the ADC IC slave addresses, channels and descriptions for power unit 1

SL_ADDR	CH_ID	Channel description
0x1D	000	Module 1 analog voltage
	001	Module 1 analog current
	010	Module 1 digital voltage
	011	Module 1 digital current
	100	Module 2 analog voltage
	101	Module 2 analog current
	110	Module 2 digital voltage
	111	Module 2 digital current
0x1F	000	Module 3 analog voltage
	001	Module 3 analog current
	010	Module 3 digital voltage
	011	Module 3 digital current
	100	Module 4 analog voltage
	101	Module 4 analog current
	110	Module 4 digital voltage
	111	Module 4 digital current
0x35	000	Module 5 analog voltage
	001	Module 5 analog current
	010	Module 5 digital voltage

	011	Module 5 digital current
	100	Module 6 analog voltage
	101	Module 6 analog current
	110	Module 6 digital voltage
	111	Module 6 digital current
0x37	000	Module 7 analog voltage
	001	Module 7 analog current
	010	Module 7 digital voltage
	011	Module 7 digital current
	100	Module 8 analog voltage
	101	Module 8 analog current
	110	Module 8 digital voltage
	111	Module 8 digital current
0x1E	000	Bias negative regulator current
	010	Bias negative regulator voltage

Once the ADC IC are configured, it is necessary to select a specific channel to read on a target ADC IC performing a write transaction to it as shown in Table 35.

Table 35: Write transaction used to select the ADC channel to read

Trans type	Sl addr + R/W		Instruction
write	[SL_ADDR]	0	00100[CH_ID]

The 3-bit field CH_ID represents the target channel to set for reading (see Table 34 for a detailed description).

At this point the voltage/current value can be read from the target ADC IC performing a read transaction as shown in Table 36.

Table 36: Read transaction used to read the preselected ADC channel

Trans type	Sl addr + R/W		Data byte 1	Data byte 2
read	[SL_ADDR]	1	$[ADC\_VAL\_M]$	$[ADC\_VAL\_L]$xxxx

The 8-bit and 4-bit fields ADC_VAL_M and ADC_VAL_L are the most significant and least significant part respectively of the 12-bit ADC_VAL which is an ADC sample coming from the preselected channel.

The following formulas can be used to determine the value of the sampled voltage/current:

a) Analog/Digital supply voltages:

$$V_{power} = \frac{2.56}{4096} ADC\_VAL$$

b) Analog/Digital supply currents (for power board v1.1, labelled v1):

$$I_{power} = \left[\left(\frac{2.56}{4096} ADC\_VAL - 0.25\right) * 1.337\right] + 0.013$$

c) Analog/Digital supply currents (for power board v1.2, labelled v1.1):

$$I_{power} = \left[\left(\frac{2.56}{4096} ADC\_VAL - 0.25\right) * 1.333\right]$$

d) Bias voltage:

$$V_{bias} = -\frac{5.12}{4096} ADC_{VAL}$$

e) Bias current:

$$I_{bias} = \frac{2.56}{4096} ADC\_VAL$$

As mentioned earlier, the dynamic range of the ADC channels is ~2.5V. Even if the system can deliver higher voltage levels, it is not recommended that this limit is exceeded. Based on how the system was designed it is expected that, using ~1m-long AWG 18 wires to provide digital power to a module, the total drop along the path (power plus return) will be below 40mV for nominal digital current conditions. In such conditions the voltage at the output of the regulator should never exceed 2.03 V or a module will be forced to work outside its safe operational voltage range, which will possibly lead to its failure.

Comment valid for power system v1.1 (labelled v1) only

The uncertainty on sampled voltages is below 2% above 100mA for the supply currents. Below 100mA the error is mostly dominated by the offset error of the chain from the first amplifier to the input of the ADC. Due to the limited common mode input voltage performance at very low current (below 50 mA) of the chosen resistor configuration for the current sensing amplifier, the current measurements provide good accuracy only in the range of output voltages below 2V. Other resistor configurations have been explorer that overcome such limitations. These will be adopted in the next version of the power board (v1.2 and next).

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9.7.1 Resistance of traces from the output of the regulators to the wire connection points on the breakout board

Voltage drops in the order of tens of mV are expected to occur at nominal current conditions along the traces that bring power to the modules (drops across bias traces are negligible). Table 37 contains a list of the resistance of these traces that can be used to compensate for such drops. The resistance of the ground connections is negligible and is not reported.

Trace Name	Trace description	Trace resistance [mΩ]
PU1 – CH1	From Regulator 1 on power unit 1 to M1A on breakout board	35
PU1 – CH2	From Regulator 2 on power unit 1 to M1D on breakout board	34
PU1 – CH3	From Regulator 3 on power unit 1 to M2A on breakout board	39
PU1 – CH4	From Regulator 4 on power unit 1 to M2D on breakout board	42
PU1 – CH5	From Regulator 5 on power unit 1 to M3A on breakout board	47
PU1 – CH6	From Regulator 6 on power unit 1 to M3D on breakout board	43
PU1 – CH7	From Regulator 7 on power unit 1 to M4A on breakout board	54
PU1 – CH8	From Regulator 8 on power unit 1 to M4D on breakout board	50
PU1 – CH9	From Regulator 9 on power unit 1 to M5A on breakout board	33
PU1 – CH10	From Regulator 10 on power unit 1 to M5D on breakout board	36
PU1 – CH11	From Regulator 11 on power unit 1 to M6A on breakout board	44
PU1 – CH12	From Regulator 12 on power unit 1 to M6D on breakout board	38
PU1 – CH13	From Regulator 13 on power unit 1 to M7A on breakout board	51
PU1 – CH14	From Regulator 14 on power unit 1 to M7D on breakout board	44
PU1 – CH15	From Regulator 15 on power unit 1 to M8A on breakout board	52
PU1 – CH16	From Regulator 16 on power unit 1 to M8D on breakout board	52
PU2 – CH1	From Regulator 1 on power unit 2 to M1A on breakout board	33
PU2 – CH2	From Regulator 2 on power unit 2 to M1D on breakout board	33
PU2 – CH3	From Regulator 3 on power unit 2 to M2A on breakout board	38
PU2 – CH4	From Regulator 4 on power unit 2 to M2D on breakout board	40
PU2 – CH5	From Regulator 5 on power unit 2 to M3A on breakout board	44
PU2 – CH6	From Regulator 6 on power unit 2 to M3D on breakout board	41
PU2 – CH7	From Regulator 7 on power unit 2 to M4A on breakout board	56
PU2 – CH8	From Regulator 8 on power unit 2 to M4D on breakout board	49
PU2 – CH9	From Regulator 9 on power unit 2 to M5A on breakout board	33
PU2 – CH10	From Regulator 10 on power unit 2 to M5D on breakout board	34

PU2 – CH11	From Regulator 11 on power unit 2 to M6A on breakout board	44
PU2 – CH12	From Regulator 12 on power unit 2 to M6D on breakout board	37
PU2 – CH13	From Regulator 13 on power unit 2 to M7A on breakout board	59
PU2 – CH14	From Regulator 14 on power unit 2 to M7D on breakout board	40
PU2 – CH15	From Regulator 15 on power unit 2 to M8A on breakout board	52
PU2 – CH16	From Regulator 16 on power unit 2 to M8D on breakout board	56

Table 37: Trace resistances from regulator outputs to wire soldering points on breakout board

9.8 MONITORING THE TEMPERATURE OF THE SYSTEM

Each power unit offers the feature to monitor its temperature (a PT100 temperature sensor is located on each power unit).

In order to read the temperature sensors it is first necessary to configure the on-board Resistance-to-Digital converters sending an I2C transaction to each of them (explained in section 9.1).

Once the RTD are configured, each temperature sensor can be read by performing a sequence of four I2C transactions via the "I2C main interface" (see Table 38).

Table 38: Sequence of transactions to read a temperature sensor connected to the power system (grey for bytes sent to slave, white for bytes sent by slave)

Trans type	Slave address + R/W bit		Instruction 1 or DB1	Instruction 2 or DB2	Instruction 3 or DB3
write	0101000	0	00000[TS_ID]	00000001	11111111
read	0101000	1	xxxxxxxx	RES_MSB	No data
write	0101000	0	00000[TS_ID]	00000010	11111111
read	0101000	1	xxxxxxxx	[RES_LSP]x	No data

The 8-bit RES_MSB field and 7-bit RES_LSB field are the most significant byte and least significant part respectively of the digitized value of the resistance of the temperature sensor (RES, 15 bits) identified by TS_ID ("No data" bytes must not be sent or received, the transaction ends the previous byte). The real value of the resistance of the temperature sensor can be extracted using the following formula (valid in the range 0°-100°, uncertainty 1%):

$$T(°C) = \frac{RES - 8192}{31.54}$$

10 INSTALLATION OF THE STAND-ALONE COOLING SYSTEM

NOTE: Please do not place the cooling system in a closed area (corner or box). Some of its components (e.g. pump) may overheat and break in the long run.

Depending on the operating mode of the power boards you have received, you may have one or more power boards with heat exchangers and stand-alone cooling systems. This section is intended to guide the user on the installation and operation of the power boards stand-alone cooling system.

The parts of the stand-alone cooling system are shown in the photograph below.

The parts include:

- Plastic jug of coolant
- Pump/radiator assembly
- Cooling tubes
- 12V Power supply
- Plug adapter

10.1 ASSEMBLY OF THE SYSTEM

Remove the plastic tube joining the output to the input of the pump/radiator assembly. Note that the systems are tested prior to shipment so the tube is installed to avoid having residual coolant leak in the box.
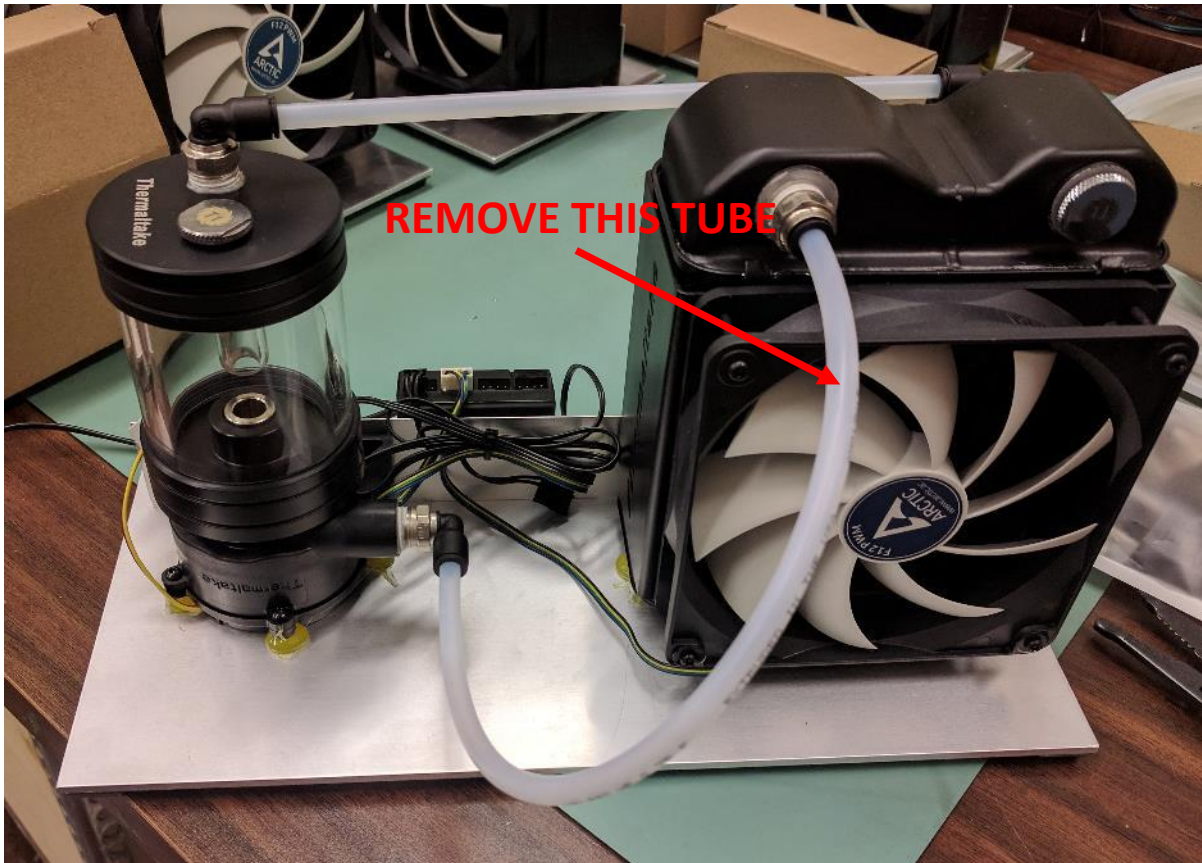

Use the supplied tubing and the mounted push-to-connect fittings to join the power board heat exchanger inlet and outlet to the pump/heat exchanger inlet and outlet ports. Note that the heat exchanger works with either direction of flow so the exact tube mating is not important. Then plug the power supply cable from the pump to the power supply.
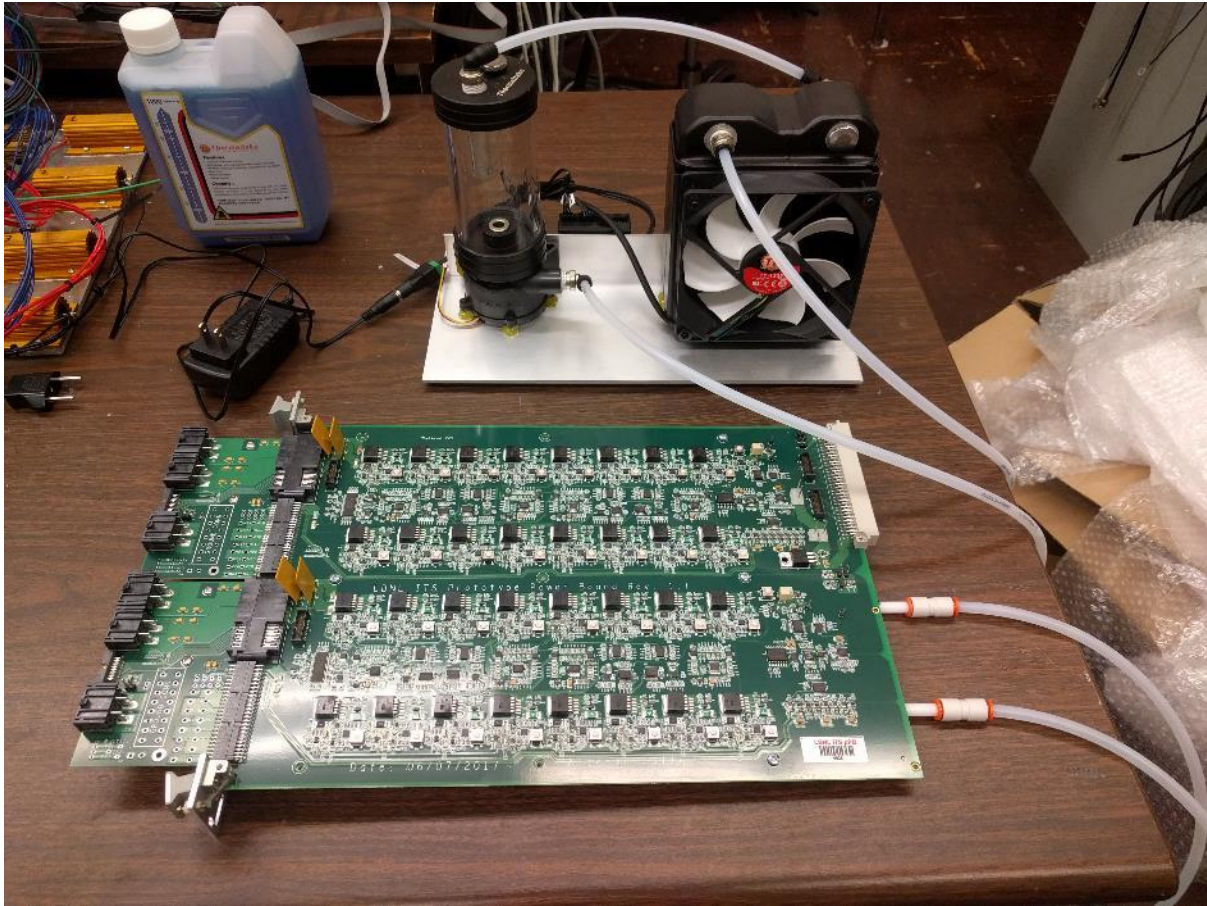
Now use the coolant to fill the reservoir on the tank through the fill port in the top of the reservoir.
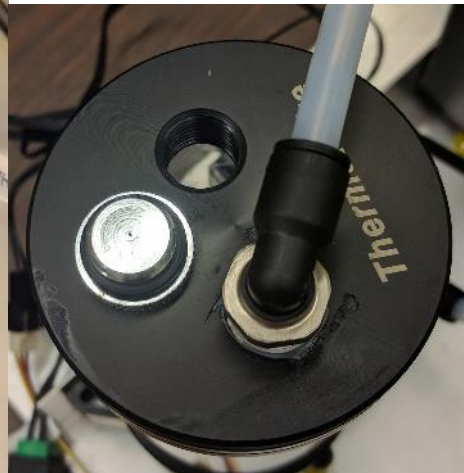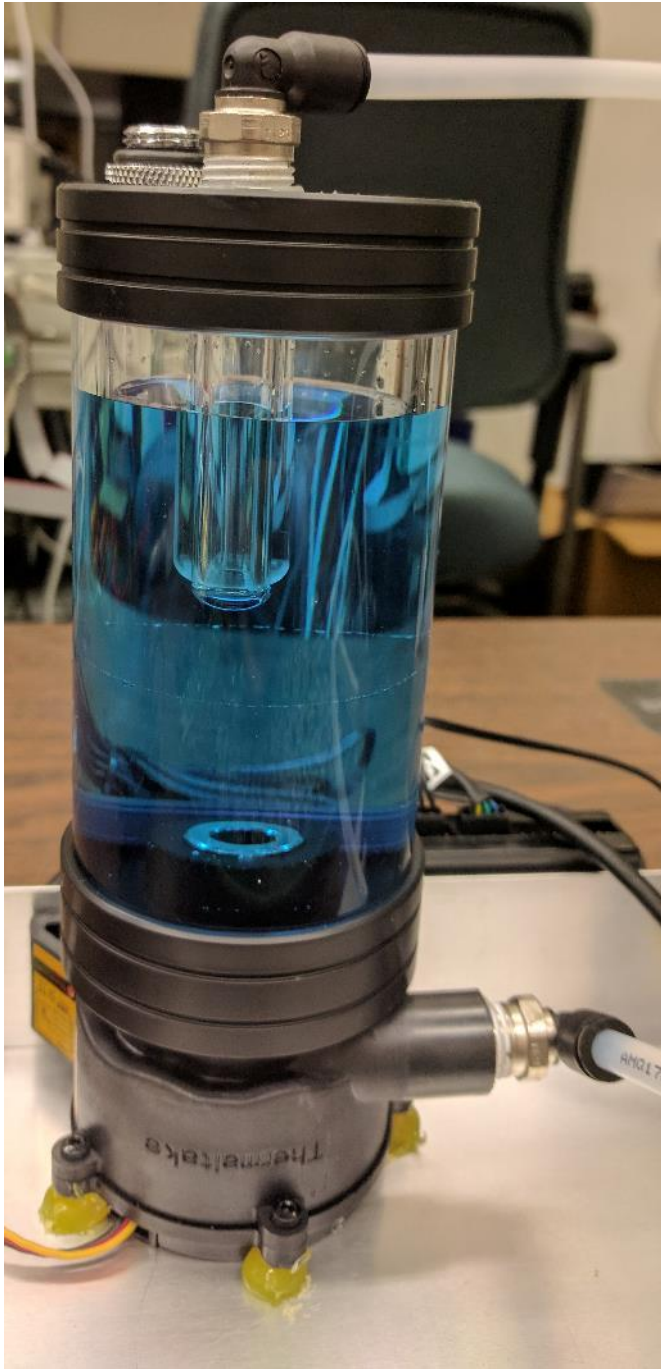
Plug the pump into the power outlet and let the pump start pumping the coolant through the tubes into the heat exchanger and radiator. The fan on the radiator should also start spinning. As the coolant level lowers, unplug the pump for ~30 seconds to let air bubbles trapped in the pump be released and add more coolant as needed. The pump should become less noisy as the trapped air is released. If the pump is still noisy after repeatedly applying and removing power, shake the cooling system from the base while it is running. This will help releasing the trapped air.

Repeat until the coolant is running from the return tube in the top of the reservoir in a steady stream and the reservoir has a good (more than half height) stock of coolant. Run for 15 minutes and check that the coolant flows well and that there are no leaks. Fix as needed.
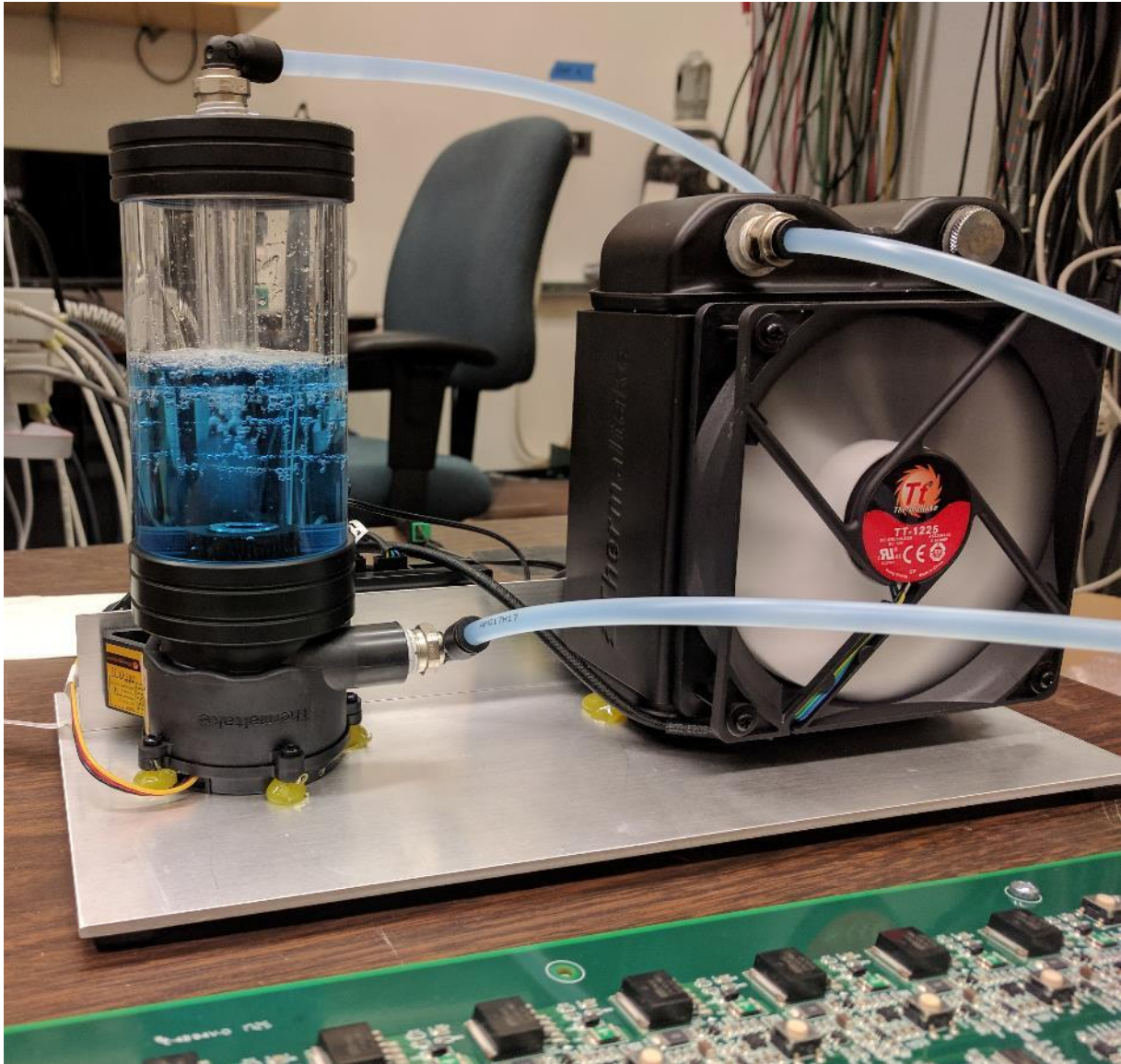
Periodically recheck that there are no leaks, that the fan is spinning and that the coolant is recirculating during use. If there are any questions or problems, please contact Alberto or Leo.

CONTACTS

In case any problems are encountered during the operation of the power system, please contact the developers:

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