IV Curve Multiplexer

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Version 1.1: Added bias voltage crosstalk test

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Contents

Goals and Specifications

Primary

- Enable unattended IV curve measurement of 100 SiPMs at working temperature (168K)
- 1pA resolution (target, may depend on conditions or require subtraction of background leakage)
- Using Keysight B2987A
- Compatible with SiPM boards designed for pulse testing

Secondary

- Possibility of placement inside chamber if number of feedthroughs needs to be minimized.

High level Architecture

Each board supplies 15 individually switched bias voltage outputs, nominally of positive polarity connected to SiPM cathodes. Connection of bias voltage is via reed relays, which are designed to be activated one at a time, to enable measurement of a single SiPM.

Each board also includes a sense switch, to selectively connect the B2987A ammeter input to the anode outputs, typically those of the 15 SiPMs to which the cathode bias switches are connected. When deactivated, the sense connection contributes <<1pA to the ammeter reading. This degree of isolation on the sense side enables several 15-channel boards to be ganged together, with minimally elevated leakage current, to reach the 100 channel requirement.

Up to 7 boards (including the master board) are supported under a single serial control connection, for a total of 105 channels. The master board is populated with an Arduino Nano Every microcontroller module (A1), and (typically) includes the B2987A bias voltage and ammeter connections, but is otherwise identical to the slave boards.

Note that the footprint is largely compatible with an earlier-version Nano, but the Nano Every model includes an independent serial port which is used here to control the board.

Interfaces

B2987A Bias Voltage (J2, J3)

Separate single-wire connections exist for Bias+ and Bias-. Nominally a positive voltage is placed on Bias+; however, there is no reason why a negative bias could not be employed if the SiPMs were reversed. The Bias+ line is switched onto the individual bias lines.

B2987A Ammeter (J4)

J4 is a triaxial (TNC) connector that connects the multiplexer sense output to the B2987A ammeter input.

Inter-board Sense Connection (J6, J9)

These MCX connectors allow connection between master and slave boards. Two MCX connectors are provided, with the intention to enable daisy-chaining from board to board.

Inter-board Control and Power Connection (J5)

J5, a 20-pin dual-inline header, connects power and ground for the control circuit, as well as analog ground and bias voltage, between master and slave boards.

SiPM Connections (J14 – J28)

Each SiPM connection consists of an MCX coaxial connector, with the bias voltage applied to the center conductor. The role of the coaxial shield varies according to the mode (see below).

SiPM Sense Connection (J7)

The SiPM sense connection is a single MCX connector used to collect the output current in mode B.

Serial Interface (J1)

A 6-pin 0.1” single inline header provides a direct TTL-level serial interface to an FTDI serial cable (TTL-232R-5V). Setting is 9600 baud, 8 bit no parity.

+12V power and Digital GND (J11 and J12)

Single-wire connectors supply +12V and digital ground.

Operational Details

Power

+12V is supplied to the multiplexer (typically the master board) and is regulated on-board. +12V powers the relays and +5V powers the Arduino on the master board, as well as the shift register chips on all boards. Although the regulator built-in to the Nano Every module may have enough capacity to power all the shift registers, it is a switcher and may be noisy, so a linear regulator was included on the board.

Shift Registers

Two cascaded 74HC595 8-bit shift registers (U2, U3) provide 16 bits of control per board. Bits 0-14 control the bias voltage relays while bit 15 controls the sense relays. Each of these shift registers drives an 8-bit Darlington transistor array which drives the relays.

The shift registers are controlled by Arduino GPIO pins, which implement a common clock signal (SRCLK, rising-edge triggered), a common shift-register to output-register strobe signal (RCLK, rising edge triggered), and seven serial data lines (SER1 through SER7), one to control each board. A common clear signal, /SRCLR, with an attached pulldown resistor, ensures that all outputs power up in the inactive state. It is deasserted (set high) after the Arduino wakes up, and is maintained inactive in normal operation.

Note that the serial connection may provide enough power, even if JP13 is not connected, to prevent the Arduino from resetting when the +12V supply is cut. *For this reason, the Arduino code resets the shift register state in its setup routine.*

Each relay control update operation proceeds as follows:

- 16 rising edges on SCLK clock the data into shift registers on each of (up to) 7 boards.
- A single RCLK rising edge updates the relay control outputs.

Bias Voltage Switching

The bias voltage from the B2987A (VB+) is switched by reed relays onto 15 individual SiPM cathode bias connections. Each reed relay is a type 2A (DPST), with its contacts connected in series with each other, to connect the bias voltage to an individual cathode connection. A 100kΩ resistor connects the guard node (VB-) to the node between the two contacts. Most of the current that may leak from VB+ through the first relay contact is conducted directly to the bias return node (VB-) by the resistor, so as to minimize leakage to the SiPM bias output pin through the second relay contact.

The switched bias voltage traces, from the relay to the MCX connector, are protected against leakage by guard rings connected to the bias return node VB-.

Sense Circuit Switching

Anode current from the SiPM is switched by two high-isolation reed relays. One relay connects the SiPM-side current-collection node to the ammeter input when the sense output is enabled. Another relay shorts the SiPM-side current-collection node directly to VB- when the sense output is disabled. High-isolation relays are chiefly required in these roles because of their extremely high coil-to-contact resistance, which prevents significant leakage of current from the 12V coil voltage node into the ammeter.

Arduino Reset

Q1 allows use of the pin 6 RTS# output from the FTDI serial connector, to reset the Arduino. Q1 can be used (to invert the signal) or the signal may be directly bridged. This was included chiefly to allow the Arduino to be held in reset in case its clock disturbed readings. This measure is probably unnecessary and Q1 and R18 could be left unpopulated.

Configuration

SiPM Connection Mode (JP2, JP14, JP15, JP16)

Two modes are supported for interfacing with SiPMs. These modes are configured using JP2, JP15, JP14 and JP16, as follows:

Mode	Jumper (board channels 1-8)	Jumper (board channels 9-15)
A	JP16	JP14
B	JP15	JP2

In mode A, the bias voltage is supplied on the center pin of the SiPM connection and the SiPM output current is conducted by the coax shield. The SiPM sense connector (J7) is not used. JP14 and JP16 connect the coax shields of the SiPM interface connectors to the SiPM output current node, prior to the high isolation relay switching.

In mode B, the bias voltage is supplied on the coax center pins as in mode A, but the coax shields are tied to the VB- (guard) node through JP2 and JP15. J7 is used to receive the SiPM output current from the SiPM board.

Mode A is more likely to be compatible with certain SiPM boards, in particular, some boards designed to work with preamplifiers used to measure SiPM optical pulse response.

Mode B may be preferable for higher sensitivity readings in the low-current portion of the IV curve, since in this mode, center-to-shield cable leakage does not contribute to the apparent SiPM current.

Analog GND to B2987A Triax Shield (JP4)

JP4 connects GNDA to the Triax shield. Normally, this jumper should be bridged. On the board, GNDA goes only to J5 (to other boards) and to JP5 for possible connection to the digital circuit (see below).

Digital to Analog GND connection (JP5)

JP5 determines the relation between the analog ground and the digital circuit. GNDA can be connected to +12V (shunt pins 1-2), to the digital ground GNDD (shunt pins 2-3), or can be left floating (leave it open). The purpose of this jumper is to allow choice of the option which minimizes the effect of coil-to-contact leakage on current readings.

Ensure that this configuration is consistent between connected boards. If one board ties GNDA to +12V and another ties it to GNDD, the 12V rail will be shorted out and in the worst case, damage may occur.

Master / Slave Board

A board is configured as the master board simply by populating the linear regulator U1, the serial connection J1, and the Arduino A1, and the bias and ammeter connections J2, J3 and J4.

Board ID

Boards are configured as board 1 to 7 by shorting the appropriate solder jumper as follows:

Board	Channels	Short jumper
1	1-15	JP6
2	16-30	JP7
3	31-45	JP8
4	46-60	JP9
5	61-75	JP10
6	76-90	JP11
7	91-105	JP12

Power Configuration

The board power scheme is fairly flexible, with three jumpers that can be used to configure the power path. For normal use, JP3 should be shorted and the others left open.

Jumper	Connection	Normal state	When used
JP13	+5V FTDI cable to the +5V rail	Open	Only to allow FTDI to power +5V rail (but does not seem to be adequate)

JP1	+12V rail to the Arduino VIN pin	Open	Could be used to allow Arduino built-in regulator to supply +5V rail in lieu of U1
JP3	+5V rail to the Arduino +5V pin	Short	Normally enables Arduino power from linear regulator U1

Arduino Firmware

The Arduino firmware implements a simple command line interface over a serial port at 9600 baud (8 bits, no parity).

At the time of writing, it was necessary to separately install the Nano Every board support library to enable the option of selecting Nano Every, prior to building the firmware.

After connection, if an empty line or invalid command is received, a help text is printed out which summarizes the available commands.

Because the command format may change, no further detail is given here.

Assembly and Testing

This section provides notes on assembly and testing of the multiplexer board.

Rev 1.0 Board Modifications

Better freewheeling diode

The following modification must be done on Rev 1.0 boards to better handle inductive kickback from high isolation relays K16 and K17, and prevent destruction of Q2.

- On the bottom side of the board, solder the common cathode pin (3) of a BAV70 dual diode to K17 pin 3 (node +12V).
- Solder an insulated rework wire (nominally AWG 30) from K17-5 to one of the anode pins of the BAV70.
- Solder an insulated rework wire (nominally AWG 30) from K16-5 to the other anode pin of the BAV70.

Series Resistor on Ammeter Connection

To protect the B2987A against potential damage in the case of a fault in the multiplexer or attached circuits, a resistor may be added in series with the J4 center pin connection. 10kΩ may be a good value to choose.

The easiest place to put this resistor is between K16 pin 1 and its pad. However in a multi-board system, in order to use a single resistor to protect against faults from all of the boards, a resistor could be place on the bottom of the board, on the (cut) trace between J6 and J4.

Assembly Sequence

All parts may be mounted in the same step. However, in order to facilitate testing, it may be advantageous to perform some tests on a partially assembled board. If this is to be done, the following sequence may be followed:

- Mount parts in groups 1-7.

- Apply +12V and check the +5V rail.
- Mount A1 (group 8).
- Configure all jumpers, except for mode A/B jumpers
- Program A1, connect FTDI cable to J4 and verify serial interface.
- Perform the bias relay basic function test. It is easier to access the switched bias voltage outputs before mounting the SiPM connectors (group 9). Also, optionally run the Mode A leakage test prior to mounting the connectors, since the connectors could contribute to the leakage.
- Mount the bias voltage connectors (group 9)
- Configure all jumpers with shunts or solder shorts

BOM?

Group	Parts	Master	Slave	Notes or special instructions
1	All parts not otherwise listed	✓	✓	
2	K1 – K15 (DIP12-2A72-21D)	✓	✓	Keep relay bodies clean i.e. free of skin oil and other contaminants. To minimize leakage, it may be helpful to clean relays after mounting. Avoid or remove excessive flux buildup around pin 14.
3	K16, K17 (HI12-1A85)	✓	✓	Connect relay contact pins 1 and 2 using a piece of scrap wire between the pin and the pad on the board.
4	J7	✓	✓	Required only for mode B SiPM connection
5	J5, J6, J9	✓	✓	Required for board interconnect, only if board is to be used in multiple-board configuration
6	J1, J4	✓	X	Serial and ammeter connections
7	J4	✓	X	Right-angle pin header may be preferred.
8	A1 (Arduino Nano Every)	✓	X	Mount and ideally test parts under A1 (e.g. Q2) before mounting A1 or its socket.
9	J14 – J28	✓	✓	Avoid or remove excessive flux buildup around center pin.

Basic Functional Tests

These tests ensure that the relays are properly connected and activate correctly.

Power Rail

Apply +12V and check the +5V rail. (It may be good to do this before mounting the Arduino.)

Bias Relay Function

For easier access to the center pin, this test may be performed prior to mounting the SiPM connectors.

With bias voltage and board power supply disconnected, check with a multimeter for 100kΩ between VB- and each relay pin 8 (or 14).

Set bias voltage to a moderate level e.g. 20V and connect to VB+ and VB-

Activating each channel in turn, verify that the bias voltage (measured relative to VB-) is switched onto each output connector center pin. For convenience, this may be done using the sequence command.

Sense relay

With power applied, and with relays in their initial (zeroed) state, verify with a multimeter that K17 contacts are closed (connected) and verify that K16 contacts are open (disconnected).

Activate the sense relay. Verify the opposite, i.e. K17 contacts open and K16 contacts closed.

Performance Tests

These tests check the amount of leakage from three distinct paths. Results may indicate need for remediation. Since acceptable levels are not yet determined, and in any case will depend on specific application requirements, expected levels given here are indicative of past performance achieved, rather than as strict thresholds to necessarily be met.

Setup and general requirements

- It is best to deactivate the bias voltage as well as the ammeter when working on the board under test or changing its configuration.
- For the ammeter readings to be sufficiently stable, these performance tests must be conducted with the board in a shielded enclosure that is connected to GNDA.
- For best results, select the “stable” setting on the ammeter by pressing “fine resolution” on the front panel.
- To avoid excessive autoranging, place the ammeter in a fixed range (e.g. 200pA).
- Leave enough settling time after each change in conditions. In some cases, it may take minutes for the current to drop to its lowest level.

Sense Relay Coil-to-Contact Isolation

This test ensures that with +12V applied to the circuit, an acceptably small amount of leakage current is conducted between the sense relay coil and contacts.

- No bias voltage is required.
- Mode jumpers JP2, JP14, JP15, JP16 are all removed.
- Power up the circuit. The relays should be in their default state.
- Activate the ammeter and read the current (sense output disabled leakage).
- Enable the sense output and read the current (sense output disabled leakage).

These results may be affected by the following:

- Dirt or residue on the PCB in the sense path, in particular, anything that bridges over the guard trace directly to the sense trace.
- Dirt or residue on the high isolation relay bodies (K16, K17)
- The state of jumper JP5.

Bias Voltage Off-State Leakage

This test checks for leakage from bias voltage relays when they are in the off state. This leakage may originate both from the bias voltage and from the relay switching voltage.

- Shunt JP2 and JP15 (select mode B) This connects the shield pins of the SiPM connectors to the guard node. (This may not make much of a difference compared with leaving the jumpers open.)
- Set the bias voltage to a nominal level, typically equal to the maximum expected voltage (e.g. 70V).
- Connecting, in turn, each SiPM connector center pin to the output node, activate the sense relay (without activating the bias relay). *Note that groups of bias outputs can be checked together if multiple center pins are connected at the same time, with any unusually high reading subsequently isolated to the relay(s) responsible.*

These results may be affected by the following:

- Dirt or residue on the PCB in the switched bias voltage path, in particular, anything that bridges over the guard trace under the relays, directly to the sense trace.
- Dirt or residue on the high isolation relay bodies (K16, K17)
- The state of jumper JP5.

Without special treatment of the relays or boards, total off-state leakage current on the order of 10pA seems to be seen on the first board built. This may be improved through cleaning of the relays and board.

If unusually high levels are seen, further diagnosis may be carried out by determining how much the bias voltage is contributing (vs the relay coil voltage).

Bias Voltage Crosstalk

This test measures current that leaks from a single active bias voltage output, into other bias voltage circuits. It can be seen as a generalization of the previous (off-state leakage) test.

- Configure as per off-state leakage test
- In addition to measuring each output with all outputs switched off, measure it with each of the other outputs on.

Mode A Leakage

This test measures the leakage current on a given channel, between the SiPM connector center pin and the shield, when the channel is configured in mode A, i.e. with the shield returning the SiPM current. Depending on the need to isolate the leakage source, the test may be run with or without the SiPM connectors soldered in place, and with or without cables plugged into the connector.

- Shunt JP14 andJP16 (and remove JP2 and JP15) to select mode A.
- Set the bias voltage to a nominal level, typically equal to the maximum expected voltage (e.g. 70V).
- Activate the ammeter, and activate each channel in turn, reading the resulting current.

Sequence Trigger and Voltage Scaler

This section describes the circuit used to provide a sequence trigger to the multiplexer controller, and how it is attached to the ammeter and multiplexer.

The sequence trigger is built on perforated board and performs the following functions:

- A 10:1 voltage divider to allow capture of the bias voltage with the B2987A voltmeter which as a range up to 20V.
- A capacitor which differentiates voltage transitions, so that a drop from the full bias voltage to zero, at the end of a VI curve measurement, can result in a low-going pulse on the order of 5V magnitude, that can be coupled to an Arduino input pin.

Currently, the SER7 input (Arduino pin 11, D8) is used as the TRIGGER input (but another unused pin will be used later). The input pin is configured as a pullup input. The pulse width resulting from a drop from ~70V to 0V is approximately 1.2mS, and pulses shorter than 500µS are rejected.

J3 connects to a coaxial cable leading to the B2987A voltmeter input. Since a triaxial cable is not needed for this application. a triaxial to BNC converter is used on the voltmeter input. Note that the shield pin of J3 is disconnected. This is because the triaxial adapter connects the triax inner shield to the coax shield. This is the voltmeter guard node, which does not need to connect to the multiplexer circuit.