Cosmic ray cube instructions

1 Introduction

The cosmic ray cube is intended primarily as an outreach tool, providing an alternative to a spark chamber for visualising cosmic rays. Cosmic ray events are detected using two vertically separated plates of plastic scintillator. The position of the event in each scintillator is determined by comparing the signals detected by four SiPMs coupled around the edge of each scintillator plate. A microcontroller handles the position calculations, and drives a 3D array of addressable LEDs to illuminate a projection of the path the cosmic ray has taken through the detector, based on these positions.

This document provides an overview of the prototype, and instructions to build a similar detector. A supply of some materials is left over from the prototype build, and this is indicated in the document. All remaining elements including code, schematics, and design files are available on the GitHub site together with this document.

2 Operating the prototype

The prototype is simple to operate and requires only a 12 V DC power supply to run. With a 12 V, 2.5 A AC adapter, it can be plugged directly into mains. To edit the software or run the test codes for the LEDs, disconnect the PCB from the power supply before loading the new code onto the ESP32. The Teensy controllers are programmed to run the LEDs as instructed by the ESP32, so the software on them should not need changing. A more detailed breakdown of the readout circuit and detector control is shown in Figure 1, and more details on the function of the software are included in Section 3.7.

Figure 2 shows a photo and corresponding diagram of the detector. The clear pipes between sections of the detector are only glued at one end, such that the sections lift off each other, and the detector can be disassembled. The SiPMs must be disconnected from the PCB, and the cables threaded carefully back through the pipes to do this. Reassembly involves threading the cables from the SiPMs back up through the pipes. Cables from the bottom scintillator run through the box containing the top scintillator, and the cables from both run through the shorter pipes up to the PCB. It is important to connect the SiPMs to the PCB in the correct order to preserve the position information of a hit in space.

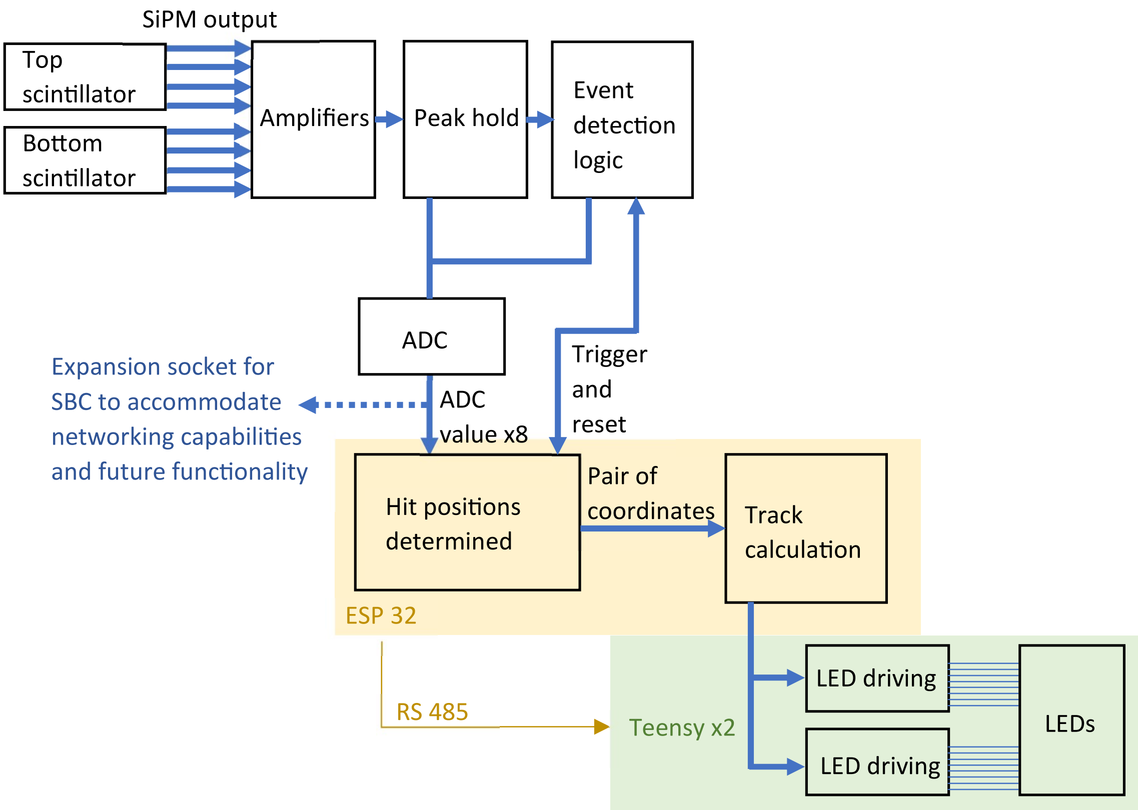

Figure 1: Block diagram showing the main stages from detection through readout to lighting up the LEDs along the track of a cosmic ray.

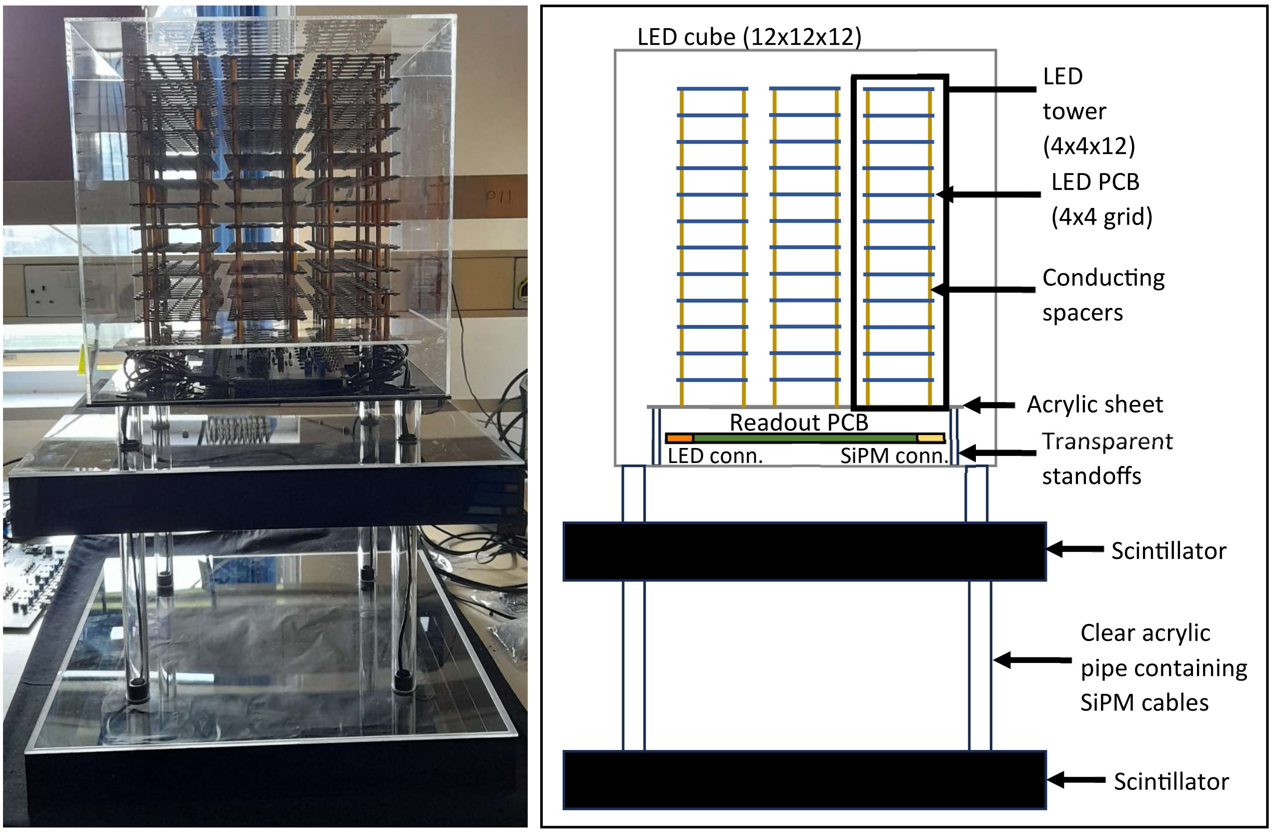

Figure 2: A photo of the finished prototype (left), alongside a labelled diagram of the detector as shown in the photo (right).

3 Building the detector

3.1 Component summary

The table below gives a brief overview of the main parts of the detector, together with notes on their function and/or the approach taken when building the prototype. This is intended as guidance for building a similar detector – see later sections for further detail.

Parts / equipment	**Notes**
Plastic scintillator	30 x 30 x 1 cm plates of EJ-200 with grooves for fibres available from prototype build (see Scintillator_geometry.pdf for dimensions).
Wavelength-shifting fibres	Prototype used Kuraray Y11 wavelength-shifting fibres – 25 cm lengths cut from a reel and heated for 12 hours at 70°C while fixed to a flat metal rod with heat-resistant tape to straighten before gluing.
Glue e.g. epoxy resin, optical glue, clear-curing resin	A 1:1 mixture of epoxy resin and hardener was used for the prototype. The mixture also included an anti-foaming agent to reduce bubbles and voids in the glue.
Reflective coating for the scintillator e.g. PTFE wrap	A 250 mm wide roll of 0.762 mm thick Teflon Relic Wrap was used for the prototype. Several layers (0.5 – 1 mm total thickness) were wrapped around the scintillator to maximise the detectable signal in the scintillator.
SiPM PCBs	Unpopulated SiPM boards are available from prototype build. Boards take 6x6 mm OnSemi C-Series SiPMs. Design files for the 3D printed clips used to hold the SiPM PCBs against the scintillator in the prototype are available under '3D_Print_Files'.
Two-core screened cables to connect SiPM PCBs to the main PCB	Tests confirmed that cable length up to 1.5 m made no appreciable difference to signal transport from SiPMs. Ideally all eight cables should be the same length.
Matte black aluminium foil (Thorlabs BKF12)	Used to cover the scintillator and SiPMs for light-tightness.
Control PCB	Schematic and build files are available under 'PCB_Files'. See Section 3.5 for setup instructions.
ESP32 Feather V2.0 and 2 x Teensy 4.0	Microcontrollers – Teensys required as timing delays are too great when pushing data from a single ESP32.
LED PCBs and metal spacers	LED PCB files are available under 'PCB_Files'. These are assembled into towers using M2 x 20 mm spacers and 5 mm M2 screws (f/m for continuous power and ground

	lines, f/f for data connections from one board to the next). Quantity will depend on desired size of LED cube.
Three-strand cable	Cables to connect LED towers to main PCB – O ring connectors allow the wires to be screwed into the conducting spacers at the base of each LED tower.
Housing	Off-the-shelf acrylic boxes/sheets/pipes used for the prototype. Pipes with a 16 mm internal diameter fit the designs for the 3D printed stoppers in ‘3D_Print_Files’.

3.2 Preparing the scintillator and wavelength-shifting (WLS) fibres

1. Prepare the scintillator and WLS for gluing by cutting the WLS to length and, if necessary, straightening them. This requires the fibres to be fixed straight and gently heated in a water bath or oven for a few hours. The amount of heating the fibres can tolerate without damage will depend on the core/cladding material of the fibre.

2. Clean scintillators and WLS with ethanol or isopropyl alcohol and a soft, lint-free cloth.

3. Glue the fibres into the grooves in the scintillator. Overfilling the grooves with glue and slowly scraping off the excess reduces bubbles and voids in the final coupling.

4. Once cured, trim the overhanging fibres around the edge of the scintillator, and gently abrade e.g. with 100-2300 grit sandpaper to give a flat face.

5. Wrap the scintillator in 0.5-1 mm of PTFE, or other reflective material to maximise the signal collected from it.

6. Leave/cut windows into the wrapping in an approximately 7x7 mm square around each fibre to allow the SiPMs to be coupled directly to the scintillator face (see Figure 4).

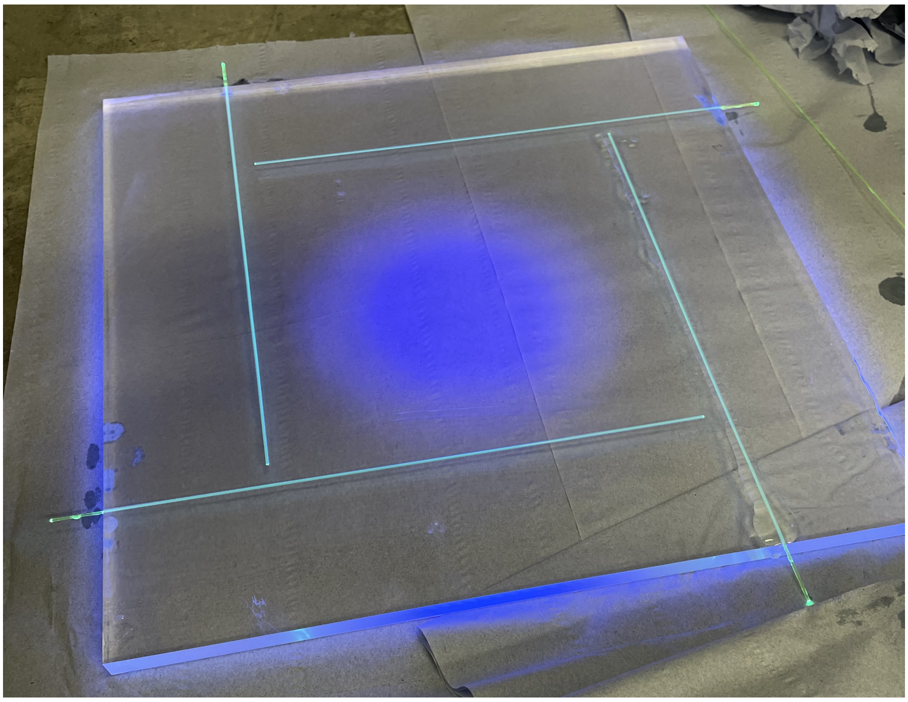

Figure 1: Scintillator plate after gluing WLS fibres illuminated with UV light.

3.3 Coupling the SiPMs

1. Populate SiPM boards – the solder joints of the connector on the SiPM face of the PCB (see Figure 4b) may need trimming and filing down to allow the SiPM to sit flush against the scintillator.

2. Cover the SiPM and exposed scintillator face with vacuum grease, and couple the two together, using the 3D printed clips to hold the SiPMs in place.

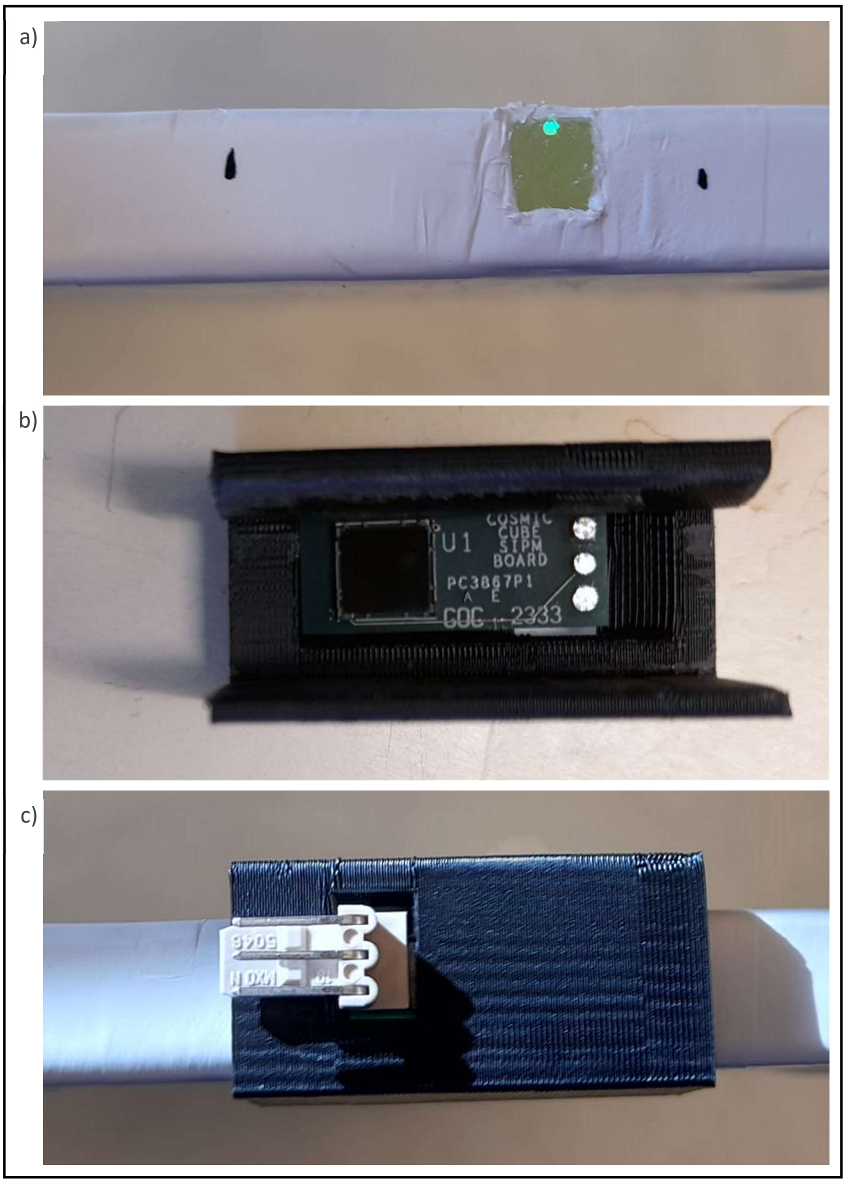

Figure 2: Coupling of SiPM to scintillator edge: a) scintillator face with window cut in PTFE for SiPM coupling; b) SiPM circuit board held in 3D-printed clip, SiPM-side-up; c) SiPM held against scintillator window shown in a) with a 3D-printed clip.

3.4 Blocking stray light

1. Connect the cables to the SiPM boards and wrap the whole scintillator-SiPM arrangement (see Figure 5) in black foil, minimising gaps.

2. Close any gaps using black insulation tape, taking particular care around the corners of the scintillator and at the exit points of the cables from the foil.

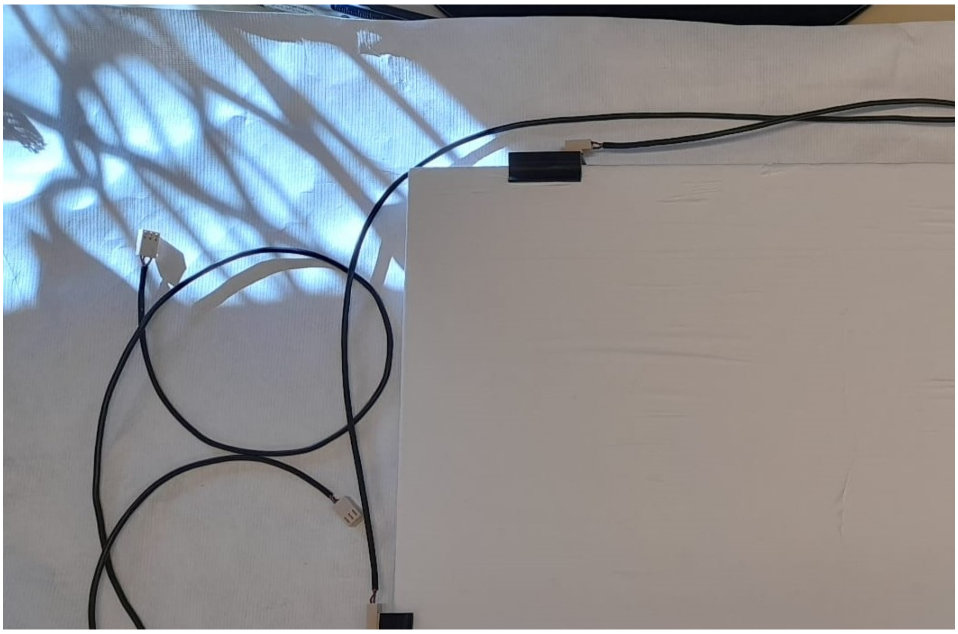

Figure 3: Scintillator wrapped in PTFE with all four SiPMs coupled around the edge. This has to be kept light tight.

3.5 Setting up the control PCB

1. Solder in sockets for U80, U81 and U82 (Teensys and ESP32)

2. Configure Teensys and ESP32 with the latest firmware.

3. Power on PCB without U80, U81 and U82 fitted and check current drawn is around 300mA.

4. Adjust RV9 and RV10 to set trigger levels at 500mV (test points 1 and 3) as a starting point. This can be adjusted as necessary.

5. Adjust RV1 through RV8 so that the HV pin to each SiPM (pin 1 of PL1 through PL8) is set to 29.5V.

6. Connect the SiPMs to the main PCB, adding shorting links between pins 2 and 3 of any SiPM inputs (PL1 through PL8) that are not going to be used (e.g. for testing) to stop amplifier output going into saturation. Refer to the schematic to align the connections on the top and bottom scintillators to preserve position information when connecting the LEDs.

7. Add shorting links to PL9 through PL16 according to desired level of SiPM events to cause a trigger:

    a. Shorting PL9, PL10, PL13 and PL14 will cause events if any two (or more) SiPMs on both scintillators are triggered.
    b. Shorting PL11, PL12, PL15 and PL16 will cause events if any three (or more) SiPMs on each scintillator are triggered.
    c. An event that triggers all four SiPMs on both scintillators will always be counted as an event.

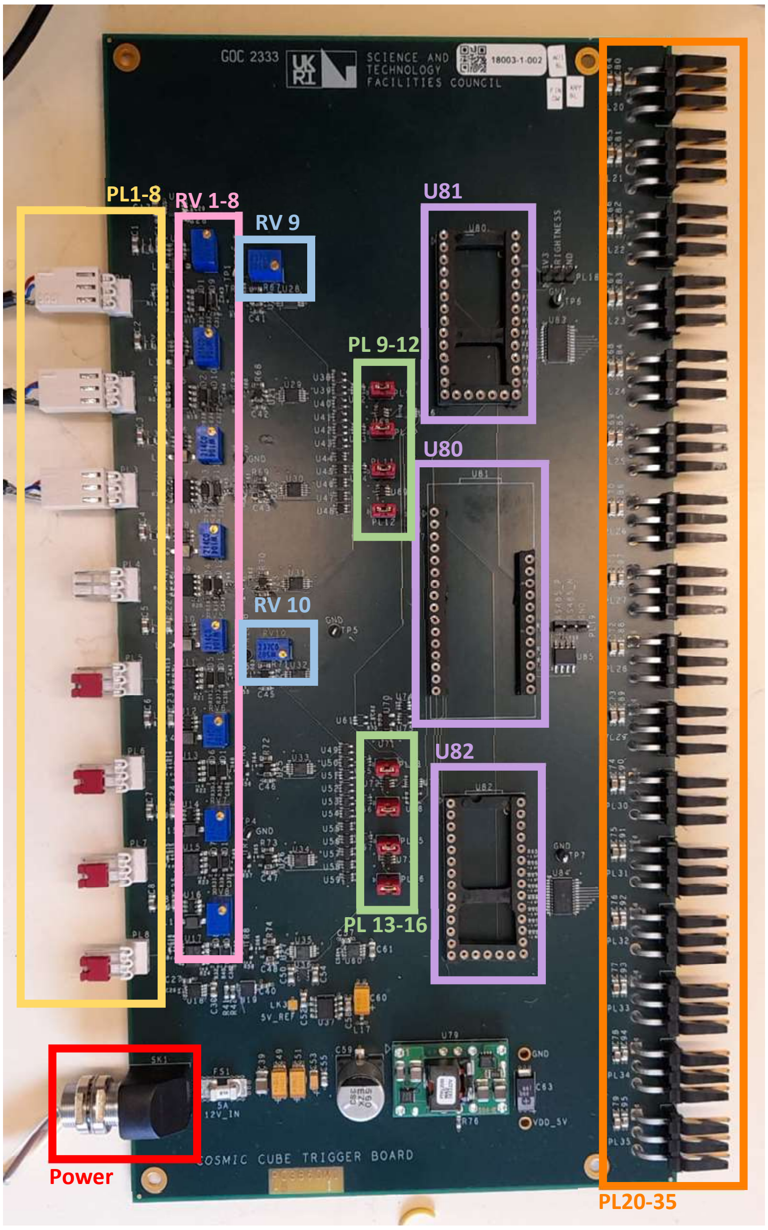

Figure 4: Photo of the main readout PCB with the following highlighted: power socket, SiPM connectors (PL1-8, the last four of which are shown shorted), potentiometers for setting the bias voltage on each SiPM (RV1-8), potentiometers for setting the trigger threshold for each scintillator (RV9 and 10), logic gates determining how many SiPM signals must be above threshold for an event to be registered (PL9-16), sockets for the microcontrollers (U80-82), connectors for up to 16 LED towers (PL20-35).

3.6 LEDs

1. Assemble up to 16 independent towers[1] from the 4x4 LED PCBs by screwing stacks of PCBs together using conductive spacers to take power, ground, and data lines through each tower.

2. Prepare three-strand cables to connect each tower to the main readout PCB. The simplest way to do this is to use O ring connectors to screw each strand to the correct standoff at the base of the tower.

3. Connect the LED towers to PL20-35 on the readout PCB. Referring to the SiPM connections on the schematic, towers are connected in order from the south to the north edge of the scintillators, moving west to east. The first LED tower connected to PL20 corresponds to the south-west corner of the scintillator stack.

3.7 Software

1. Always ensure the PCB is powered off while the microcontrollers are connected via USB to prevent dual power draw.

2. Compile and upload the relevant code to each microcontroller in turn. This is easily done using PlatformIO and the .ini file included in this repository. **Note for the Teensys** that each must be assigned BOARD_NUM 0 or 1 in **teensy_cube.h** before compiling.

3. Compile the code to check LED function and connection order:

    a. Ensure that the size of the LED cube, including the cube size, and number of LED strands connected to the board are defined in **led_cube.h**.
    b. Define TEST_LAYERS in **esp32_cube.h**, compile, and upload to ESP32.
    c. Define BOARD_NUM in **teensy_cube.h** as 0, and check that the connected pins for this board are correctly defined before compiling and uploading to the first Teensy. Set BOARD_NUM to 1 and repeat for the second Teensy.

4. Compile the code to show cosmic ray tracks:

    a. Comment out TEST_LAYERS from **esp32_cube.h**, compile, and upload to ESP32.
    b. If the geometry of the LED cube is the same as the prototype, i.e. 12x12x12 LEDs, with 3 towers connected to Teensy 0 and 6 to Teensy 1, no further changes are necessary.
    c. For accurate track projection onto an LED cube with a different geometry to the prototype, the IS_OUR_LED method, defined in **teensy_cube.h**, determining whether an LED is controlled by that Teensy, must be amended in source code to reflect the changes.

[1] Elements of the source code will need modifying to project cosmic ray tracks onto a cube of different dimensions to the current 12x12x12 prototype.

5. An expansion socket is included on the main PCB for a single board computer to extend the functionality of the cube if desired. Alternatively, the ESP32 comes with some networking capability which could be exploited instead.

3.8 Construction

There is considerable flexibility in the construction and housing of the detector components. The prototype was designed and constructed with simplicity, cost, and visibility of the detector components in mind. The acrylic sheets, boxes, and pipes were all bought off-the-shelf in standard sizes, and only modified by drilling holes to allow the pipes and standoffs between sections to be secured in place.

While there is some flexibility in the exact arrangement of the two scintillators, the PCB and the LED cube, it is important to **note that the individual SiPMs and LED towers must be connected to the correct location on the main PCB** for the position calculations to give accurate tracks. In this regard, the construction of the prototype could be improved by:

1) Labelling the connections from the scintillator/SiPMs and LEDs to the PCB to ensure consistent and correct dis/assembly.
2) Developing a method to secure the scintillators in place within the housing, both to maintain alignment between the two scintillators and to reduce the likelihood of damage during transport.