JSNS^2 nanopulser optical calibration system

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ABSTRACT

This note describes the the JSNS^2 nanopulser optical calibration system. The document discusses the requirements, design, testing, as well as the control software and the operation. This is a live document and should be updated as the system expands[1].

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Introduction

The JSNS^2 experiment[2] is a relatively small liquid scintillator detector. It relies on precise timing in order to seperate the scintillation light from Cherenkov light, which is crucial for background and signal separation. This note describes the JSNS^2 nanopulser optical calibration system that will be used to do the timing calibration, as well as the gain calibration.

We start with a description of the requirements as set by the JSNS^2 collaboration. Next is a description of the system in the experiment. We then describe the control software, followed by a section on the analysis strategy.

This document is maintained by the corresponding author and can be downloaded or cloned from github[1]. If you have any updates, please contact him (details above).

Requirements

The calibration system has the following requirements:

1. The system is controllable via simple to use, and flexible software.
2. The part of the system that is inside the LAB filled volume is compatible with LAB.
3. The system does not cause interference on the PMT array.
4. Each pulser produces a very small width in time optical pulse (less than 1 ns risetime at low intensities and less than 2 ns falltime).
5. The system provides full optical coverage of the PMT array for both 420 nm and 355 nm.
6. The system provides a trigger pulse that can be delayed, with negative amplitude and less than 1 1 V, to be read-out with one channel of the VX1721 flash ADC read-out system.

System design

In this section, we discuss the overall layout of the system, the electronic and mechanical design and the software.

Overall design

The design is based on the initial proposal by Matsubara-san, with some modifications to ease installation and improve the coverage of the light on the PMT array. The cables, electronics, and housing were manufactured by Interface2 Ltd.[3].

System configuration

Figure 11 shows the overall layout of the system. The LEDs are mounted on next to the PMTs, on the boards holding them. The system consists of six 'branches': a cable string with a data and power line that at certain intervals holds a 'pulserhead': an electronics board with digital logic and an ultra-fast LED pulser. Each string has either two or three pulserheads. In total, there are twelve pulserheads with a 420 nm LED and two pulserheads with a 355 nm LED (the 355 nm light will be absorbed almost immediately and emitted randomly in all directions as a longer wavelength). Each branch is terminated with a connector containing a 120 Ω resistor on the data line.

The cable exit the experiment through four flanges. The cables, made out of (expensive) teflon coated cables are then connected to a junction box, where they connected to (cheap) 15 m long ethernet cables. These cables are connected to the nanopulser control box, located in the DAQ racks. The controller box talks to the DAQ via the network (ssh to the raspberry pi inside the controller box). The junction box is grounded and a ground cable connects to the controller box as well. The controller box also provides a trigger signal in-sync with the optical pulse. There are programmable delays that control the timing between the optical pulse and the trigger pulse for each of the pulserheads.

Table 1 shows the overall configuration of the branches, as well as the branch and the pulserhead IDs. Furuta-san has produced a paper indicating the exact mounting pounts.

SJMP: add docdb entry for Furuta-san's document, once on docdb

Table 1. Configuration of the $JSNS^2$ nanopulser optical calibration system, up to the junction box.

		Cable	Pulserhead		Cable	Pulserhead		Cable	Pulserhead	
Branch	Flange	length (m)	ID	λ_{LED} (nm)	length (m)	ID	λ_{LED} (nm)	length (m)	ID	λ_{LED} (nm)
1	2	5.5	1	420	2.2	2	355	2.2	3	420
2	2	4.5	4	420	3.0	5	420			
3	2	9.0	6	420	3.0	7	420			
4	2	13.5	8	420	3.0	9	420			
5	2	9.0	10	420	3.0	11	420			
6	2	10	12	420	2.2	13	355	2.2	14	420

The cables for the branches are teflon-coated with four twisted-pairs wires inside, and a grounding shield. The connectors are Bulgin buccanneer 400[4]. The O-rings used are TRP White FFKM[5] (all the orignal connector O-rings were been replaced with FFKM O-rings).

All materials used in the branches (up to the junction box) have been shown to be compatible with LAB (see monthly meeting reports). It has also been shown that the branches can be safely deployed into liquid, for up to 2 bar over pressure (at least).

System performance

Pulserhead

Note that for transfer the maximum energy in a fast pulse, that we found that it is important that the legs of the LEDs are not shortened, but bend out to fit.

A detailed schematic is given in Appendix A. The glue used is in the assembly is Weldon 42[6].

The LED emission (in air) was close to a Lambertian distribution[?]. This corresponds an opening angle of LEDs of approximately 30 degrees. However, this depends on the selection of light, and on the individual LEDs.

The wavelength distribution of the LEDs is reasonably well described by a 'double Gaussian', with a mean of either 355 nm or 420 nm, and a lower sigma of 10 nm and a higher sigma of 15 nm. The exact spectra is given in Figures 7 and 8. (The input data for these figures is provided in for reference.)

Pulserhead programming

The Pulserheads are each programmed for a specific position on the branch and with its own unique ID (1-14). The programming can be done separately from the system, as shown in Figure 9, with a custom cable providing the 9 V power for the PIC chip[1]. The code is loaded onto the PIC chip via a commercial interface (microchip PICkit3) with a custom cable to the pulserhead. Note that, as shown in Figure 9, the grey lead lines up with the arrow on the PICkit3 interface. On the other side, the green lead is closest to the LED on the pulserhead. The connector on the pulserhead is slanted an slightly bend, to make it fit into the pulserhead's acrylic housing. Therefore, take extra care when connecting to make sure a good contact is make.

[1] Make sure the battery has enough power left to power the PIC chip.

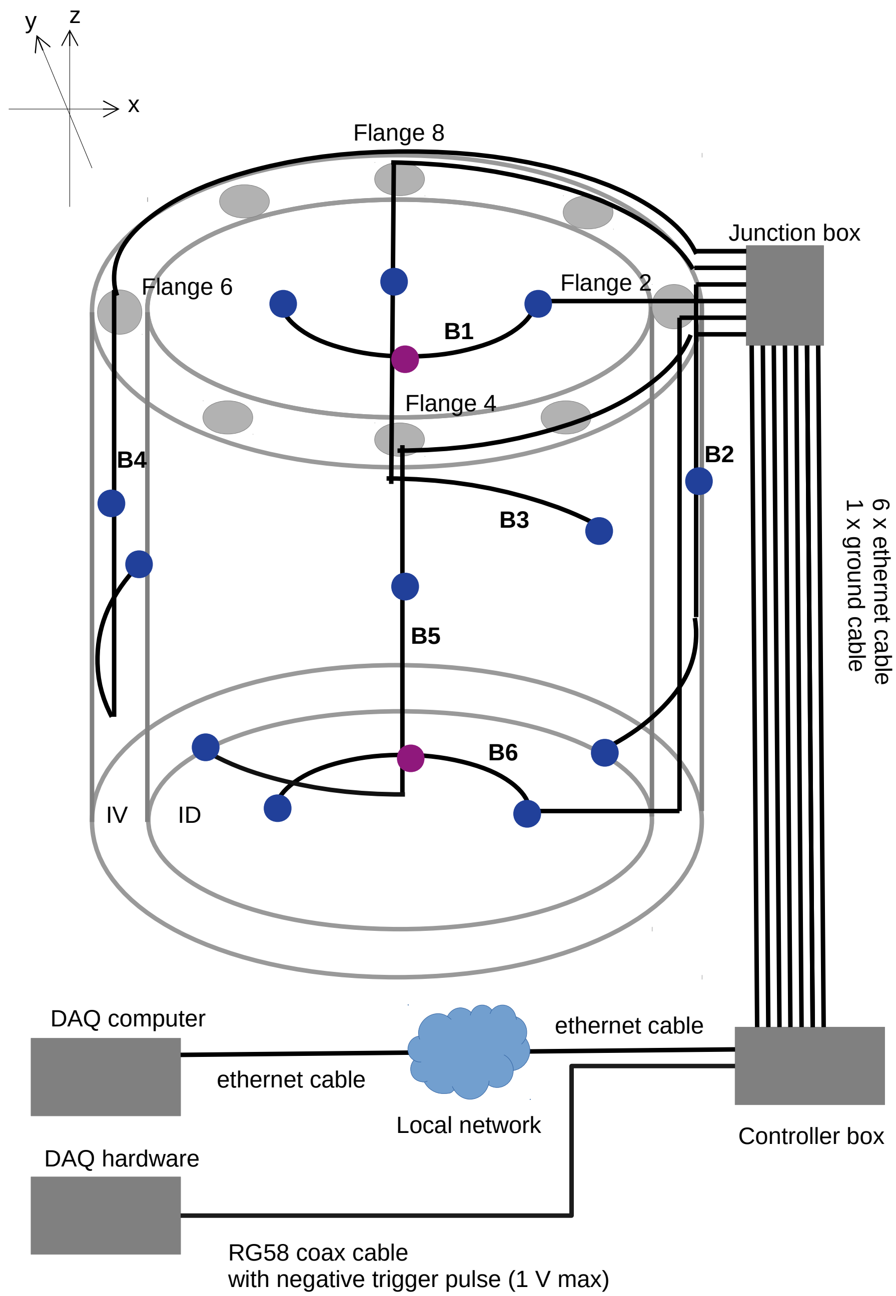

Figure 1. A schematic overview of the nanopulser optical calibration system. The (two) purple points indicate the position of the pulserheads (LED driver boards) with a 355 nm LED, the (twelve) blue points indicate pulserheads with a 420 nm LED. All LEDs point inwards. The numbers B1-B6 indicated the different branches. IV is the Inner Veto volume and ID is the Inner Detector volume.

Figure 2. A picture of one of the JSNS^2 nanopulser branches.

The software for the pulserhead programming can be found on github[7]. This contains a zip file (PICkit3.zip), which contains the windows compatible executable file PICkit3.exe, as well as other (required) input files for the program. It also contains the 14 hex files to be loaded onto the pulser: nanoSlaveTrig_X.hex, where X is a letter from A-N. This corresponds to pulser ID 1-14, respectively, as shown in Table(i.e., A is for pulser head 1, etc.).

The program PICkit3.exe is started by double-clicking (make sure the PICkit3 device is connected and recognised, otherwise the next step is not possible). Next, select the PIC chip to program: under menu 'Device family', select **MidRange**. Then, under 'Device', select **PIC16F88** (note there are a lot of models). If the set-up is correct, you can now read the PIC chip by pressing the 'Read' button. This take a little and a green progress bar will appear until the commend read has finished. This should change the hex values shown in Program Memory from their default values to all different values.

If this was successful, load a hex file by clicking 'Import Hex' from the 'File' menu. Next, click 'Write'. Again a green progress bar should appear to show the progress. Wait until the process has been completed. After this, the PIC chip has been programmed and can be disconnected from the power supply and the PICkit3 device.

The perfomance of the pulserheads is documented on github[8], and is summarised in Figure 10.

Nanopulser control box

One symptom of a blown fuse can be that the pulser does communicate but either does not produce light, or produces a wide pulse (of the order of 100 ns).

The control box has two indicator lights: a red light and a green light. The red light is connected to the 5 V supply to indicate the unit is powered up. The green light is labeled 'active', and indicates that any one of the slave units is emitting light.

Cable design

The ethernet cables should **never** be unplugged from the box, while the power is on, as the power for both the digital electronics, as well as for the pulser circuits runs through them. Note: accidental hot-swapping can result in one of the fuses blowing. Therefore, always power the system off before connecting or disconnecting the ethernet cables to the control box.

Junction box

At the final installation, the cables should be wrapped with a tie wrap inside the junction box, to avoid damage to the connection by accidentally pull the cables. Note that the (longer) ground cable also needs to be connected to the junction box chassis (see Figure 12).

The complication are that there are four white wires, one for each twisted pair. If the association between white and coloured wire pairing is lost, this can be recovered in the following way, using a resistance measurement:

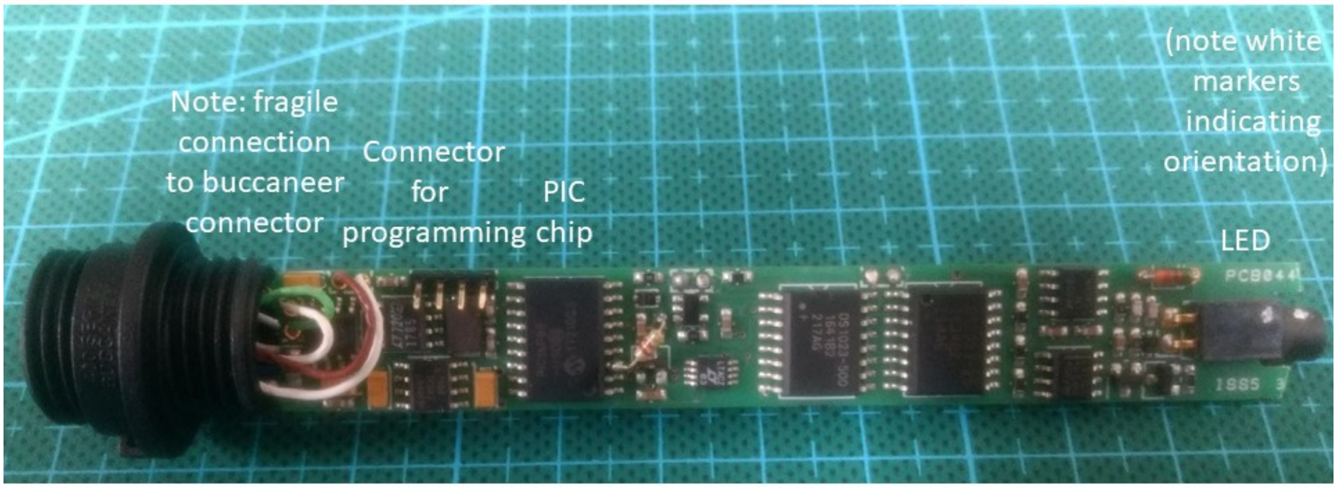

Figure 3. Photo of the a pulserhead, outside of its acrylic housing, with the main components indicated.

Figure 4. Rendered drawing of the acrylic housing, with an O-ring (black in this image, but white in reality).

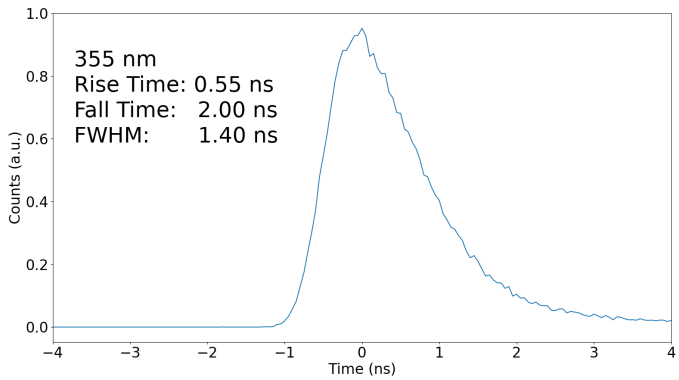

Figure 5. The nominal optical pulse shape of the 355 nm pulserhead.

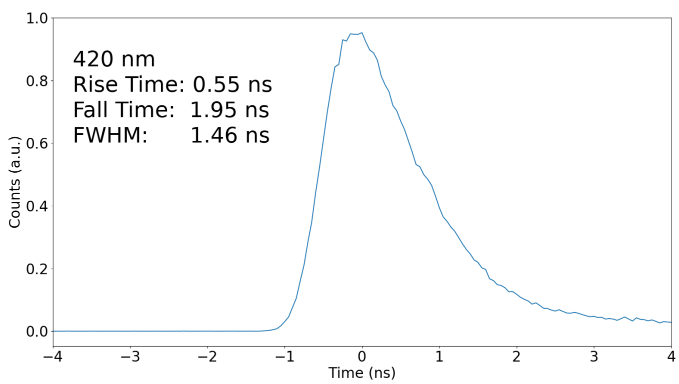

Figure 6. The nominal optical pulse shape of the 420 nm pulserhead.

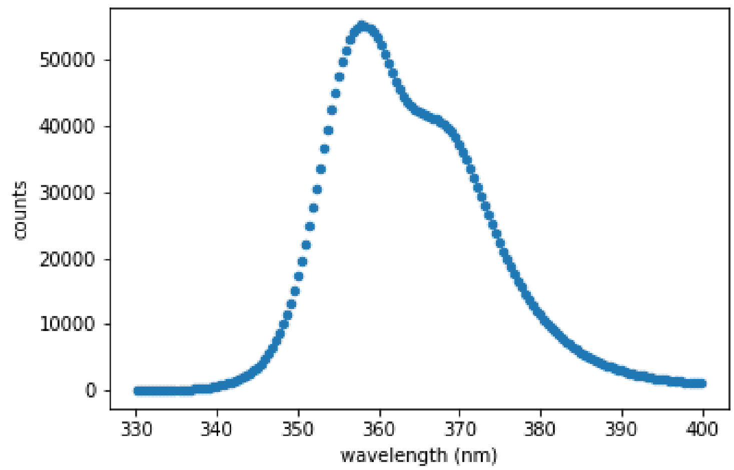

Figure 7. The optical spectrum of the 355 nm pulserhead.

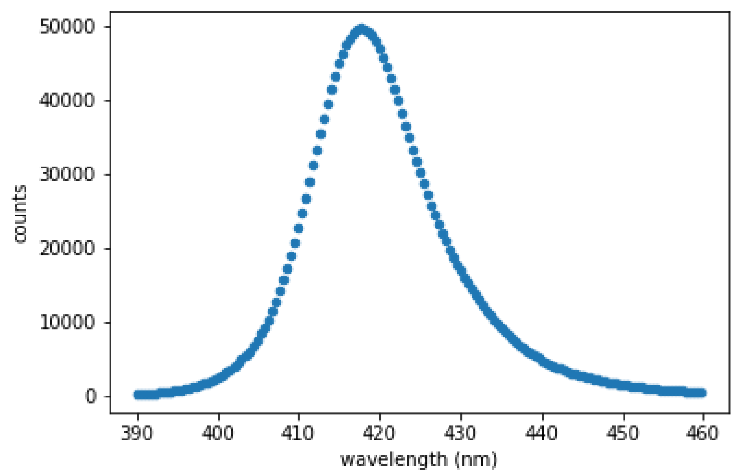

Figure 8. The optical spectrum of the 420 nm pulserhead.

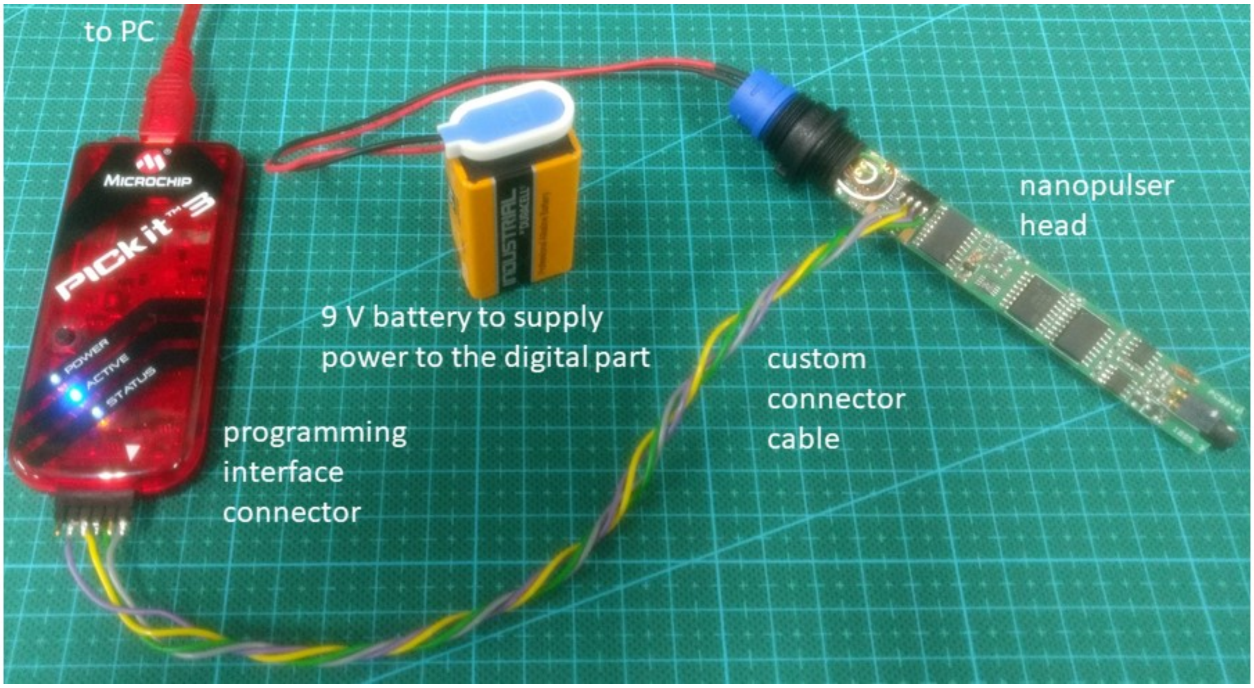

Figure 9. The pulserhead programming set-up (window10 computer needed, not shown here).

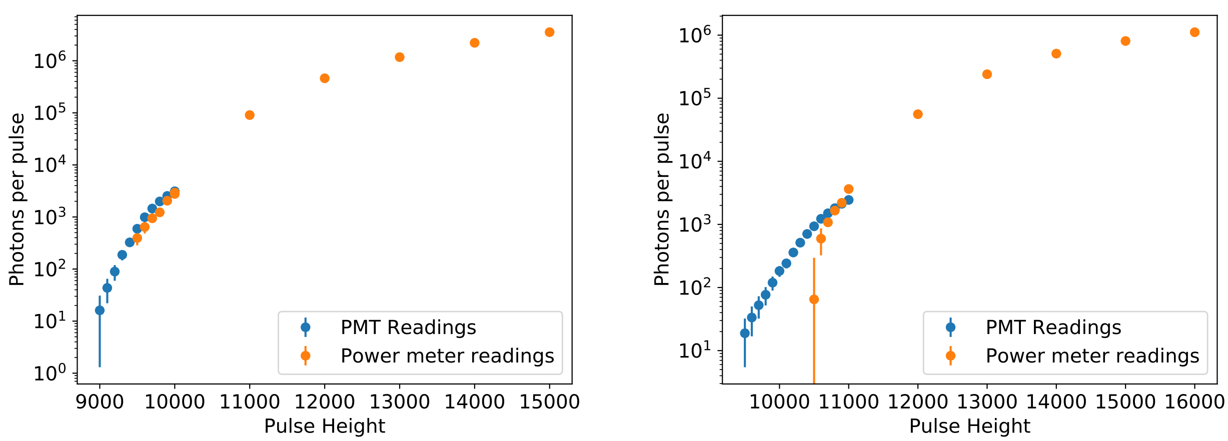

Figure 10. The optical output of the pulserheads with 420 nm LEDs (left) and 355 nm LEDs (right). The x-axis is the digital setting used for the measurements. Most of the range is observed with a calibrated optical power meter. At the low end, however, this device was not sensitive enough and a careful extrapolation based on measurement using a PMT is shown.

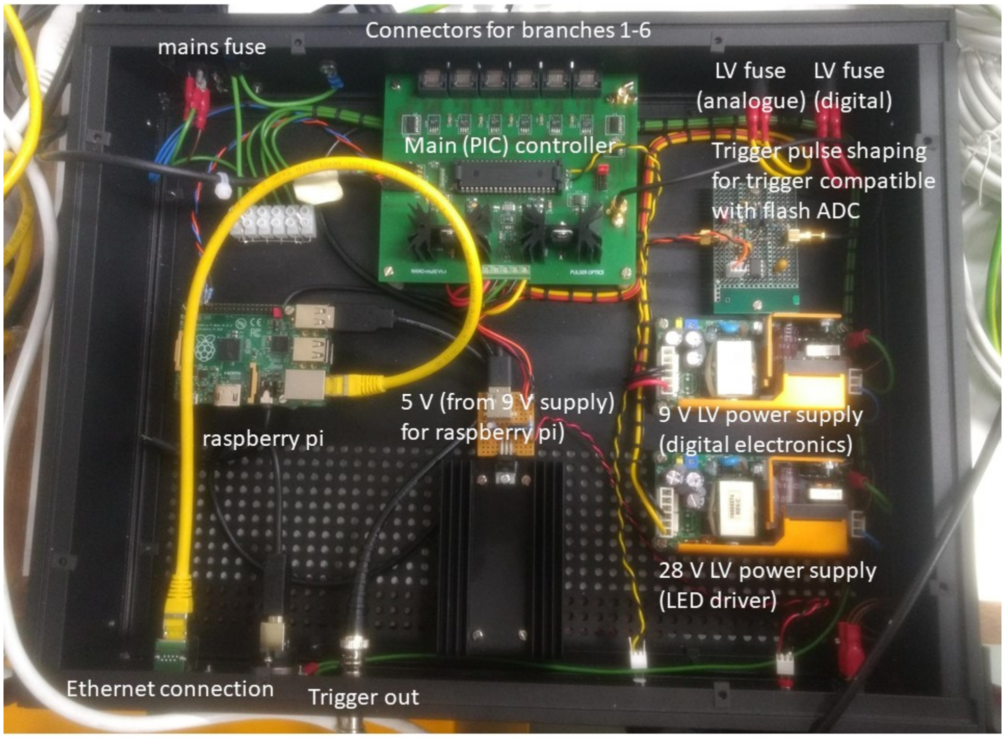

Figure 11. Photo of the control box during commissioning at the University of Sussex, with the main components indicated. Note that all the fuses and connections can be accessed from the outside.

1. Check for a short circuit between any two of the white wires. When found these are the ones associated with the green and orange wires. As they are both grounded these white wires can be safely interchanged.

2. Now check from the resistance between the brown and each of the remaining two white wires. when you see a resistance of approximately 120 Ω, you have found the white wire, associated with the brown wire.

3. The remaining wire is the associated with the black wire.

Trigger delay

When the slave board receives a 'run' command, it outputs a (trigger) pulse, which is sent back to the control board. The time it takes to receive by the control board depends on the cable length. This pulse is internally delayed on the slave board before triggering the LED driver circuit. The delay is preset using two delay lines of step size 5 ns (called 'course trigger delay') and 0.25 ns (called 'fine trigger delay'). By matching the total delay to the cable length, the trigger pulse received at the control box (or beyond) can be made co-incident with the light pulse. The number of programmable steps is 255 for each delay line. Thus the maximum delay is 1,338.75 ns (1275 ns plus 63.75 ns).

Control software

The software is kept in a github repository[9]. (An older, depricated, version with documentation is also kept in a different github repository[8], for reference only).

A raspberry pi computer, which runs the control software, is situated within the control box. To operate the box you need to ssh into the raspberry pi using `ssh pi@<IP address>`. The MAC address of the raspberry pi ethernet port is `b8:27:eb:ef:45:ee`.

The control software for the driver board are located in the folder: `/home/pi/JSNS2PulserControl/ControlSoftware/`. The script to control the driver boards is: **`test_run.py`**. It takes the following arguments:

`-c` - The pulserhead ID to pulse
`-p` - The pulse height for the driver board, this controls the intensity of each LED pulse. (Ranges from 0 to 16384)

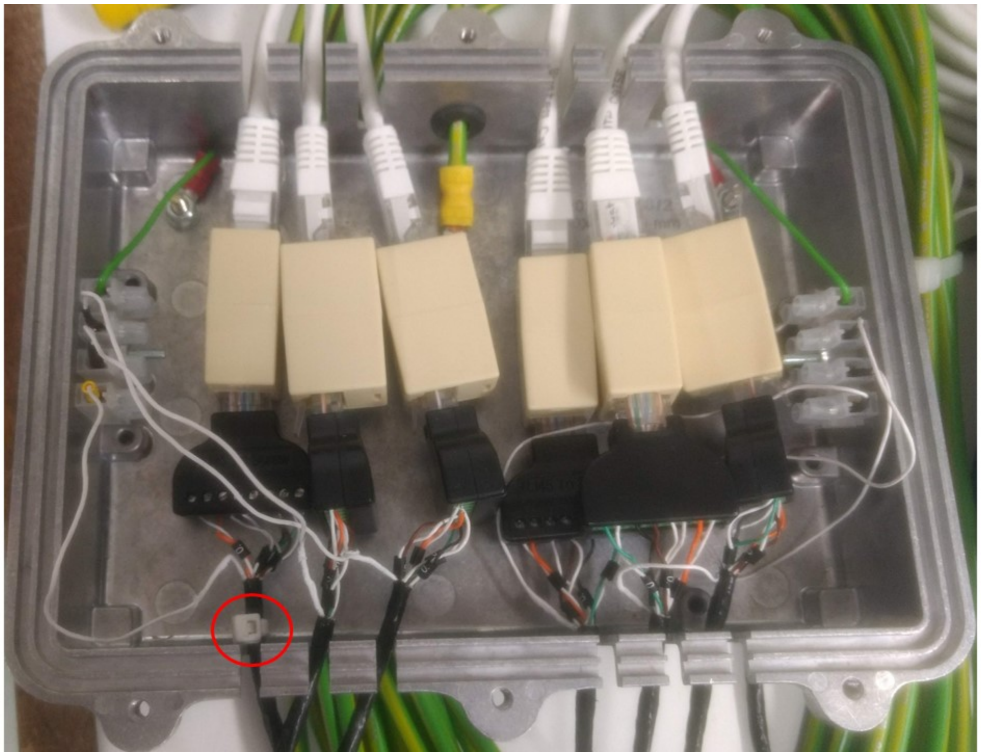

Figure 12. Photo of the junction during commissioning at the University of Sussex. The ethernet cables on the top connect to the back of the control box (this is labeled 1-6 for the branch numbers). The cables coming from the connector need to be wired to the black eight-way connectors in the pictures (details given below). The cables are then connected with the beige mating connectors. After final assembly in the flange, a tie wrap should be wrapped on each cable as a strain relief. This is demonstrated in the bottom left cable (red circle).

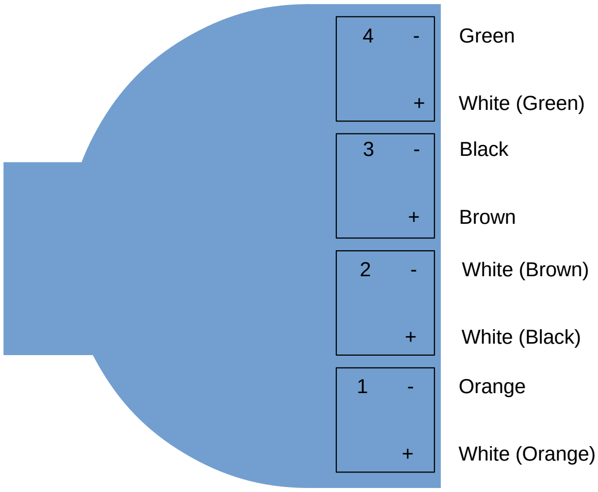

Figure 13. A diagram indication how the eight-way connector should be connected to the cables going into the vessel.

`-d` - The delay between pulses in milliseconds
`-n` - Number of pulses. The number of pulses must be a multiple of 1000, up to 65,025
All arguments are required for this example scripts. (Note that continuous running is not possible for this system, but it is in the library. Also, the coarse and fine fibre delays are set to default values in this script.) The python scripts making up the control software provide detailed information on the possible commands.

System commissioning

Commissioning at the University of Sussex

Initial commissioning

The nanopulser optical calibration system (serial nr OP_12_420_2_355) has been tested at the University of Sussex in February 2019, and the results of this are shown in Table 2.

The system was then shipped to Japan and tested again for functionality at the JSNS^2 lab in the KEK building at J-PARC. The system was found to be working as expected, expect for pulserhead 7. This was replaced with a spare one (programmed to reflect the position), which worked correctly.

Table 2. Results of the commissioning at the University of Sussex. The measurements are only relative: settings indicated are for which the trigger pulser and the light pulse were observed at the same time, using the specific test set-up at Sussex. The amplitude was as measured with a Hamatsu mini-PMT (H10721-210) with mylar filter using the maximum light output setting. Note that the PMT's quantum efficiency for the UV LEDs, pulserheads 2 and 13, is much lower. (Note: for the fine trigger delay the setting is given. To get the corresponding delay time, multiply with 0.25 ns.)

Branch	LED1				LED2				LED3			
	Pulser head	Coarse trigger delay (ns)	Fine trigger delay (setting)	Amp. (V)	Pulser head	Coarse trigger delay (ns)	Fine trigger delay (setting)	Amp. (V)	Pulser head	Coarse trigger delay (ns)	Fine trigger delay (setting)	Amp. (V)
1	1	810	21	2.7	2	830	18	1.1	3	815	7	1.8
2	4	795	7	3.5	5	810	19	5.0				
3	6	810	19	3.3	7	815	12	3.5				
4	8	800	32	5.0	9	850	8	3.0				
5	10	825	0	3.0	11	835	11	4.0				
6	12	830	17	1.5	13	830	2	0.5	14	850	4	2.5

Further commissioning

The following tasks still remain for commissioning:

- Estimate the delay needed for the system once installed.
- Confirm the settings of Table 2 and find the values for the estimated delay between optical pulse and the trigger. Try to get the all channels as close as possible. Note the (estimated) magnitude of (any) trigger jitter, if observed.
- Find the optical range for each channel - the minimal pulse is around pulse height setting 10,000. Find the actual minimal value and note the pulse integral observed in the PMT used, as well as the pulse integral when using the maximum value pulse height setting.

Analysis

The calibration of the system is done in the lab. Experience shows, that once installed in the experiment, things change - generally both due to changes in the system as well as due to different routing and noise environment. Therefore, the system will need to be recalibrated, or at least verified in analysis.

This is ok, for the following reasons:

- The individual offsets can be obtained (or avoided) by using the overlap in light distributions from the different pulserheads. Using a bootstrap method, the entire system can be brought inline. There then only remains one overall offset, which can be determined by using a deployed source, or by calculating the time it takes for the light from LED to PMT (time-of-flight).

- The absolute light level is not important. To obtain single photon mode, one must ensure that the occupancy is less than 5% (i.e. less than 5% of pulses produces a signal in the PMT). This ensures that, according to Poisson statistics, the number of times that two or more photons hit the PMT is less than 1% of the total times that the PMT records data).
- The light patterns that the LED array will generate will depend on the individual LED, as well as the exact geometry of the detector (including bubblers pipes). Therefore, the light levels that are needed to calibrate the timing (which has be in single photon mode) has to be assessed in-situ.

References

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2. Ajimura, S. *et al.* Technical Design Report (TDR): Searching for a Sterile Neutrino at J-PARC MLF (E56, JSNS2). *Arxiv:1705.08629* (2017).

3. Interface2 Ltd. Unit 16, Euro Business Park, Newhaven, East Sussex, BN9 0DQ, UK (+44 12173 611008).

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6. SCIGRIP IPS WELD ON 42 clear low voc acrylic adhesive 10:1 50ml. https://scigrip.com/assets/tds/SG-42_TDS-1112.pdf.

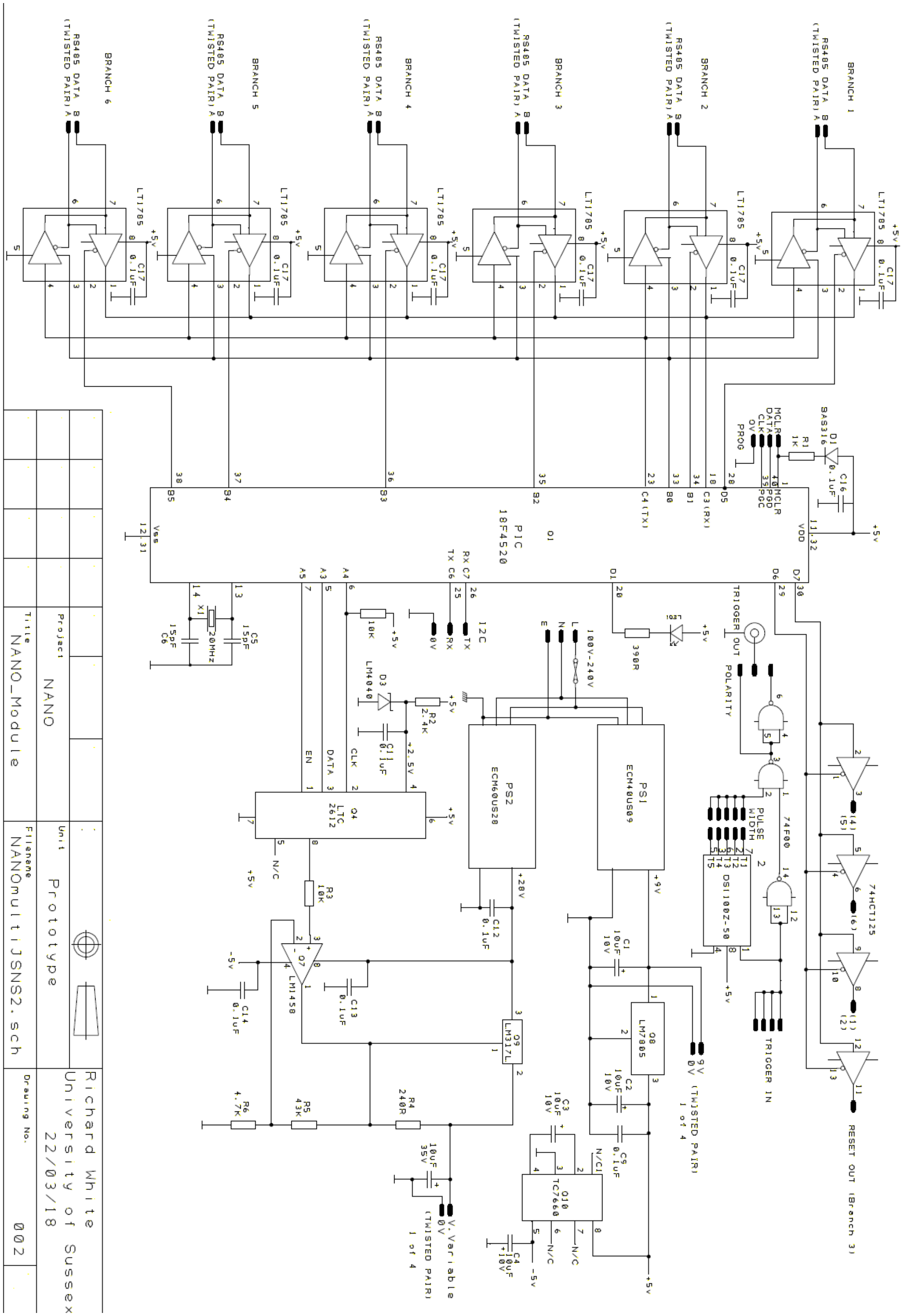
7. White, R. JSNS^2 nanopulser PIC programming software and code. https://github.com/sjmpeeters/nanopulser_pic_programming.git (2019).

8. Stringer, M. Operation and performance of the JSNS^2 driver system. https://github.com/Sussex-Invisibles/JSNS2PulserControl (includes legacy control software, however, this for reference only) (2018).

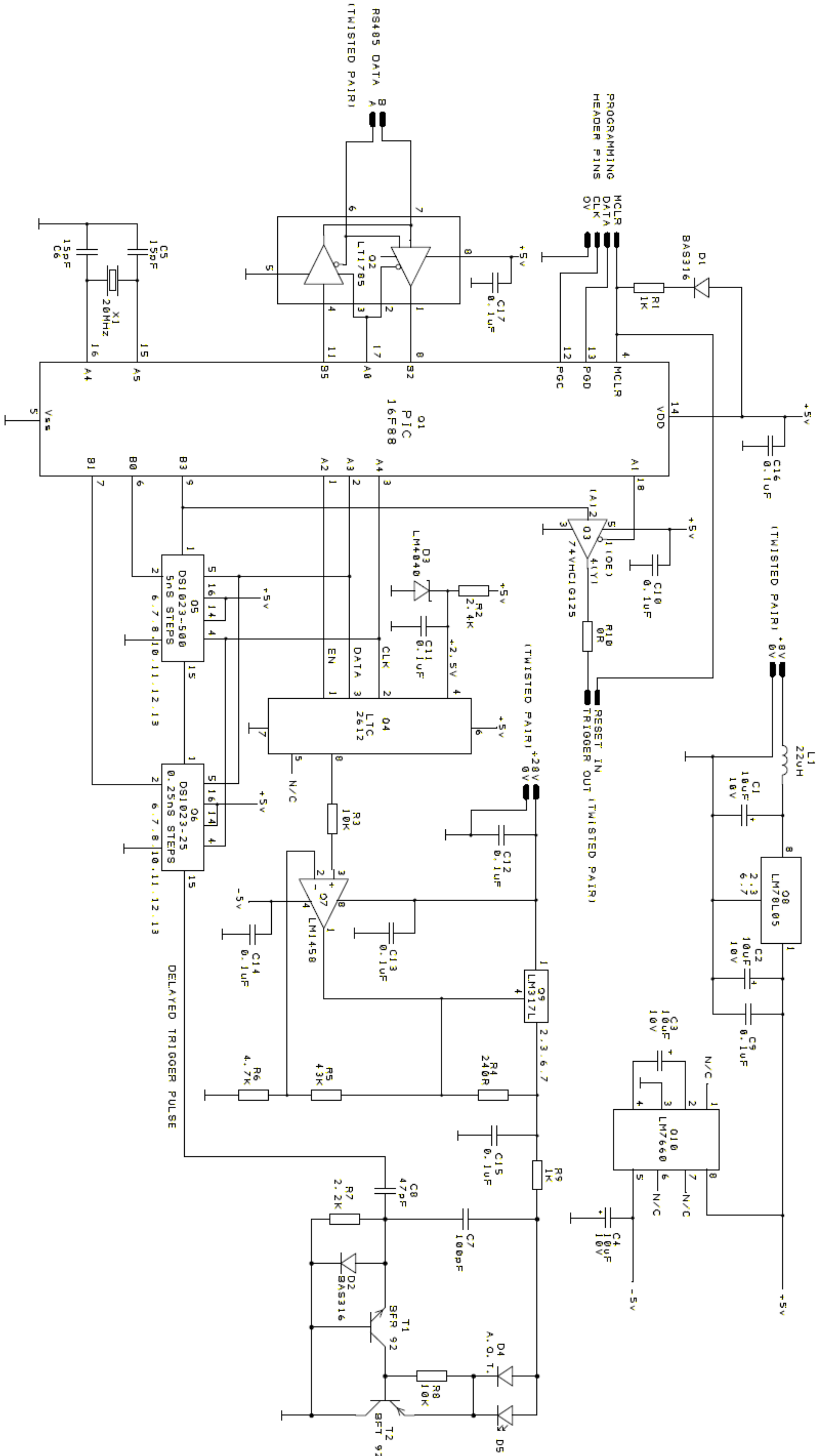
9. Waterfield, J. JSNS^2 nanopulser control software. https://github.com/sjmpeeters/JSNS2_nanopulser_control_software.git (2019).

A Electronic schematics

Control box schematics



Pulserhead schematics



B Internal control codes

The control box will has an integral Raspberry Pi computer running the control program (written in python). The Raspberry Pi is accessible remotely via Ethernet. A USB port for direct control via a laptop is available.

The control codes are given here for reference (although it is recommended to use the python code available):

- G= numberlo
- H= numberhi
- I= singleselect
- L= heighthi
- M= heightlo
- P= loadheight
- a= continuous
- d= triggerdelay5ns
- e= triggerdelay025nS
- g= run
- x= stop
- R=reset

Slave boards are individually assigned a unique number in the range 1 to 26. For example: to send commands to board 5 send ‘I’ ‘5’, a reply of ‘B5’ will be received. Subsequent commands will go to board 5 until another board is selected. A master hard reset of all slave boards is available via ‘R’, which will reset all the remote slave boards irrespective of the previous board selection.

Number of pulses is set with ‘G’ and ‘H’.

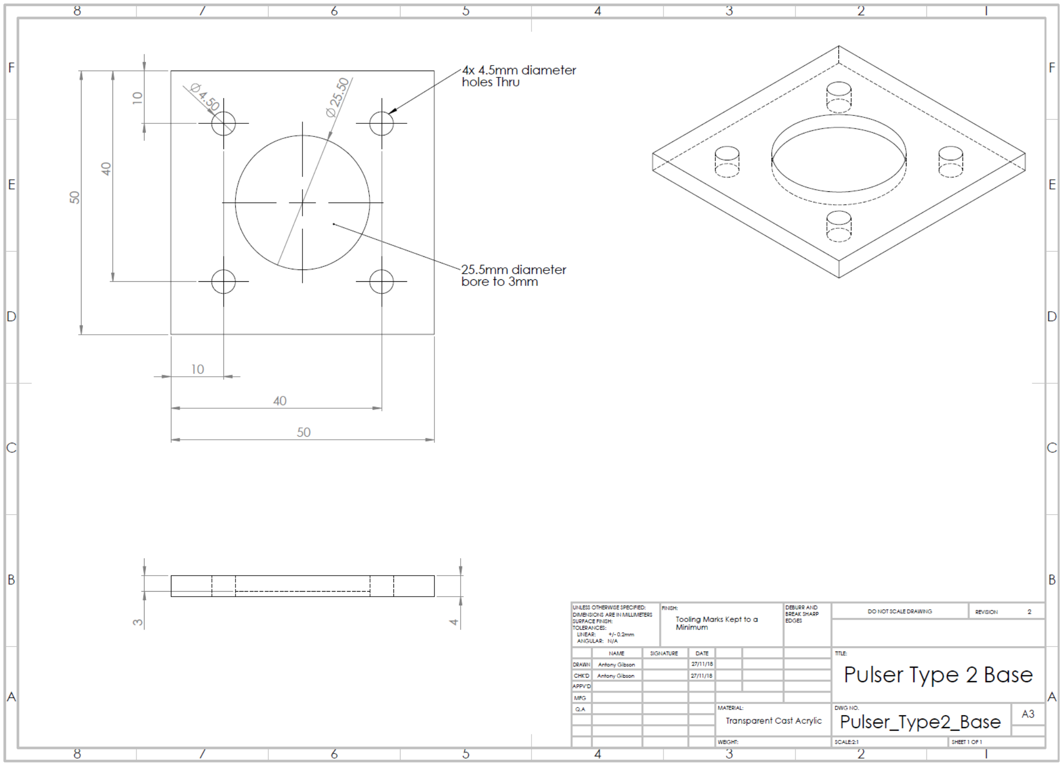
Pulse amplitude is selected with ‘L’ and ‘M’ and loaded with ‘P’.

A sequence is initiated with ‘g’ or continuous output with ‘a’.

Output can be stopped at any time with ‘x’.

205 # C Pulserhead encapsulation design

206 ## Pulserhead base



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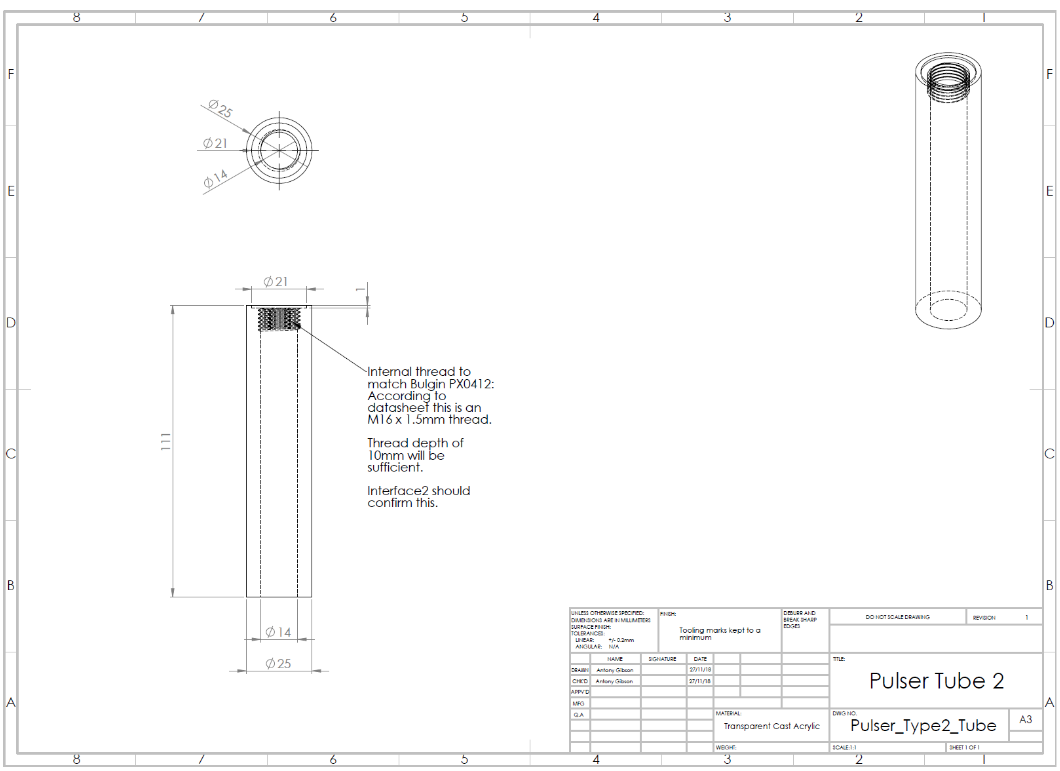
208 ## Pulserhead tube



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D LED spectra

Blue LED

Table 3. Spectrum for the 420 nm LEDs

λ (nm)	counts	λ (nm)	counts	λ (nm)	counts	λ (nm)	counts
390.11	169.68	408.45	17203.24	426.75	24410.80	445.00	2616.92
390.57	192.48	408.91	18916.24	427.20	23145.52	445.45	2489.24
391.03	218.96	409.37	20723.72	427.66	21978.16	445.91	2358.24
391.49	247.40	409.82	22630.68	428.12	20831.16	446.36	2235.00
391.95	281.00	410.28	24659.96	428.57	19756.40	446.82	2117.92
392.41	321.08	410.74	26758.92	429.03	18739.64	447.28	2001.92
392.87	363.52	411.20	28914.56	429.49	17763.76	447.73	1887.08
393.32	414.56	411.65	31087.52	429.94	16828.40	448.19	1789.76
393.78	472.84	412.11	33262.12	430.40	15950.64	448.64	1687.04
394.24	536.92	412.57	35417.36	430.86	15115.20	449.10	1596.04
394.70	606.40	413.03	37500.80	431.31	14321.16	449.55	1507.60
395.16	684.12	413.49	39511.04	431.77	13567.00	450.01	1429.08
395.62	775.24	413.94	41448.80	432.23	12840.28	450.47	1349.56
396.08	873.04	414.40	43232.64	432.68	12160.68	450.92	1280.08
396.54	984.80	414.86	44818.76	433.14	11510.76	451.38	1210.48
396.99	1113.80	415.32	46225.28	433.59	10862.48	451.83	1152.92
397.45	1258.12	415.77	47373.92	434.05	10262.16	452.29	1090.96
397.91	1409.12	416.23	48278.08	434.51	9699.12	452.74	1029.68
398.37	1582.48	416.69	48946.60	434.96	9148.72	453.20	974.80
398.83	1775.36	417.15	49375.80	435.42	8624.04	453.65	921.12
399.29	1982.88	417.60	49551.16	435.88	8138.32	454.11	871.16
399.75	2214.52	418.06	49489.64	436.33	7664.64	454.56	823.20
400.20	2479.32	418.52	49175.72	436.79	7217.20	455.02	782.44
400.66	2775.24	418.97	48612.32	437.25	6795.44	455.47	741.48
401.12	3099.52	419.43	47825.40	437.70	6397.80	455.93	701.72
401.58	3473.88	419.89	46839.28	438.16	6027.64	456.38	661.16
402.04	3887.60	420.35	45671.64	438.61	5691.88	456.84	629.84
402.50	4344.40	420.80	44366.76	439.07	5370.20	457.29	597.68
402.95	4854.16	421.26	42947.08	439.53	5071.40	457.75	567.96
403.41	5420.00	421.72	41433.60	439.98	4787.52	458.20	539.48
403.87	6040.96	422.18	39853.04	440.44	4523.44	458.66	516.52
404.33	6729.72	422.63	38214.60	440.89	4270.84	459.11	490.52
404.79	7498.96	423.09	36545.12	441.35	4035.40	459.57	465.44
405.24	8345.04	423.55	34888.60	441.81	3812.36		
405.70	9269.32	424.00	33241.76	442.26	3613.80		
406.16	10314.44	424.46	31636.24	442.72	3425.92		
406.62	11467.32	424.92	30097.96	443.17	3239.44		
407.08	12727.96	425.37	28579.20	443.63	3070.84		
407.53	14116.40	425.83	27130.92	444.09	2914.56		
407.99	15610.92	426.29	25741.80	444.54	2761.48		

UV LED

Table 4. Spectrum for the 355 nm LEDs

λ (nm)	counts	λ (nm)	counts	λ (nm)	counts	λ (nm)	counts	λ (nm)	counts
330.22	40.68	344.54	3022.24	358.84	54855.72	373.11	27908.76	387.36	4253.12
330.68	44.72	345.01	3523.24	359.30	54196.32	373.57	26478.80	387.82	4015.12
331.15	46.52	345.47	4096.88	359.76	53270.04	374.03	25064.00	388.28	3797.56
331.61	51.68	345.93	4771.16	360.22	52117.44	374.49	23700.68	388.74	3576.20
332.07	56.16	346.39	5553.16	360.68	50849.00	374.95	22387.92	389.19	3376.76
332.53	61.96	346.85	6460.12	361.14	49465.80	375.41	21113.28	389.65	3191.92
332.99	66.96	347.31	7507.88	361.61	48099.56	375.87	19889.04	390.11	3012.08
333.46	77.28	347.77	8706.92	362.07	46779.64	376.33	18747.28	390.57	2848.40
333.92	86.28	348.24	10067.80	362.53	45589.32	376.79	17634.20	391.03	2698.68
334.38	97.60	348.70	11598.76	362.99	44535.32	377.25	16593.56	391.49	2553.56
334.84	111.96	349.16	13320.68	363.45	43665.72	377.71	15612.28	391.95	2417.40
335.31	129.32	349.62	15218.56	363.91	42962.24	378.17	14689.04	392.41	2297.60
335.77	148.48	350.08	17311.44	364.37	42470.84	378.63	13798.12	392.87	2179.28
336.23	171.96	350.54	19615.96	364.83	42082.00	379.09	12983.24	393.32	2070.16
336.69	203.96	351.00	22112.48	365.29	41798.84	379.55	12190.52	393.78	1965.84
337.15	241.96	351.47	24778.36	365.75	41597.08	380.01	11460.00	394.24	1870.68
337.62	287.28	351.93	27600.52	366.21	41416.32	380.47	10766.72	394.70	1776.72
338.08	338.56	352.39	30551.12	366.67	41208.20	380.93	10109.24	395.16	1692.00
338.54	404.88	352.85	33521.68	367.13	40986.12	381.39	9487.80	395.62	1612.20
339.00	477.80	353.31	36536.76	367.59	40670.12	381.85	8920.28	396.08	1538.68
339.46	562.36	353.77	39491.16	368.05	40253.40	382.31	8375.68	396.54	1466.48
339.93	662.16	354.23	42346.24	368.51	39696.96	382.77	7861.44	396.99	1404.12
340.39	778.28	354.69	45030.04	368.97	39057.12	383.23	7384.84	397.45	1342.12
340.85	908.20	355.15	47508.08	369.43	38216.44	383.68	6938.08	397.91	1281.60
341.31	1056.56	355.61	49667.84	369.89	37265.96	384.14	6508.72	398.37	1226.64
341.77	1232.72	356.08	51527.68	370.35	36176.36	384.60	6107.04	398.83	1176.64
342.24	1430.48	356.54	52989.20	370.81	34995.32	385.06	5739.96	399.29	1127.32
342.70	1659.60	357.00	54099.80	371.27	33638.28	385.52	5395.60	399.75	1082.88
343.16	1925.00	357.46	54828.68	371.73	32271.88	385.98	5067.88		
343.62	2235.40	357.92	55194.92	372.19	30835.76	386.44	4778.32		
344.08	2596.20	358.38	55169.92	372.65	29375.44	386.90	4509.56		

Todo list