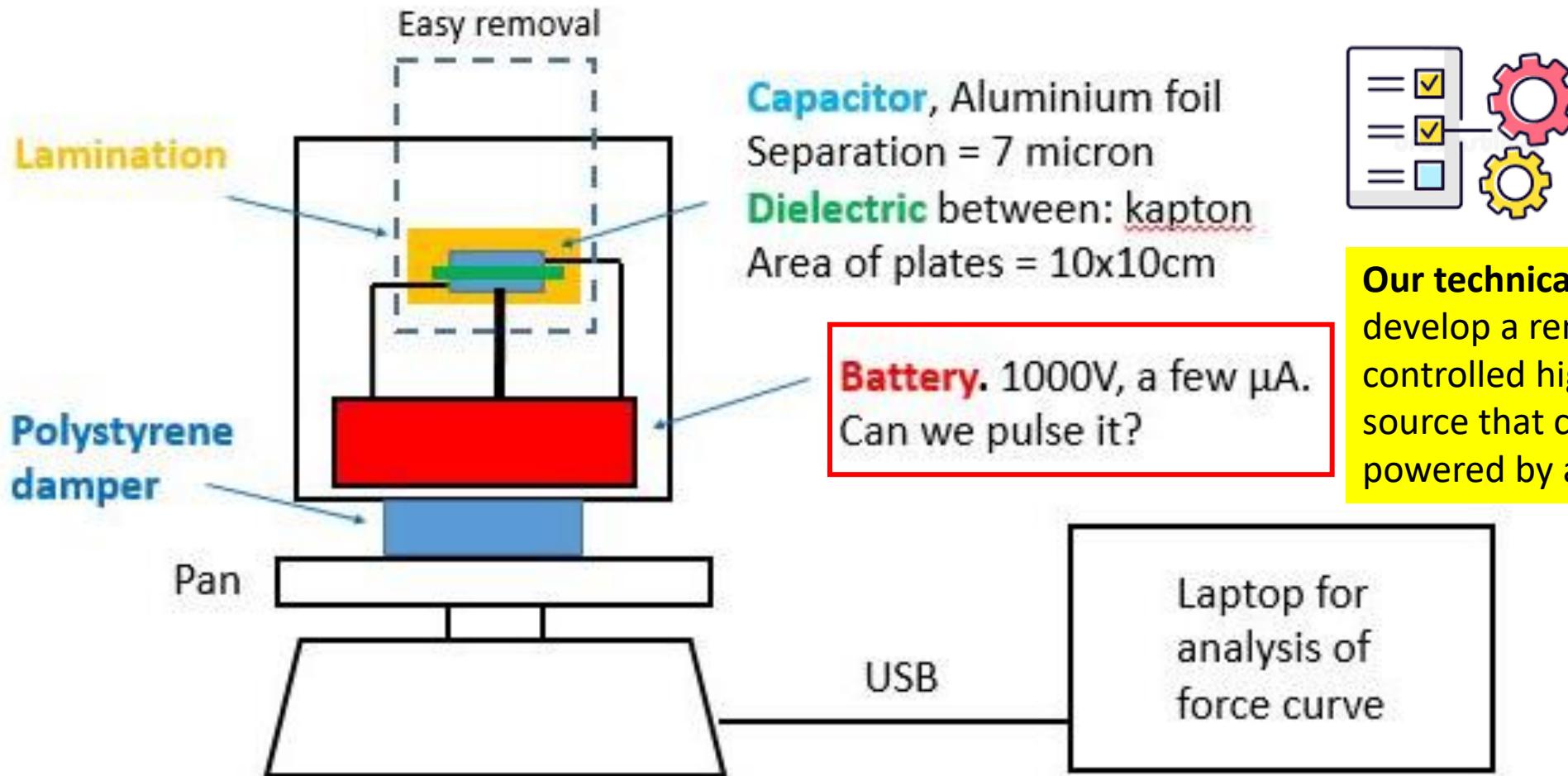


# Original sketch of a capacitor QI thruster provided by Dr. Mike McCulloch



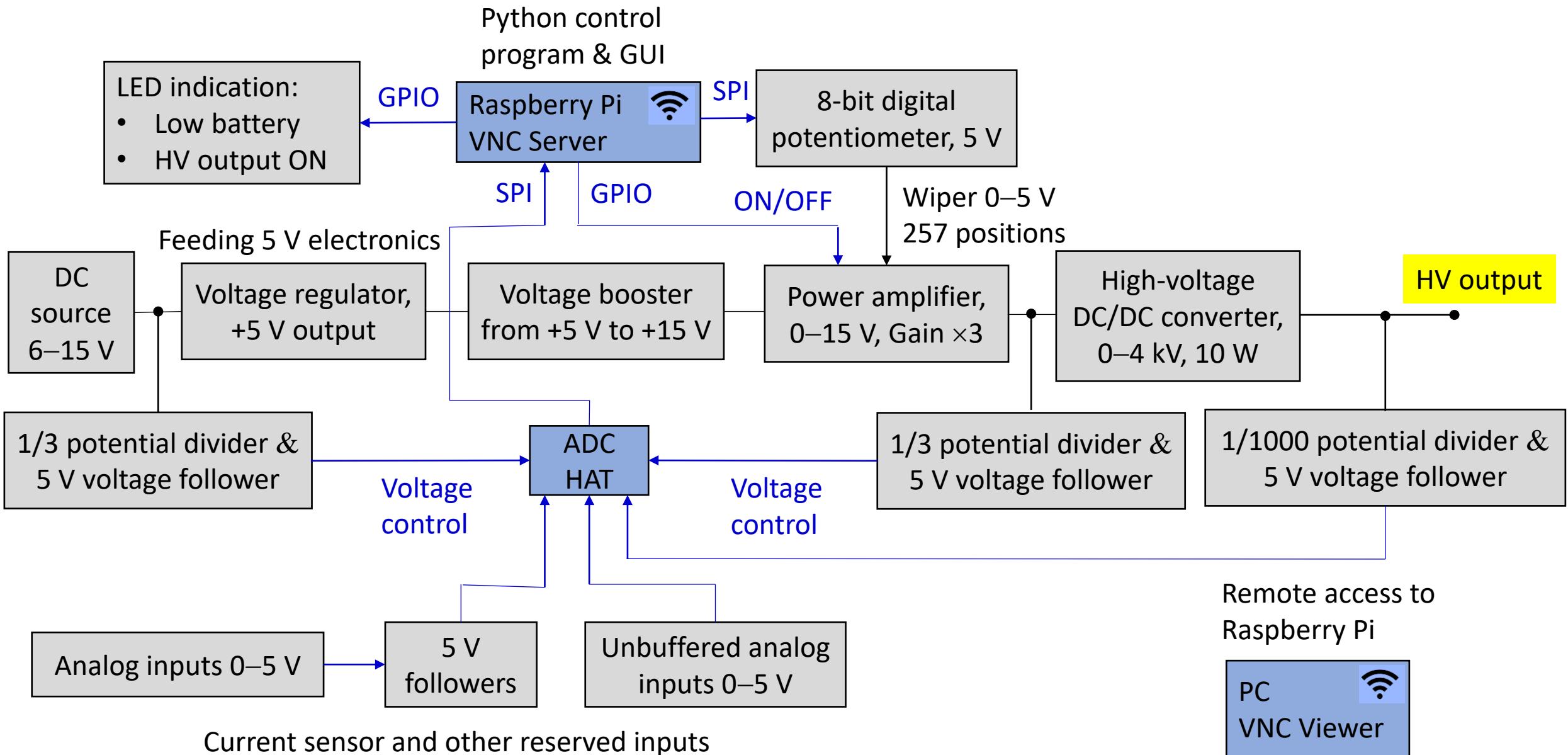
Digital Scales. Accuracy 0.1g. Capacity = 2kg

The force = 50mN. The mass change should be  $\sim$  5g.

$$F = \frac{0.00014IA}{d^2}$$

QI project links: <http://physicsfromtheedge.blogspot.com>, <https://twitter.com/memcculloch>,  
[https://twitter.com/Arundal\\_Astro](https://twitter.com/Arundal_Astro)

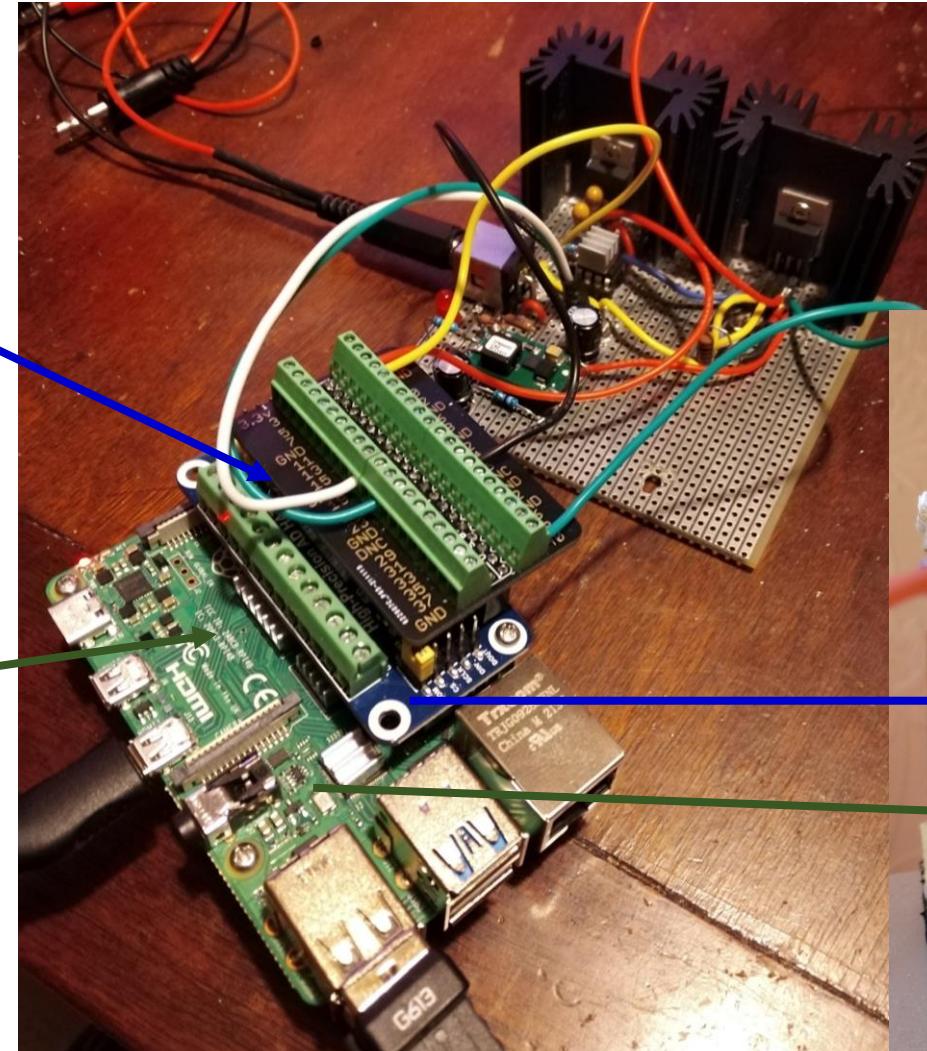
# Architecture of the remotely controlled high-voltage source (0–4 kV, 10 W)



# 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

Project structure: 4 Python files for QI-1

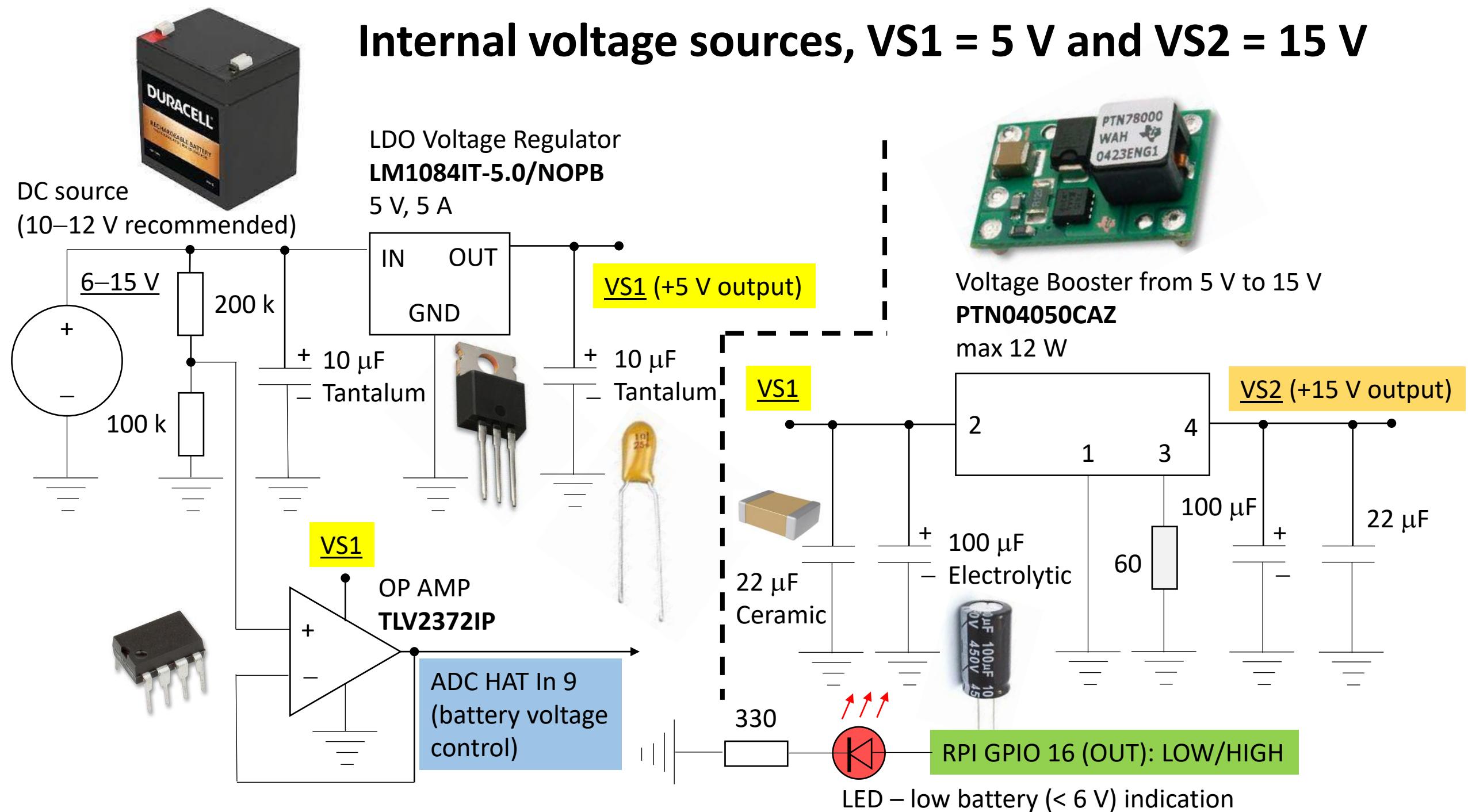
```
from Functions import *
import numpy as np
import time
from pynput import keyboard
from datetime import datetime
```

Program codes: <https://github.com/QIthruster?tab=repositories>

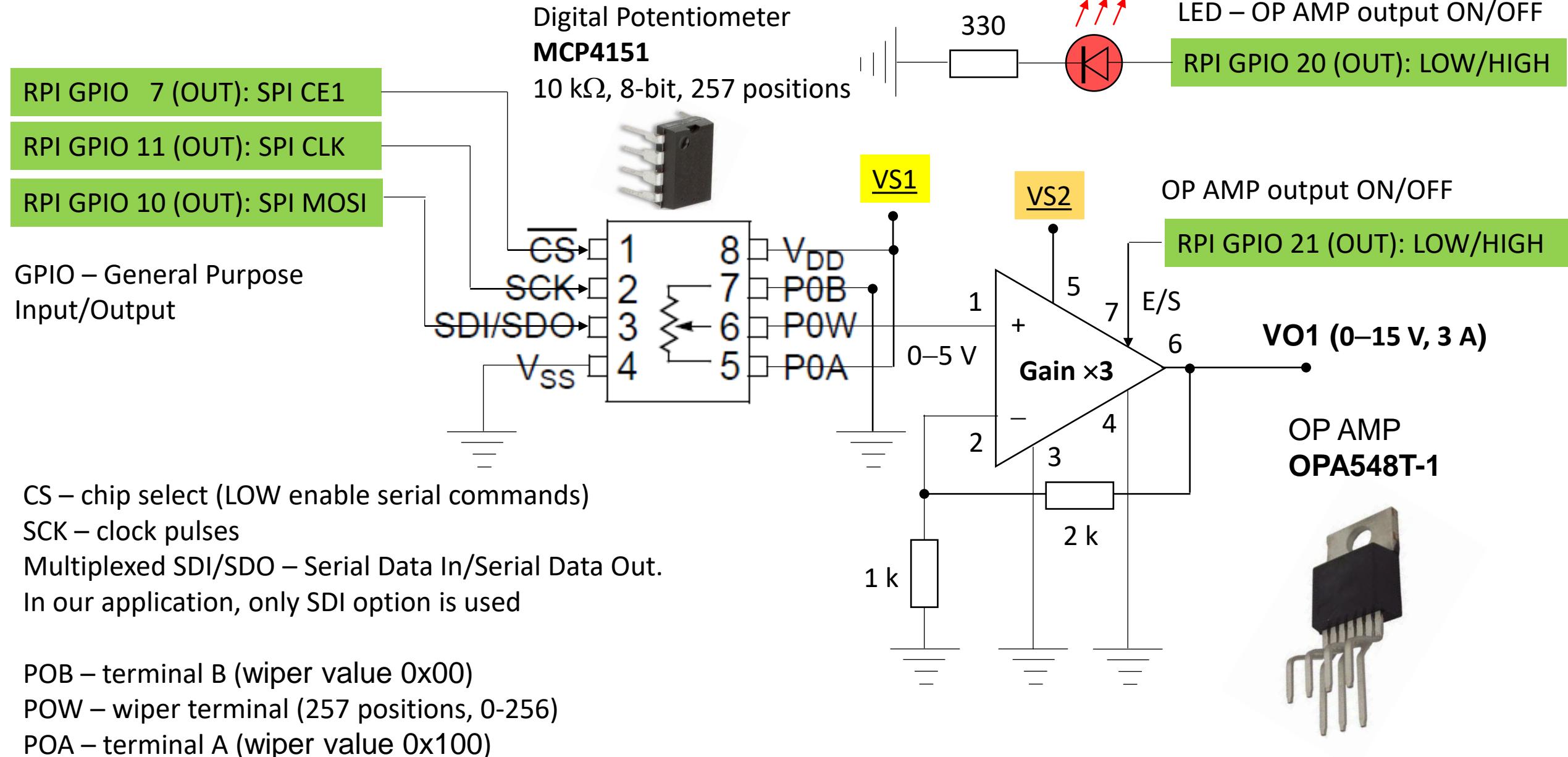
Project structure: 6 Python files for QI-2\_GUI

```
from PyQt5 import QtCore, QtGui, QtWidgets
from PyQt5.QtCore import QProcess, pyqtSignal, Qt, QObject
import main
import init
from threading import Thread
```

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



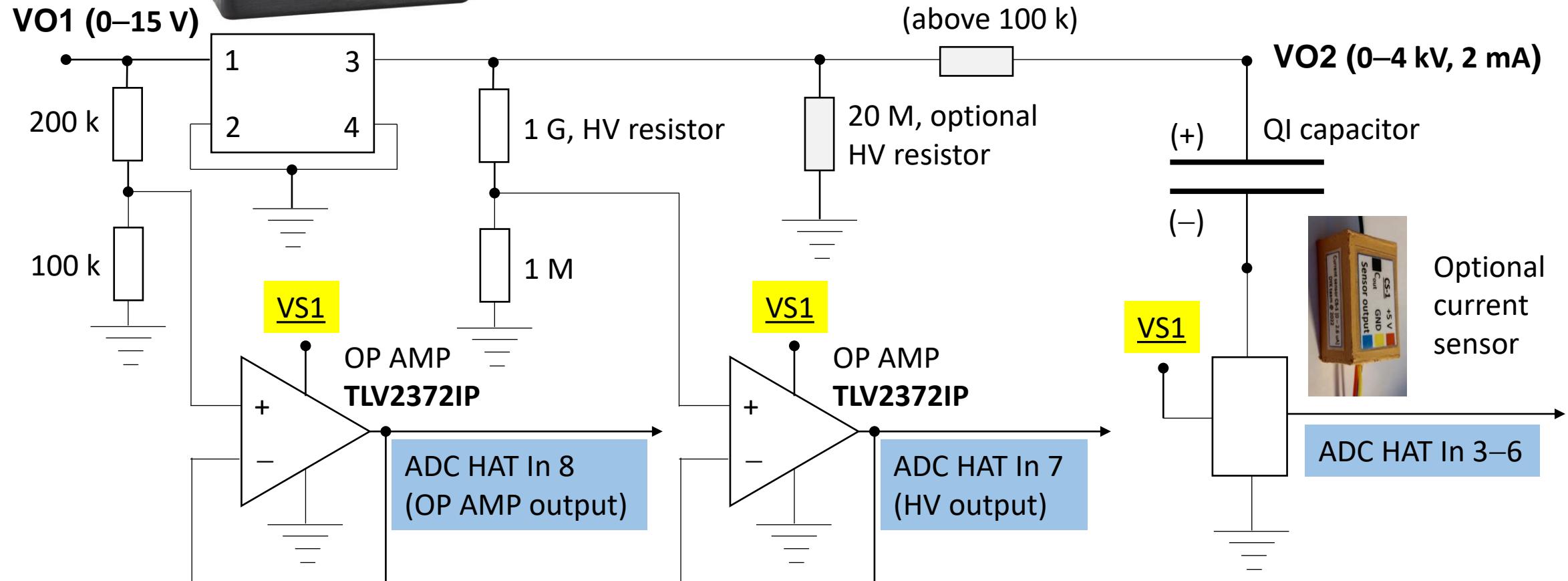
# Programmable power supply 0 – 15 V (257 voltage points)



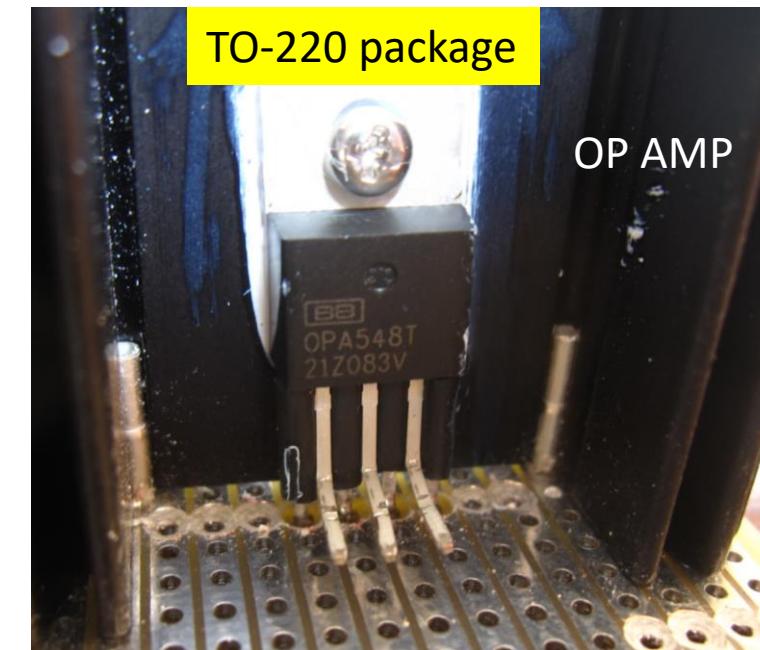
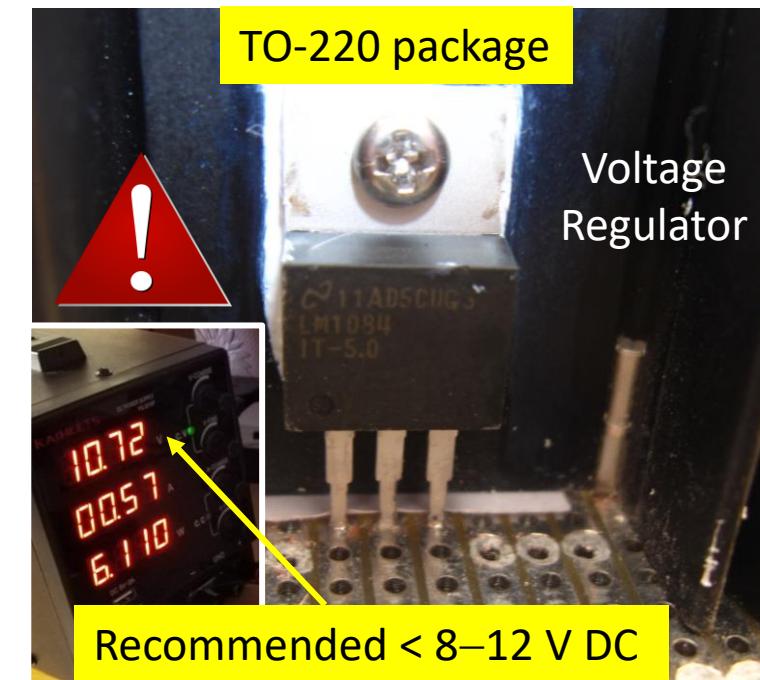
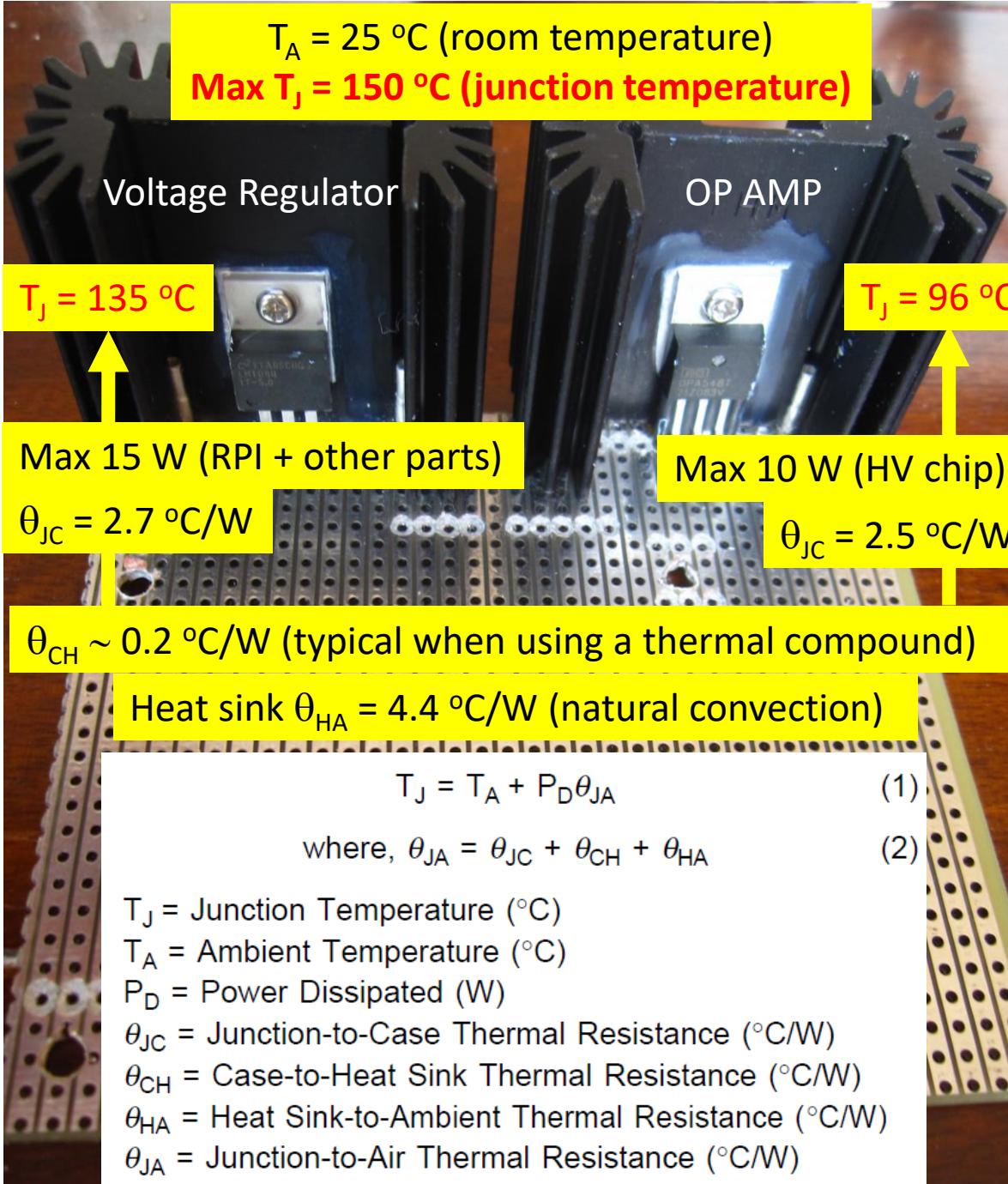
# High-voltage DC/DC converter 0–4 kV, 10 W

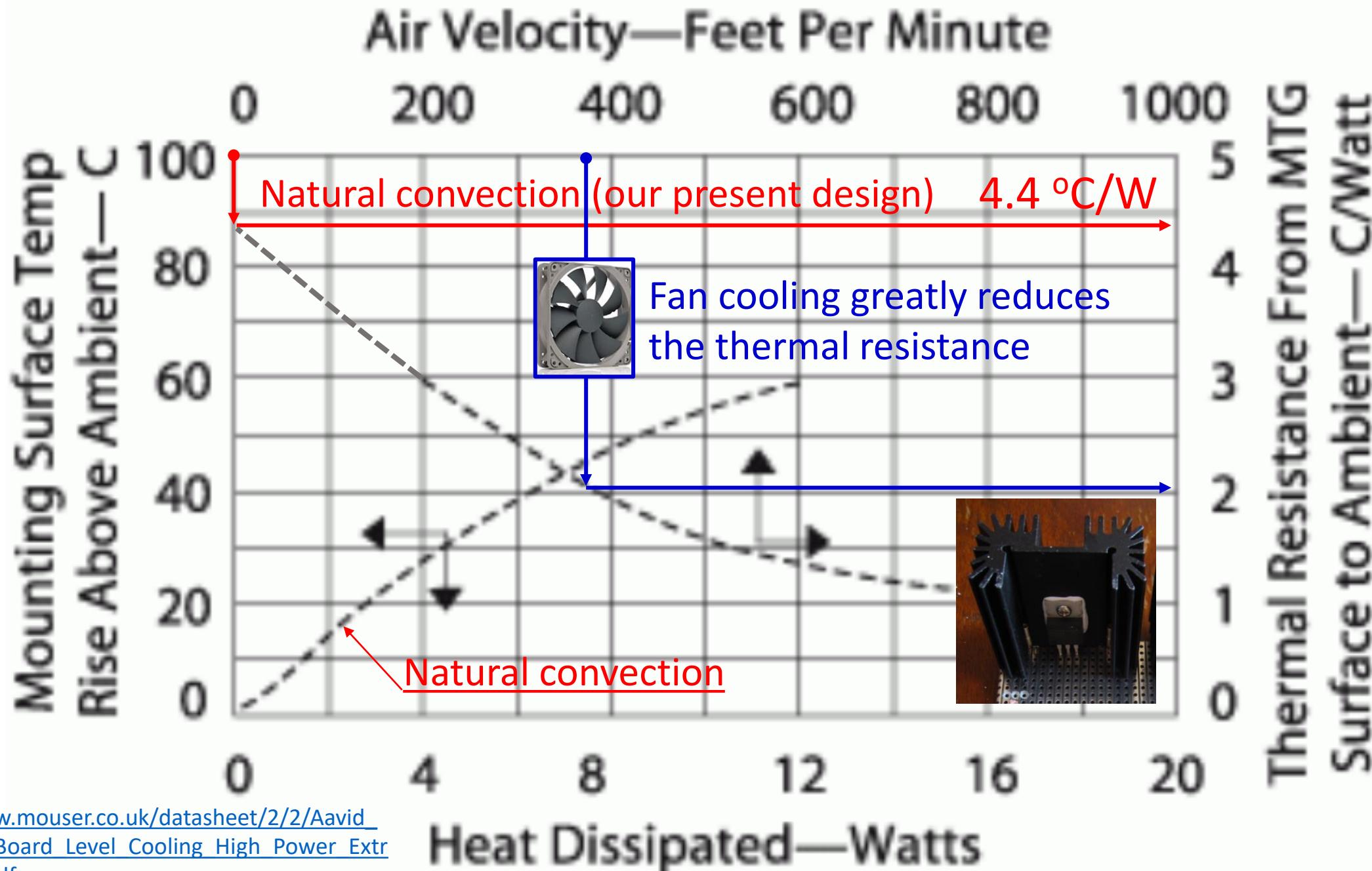


High-voltage DC/DC converter  
**XP Power F50**  
Up to 5 kV and 2 mA output (1.5 A input), 10 W



# Heat management in the circuit





# 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

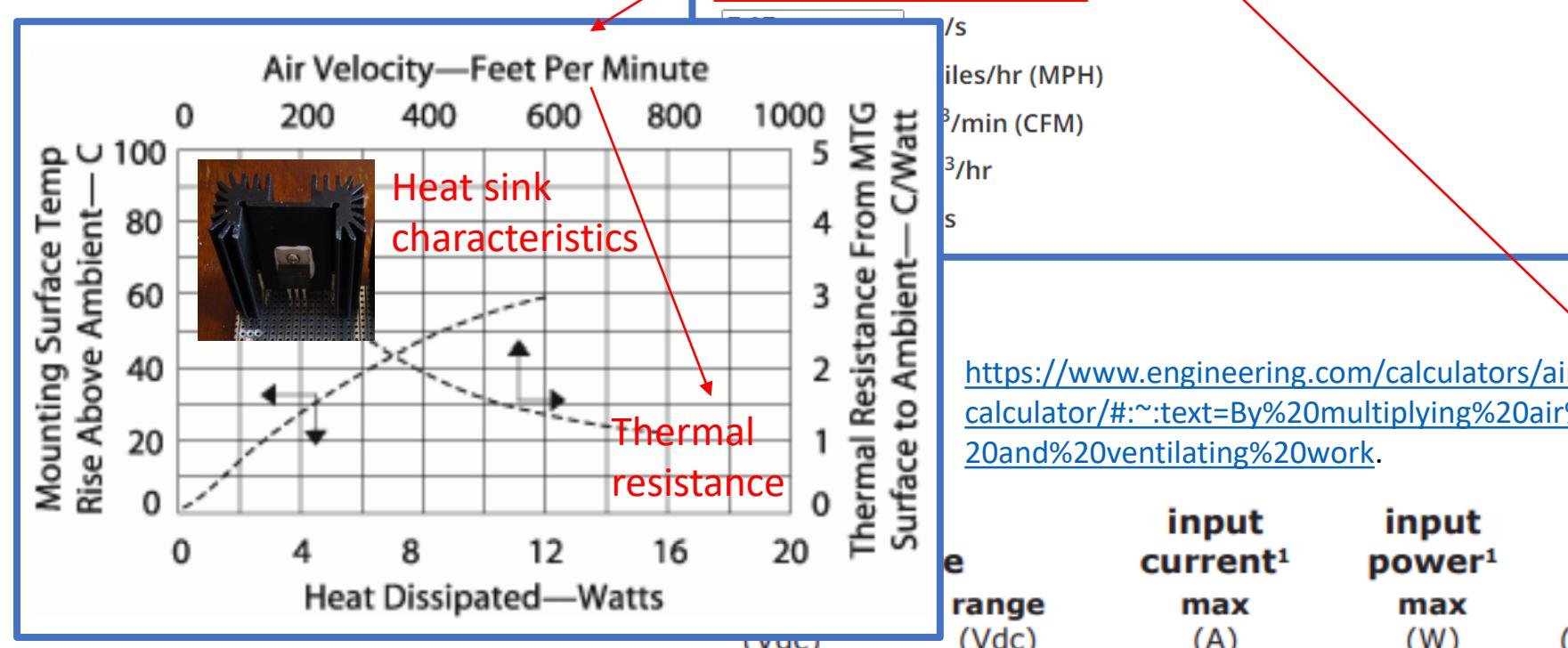
Calculate Clear

Results: 1392.32 ft/min (LFM)

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

$$\text{Cross-Sectional Area} = \pi R^2 \text{ [sq. ft]}$$

Transfer R to feet!



CFM-A225BF-153-577

12

10.8~13.2

1.87

22.44

5,300

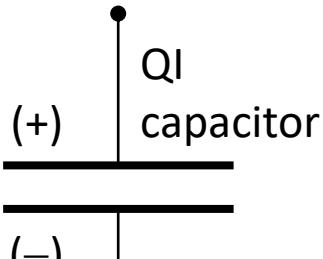
169.5

0.82

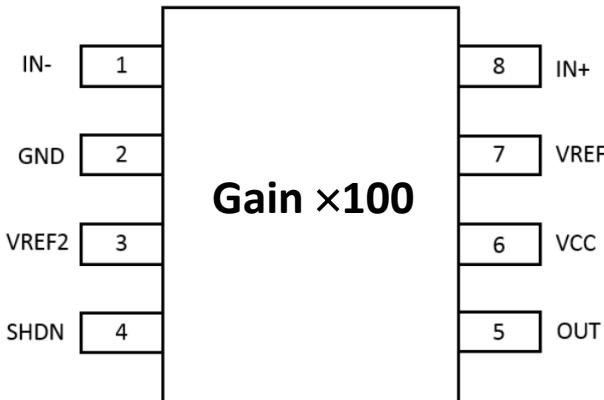
# Current sensor CS-1 for measuring the leakage current



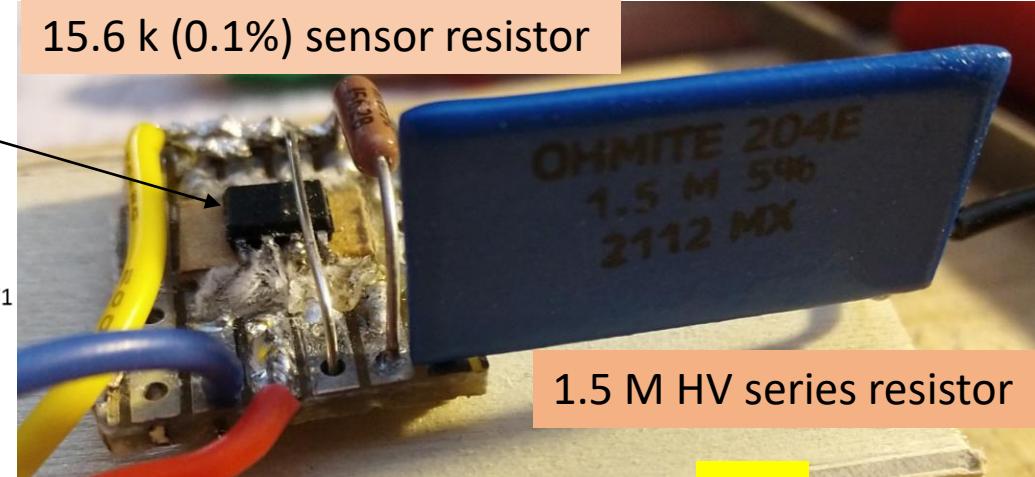
VO2 (0–4 kV, 2 mA)



Current sense amplifier  
TSC2012HYDT

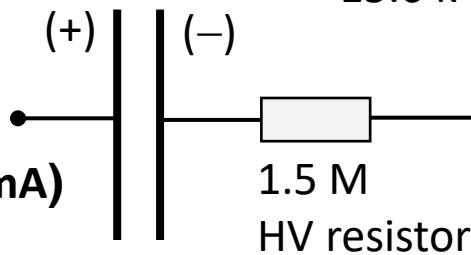


15.6 k (0.1%) sensor resistor



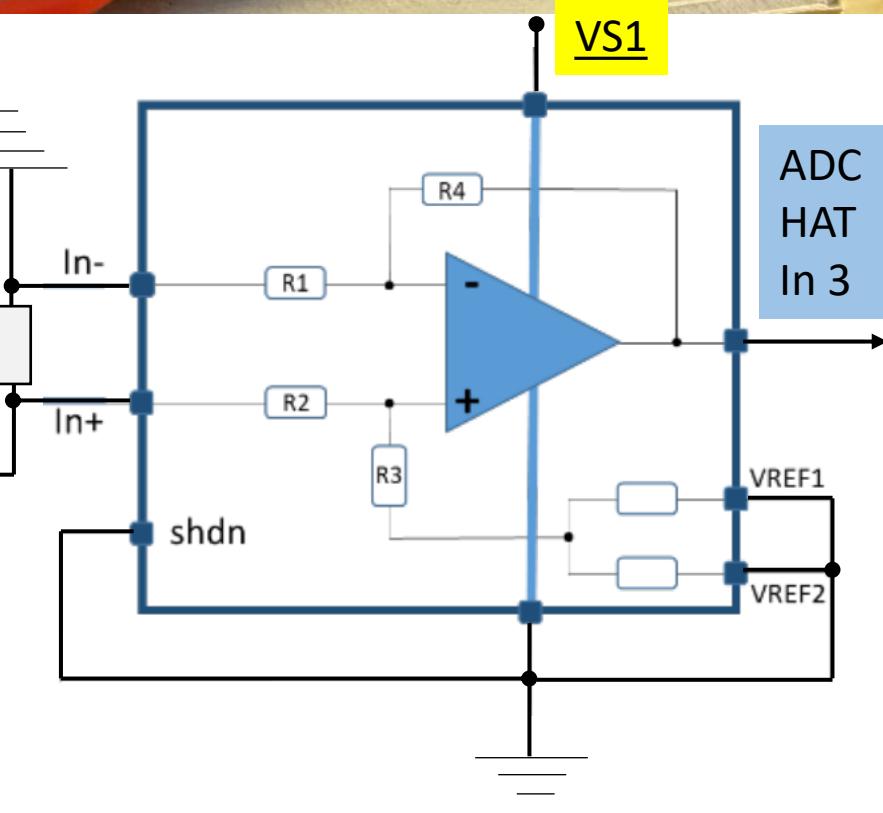
1.5 M HV series resistor

ADC HAT In 3



Low side sensing

VO2 (0–4 kV, 2 mA)

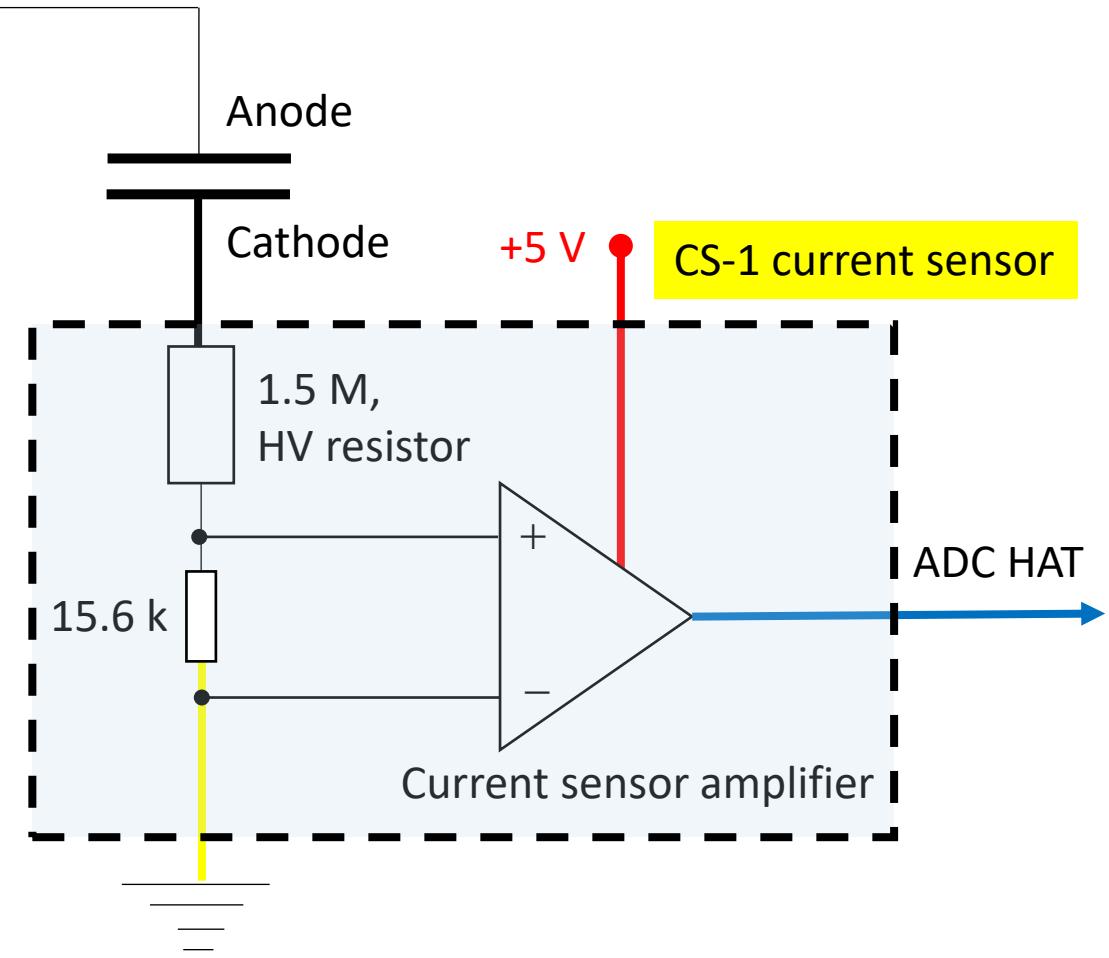
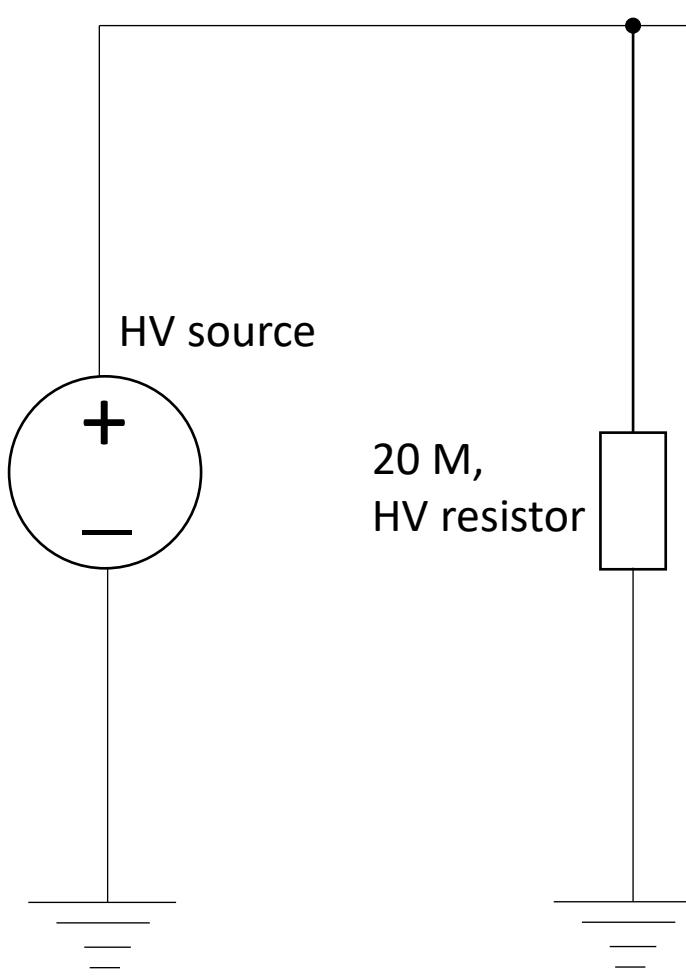


VS1

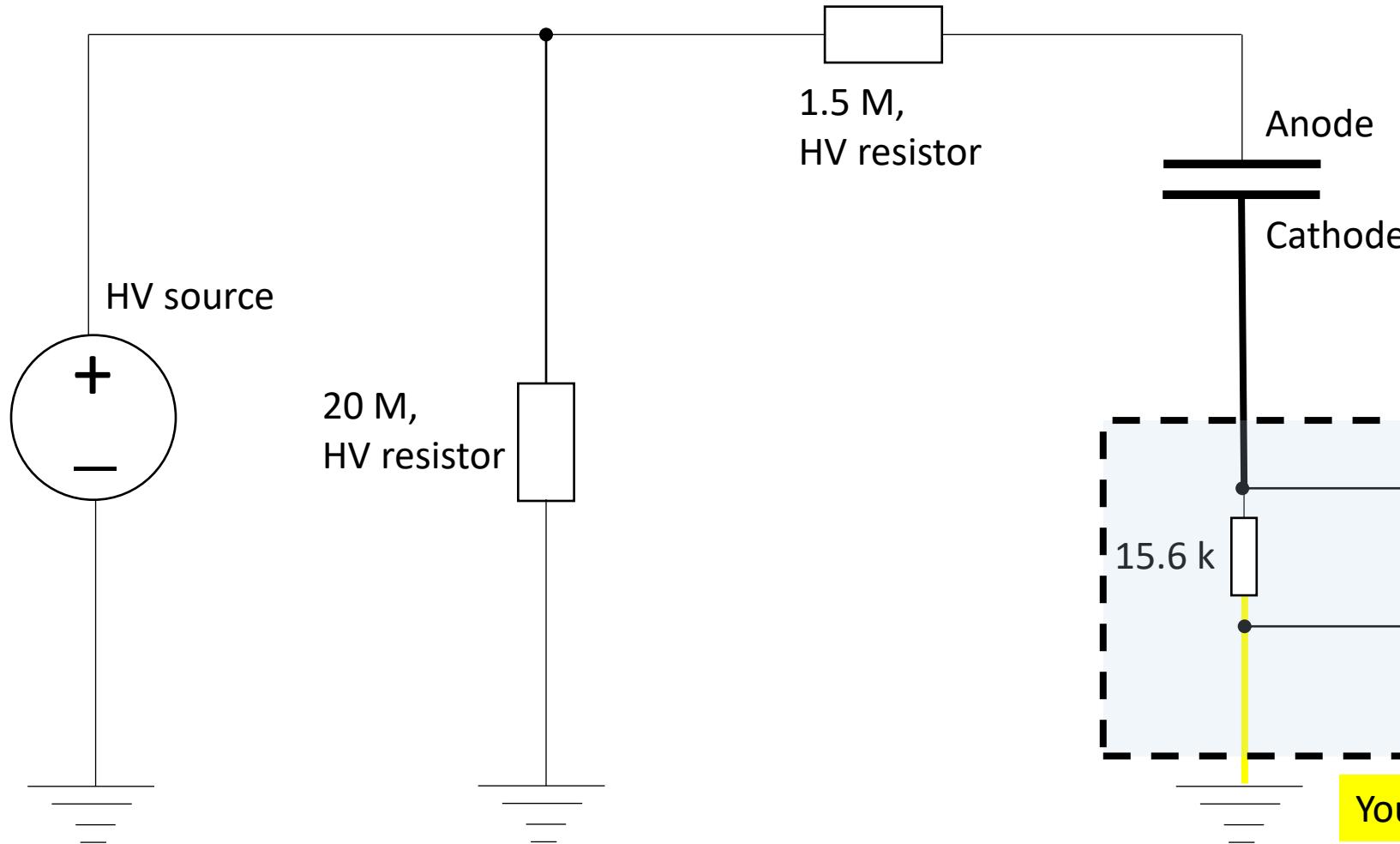
ADC  
HAT  
In 3

We connect the sensor output to ADC HAT In 3, which is unbuffered.

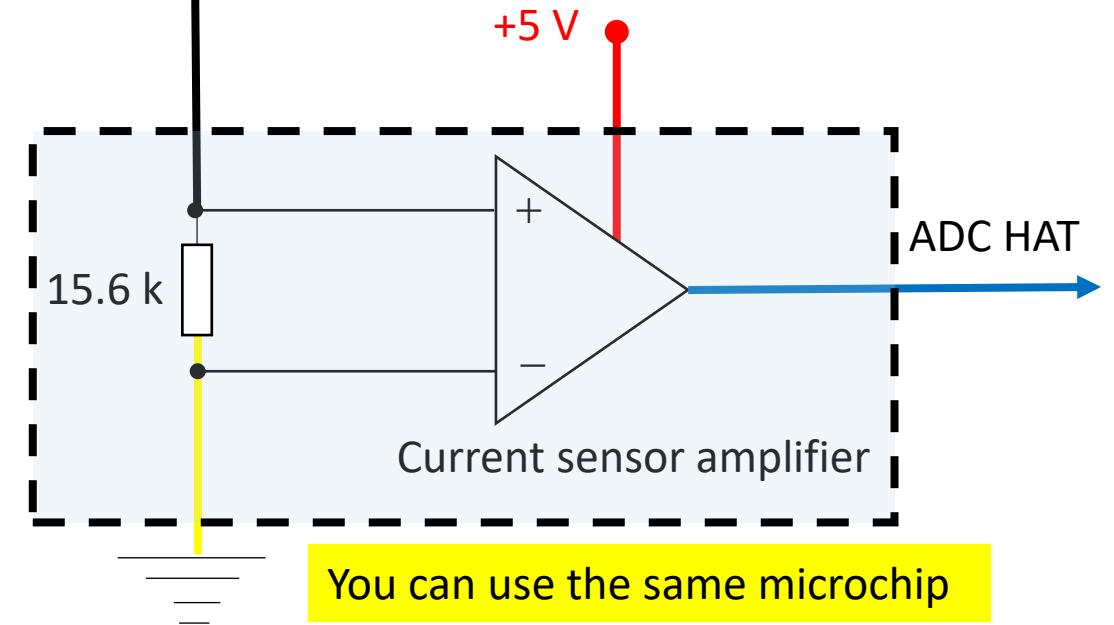
The sensor can also be connected to In 4 (unbuffered) or In 5, 6 (buffered).



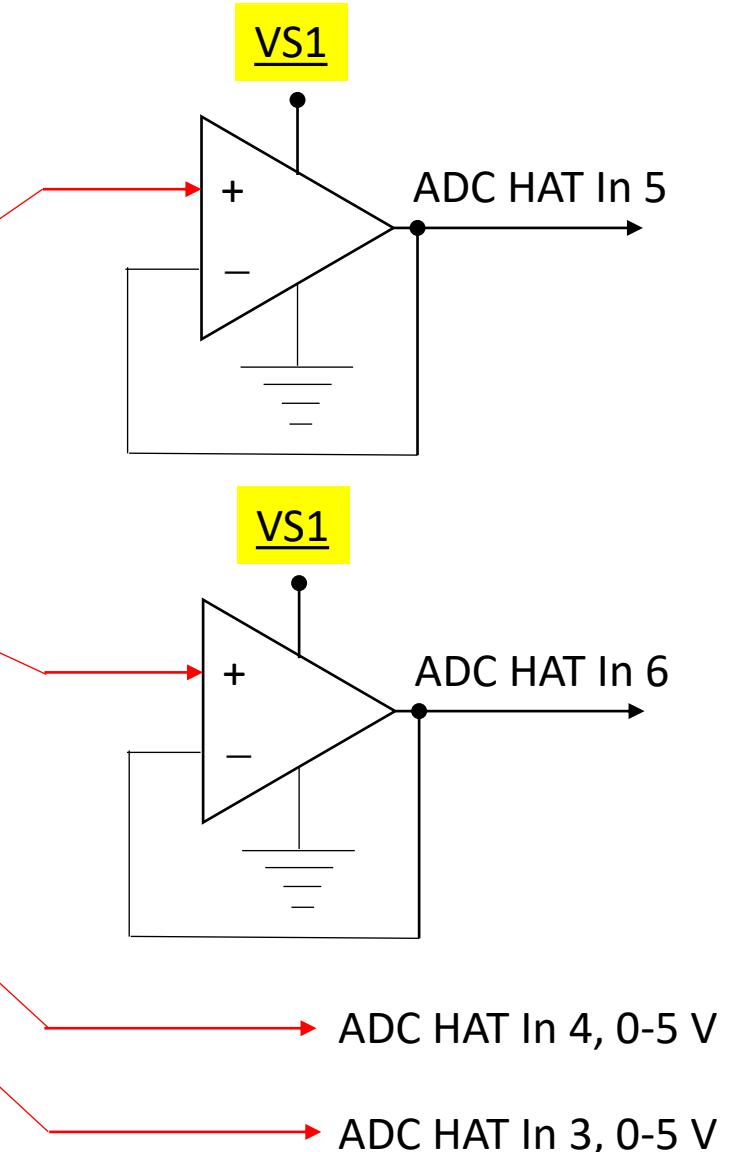
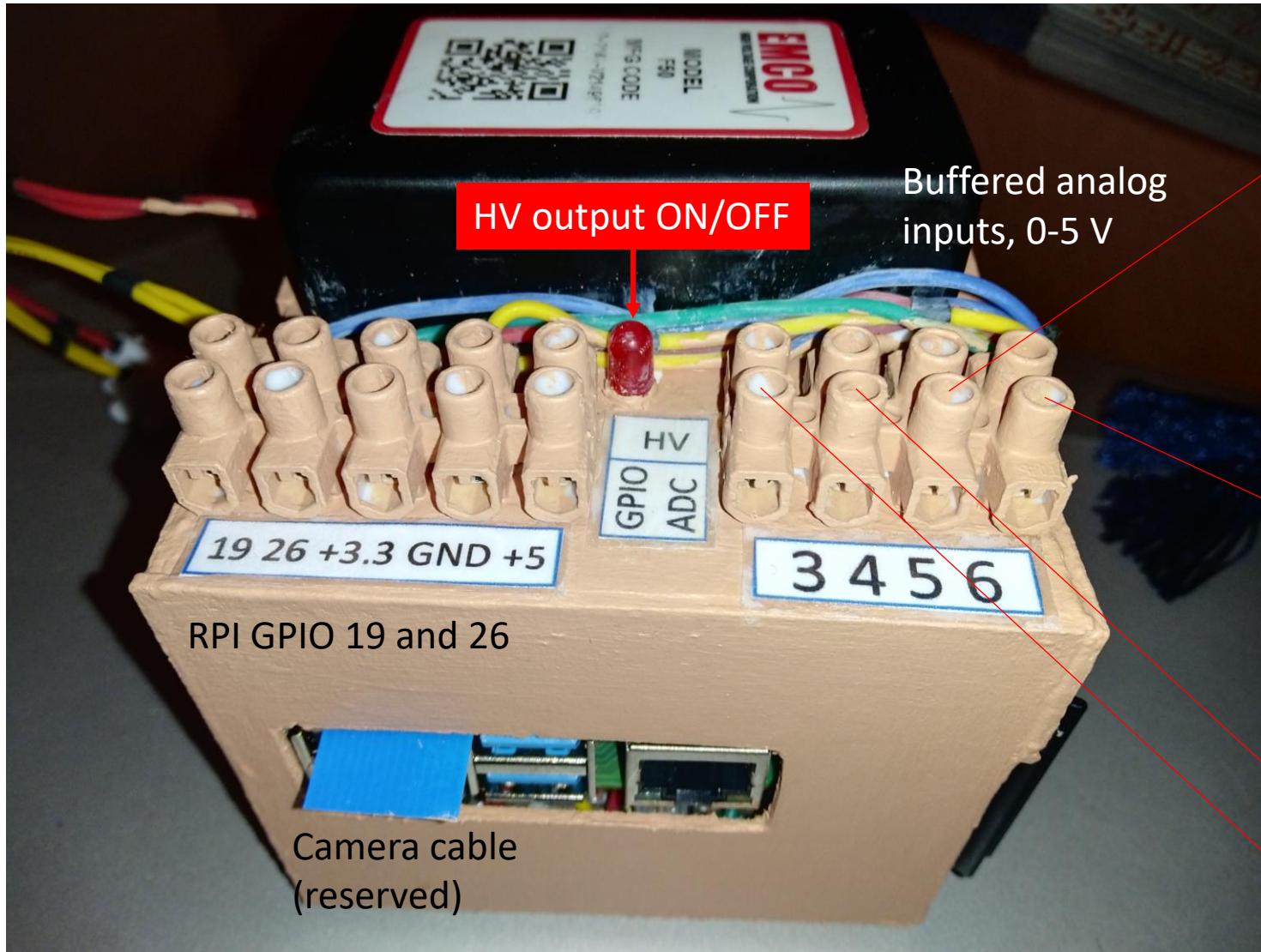
During dielectric breakdown, the capacitor cathode and the resistor network down to ground work as a current generator with a very large internal resistor  $1.5\text{ M}\Omega$  inside the sensor. This resistor limits the current and therefore may prevent “the avalanche”. That is why you may not hear “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  $\text{k}\Omega$  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

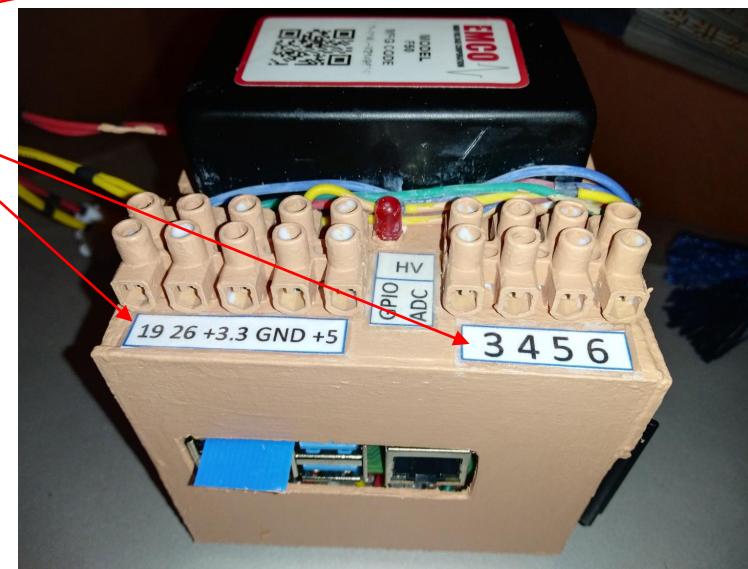


RPI GPIO 19 and 26 can be used, for example, for multiplexing the current sensor ranges in the future designs. This option has been already reserved for the current sensor function in the Python program.

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

```
1. # Measurement parameters (program inputs)
2. R_series = 1.5 # resistance in series with the QI capacitor in MOhms
3. R_shunt = 25.0 # shunting resistor across the QI capacitor in MOhms
4. C = 0.01 # estimated QI capacitance in uF (micro Farads)
5. factor_up = 5.0 # (factor_up * tau_up) is the waiting time for the capacitor full
charge
6. factor_down = 5.0 # (factor_down * tau_down) is the waiting time for the capacitor full
discharge
7. current_range = 1 # operational range of the current sensor; range 1 - GPIO 19, range 2
- GPIO 26
8. Ch = 3 # Your channel1 (ADC In 3 - In 6) for the current sensor. In 5 and 6 are
internally buffered.
9. # The current sensor function CurrentSensor(bias, Ch) is in Functions.py
```

```
1. def CurrentSensorRange(range):
2.     range1 = 19
3.     range2 = 26
4.     GPIO.setup(range1, GPIO.OUT)
5.     GPIO.setup(range2, GPIO.OUT)
6.     GPIO.output(range1, GPIO.LOW)
7.     GPIO.output(range2, GPIO.LOW)
8.     if range == 1:
9.         GPIO.output(range1, GPIO.HIGH)
10.    elif range == 2:
11.        GPIO.output(range2, GPIO.HIGH)
```



Program codes:  
[https://github.com/  
Qlthruster?tab=repo  
sitories](https://github.com/Qlthruster?tab=repositories)

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

# QI-2\_GUI. Run “UI.py”.

## Quantised Inertia Test Device

GUI and program code by Yujie Zhao and Dmitriy Makhnovskiy

DYK team

St. Andrews - Plymouth, UK, 10.09.2022

R<sub>series</sub> (MΩ)

1.5

R<sub>shunt</sub> (MΩ)

25.0

C (μF)

0.01

Factor up

5

Factor down

5

Current range

1

Channel

3

File name

Current sensor

Op Amp output = 0.9010050472245002 V

Actual HV output = 0.14718889731317242 kV

Current through the capacitor = 0.13414751703667827

uA

Thrust is: 0.0 mg

Type in "Thrust box". Then enter SHIFT, CTRL or ESC

Battery voltage = 12.377796693415288 V

Op Amp output = 0.9215594506457259 V

Actual HV output = 0.15767505796758393 kV

Current through the capacitor = 0.14483288744311962

uA

Thrust is: 0.0 mg

Type in "Thrust box". Then enter SHIFT, CTRL or ESC

Battery voltage = 12.376664780255716 V

Op Amp output = 0.9370851101992117 V

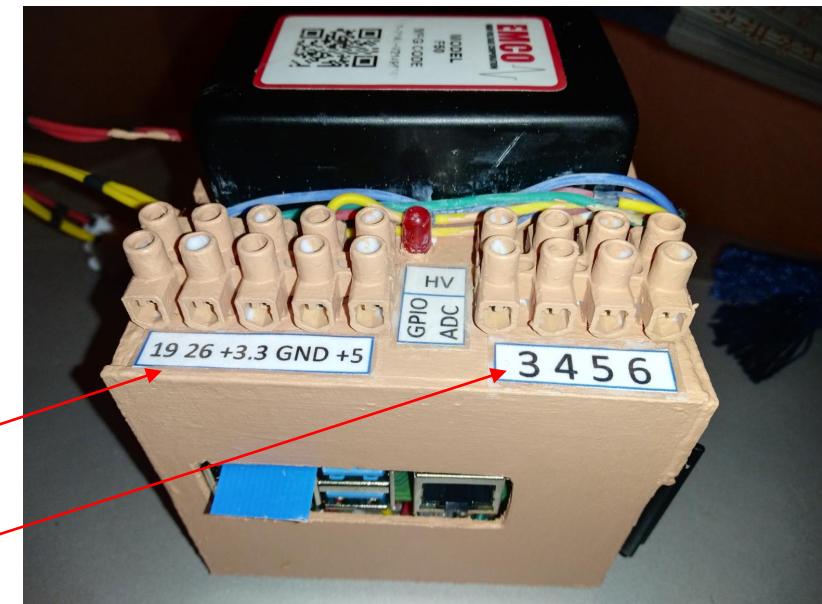
Actual HV output = 0.16835607596130858 kV

Current through the capacitor = 0.1571006634930443

uA

Thrust (mg)

Run

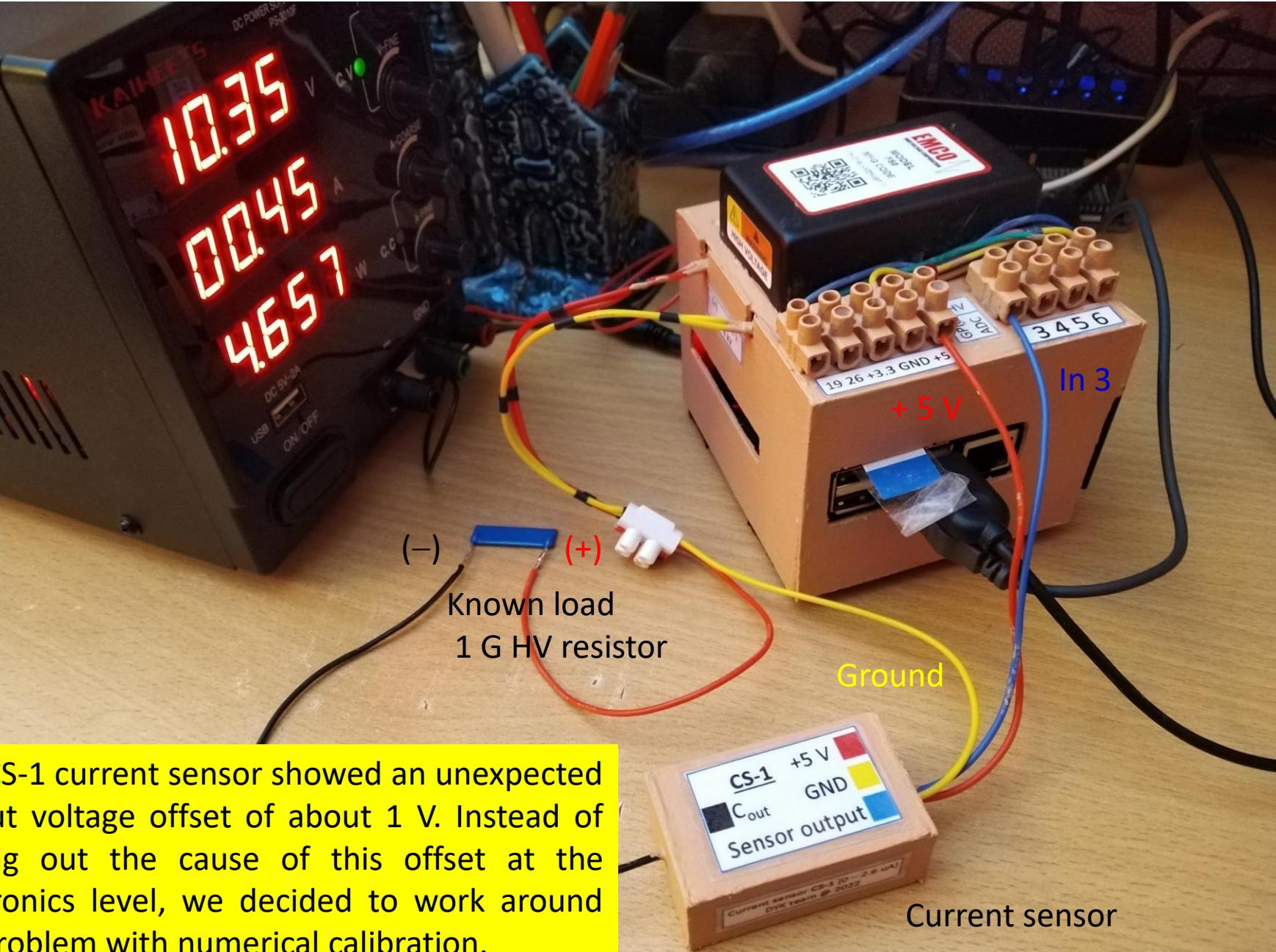


Program codes:

<https://github.com/QIthruster?tab=repositories>

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

# Current sensor calibration: circuit



# 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,  $\pm$  20%, 1.8 V (x1) <https://www.mouser.co.uk/ProductDetail/Microchip-Technology-Atmel/MCP4151-103E-P?qs=hH%252BOa0VZEiCcBDYaXnd0Yg%3D%3D&gclid=Cj0KCQjw1vSZBhDuARIsAKZlijTUOSfpThWQ7DDjQ6e7MBO8J0pd4FaWfxlr5qg8UguUVpjCefRdbN0aAm58EA>  
Lw\_wcB

Isolated DC/DC Converters SINGLE O/P, DC-HV DC PCB MOUNT, 10W, 5000V (x1) <https://www.mouser.co.uk/ProductDetail/XP-Power/F50?qs=w%2Fv1CP2dgqp9eWErQLdwfA%3D%3D>

Operational Amplifier, 1 Amplifier, 1 MHz, 10 V/ $\mu$ s,  $\pm$  4V to  $\pm$  30V, TO-220, 7 Pins (x1) <https://uk.farnell.com/texas-instruments/opa548t-1/ic-op-amp/dp/3005043?st=opa548t-1>

Operational Amplifier, 2 Amplifier, 3 MHz, 2 V/ $\mu$ s, 2.7V to 16V, DIP, 8 Pins (x4) <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 (x1) <https://uk.farnell.com/texas-instruments/ptn04050caz/ic-isr-12w-smd-4050/dp/3009745?st=ptn04050c>

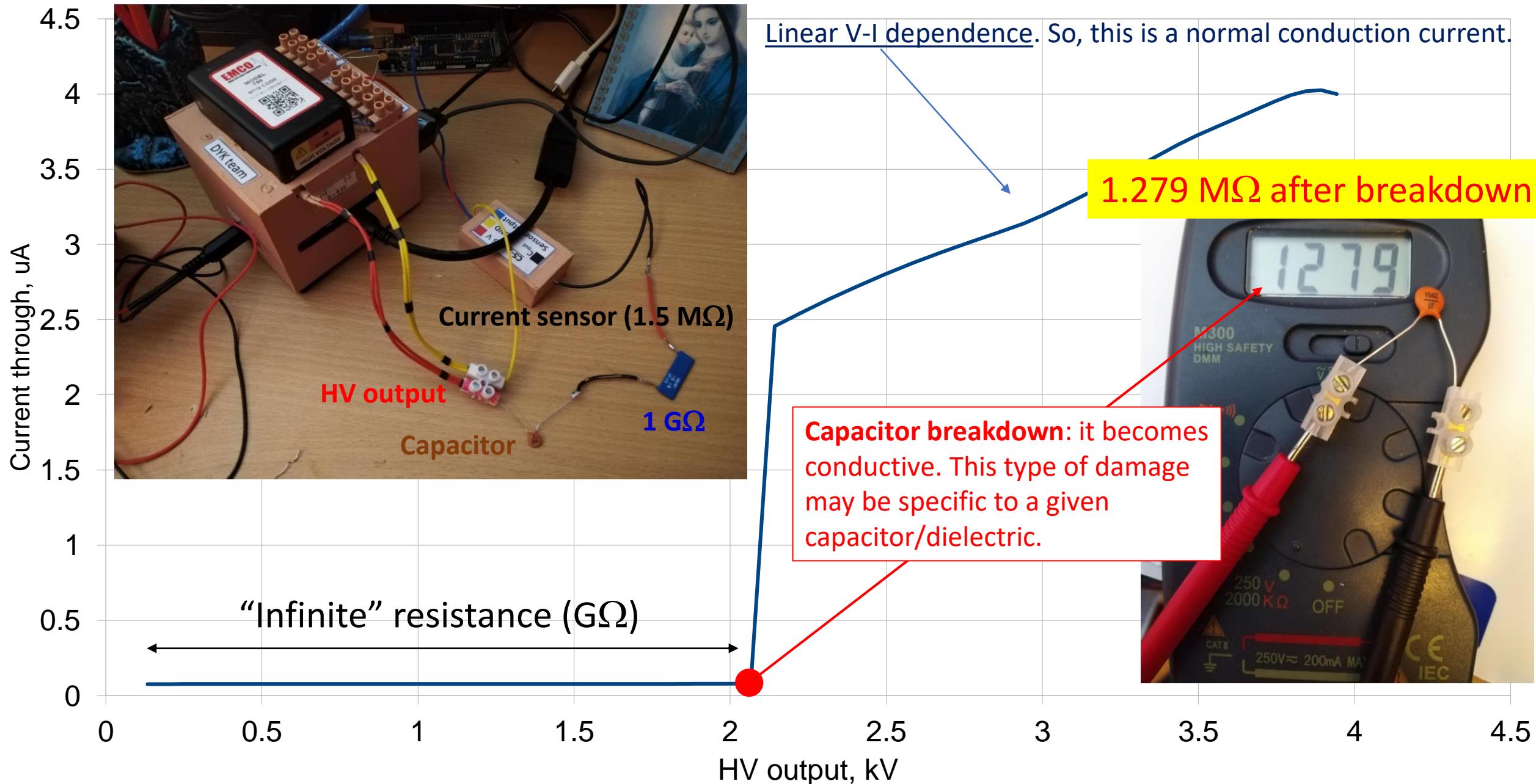
Fixed LDO Voltage Regulator, 2.6V to 27V, 1.3V Dropout, 5Vout, 5Aout, TO-220-3 (x1) <https://uk.farnell.com/texas-instruments/lm1084it-5-0-nopb/ldo-fixed-5v-5a-to-220/dp/3121986>

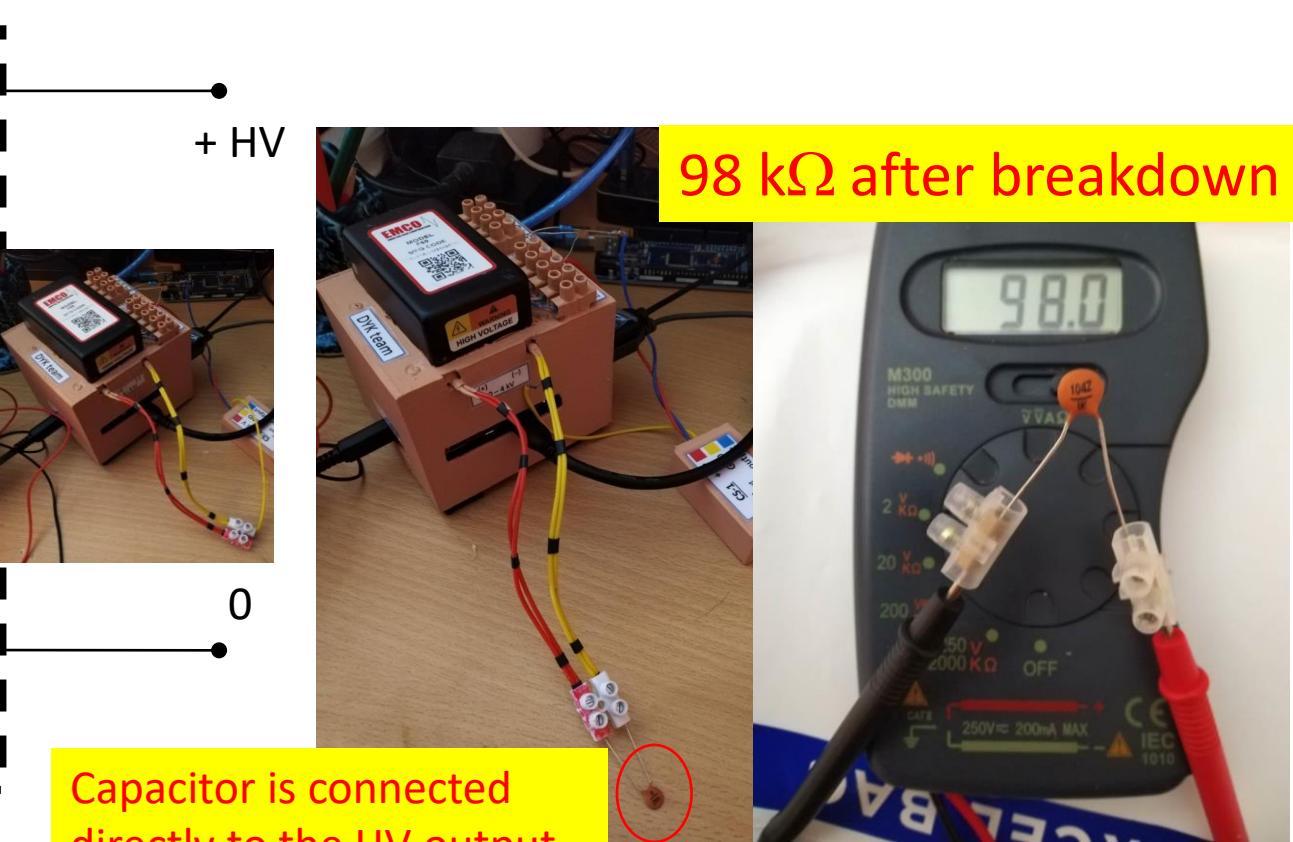
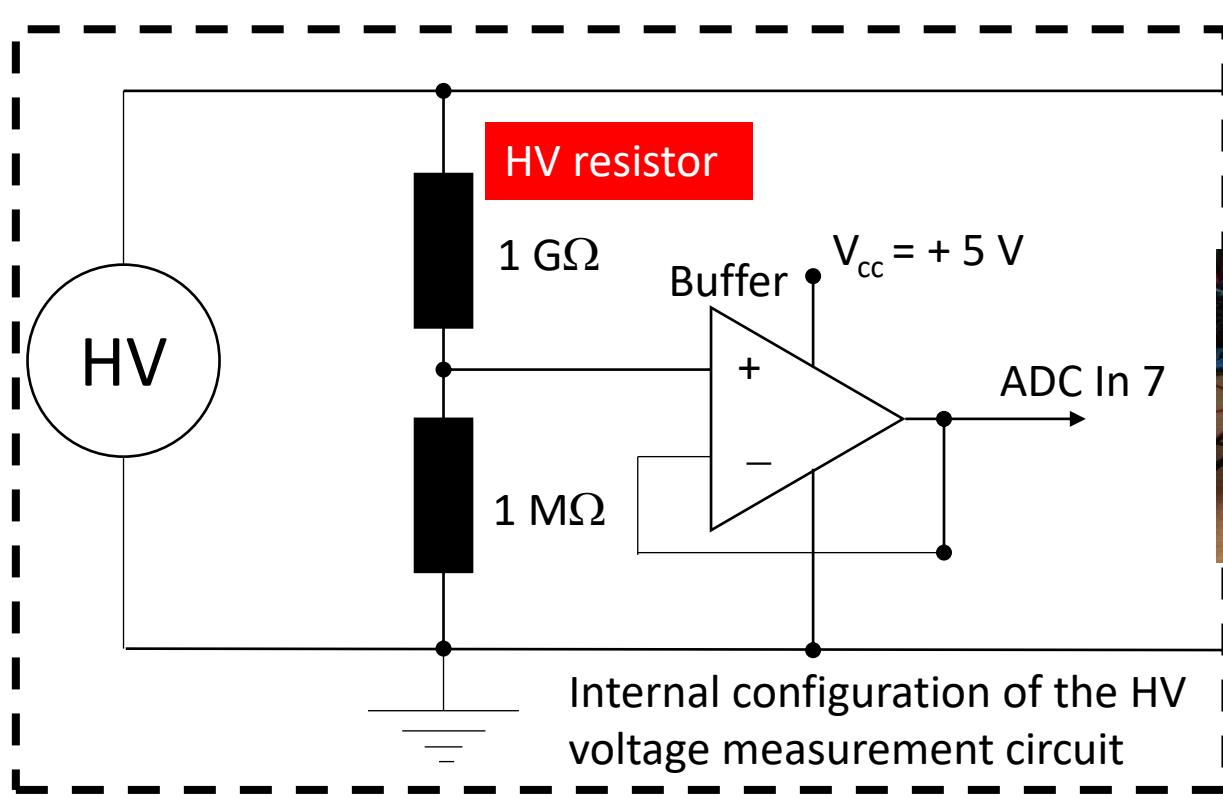
Heat Sinks Heat Sink, MULTIWATT, Radial Fin, Straight Pin, Vertical, 4.4C/W, 2.89mm Hole (x2)  
<https://www.mouser.co.uk/ProductDetail/Aavid/6398BG?qs=U7T%2FEnMyvTt1NN5UEAtP6Q%3D%3D>

RPi GPIO Terminal Block (x1) [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](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 (x1)  
<https://www.mouser.co.uk/ProductDetail/STMicroelectronics/TSC2012HYDT?qs=XAiT9M5g4x9j5E5ITSULeg%3D%3D>

# Testing the device with a commercial capacitor





Capacitor is connected directly to the HV output

This configuration was chosen for loads with a very high internal resistance ( $G\Omega$ ), such as a capacitor before breakdown. If the load resistance drops to  $M\Omega$  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  $1 G\Omega$  resistor. That is, a  $M\Omega$  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.**

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 the electronic scale:

**2 kV**

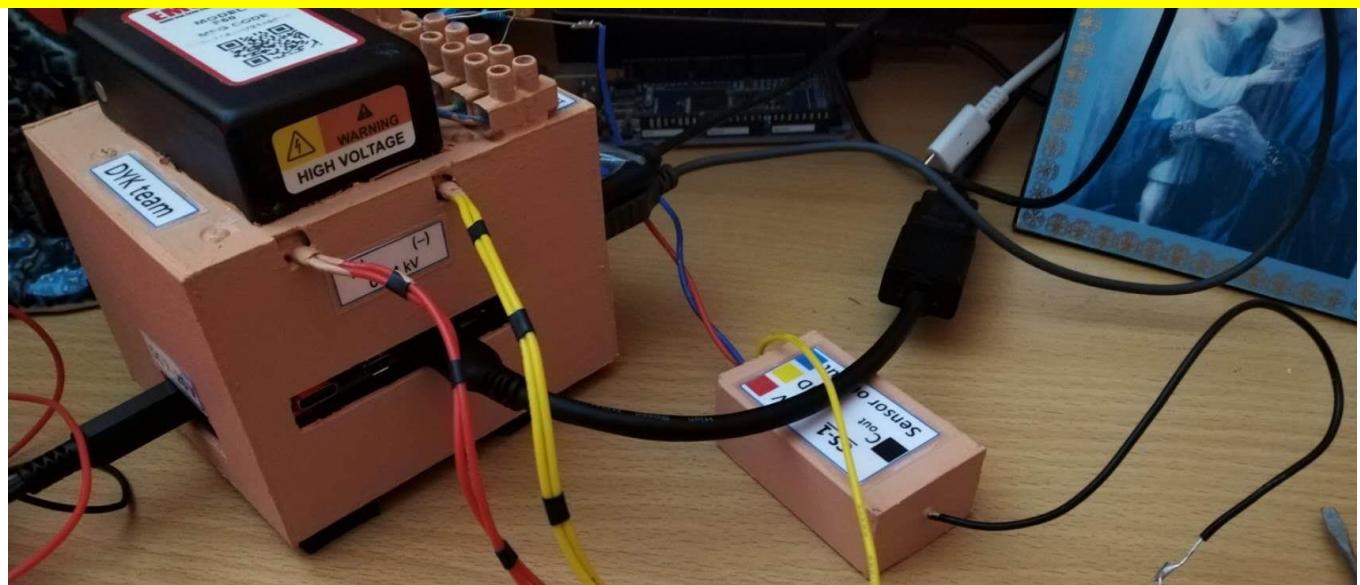
Battery voltage = 13.788830469729767 V  
Op Amp output = 3.539873637976066 V  
Actual HV output = 0.7246848594977916 kV  
Current through the capacitor = -108.82935841017131 uA  
Enter the thrust reading (any units) from the electronic scale:

**Sudden voltage drop during the capacitor breakdown**

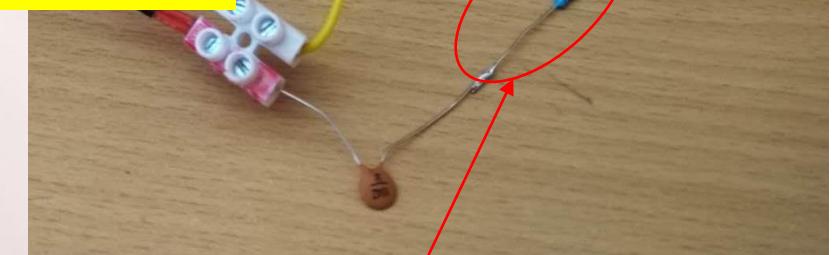
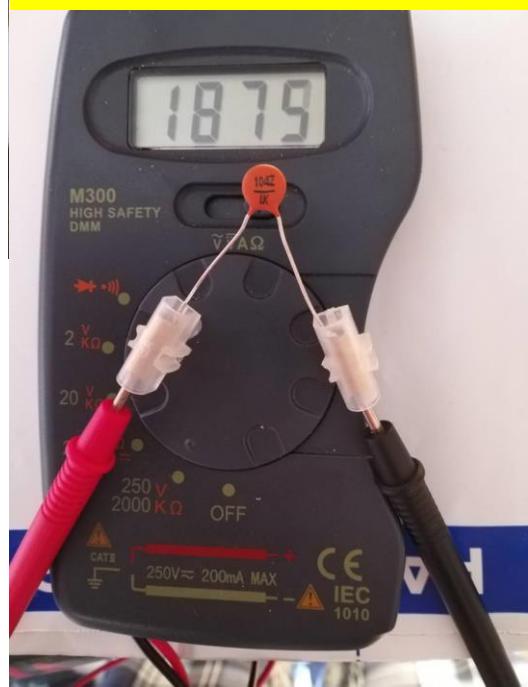
The character of breakdown may depend on the current through the capacitor and the type of dielectric.



98 k $\Omega$  after breakdown



1.879 M $\Omega$  after breakdown

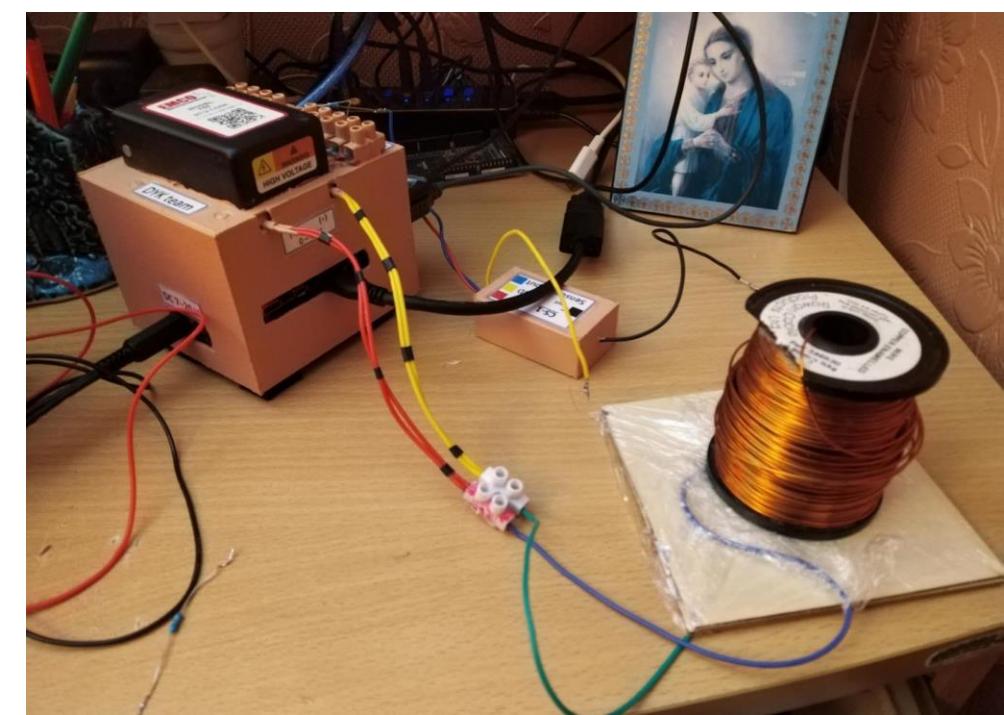


Additional 1 M $\Omega$  series resistor + 1.5 M $\Omega$  resistor inside the current sensor

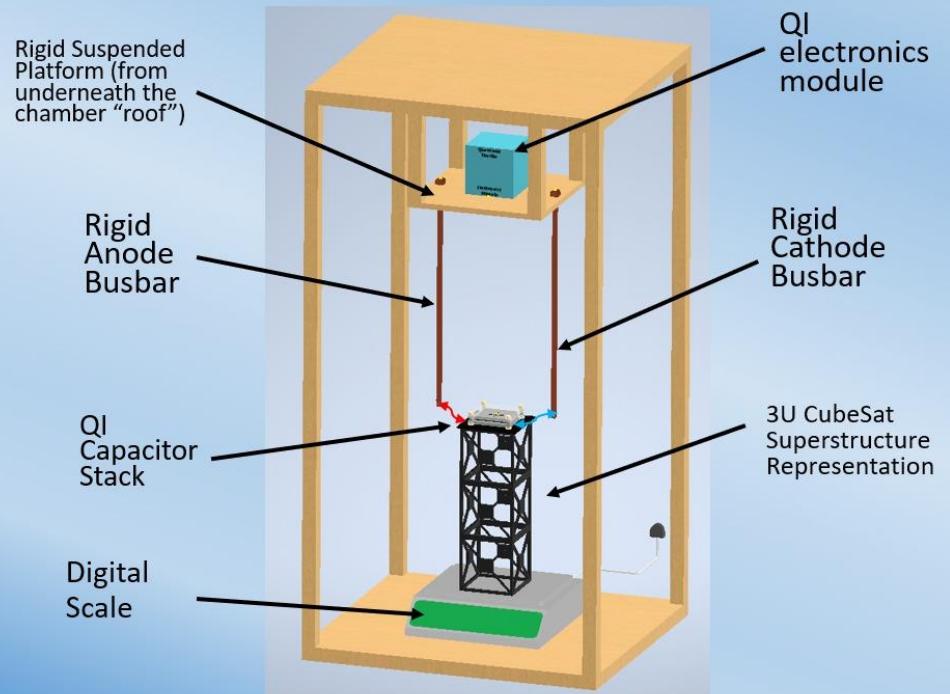


Wire end bundle for foil contact

"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.



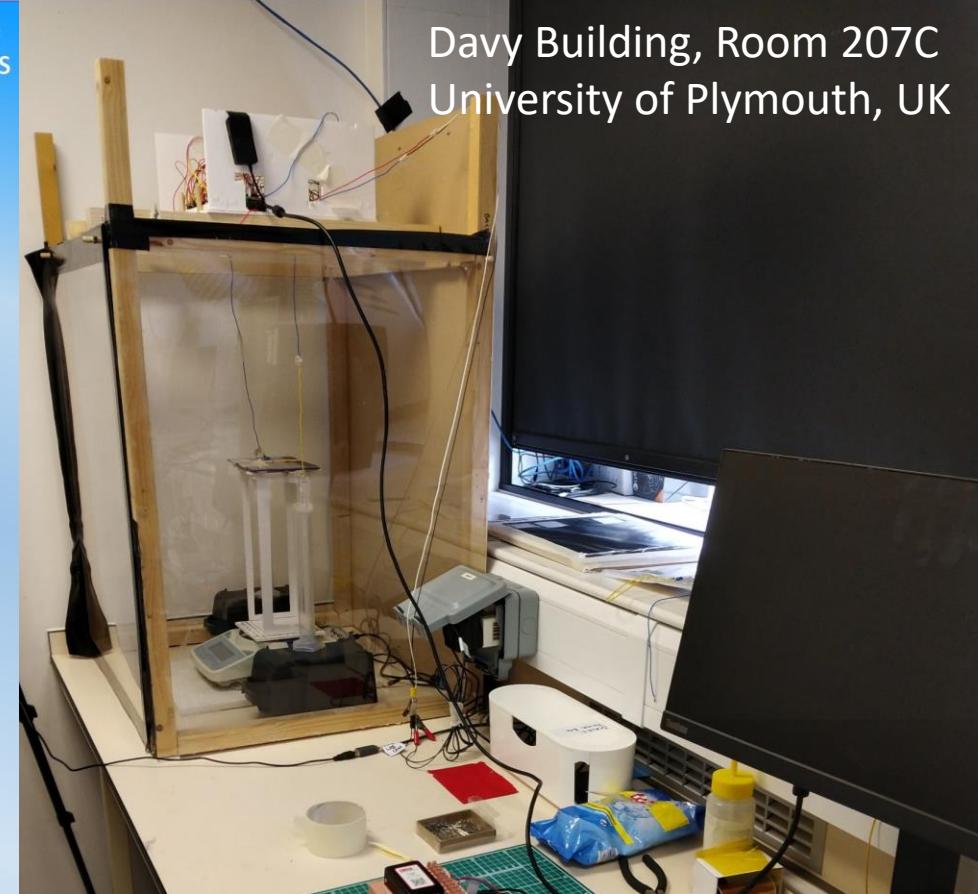
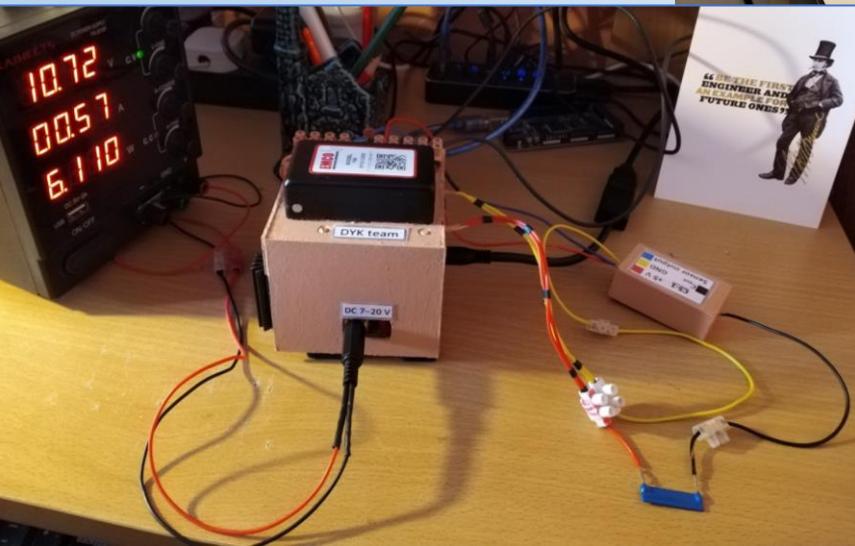
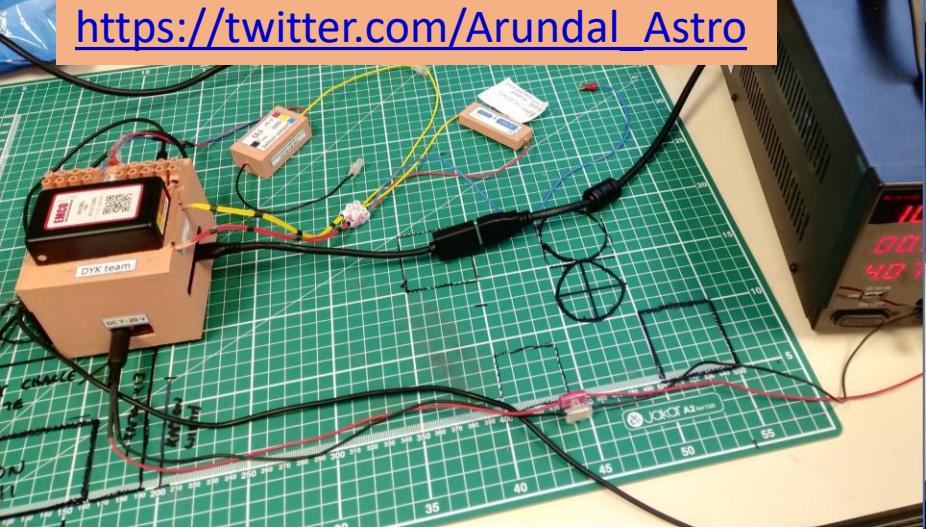
# QI Test Chamber V1 (Non Vacuum)



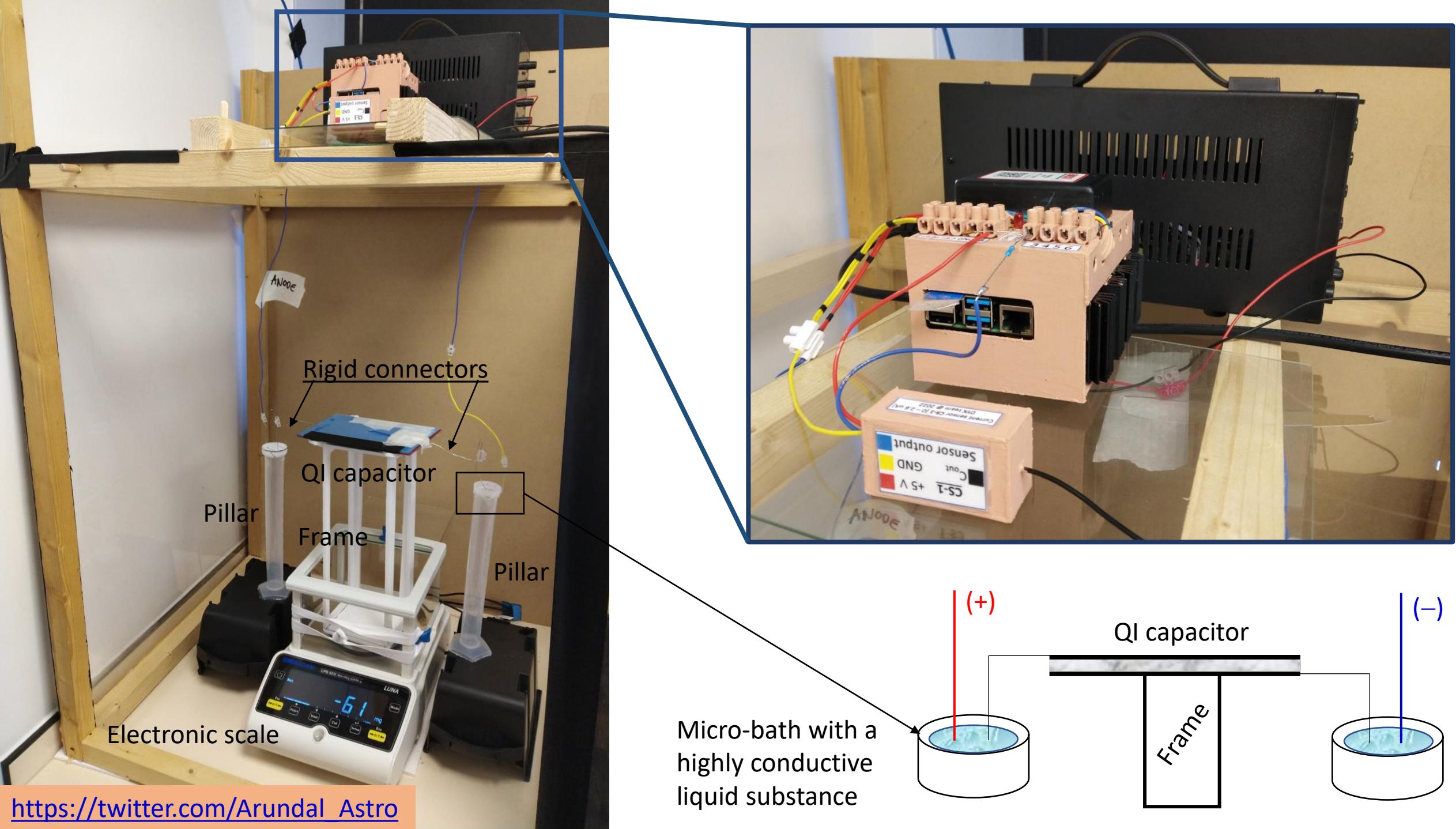
## Revised Quantised Inertia Test Chamber

- 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)

[https://twitter.com/Arundal\\_Astro](https://twitter.com/Arundal_Astro)



Davy Building, Room 207C  
University of Plymouth, UK



Electronic scale

Rigid connectors

QI capacitor

Frame

Pillar

Pillar

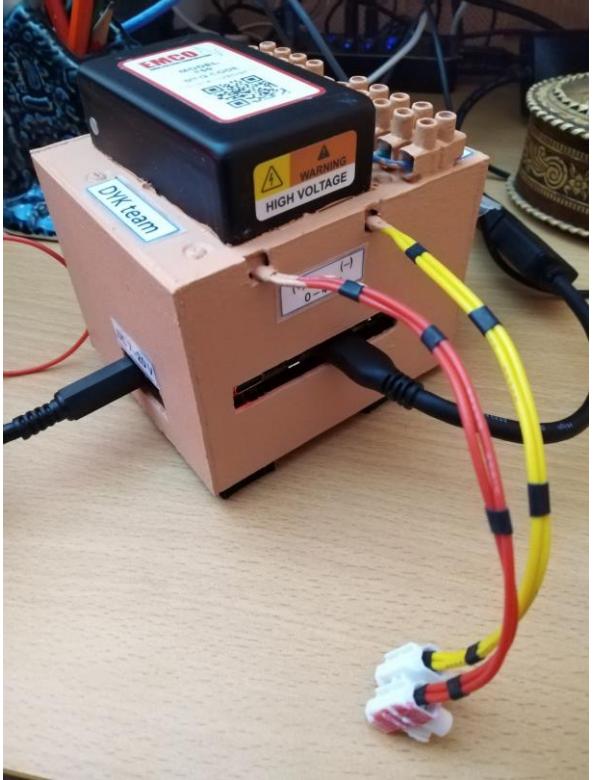
Micro-bath with a  
highly conductive  
liquid substance

(+)

QI capacitor

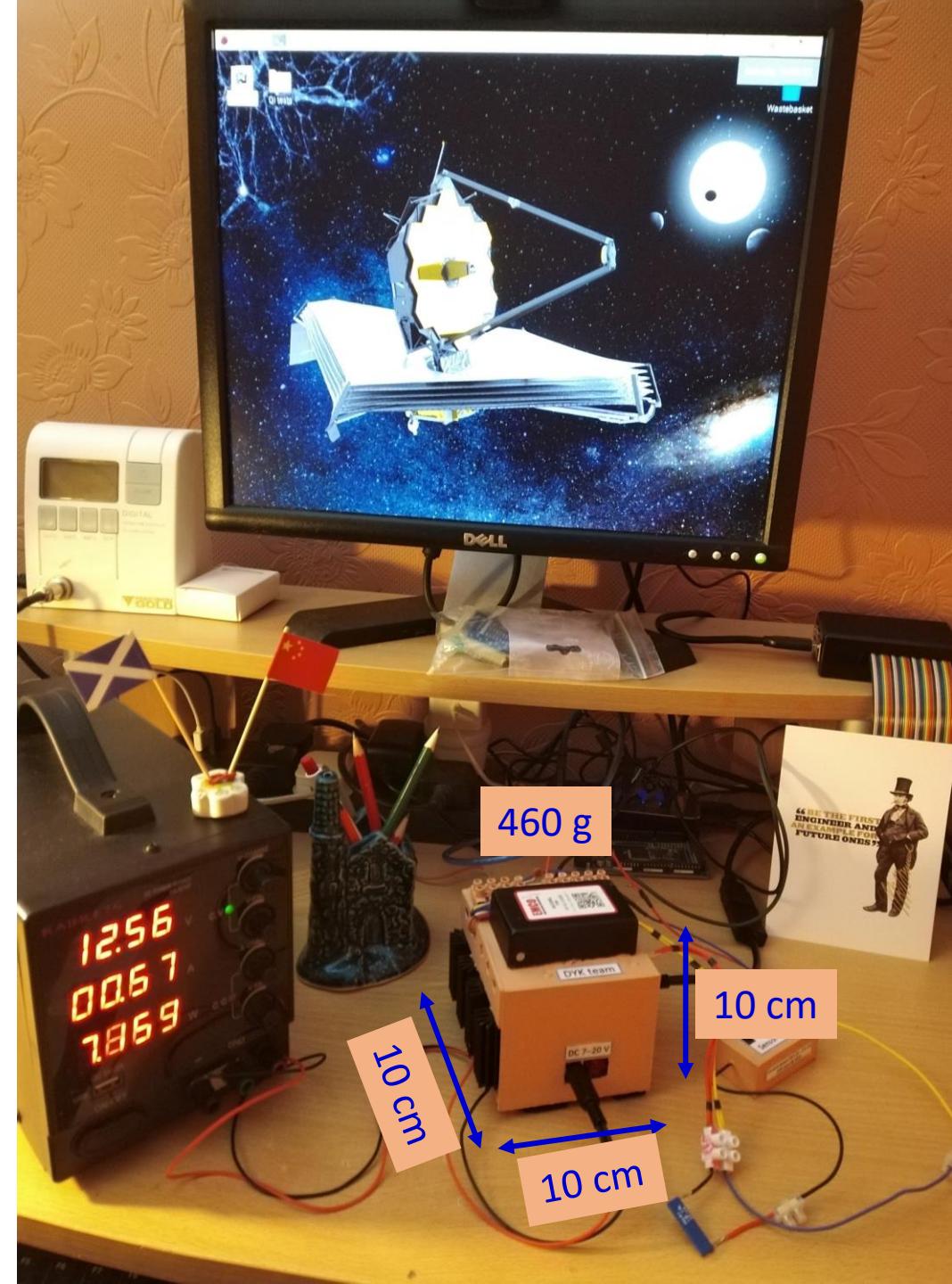
Frame

(-)



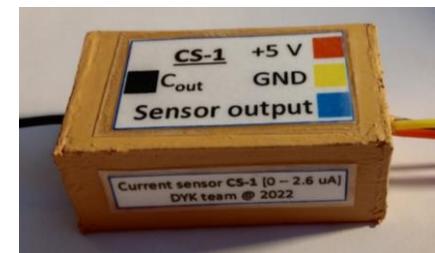
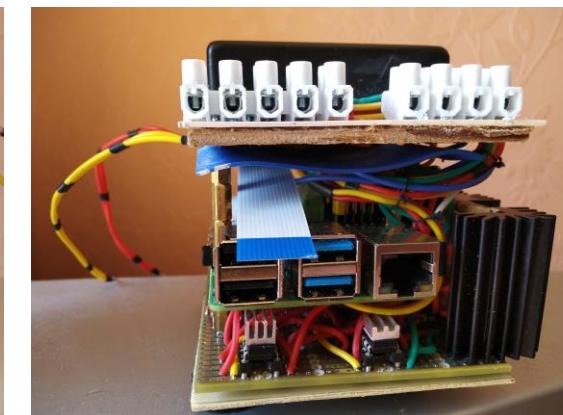
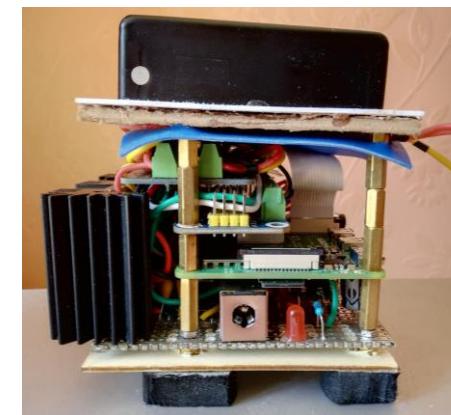
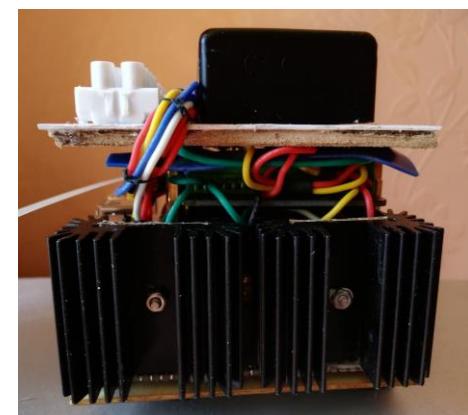
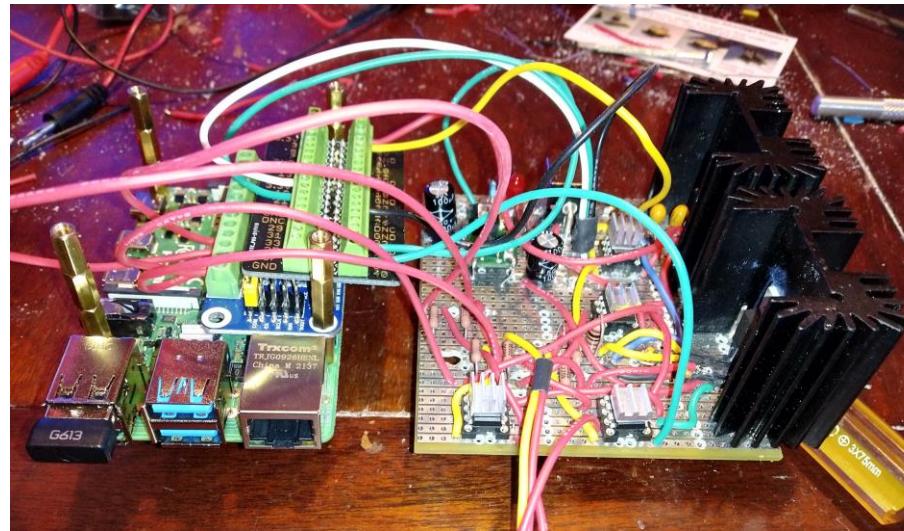
Our design satisfies the CubeSat standards (<https://en.wikipedia.org/wiki/CubeSat>): a class of miniaturized satellite based around a form factor consisting of 10 cm (3.9 in) cubes. CubeSats have a mass of no more than 2 kg (4.4 lb) per unit, and often use commercial off-the-shelf (COTS) components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

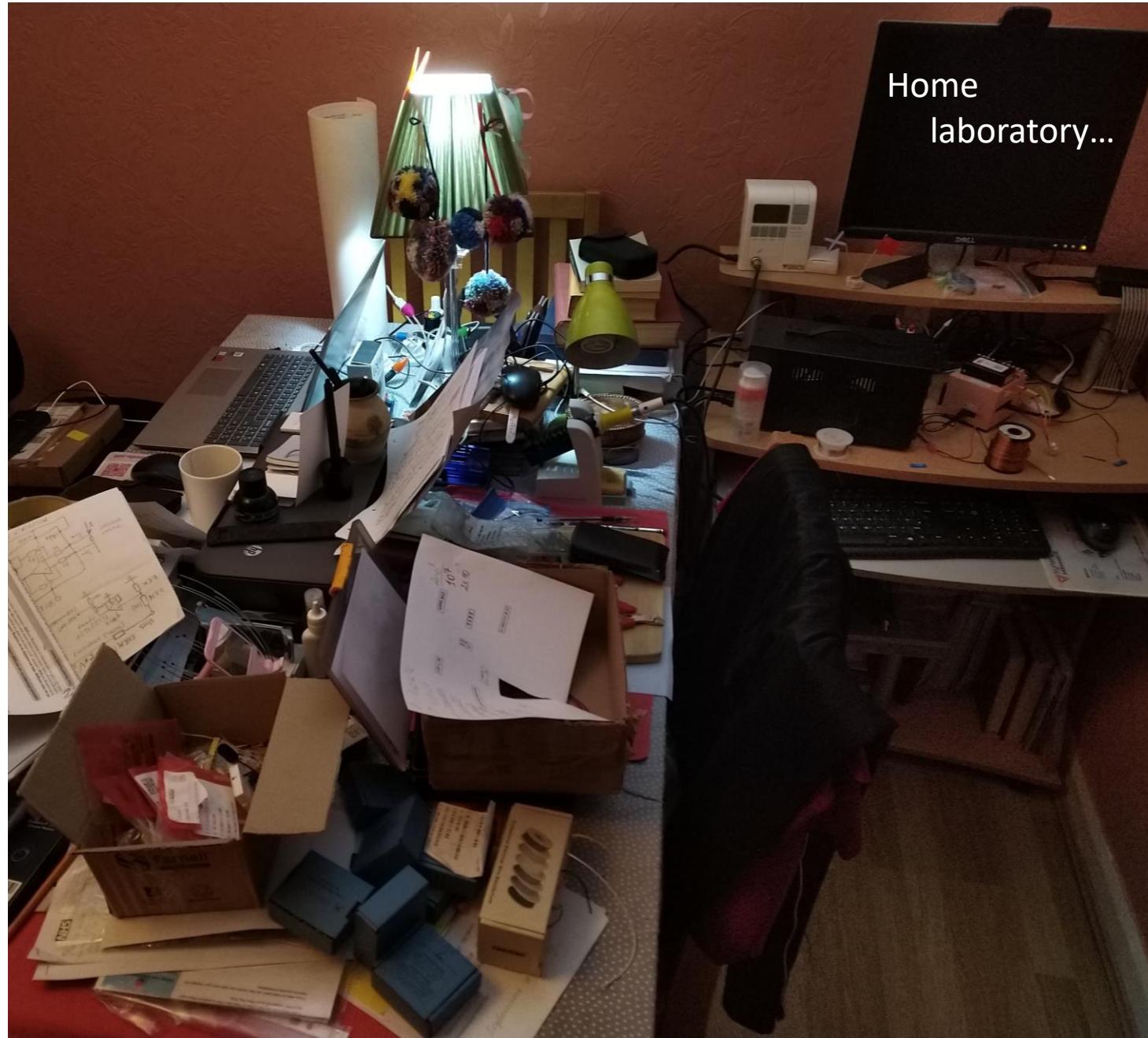


# Design gallery: assembly

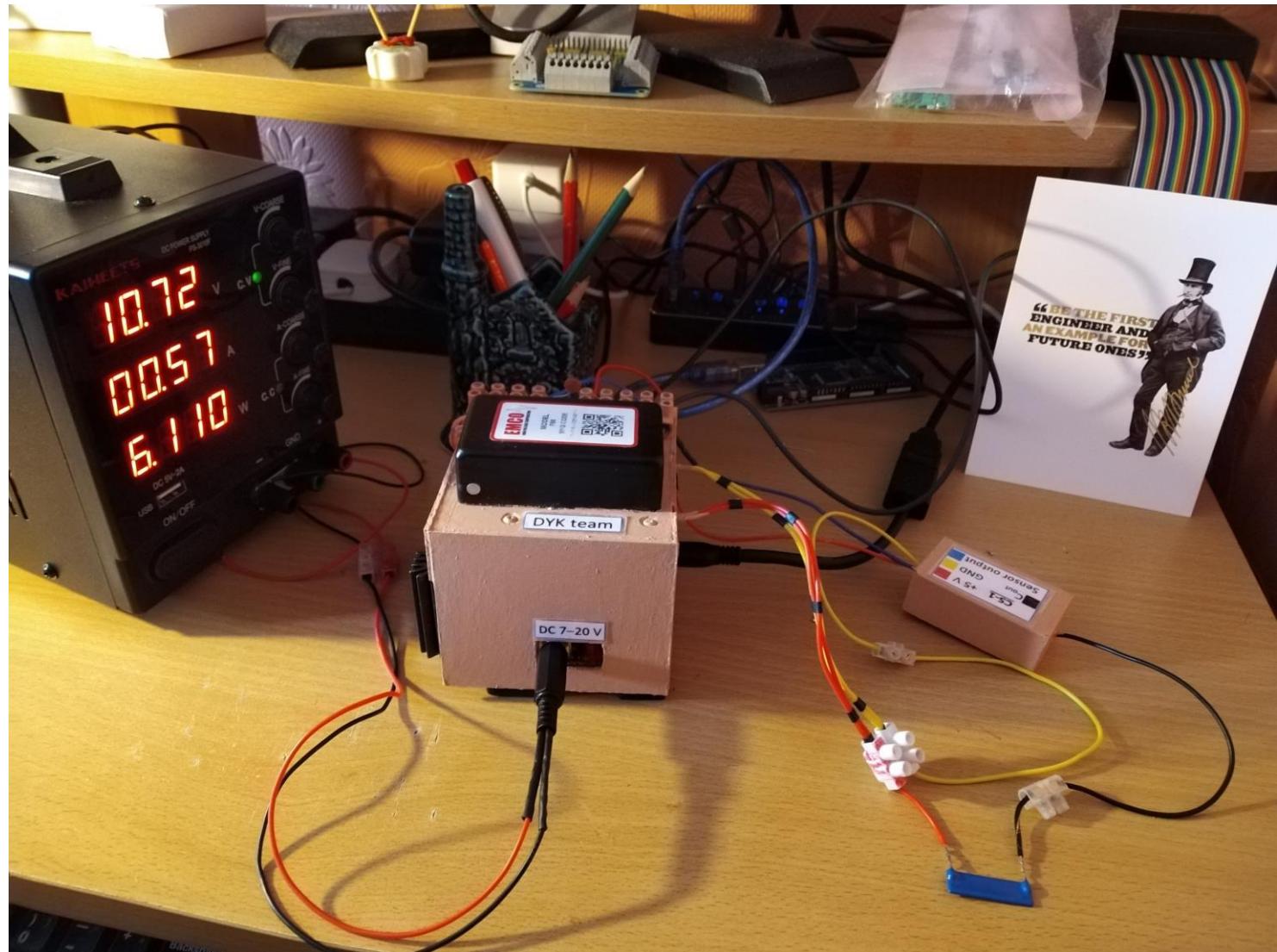
Home laboratory...



# Design gallery: final testing



# Design gallery: before departure



# Design gallery: passed to university

