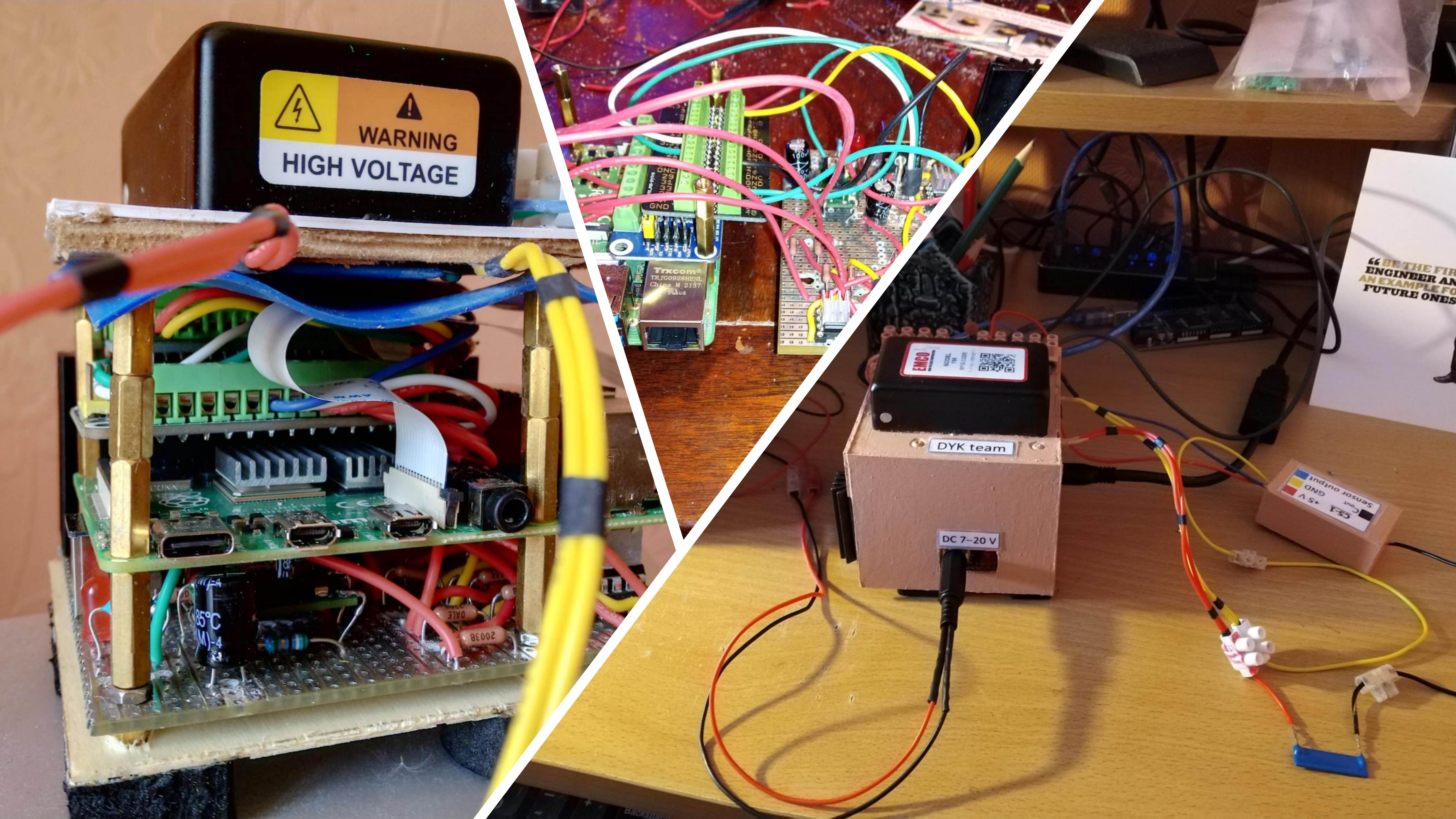
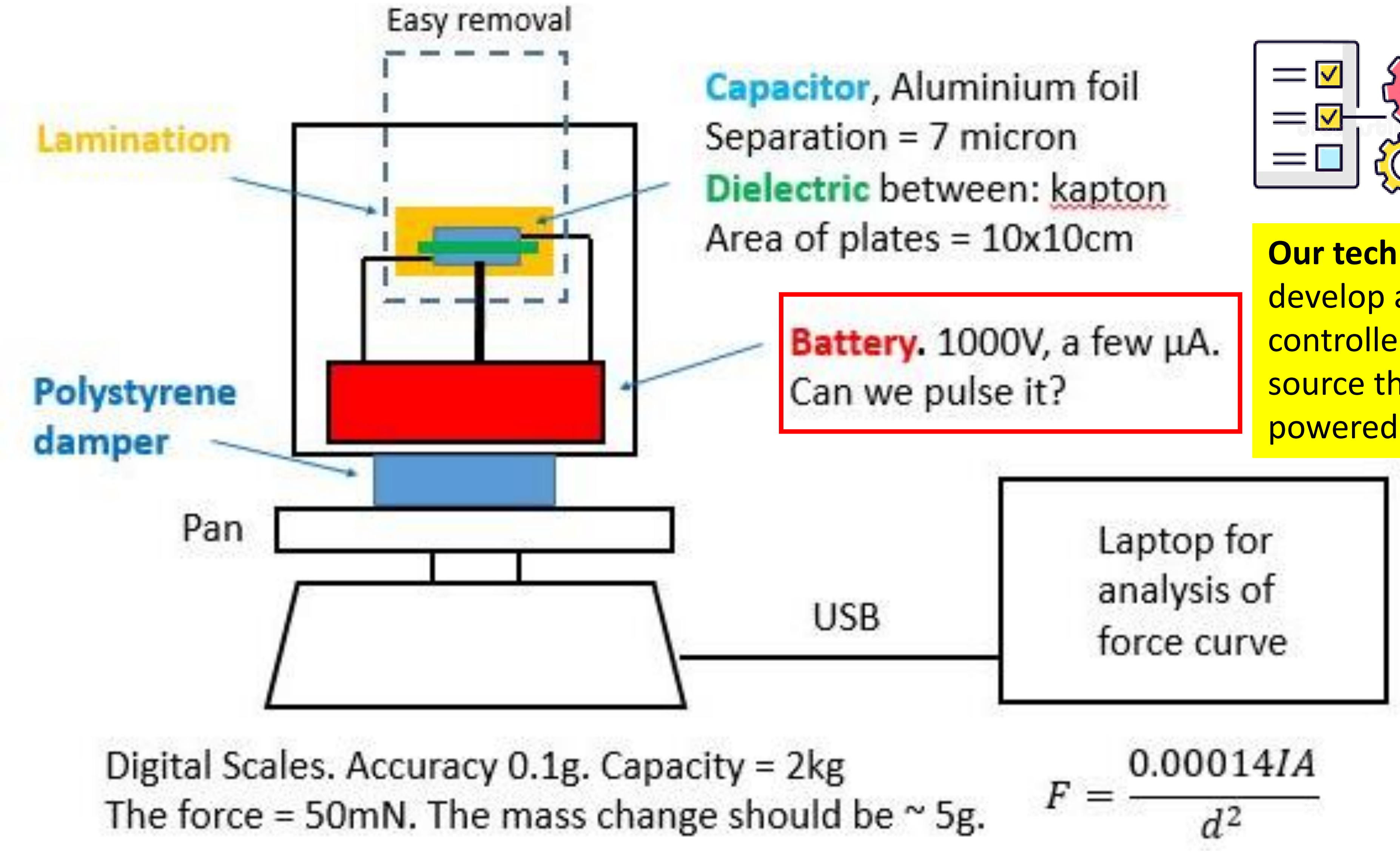

WARNING
HIGH VOLTAGE
Trxcom
EMCO
DYK team
DC 7–20 V

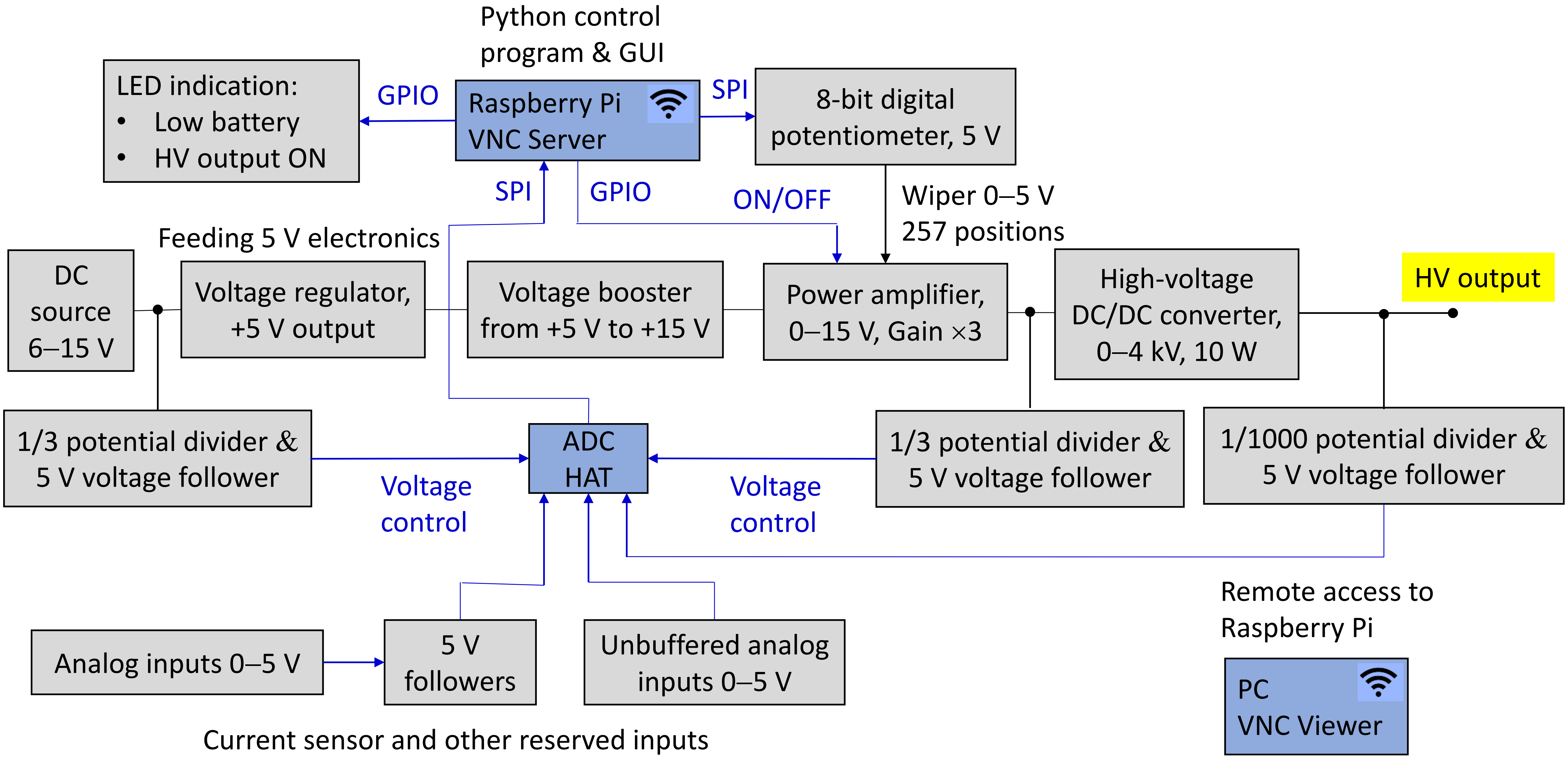
Original sketch of a capacitor QI thruster provided by Dr. Mike McCulloch



Our technical task: to develop a remotely controlled high-voltage source that could be powered by a battery

QI project links: http://physicsfromtheedge.blogspot.com, https://twitter.com/memcculloch, https://twitter.com/Arundal_Astro

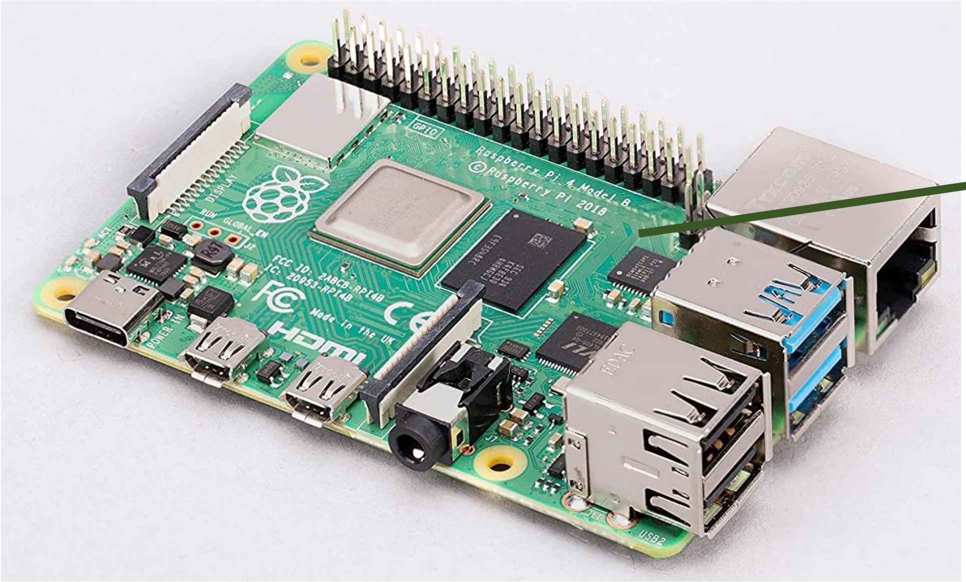
Architecture of the remotely controlled high-voltage source (0–4 kV, 10 W)

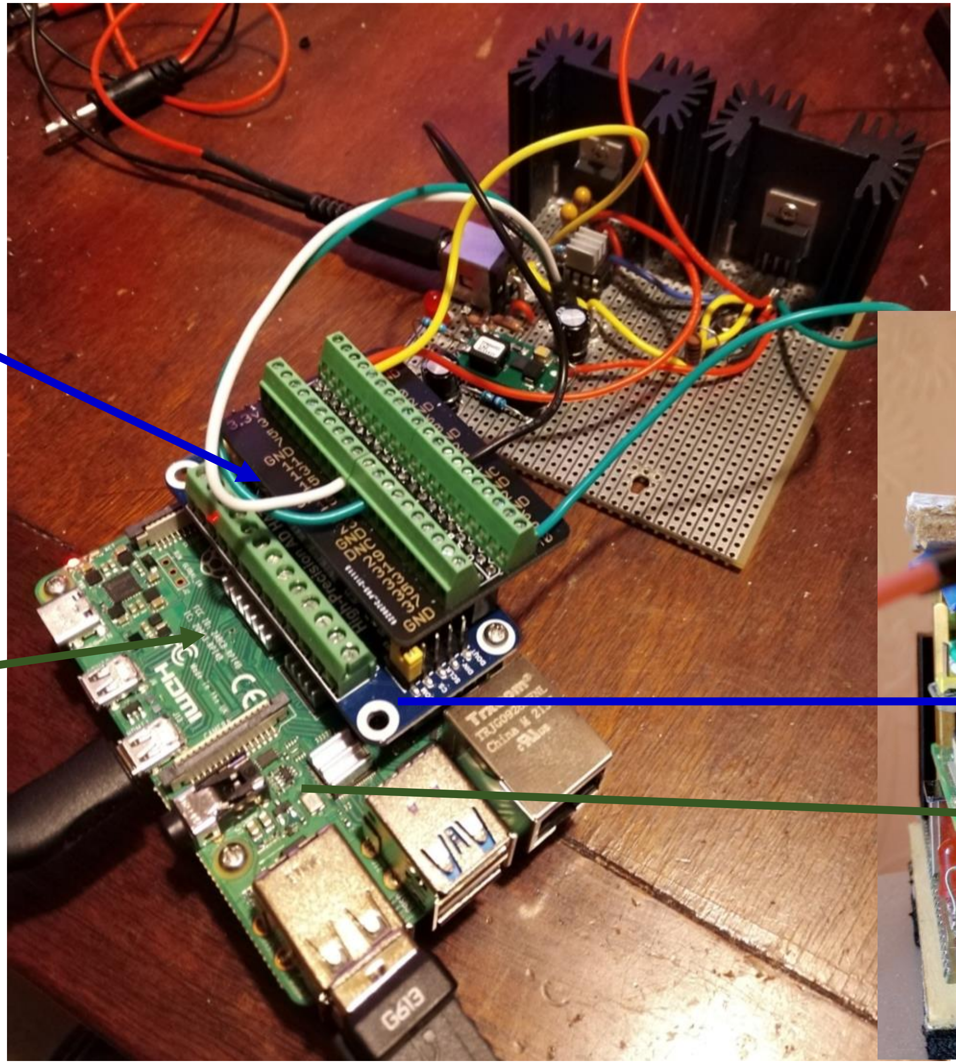


RPI: Raspberry Pi 4 B, 8 GB RAM, 128 GB microSD Card

ADC HAT: Analog-to-Digital Converter, 10 channels, 32-bit resolution

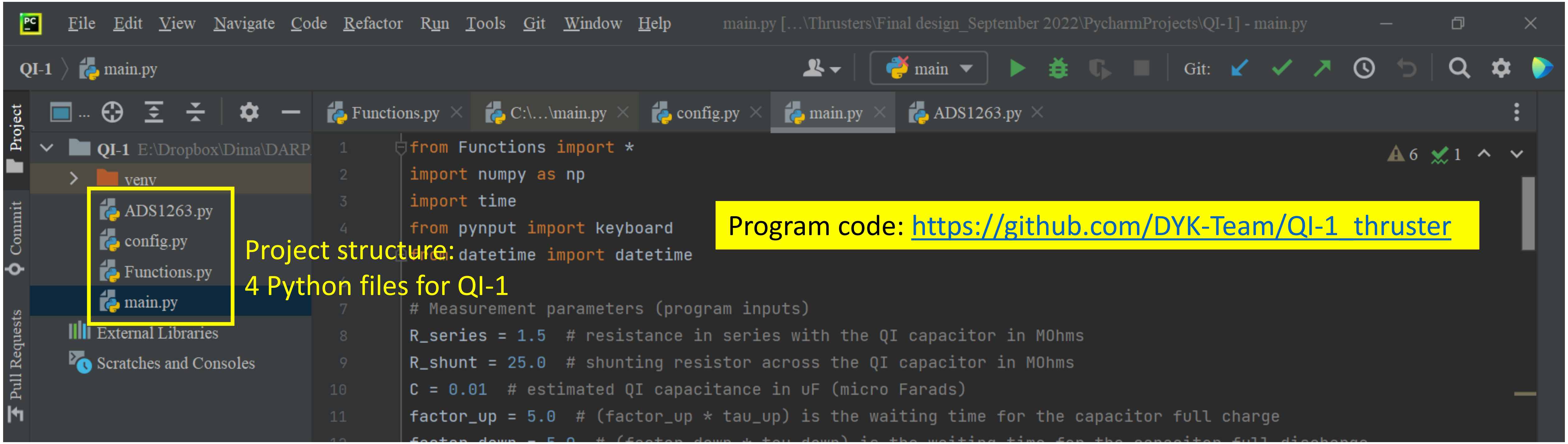
https://www.waveshare.com/18983.htm

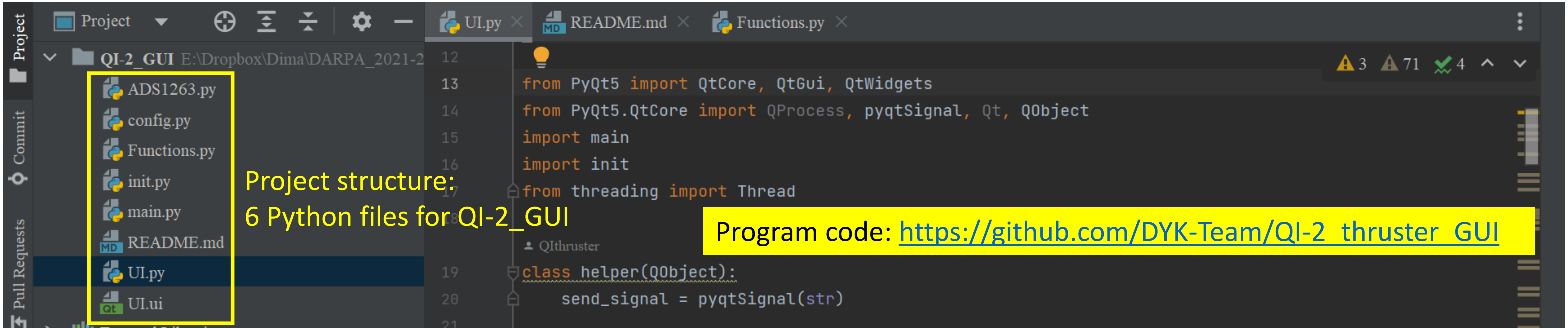




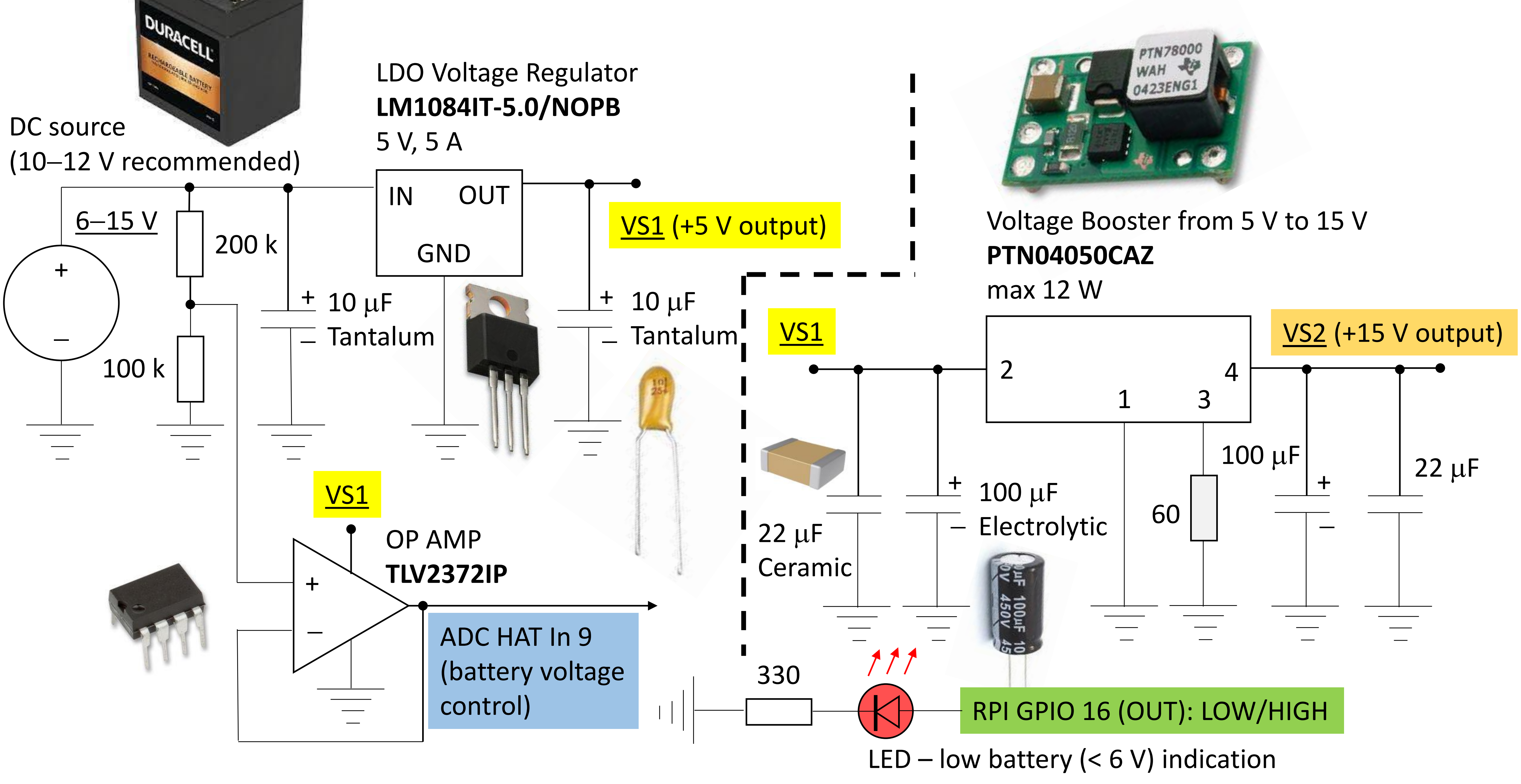
Stacked PCB with electronics, RPI, ADC HAT, and high-voltage converter

We use PyCharm IDE which is installed on RPI

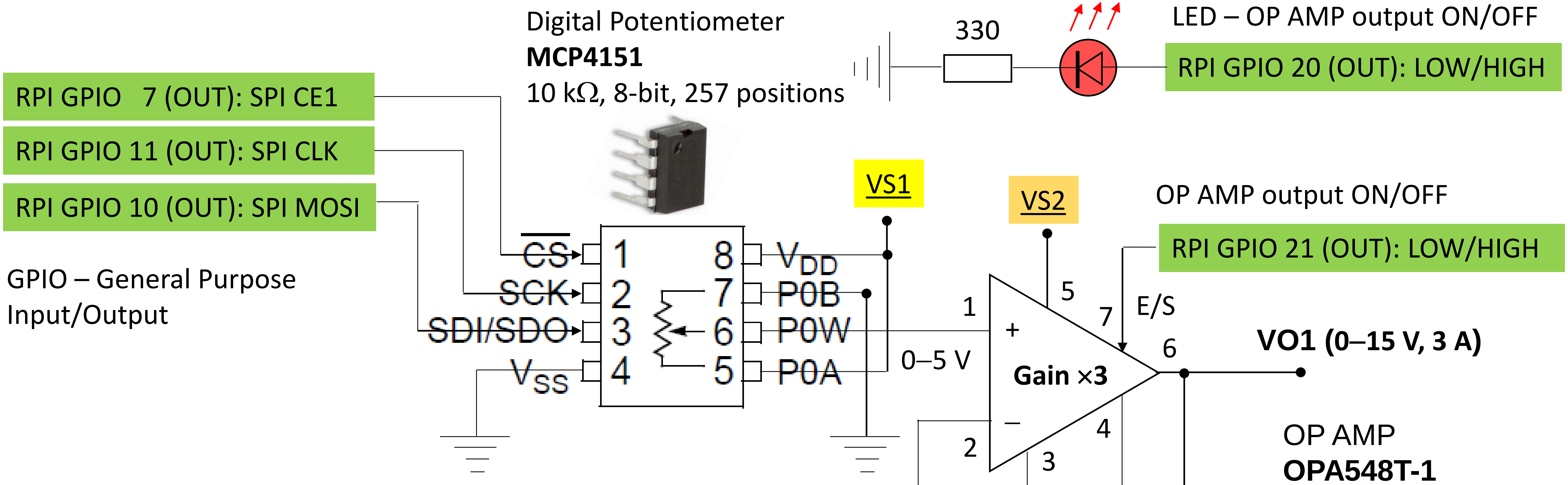


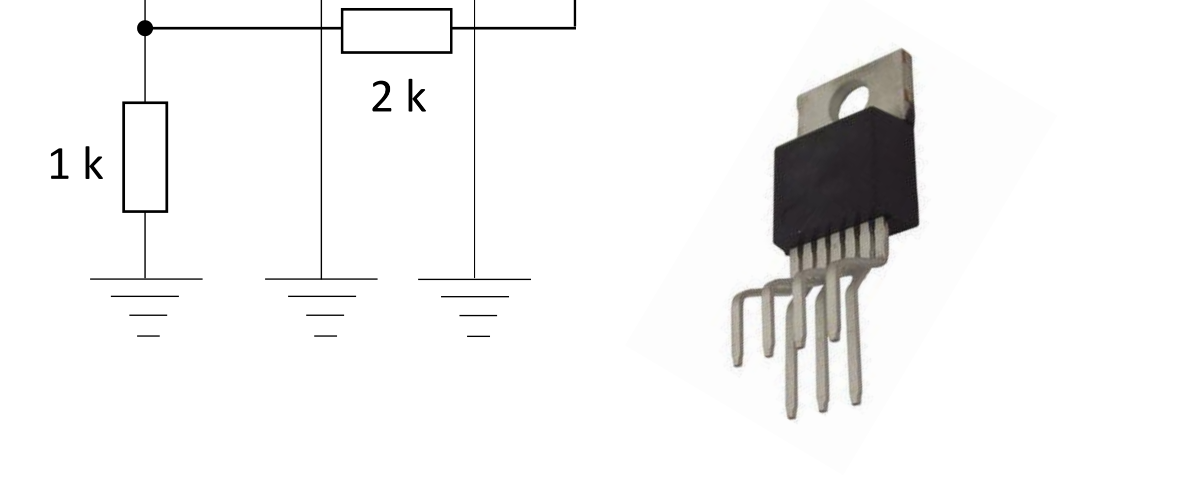


Internal voltage sources, VS1 = 5 V and VS2 = 15 V



Programable power supply 0 – 15 V (257 voltage points)

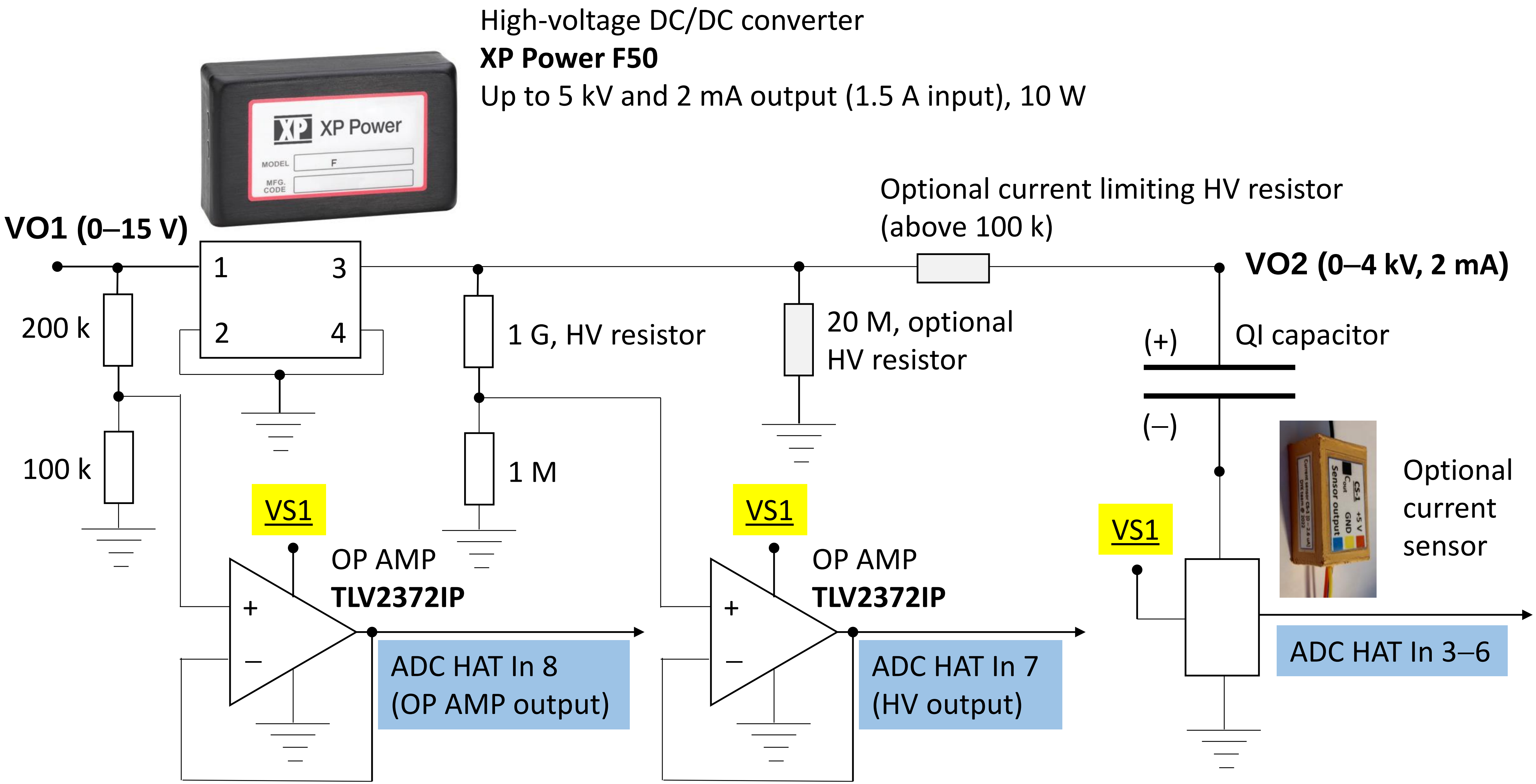




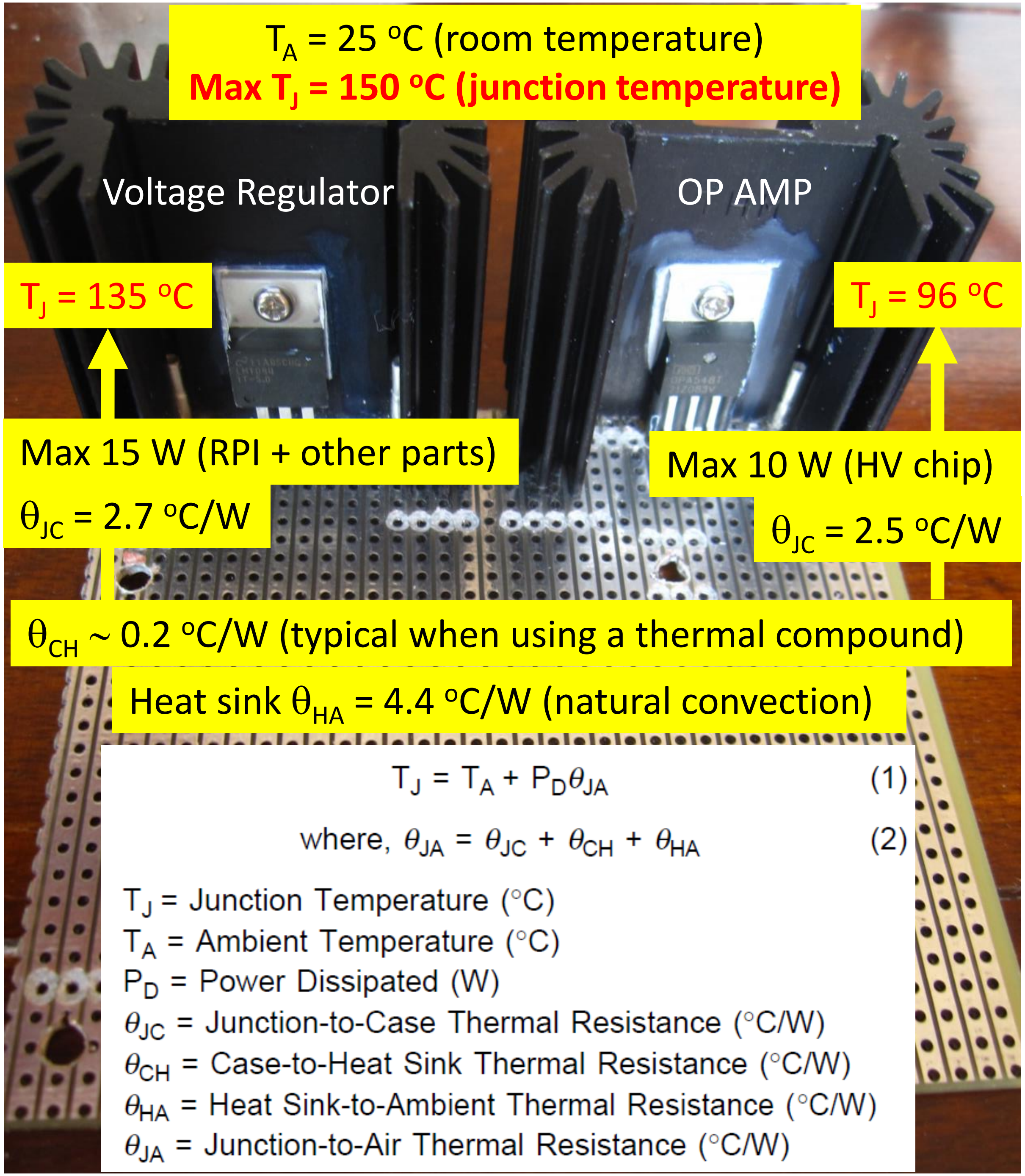
CS – chip select (LOW enable serial commands)
SCK – clock pulses
Multiplexed SDI/SDO – Serial Data In/Serial Data Out.
In our application, only SDI option is used

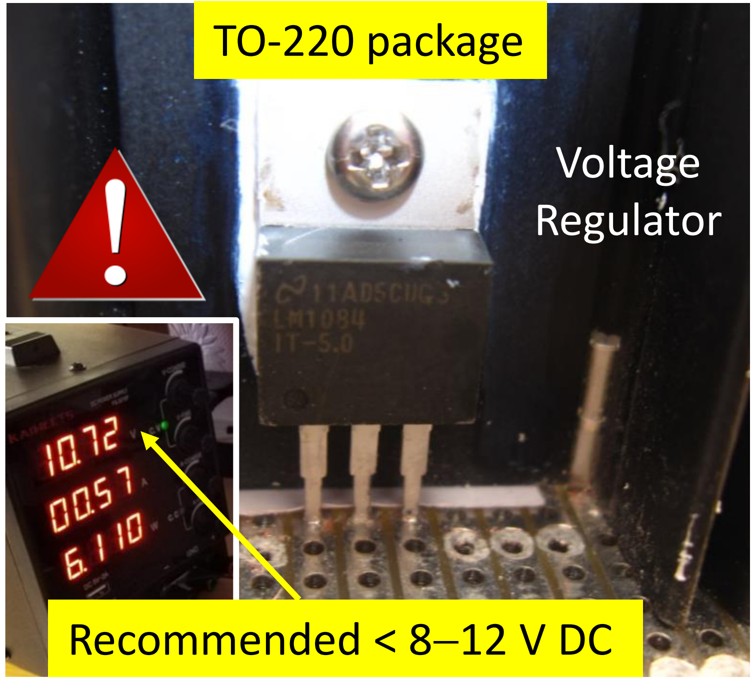
POB – terminal B (wiper value 0x00)
POW – wiper terminal (257 positions, 0-256)
POA – terminal A (wiper value 0x100)

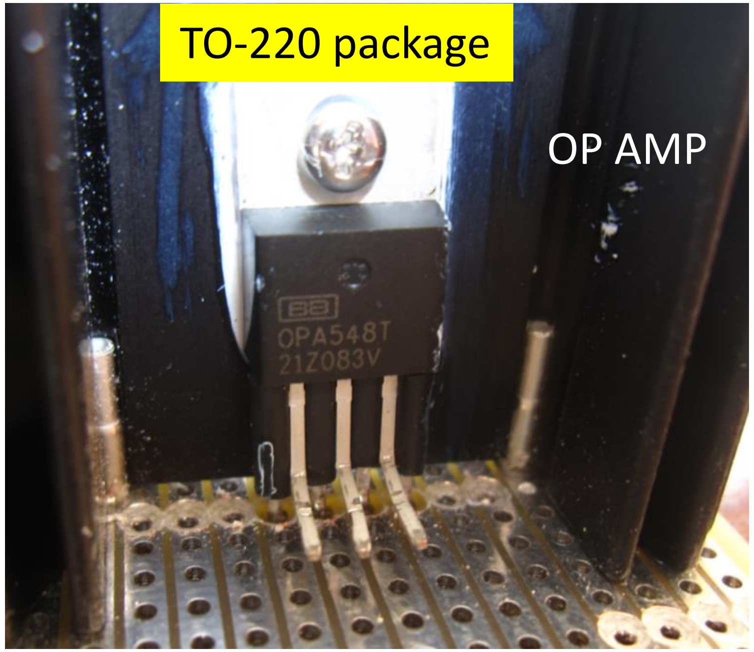
High-voltage DC/DC converter 0–4 kV, 10 W

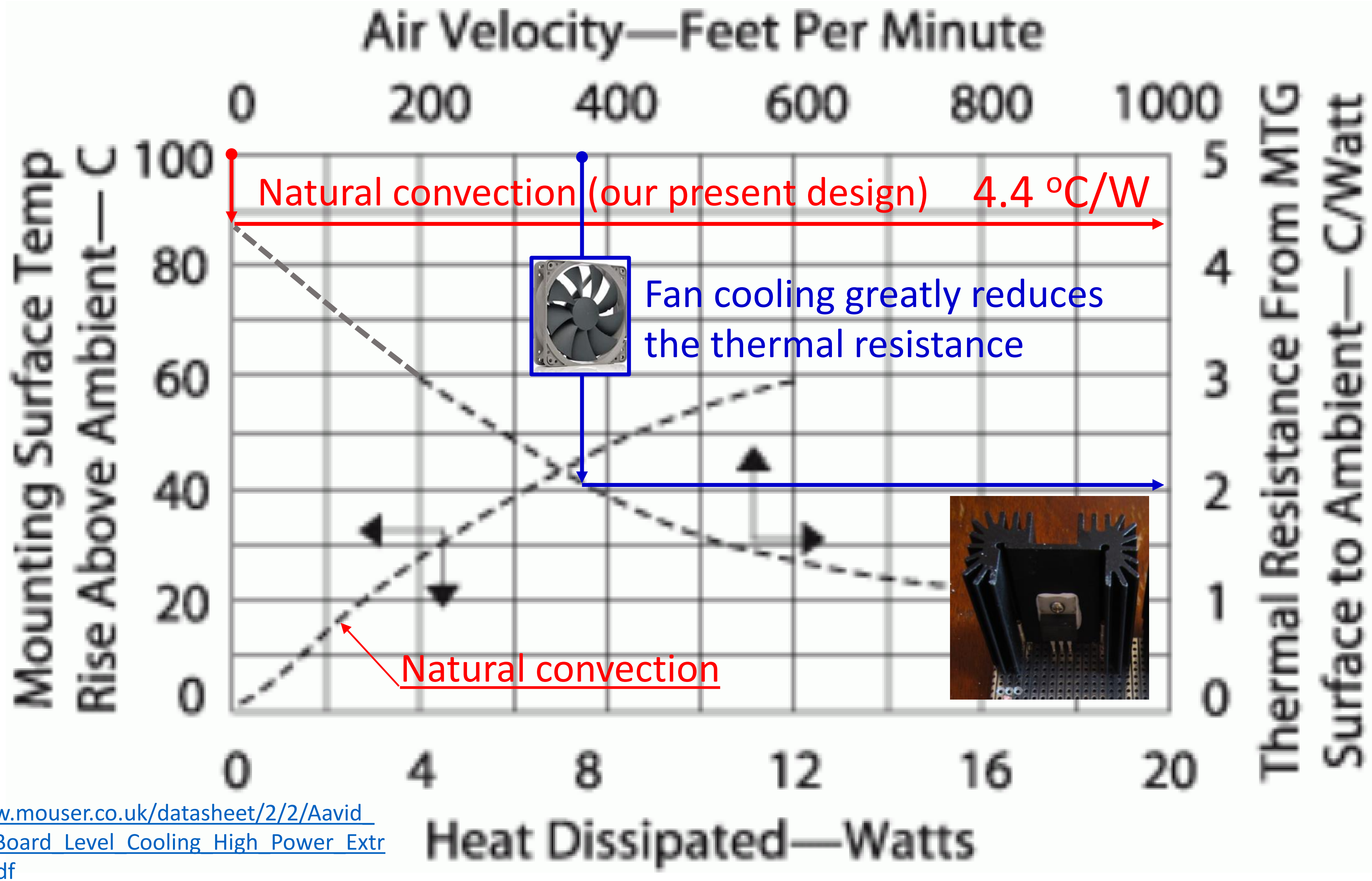


Heat management in the circuit









https://www.mouser.co.uk/datasheet/2/2/Aavid_01112021_Board_Level_Cooling_High_Power_Extr-1953733.pdf

Understanding fan characteristics: CFM (cubic feet per minute) and LFM (linear feet per minute)

FEATURES

- dual ball bearing system
- 120 x 120 mm frame
- multiple speed options
- tachometer signal available

Online calculator

Air Flow: 169.5 CFM

☐ Rectangle Duct

H: W: in

☑ Circular Duct

R: 60 mm

Calculate Clear

Results:

1392.32 ft/min (LFM)

/s

iles/hr (MPH)

^{3}/min (CFM)

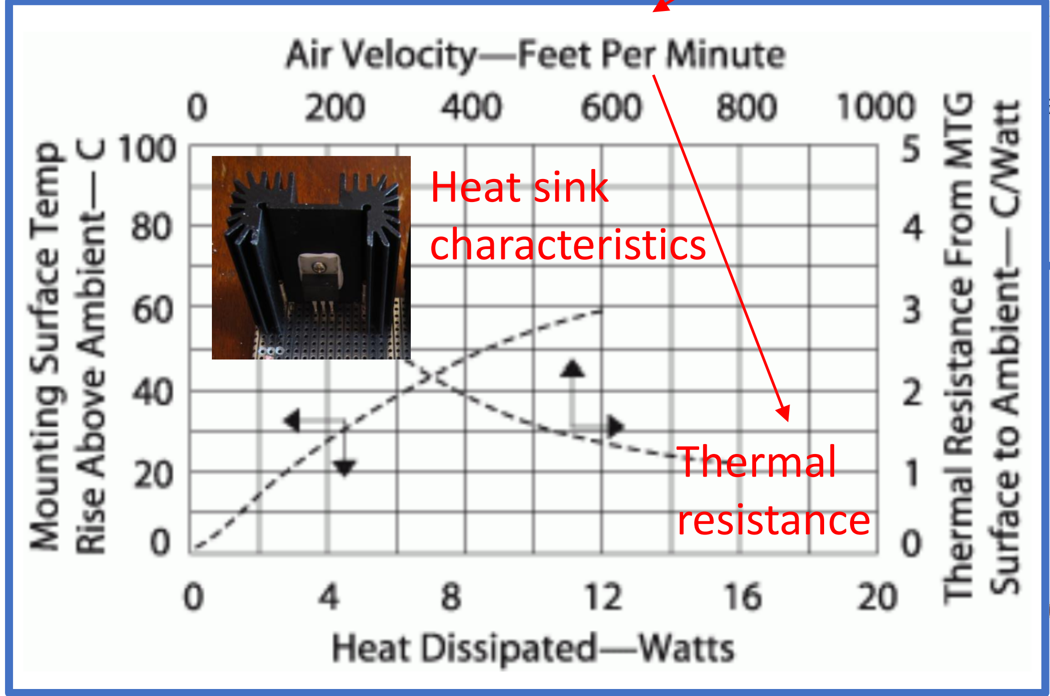
^{3}/hr

s

$$LFM = \frac{CFM}{Cross\text{–}Sectional\ Area}$$

Cross-Sectional Area = πR^2 [sq. ft]

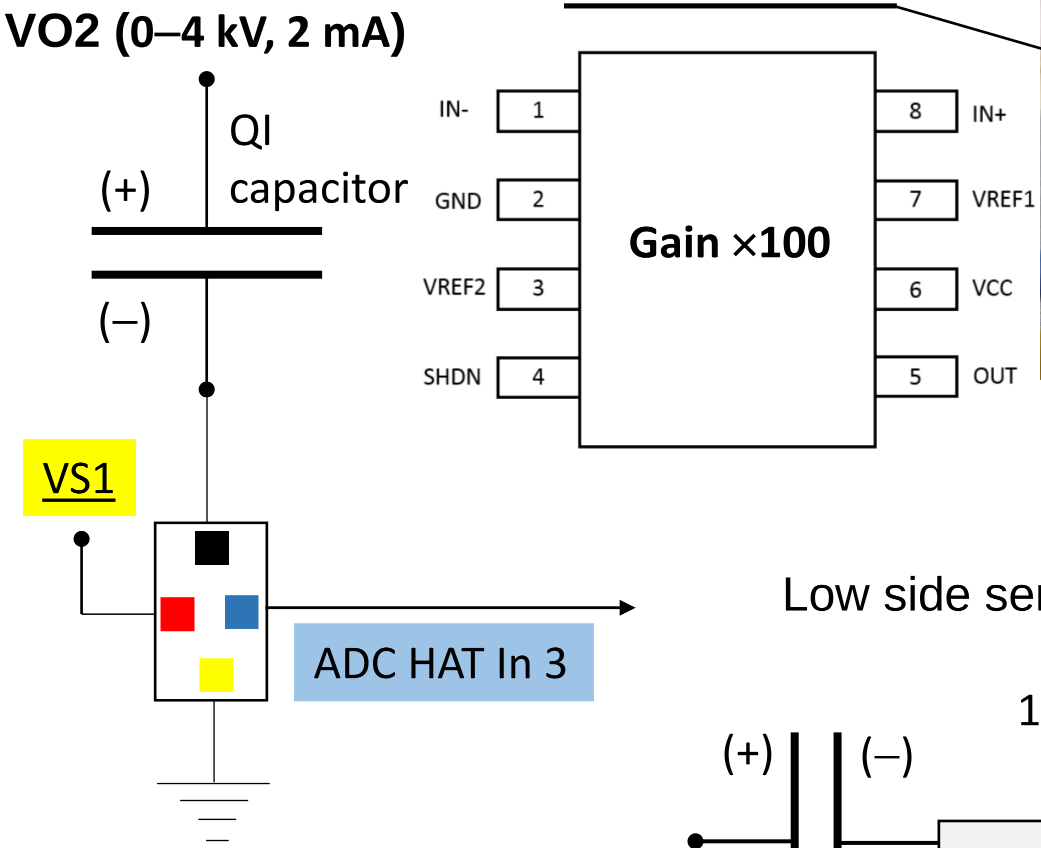
Transfer R to feet!

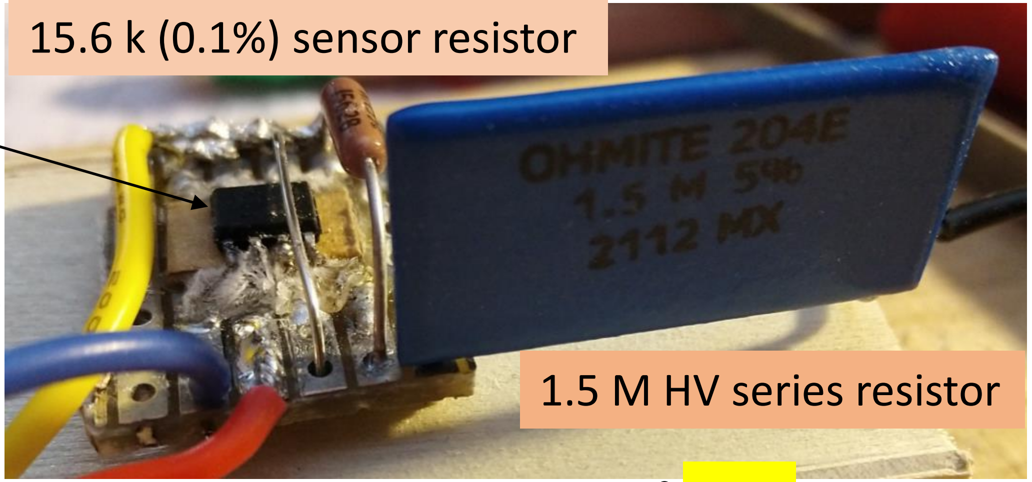


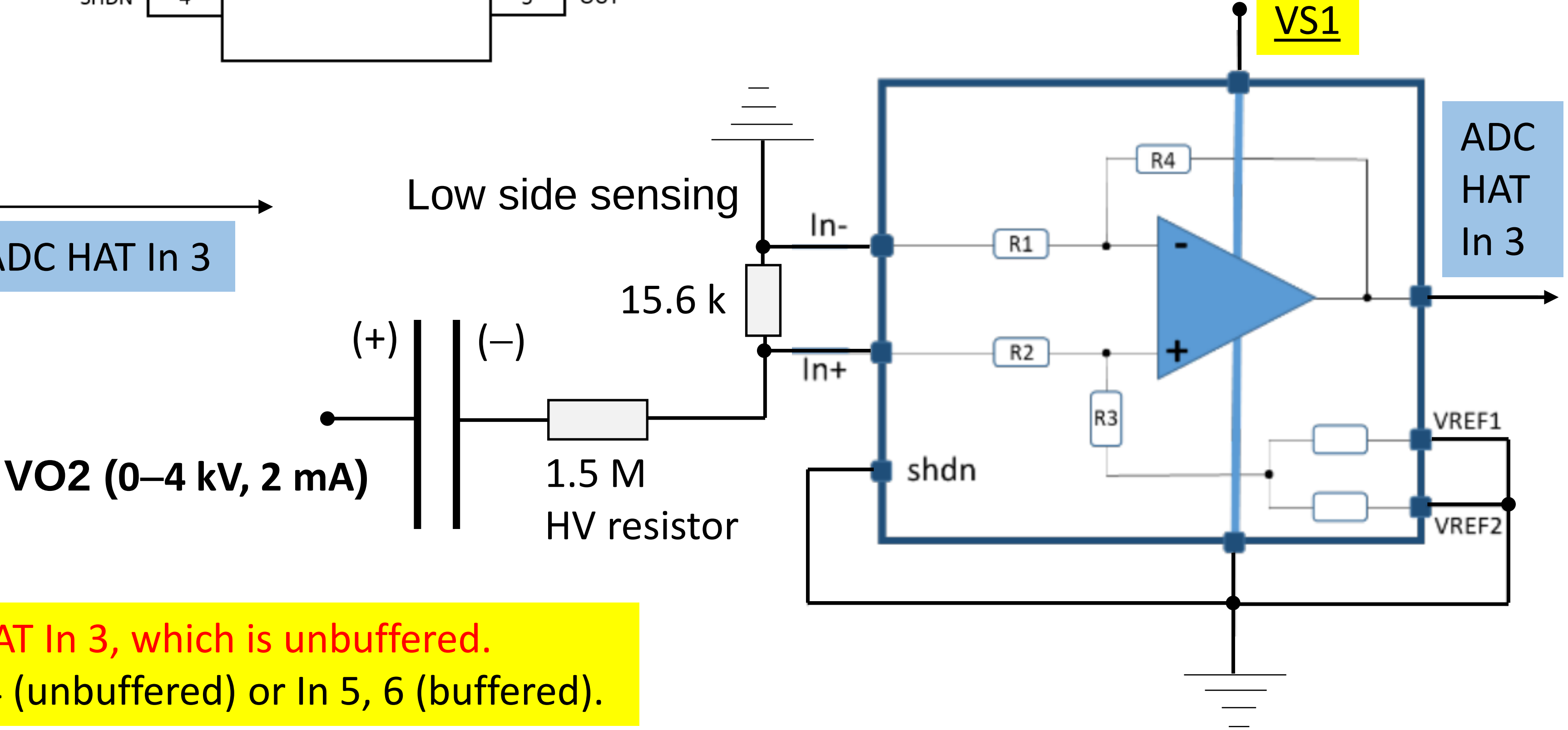
https://www.engineering.com/calculators/air-flow-conversion-calculator/#:~:text=By%20multiplying%20air%20velocity%20by,conditioning%2C%20heating%20and%20ventilating%20work.

	(Vdc)	e range (Vdc)	input current[1] max (A)	input power[1] max (W)	rated speed[1] typ (RPM±10%)	airflow[2] (CFM)	static pressure[3] (inch H_2O)	r
CFM-A225BF-153-577	12	10.8~13.2	1.87	22.44	5,300	169.5	0.82	

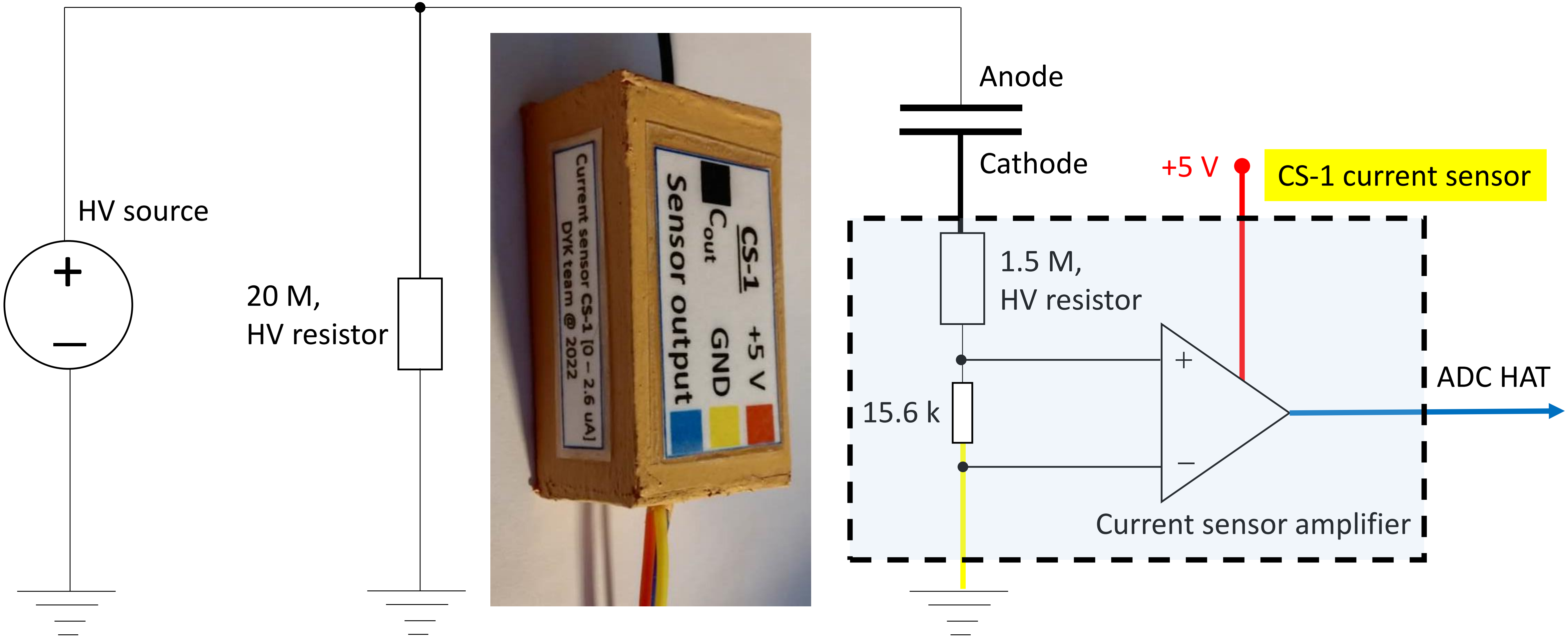
Current sensor CS-1 for measuring the leakage current



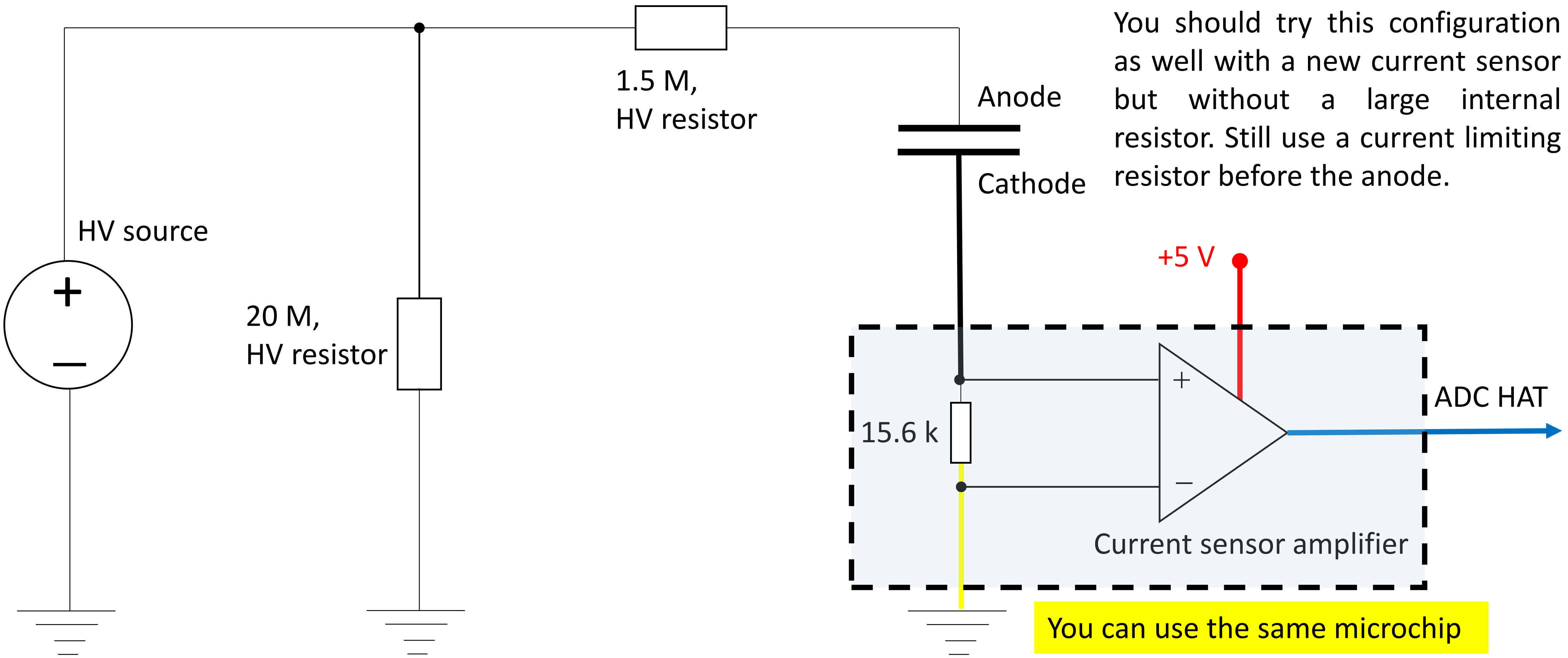




We connect the sensor output to ADC HAT In 3, which is unbuffered.
The sensor can also be connected to In 4 (unbuffered) or In 5, 6 (buffered).

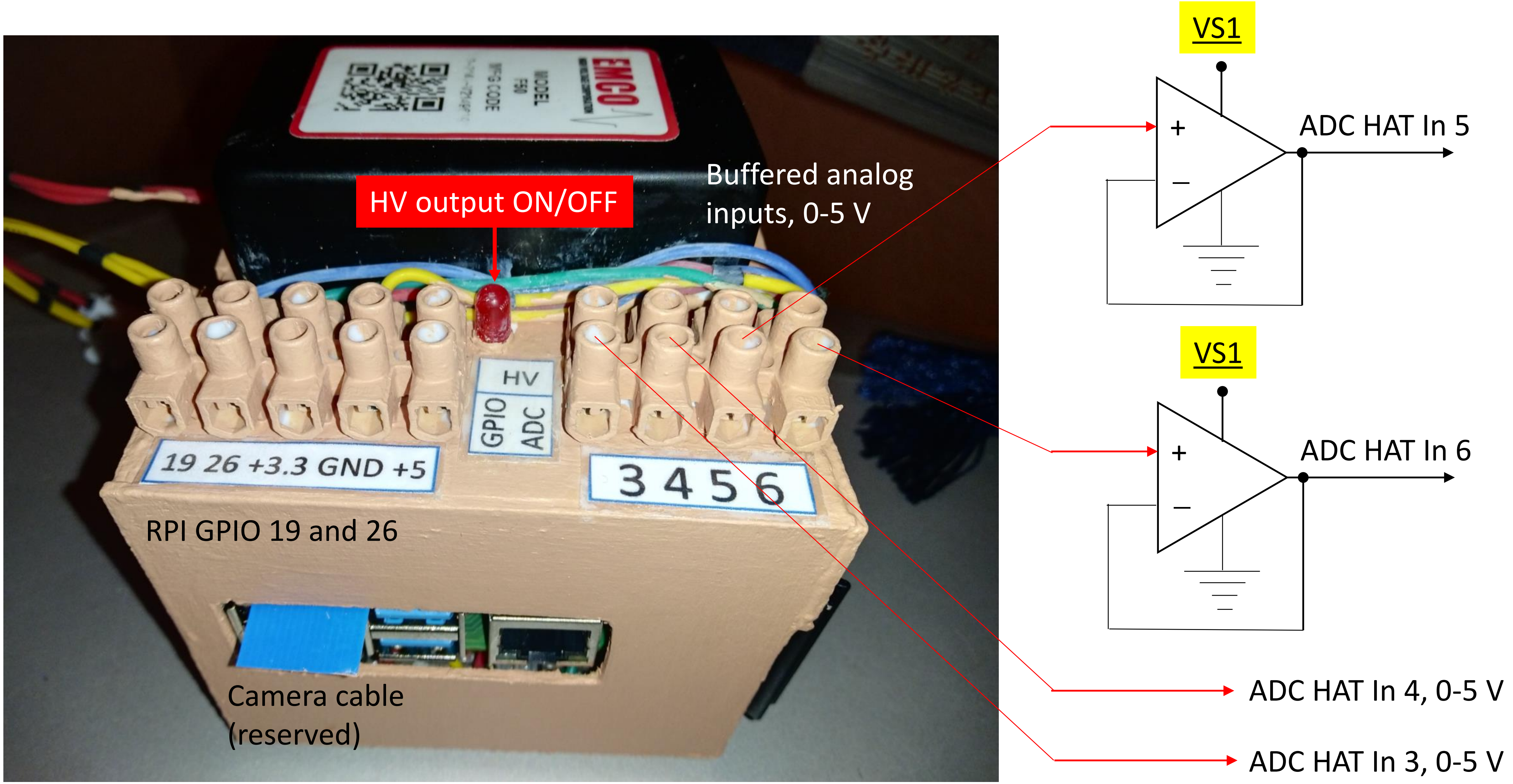


During dielectric breakdown, the capacitor cathode and the resistor network down to ground work as a current generator with a very large internal resistor 1.5 MΩ inside the sensor. This resistor limits the current and therefore may prevent "the avalanche". That is why you may not hear "snaps". You should explore other configurations, where a current limiting HV resistor is placed before the anode, while the low side sensor has only a kΩ sensor resistor (next slide).



You should try this configuration as well with a new current sensor but without a large internal resistor. Still use a current limiting resistor before the anode.

Device ports

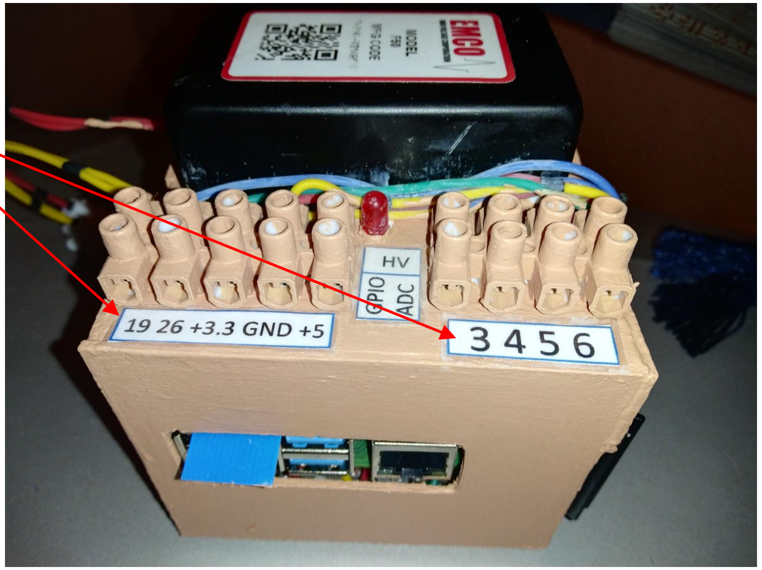


RPI GPIO 19 and 26 can be use, for example, for multiplexing the current sensor ranges in the future designs. This option has been already reserved for the current sensor function in the Python program.

QI-1 interface without GUI. Run “main.py”.

```
# Measurement parameters (program inputs)
R_series = 1.5  # resistance in series with the QI capacitor in MOhms
R_shunt = 25.0  # shunting resistor across the QI capacitor in MOhms
C = 0.01  # estimated QI capacitance in uF (micro Farads)
factor_up = 5.0  # (factor_up * tau_up) is the waiting time for the capacitor full charge
factor_down = 5.0  # (factor_down * tau_down) is the waiting time for the capacitor full discharge
current_range = 1  # operational range of the current sensor; range 1 - GPIO 19, range 2 - GPIO 26
Ch = 3  # Your channel (ADC In 3 - In 6) for the current sensor. In 5 and 6 are internally buffered.
# The current sensor function CurrentSensor(bias, Ch) is in Functions.py
```

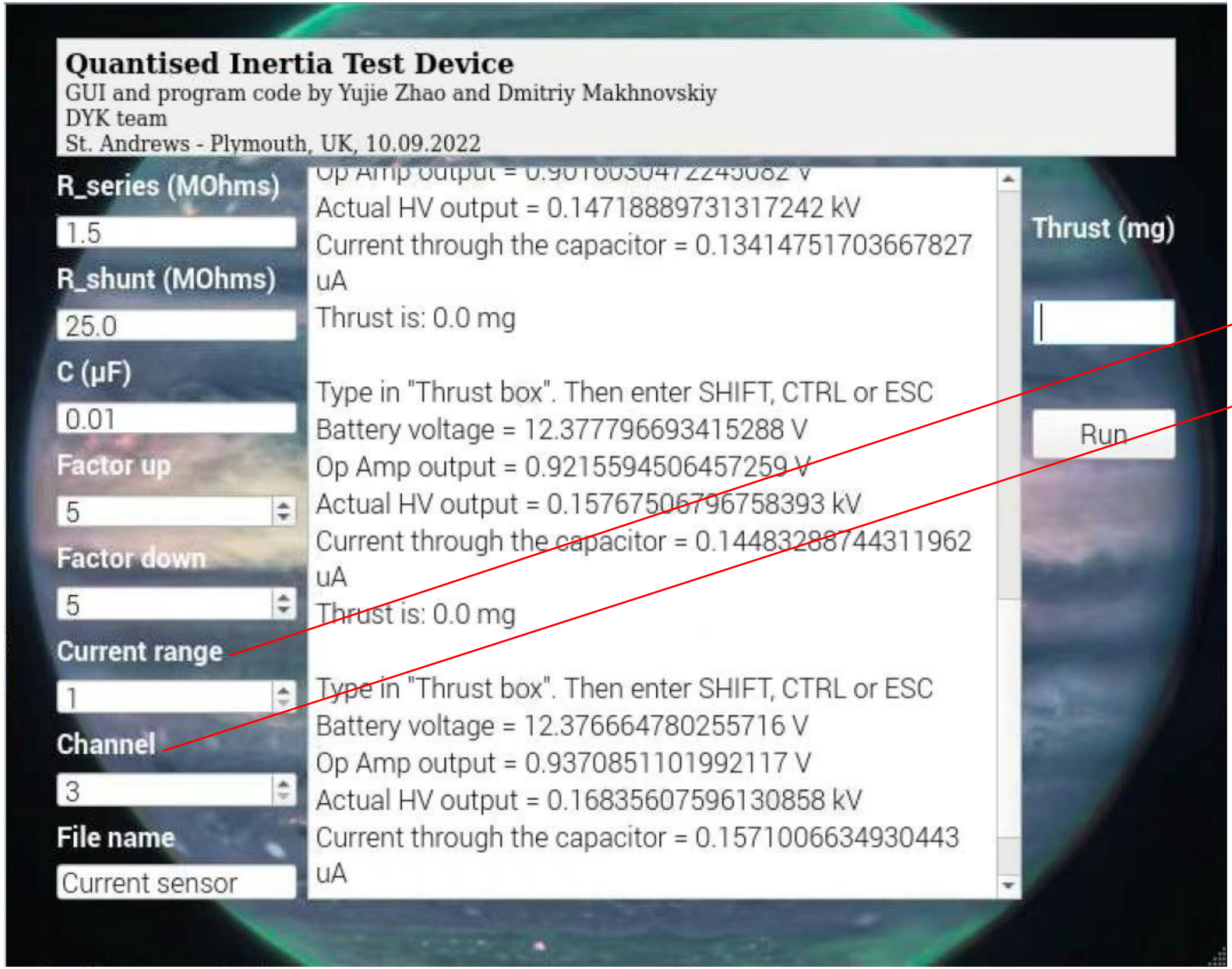
```
def CurrentSensorRange(range):
    range1 = 19
    range2 = 26
    GPIO.setup(range1, GPIO.OUT)
    GPIO.setup(range2, GPIO.OUT)
    GPIO.output(range1, GPIO.LOW)
    GPIO.output(range2, GPIO.LOW)
    if range == 1:
        GPIO.output(range1, GPIO.HIGH)
    elif range == 2:
        GPIO.output(range2, GPIO.HIGH)
```

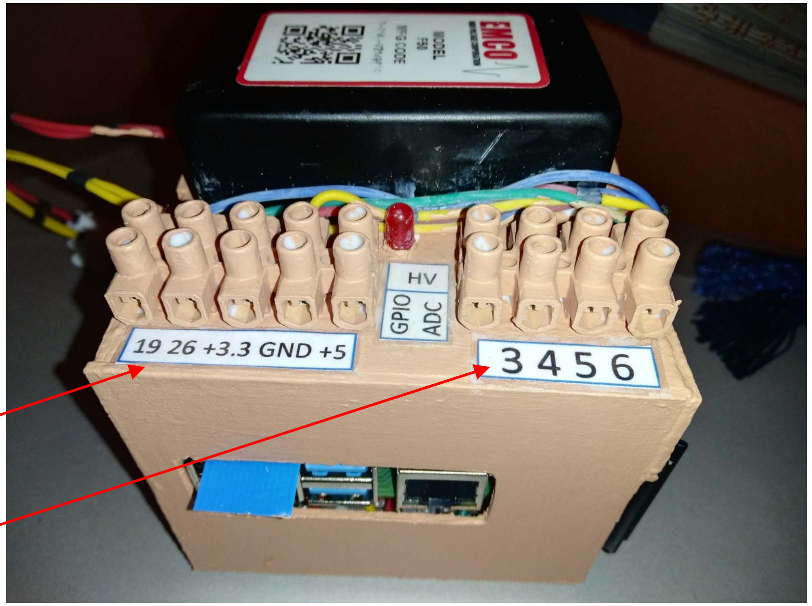


Program code: https://github.com/DYK-Team/QI-1_thruster

Current sensor CS-1 does not use multiplexing but in the function this option has been reserved.

QI-2_GUI. Run "UI.py".

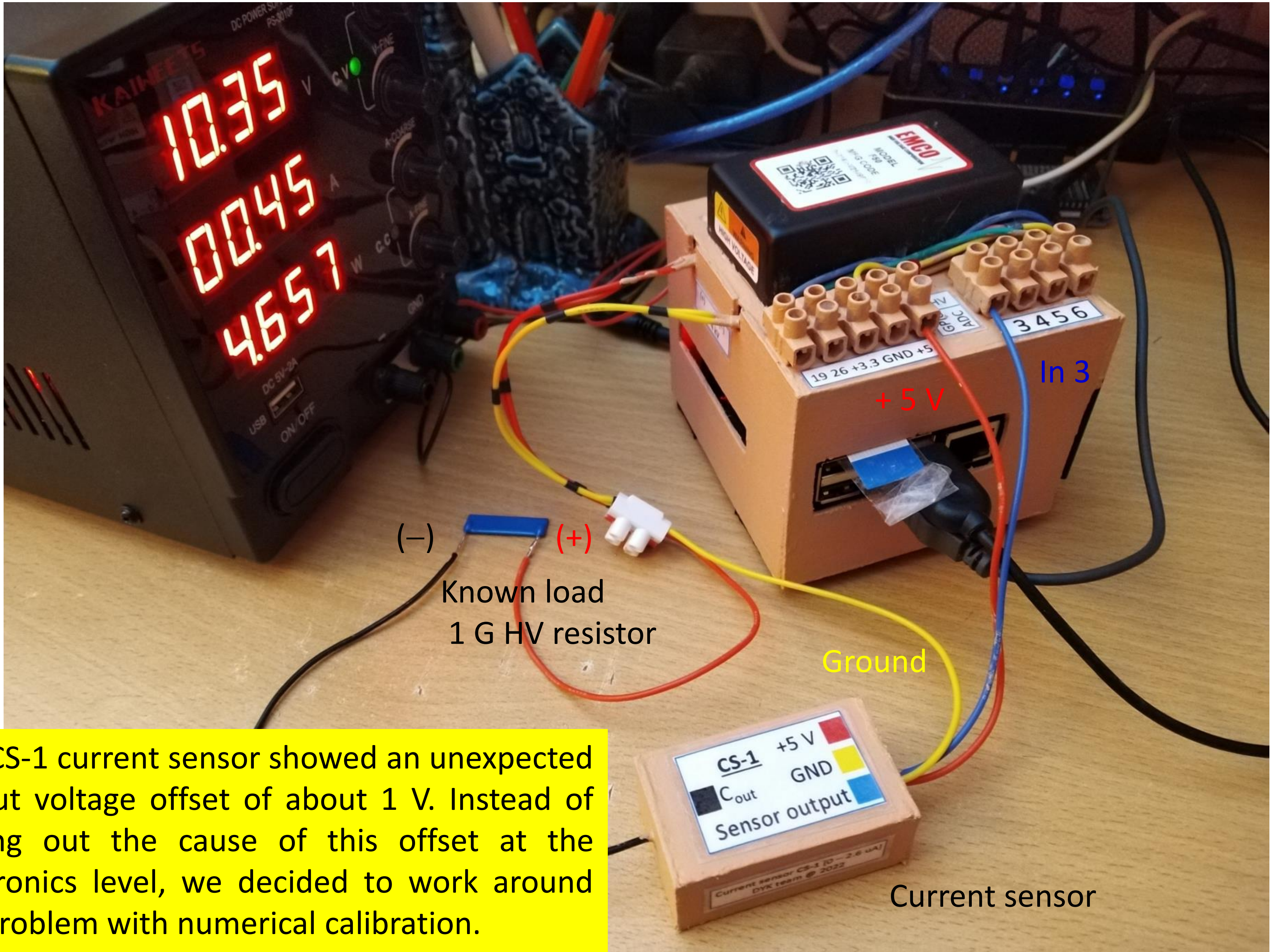




Program code: https://github.com/DYK-Team/QI-2_thruster_GUI

Current sensor CS-1 does not use multiplexing but in the function this option has been reserved.

Current sensor calibration: circuit



Our CS-1 current sensor showed an unexpected output voltage offset of about 1 V. Instead of finding out the cause of this offset at the electronics level, we decided to work around the problem with numerical calibration.

Current sensor calibration: procedure

1. Connect a 1 G (1%) HV resistor instead of the QI capacitor as shown in the previous slide.
2. In the file “Functions.py”, modify the current function “CurrentSensor(bias, Ch)”, by uncommenting the line 6, see below. The function will return the x-value, not y.

```
1.  def CurrentSensor(bias, Ch):
2.      x = (Read_ADC(Ch) - bias)
3.      y = -0.11372504497803 * x**8 + 1.4343168169319 * x**7 -7.3278668065487 * x**6 + \
4.          19.4325718360446 * x**5 - 28.448512253201 * x**4 + \
5.          22.3174566367283 * x**3 - 7.6319260686742 * x**2 + 1.1951000922818 * x
6.      #return x  # used during the sensor calibration
7.      return y
```

3. Run the program and increase the HV voltage output step by step (SHIFT button) up to the maximum value 4 kV. Put zero thrust after each step. The program will calculate the offset automatically (bias) and subtract it.
4. After achieving 4 kV, stop the program (ESC).
5. The program will create an output file with four columns: OP AMP output (V), HV output (kV), current sensor output (arb units during the calibration), and thrust (your units).
6. In Excel, draw the scatter graph “HV output” (y-axis) vs. “current sensor output” (x-axis).
   a) Draw the trend line of this graph, choosing “polynomial” of the order 8 (RPI Office allows 8 and higher orders).
   b) Visualise the equation of the polynomial.
   c) Put the new polynomial coefficients into the function above.
7. Comment (#) the line 6 in the function “CurrentSensor(bias, Ch)” so that the function returns the y-value.
8. When you run the program again, the current units will be uA.
9. Leave the resistor connected and run the program again to check the calibration. You must obtain almost straight line with 1:1 correspondence between HV output (x-axis) and current sensor output (y-axis).

List of the main electronic components

Volatile Digital Potentiometer, 10 kohm, Single, SPI, Linear, ± 20%, 1.8 V (×1) https://www.mouser.co.uk/ProductDetail/Microchip-Technology-Atmel/MCP4151-103E-P?qs=hH%252BOa0VZEiCcBDYaXnd0Yg%3D%3D&gclid=Cj0KCQjw1vSZBhDuARIsAKZlijTUOSfpThWQ7DDjQ6e7MBO8J0pd4FaWfxIr5qg8UguUVpjCefRdbN0aAm58EALw_wcB

Isolated DC/DC Converters SINGLE O/P, DC-HV DC PCB MOUNT, 10W, 5000V (×1) https://www.mouser.co.uk/ProductDetail/XP-Power/F50?qs=w%2Fv1CP2dgqp9eWErQLdwfA%3D%3D

Operational Amplifier, 1 Amplifier, 1 MHz, 10 V/µs, ± 4V to ± 30V, TO-220, 7 Pins (×1) https://uk.farnell.com/texas-instruments/opa548t-1/ic-op-amp/dp/3005043?st=opa548t-1

Operational Amplifier, 2 Amplifier, 3 MHz, 2 V/µs, 2.7V to 16V, DIP, 8 Pins (×4) https://uk.farnell.com/texas-instruments/tlv2372ip/ic-op-amp-3mhz-rri-o-2372-pdip8/dp/3005254

Non Isolated POL DC/DC Converter, 12 W, 5 V, 15 V, 2.4 A, Adjustable (×1) https://uk.farnell.com/texas-instruments/ptn04050caz/ic-isr-12w-smd-4050/dp/3009745?st=ptn04050c

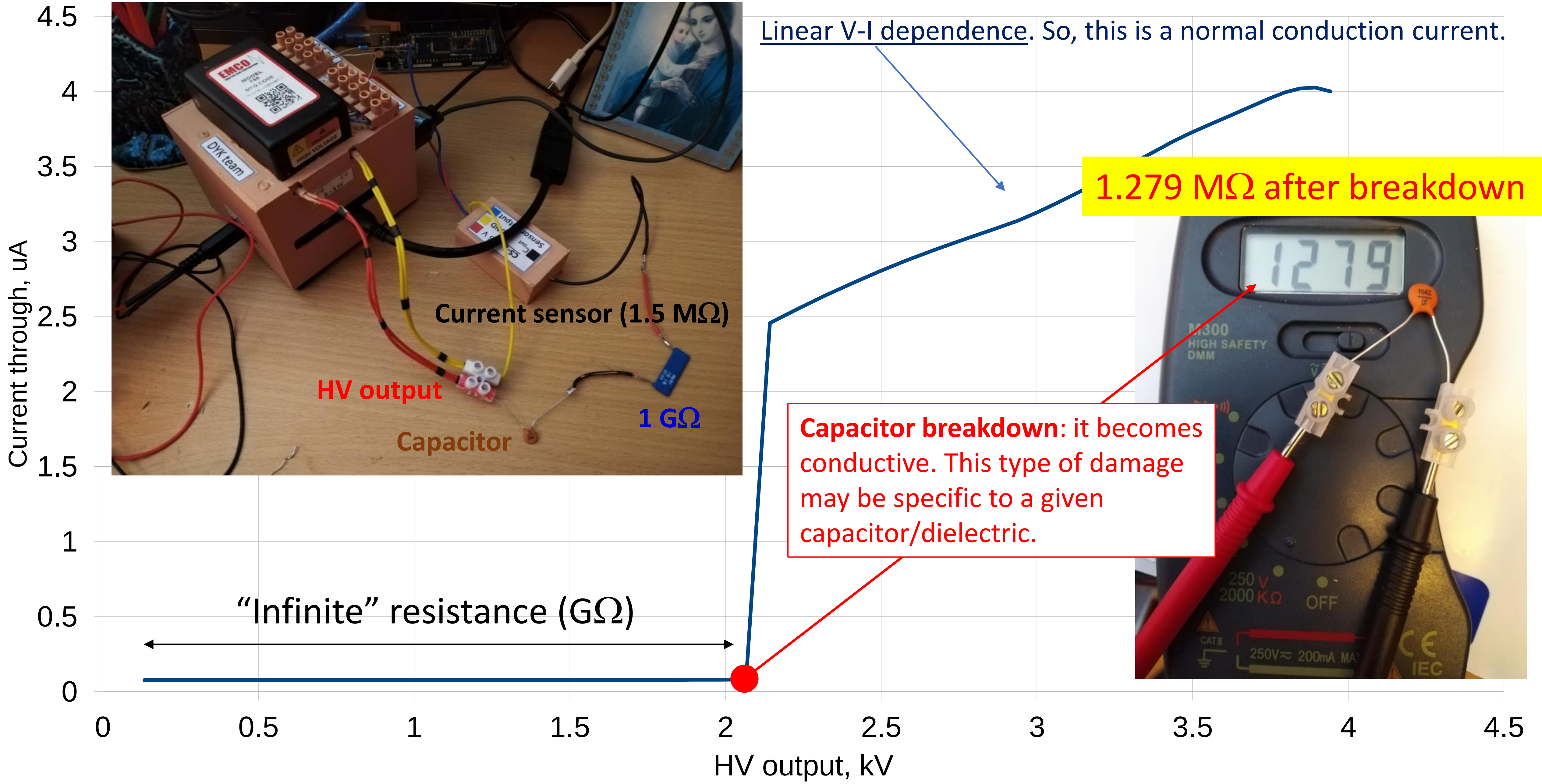
Fixed LDO Voltage Regulator, 2.6V to 27V, 1.3V Dropout, 5Vout, 5Aout, TO-220-3 (×1) https://uk.farnell.com/texas-instruments/lm1084it-5-0-nopb/ldo-fixed-5v-5a-to-220/dp/3121986

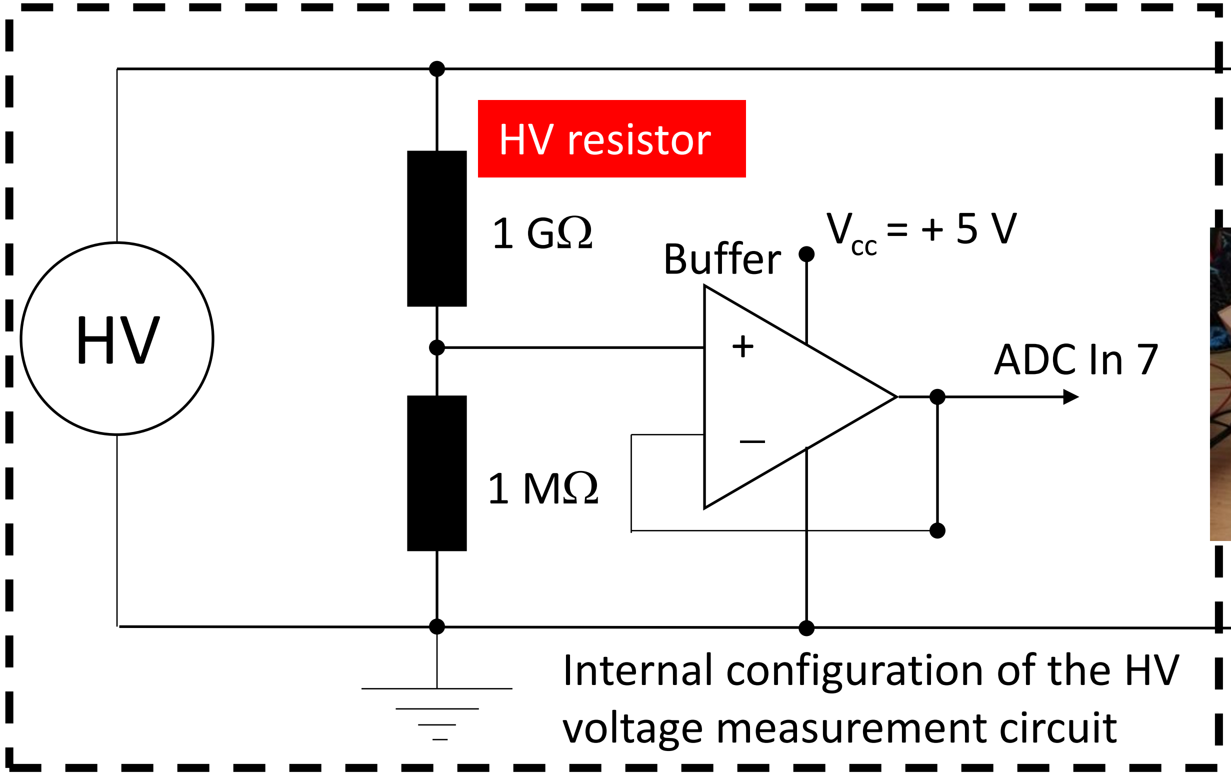
Heat Sinks Heat Sink, MULTIWATT, Radial Fin, Straight Pin, Vertical, 4.4C/W, 2.89mm Hole (×2) https://www.mouser.co.uk/ProductDetail/Aavid/6398BG?qs=U7T%2FEnMyvTt1NN5UEAtP6Q%3D%3D

RPi GPIO Terminal Block (×1) https://www.amazon.co.uk/Treadax-Terminal-Expansion-Compatible-Raspberry/dp/B09SP8BQ6S/ref=sr_1_20?crid=ULHNUGQ183LP&keywords=raspberry+pi+4b+expansion+board&qid=1657927292&sprefix=raspberry+pi+4b+expansion+board%2Caps%2C72&sr=8-20

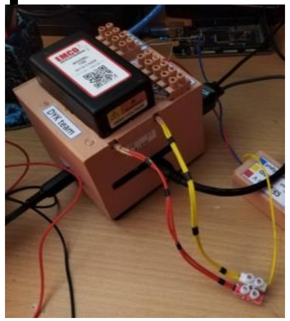
Current Sense Amplifiers High voltage, precision, bidirectional current sense amplifier (×1) https://www.mouser.co.uk/ProductDetail/STMicroelectronics/TSC2012HYDT?qs=XAiT9M5g4x9j5E5lTSULeg%3D%3D

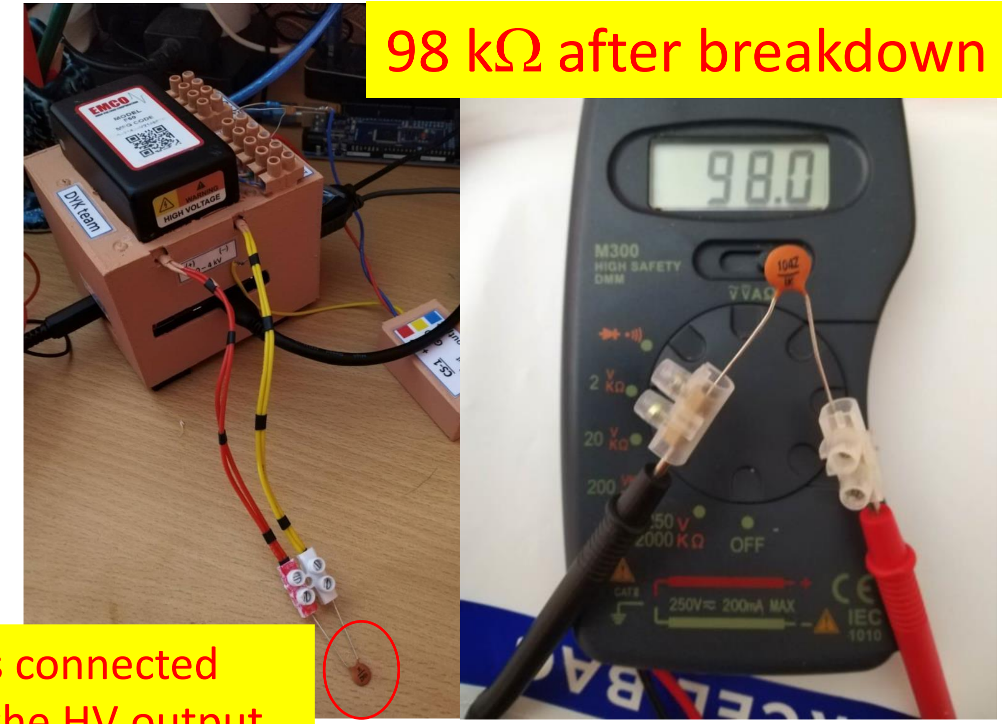
Testing the device with a commercial capacitor





Internal configuration of the HV voltage measurement circuit





Capacitor is connected directly to the HV output

This configuration was chosen for loads with a very high internal resistance (GΩ), such as a capacitor before breakdown. If the load resistance drops to MΩ or lower , the device will show ~zero HV voltage (reading at ADC In 7), since all current will flow through the load, and not through the internal 1 GΩ resistor. That is, a MΩ load will be like a short circuit for the internal voltmeter. However, this configuration makes it possible to catch the moment of breakdown of the capacitor if the current through it is too large to be measured.

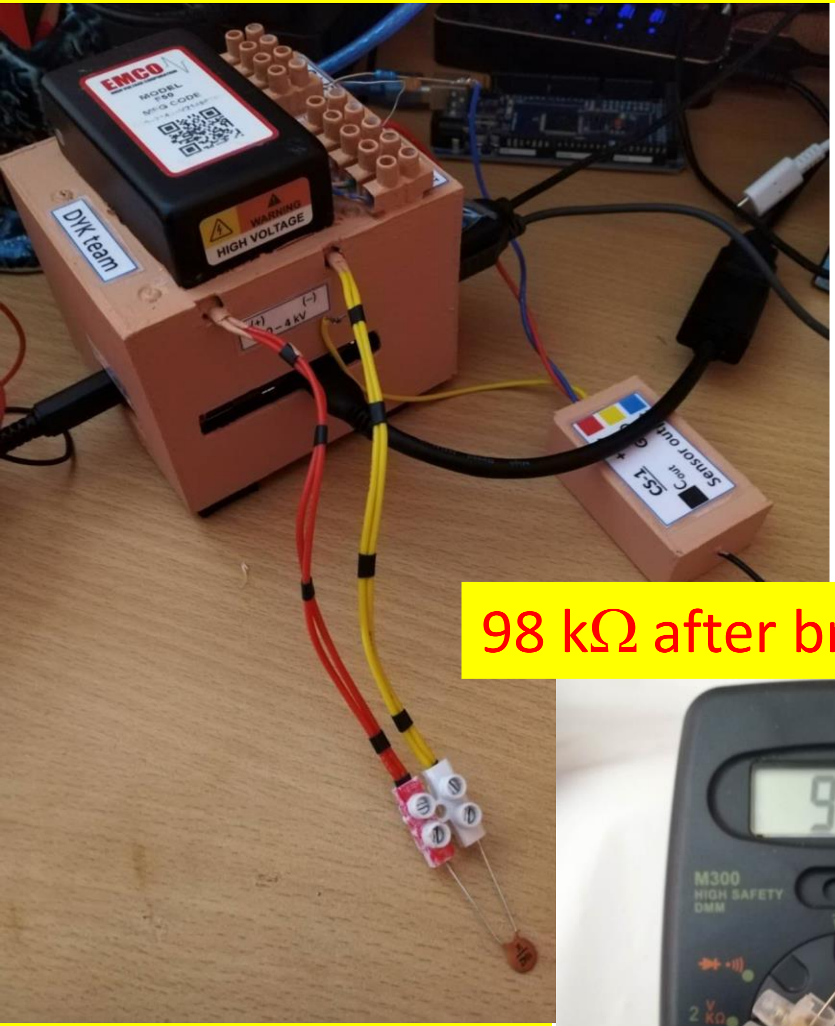
2 kV

```
Battery voltage =  13.797578431571639  V
Op Amp output =  3.422681863150877  V
Actual HV output =  2.0696453247543634  kV
Current through the capacitor =  0.08494084194500984  uA
Enter the thrust reading (any units) from

Battery voltage =  13.788830469729767  V
Op Amp output =  3.539873637976066  V
Actual HV output =  0.7246848594977916  kV
Current through the capacitor =  -108.82935841017131  uA
Enter the thrust reading (any units) from the electronic scale:
```

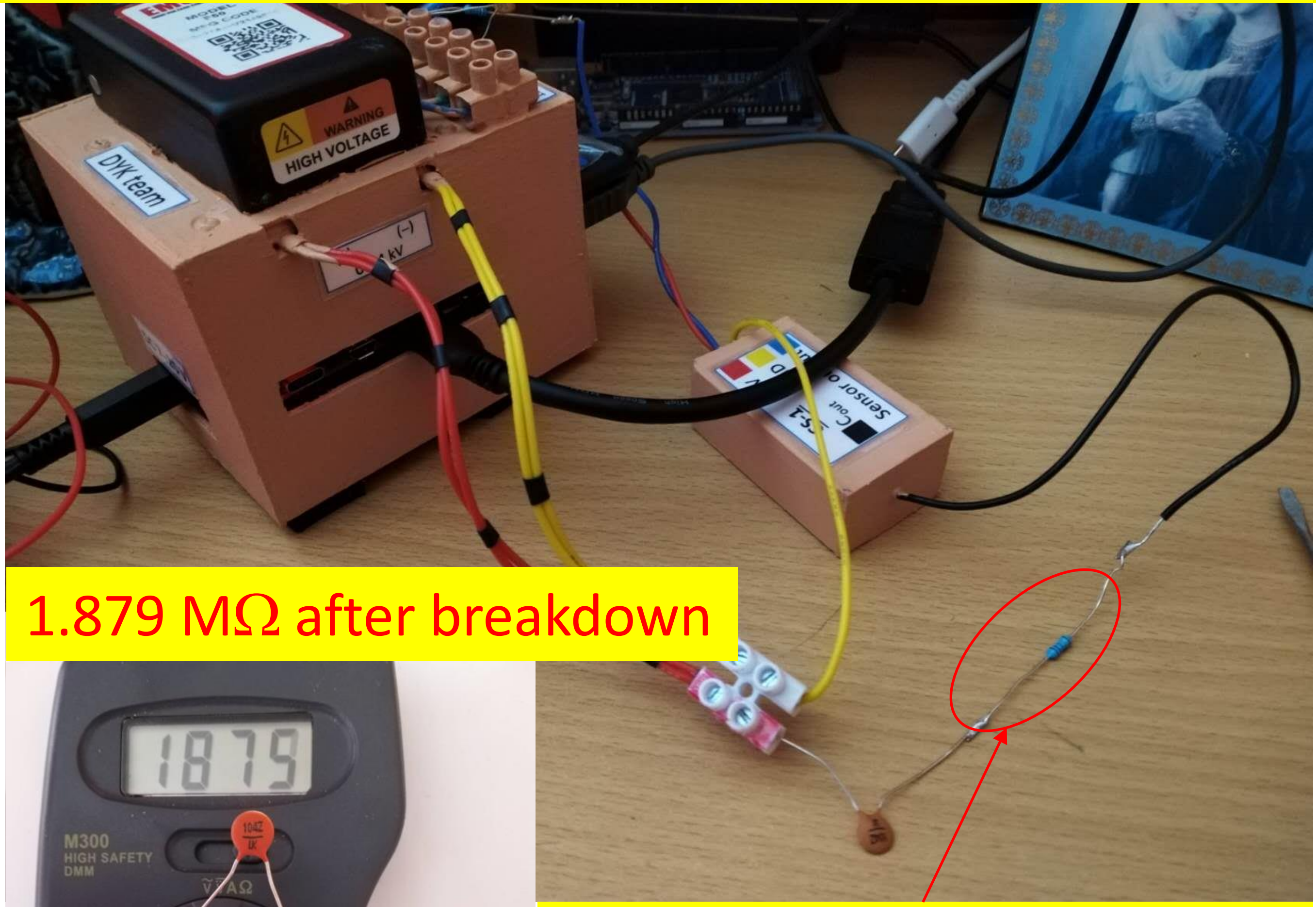
Sudden voltage drop during the capacitor breakdown

The character of breakdown may depend on the current through the capacitor and the type of dielectric.

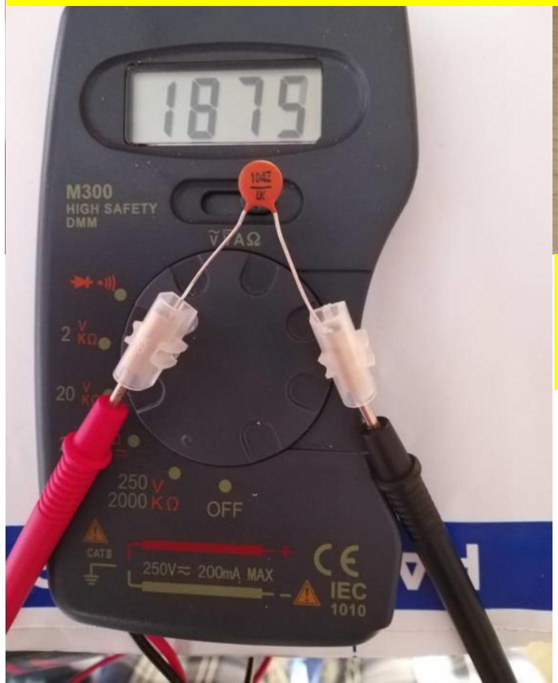


Capacitor is connected directly to the HV output

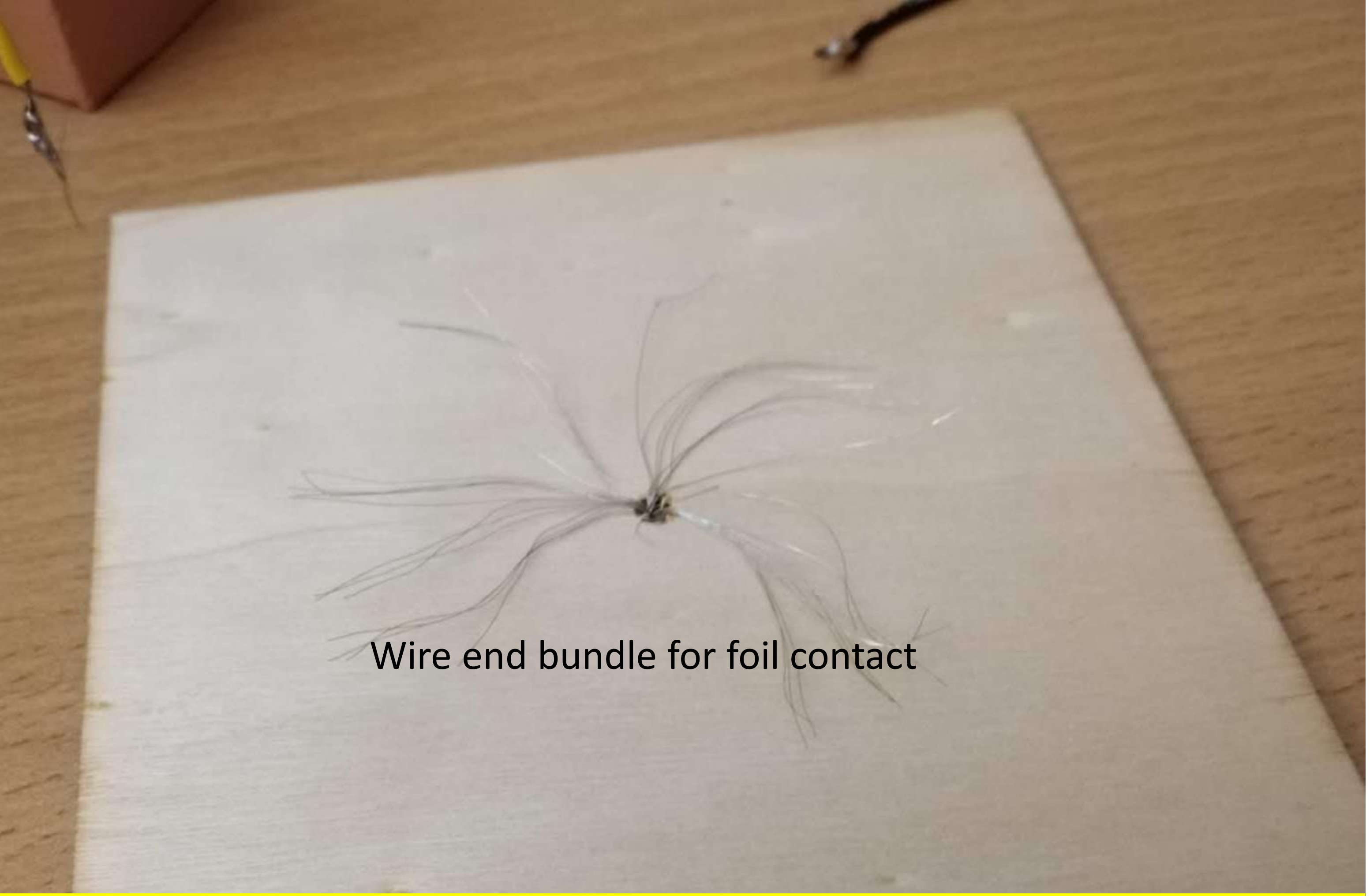
98 kΩ after breakdown



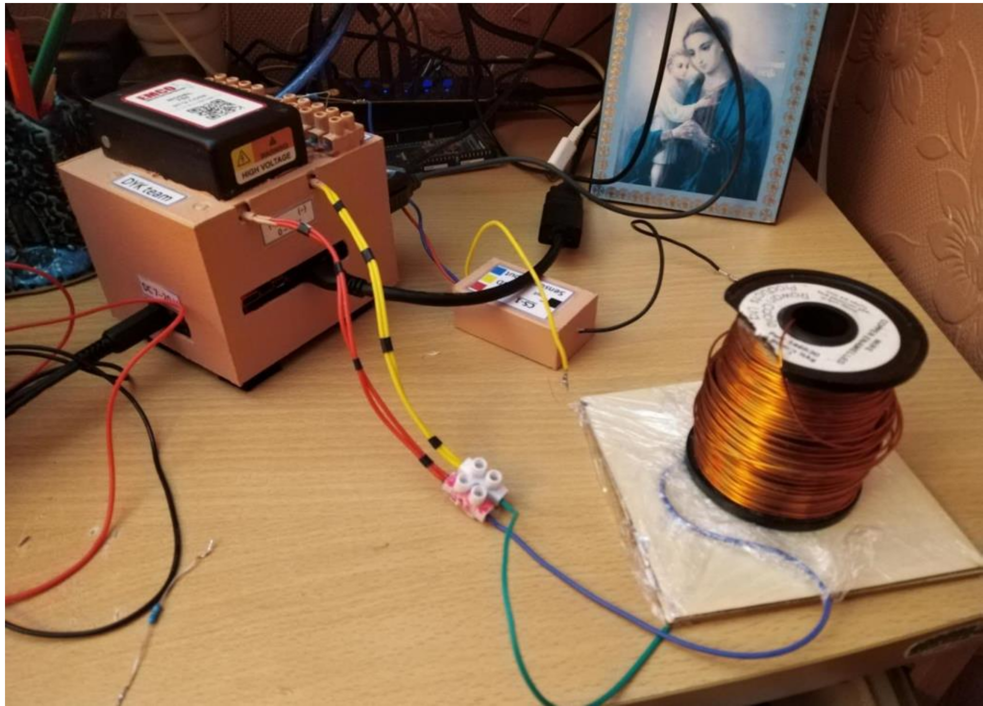
1.879 MΩ after breakdown



Additional 1 MΩ series resistor + 1.5 MΩ resistor inside the current sensor

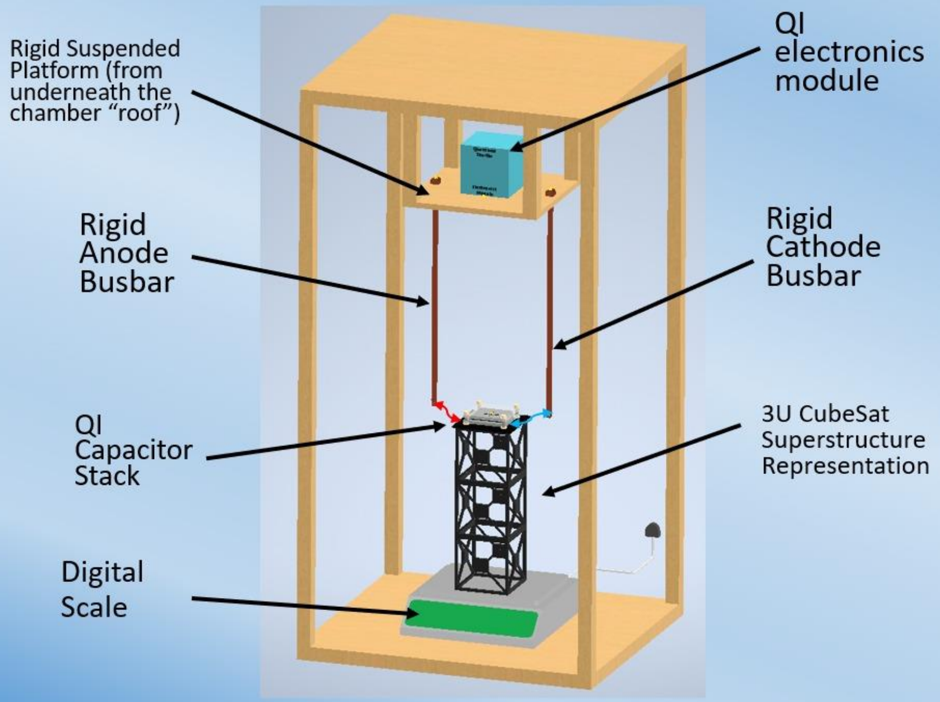


"QI Capacitor" testing: plywood pads, kitchen foil electrodes, and two layers of kitchen cling film. The capacitor was connected directly to the HV output without a current sensor. The first single discharges began at ~1.6 kV. This was followed by a series of discharges through 2 kV. A series resistor (current conditions) may affect this scenario… During discharges, ADC began to show errors, but Raspberry Pi did not collapse. Therefore, there was time to stop the process.



QI Test Chamber V1 (Non Vacuum)

ARUNDAL ASTRONAUTICS

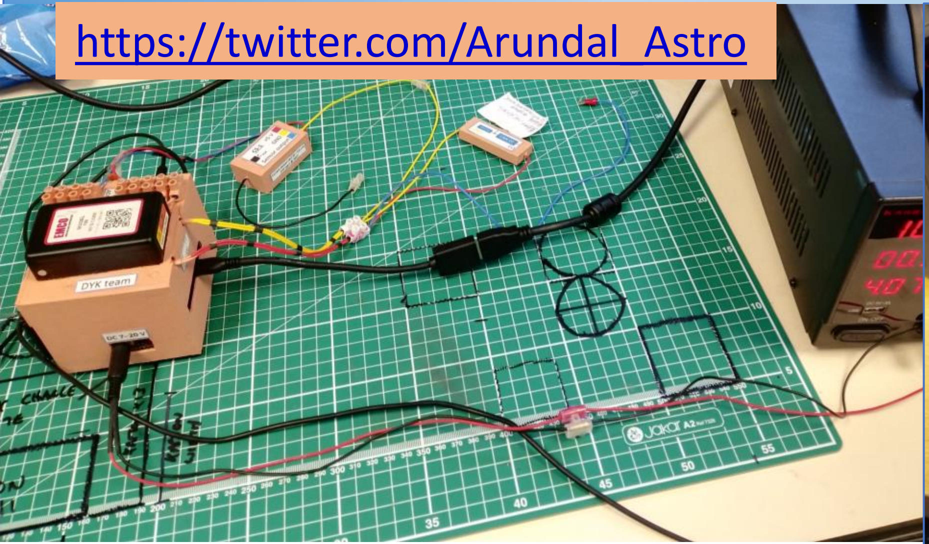


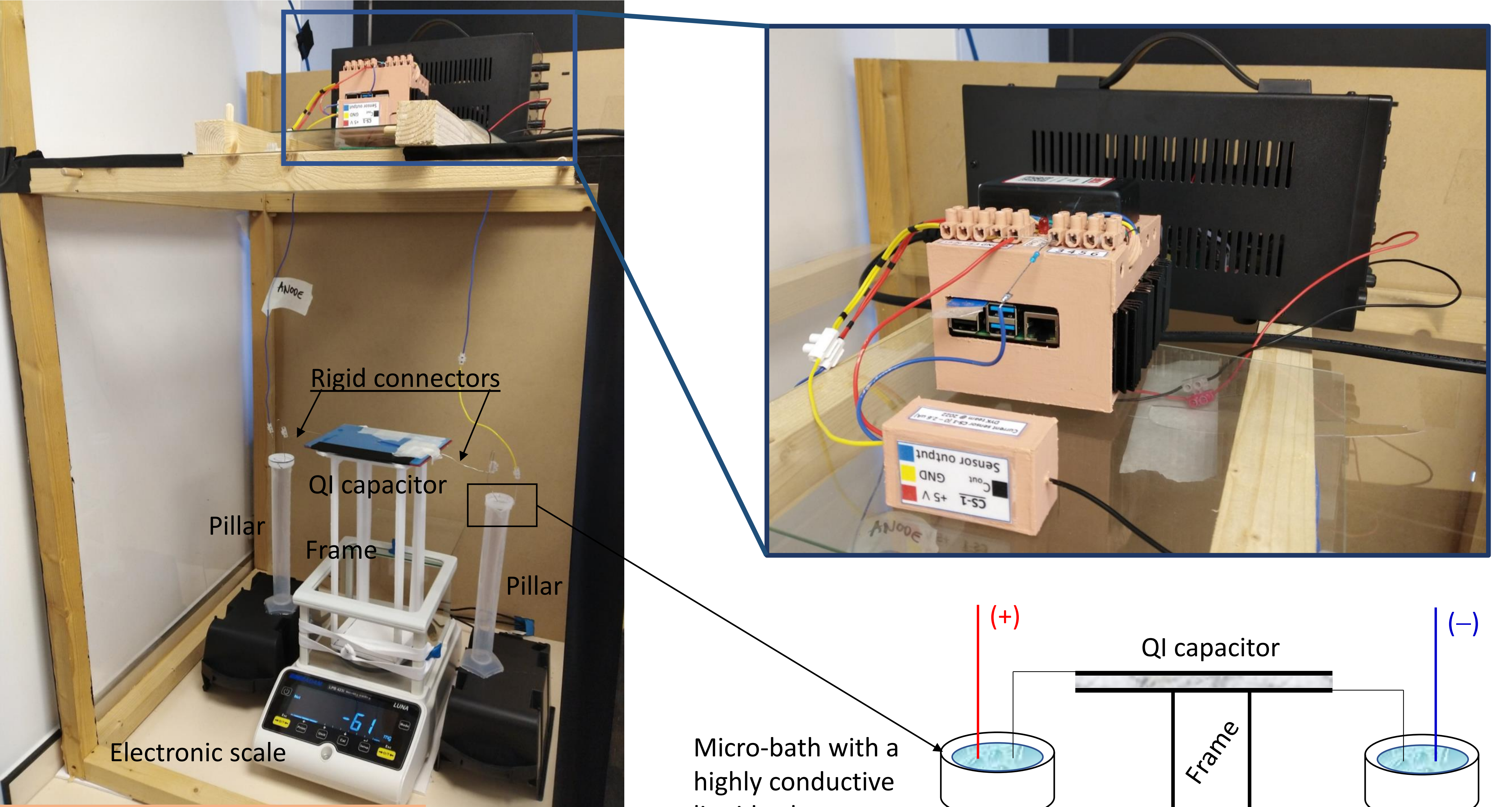
Revised Quantised Inertia Test Chamber

- Wooden frame to avoid any undesired conduction
- Adjustable height Rigid bus bars suspended for anode / cathode conductors linked to the QI electronics module
  - End stage connectors using typical wires to link with the QI capacitor
- QI Capacitor rests upon 3U CubeSAT superstructure (and also to add distance from digital scale in case of electromagnetic interference)

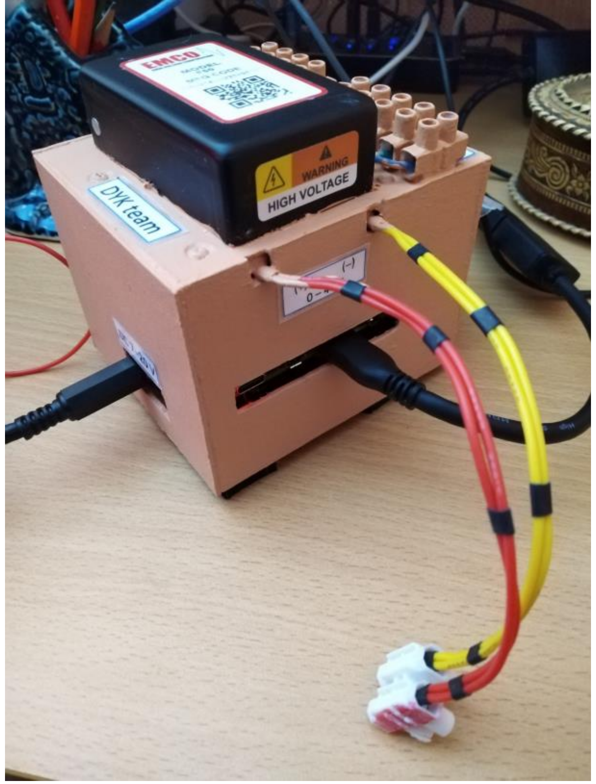
Davy Building, Room 207C
University of Plymouth, UK

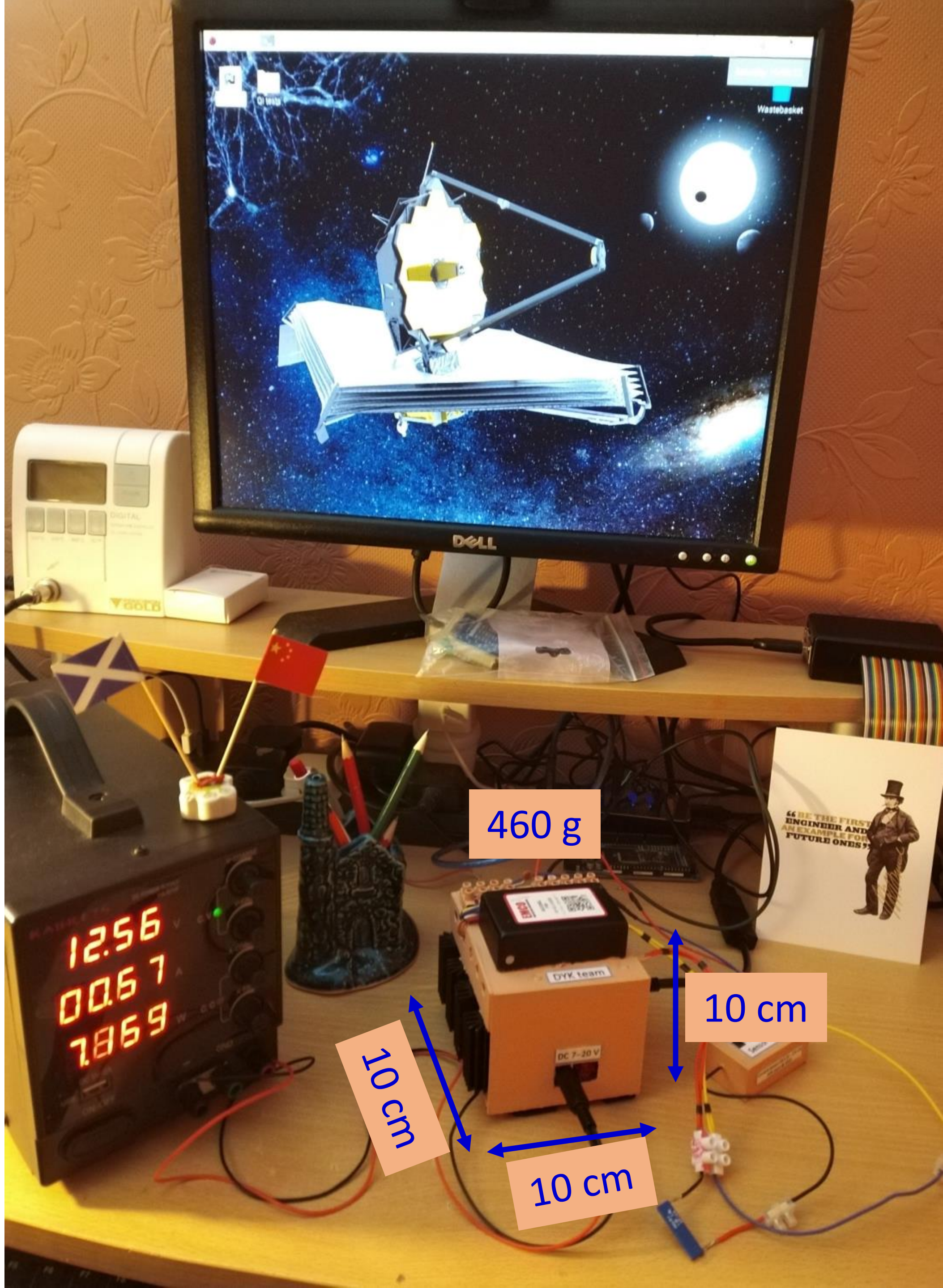
https://twitter.com/Arundal_Astro





https://twitter.com/Arundal_Astro

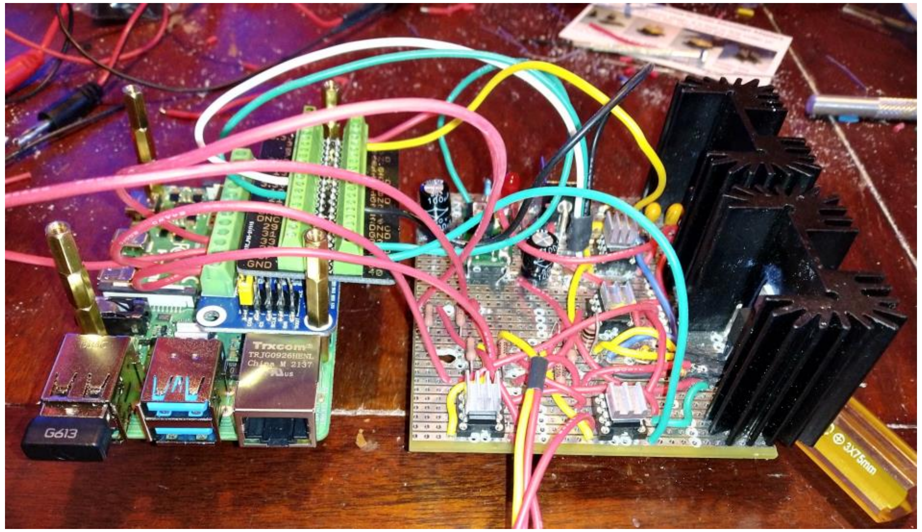


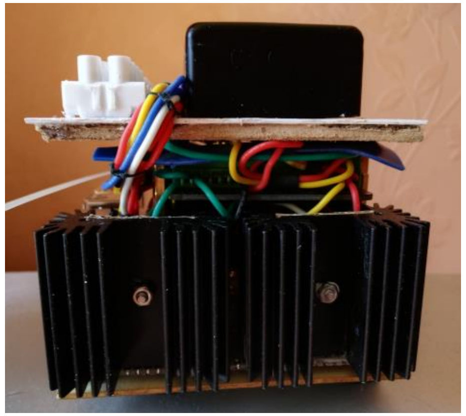


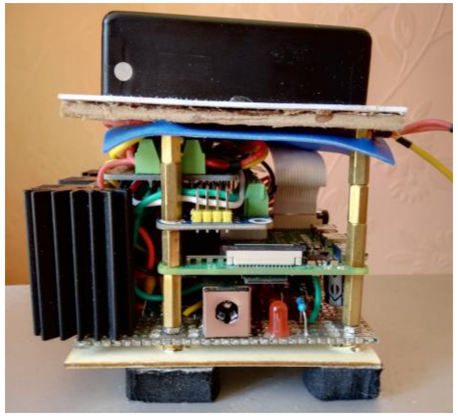
Our design satisfies the CubeSat standards (https://en.wikipedia.org/wiki/CubeSat): a class of miniaturized satellite based around a form factor consisting of 10 cm (3.9 in) cubes. CubeSats have a mass of no more than 2 kg (4.4 lb) per unit, and often use commercial off-the-shelf (COTS) components for their electronics and structure.

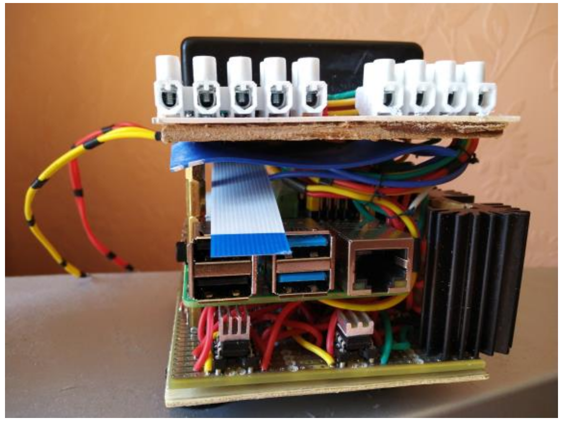
An example of CubeSat design: *"New CubeSat propulsion system uses water as propellant"* https://www.purdue.edu/newsroom/releases/2017/Q3/new-cubesat-propulsion-system-uses-water-as-propellant.html

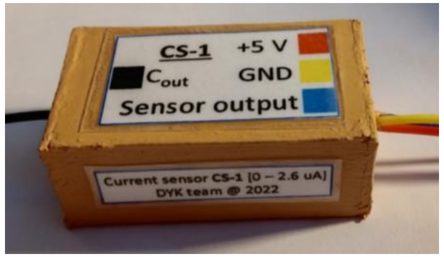
Design gallery: assembly



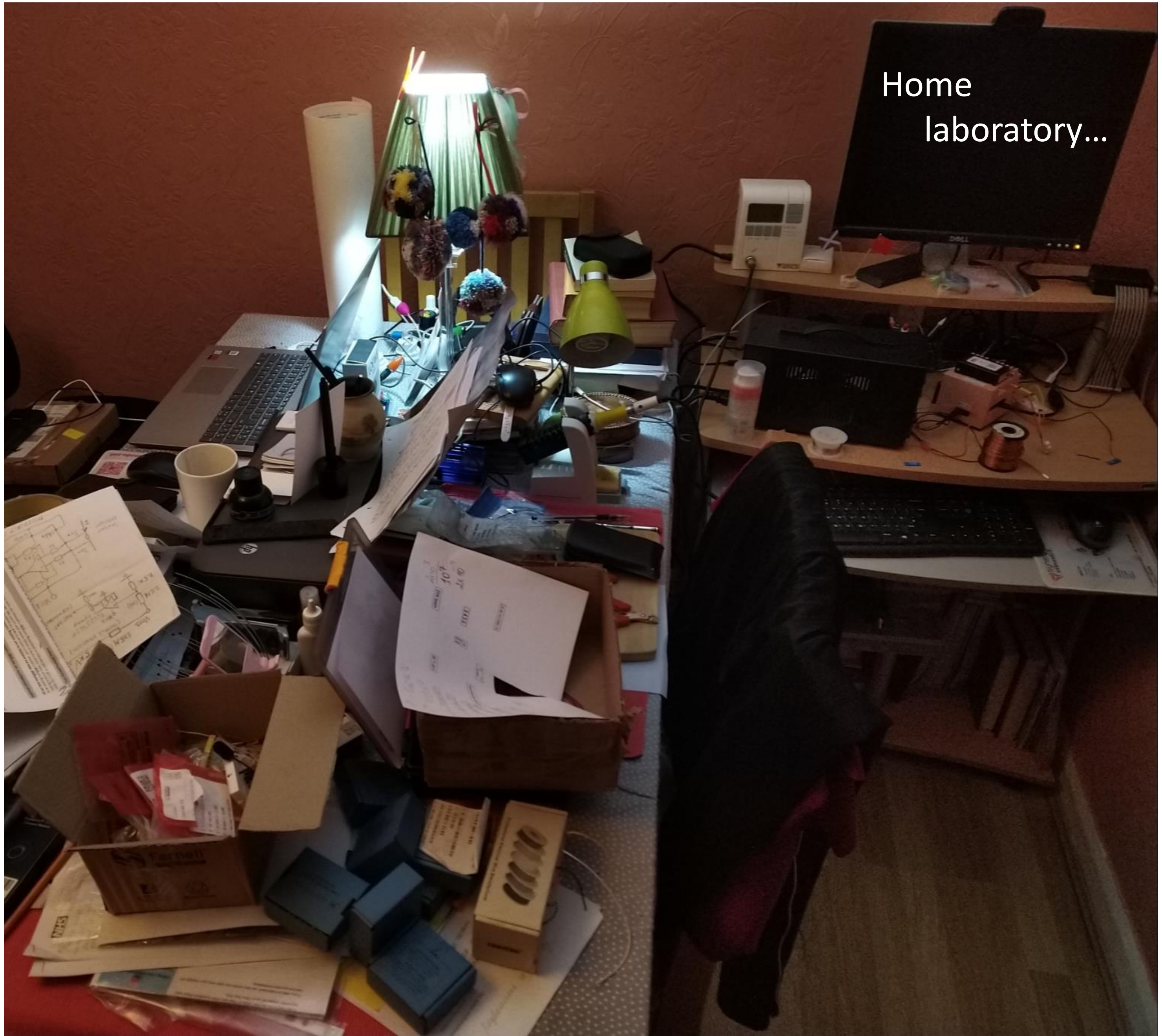




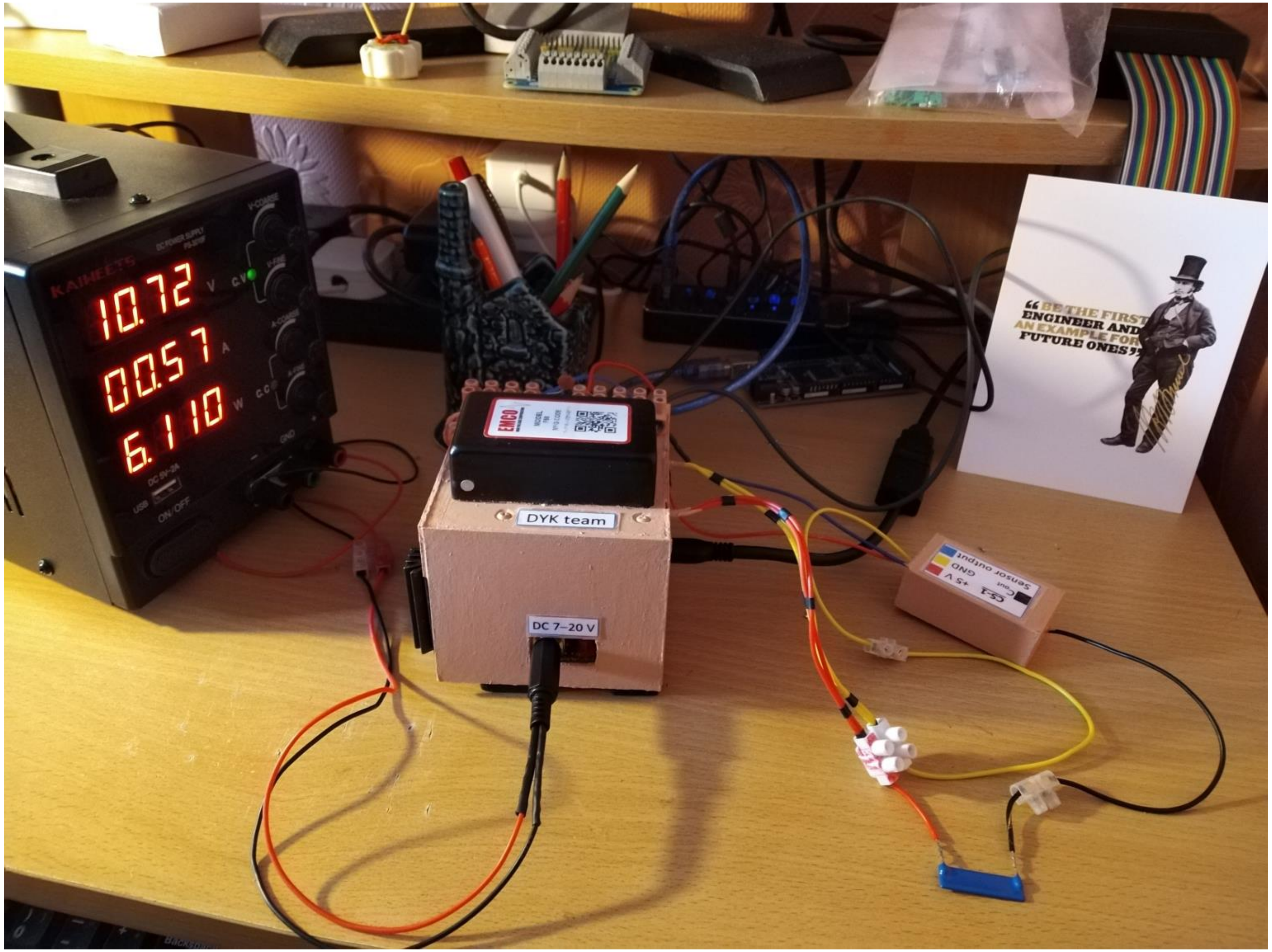




Design gallery: final testing



Design gallery: before departure



Design gallery: passed to university