UNCUT GEM

Open Source Quantum Sensing

Dr Mark Carney

1st December 2025 | Quantum Village @ QUEST-IS, Paris

What is |QUANTUM> |VILLAGE>

A place to engage, explore, and enable the future of quantum tech.

Quantum Village is a 501(c)(3) non-profit quantum company and global community working in the critical intersection between quantum technologies, cybersecurity, and creativity.

Victoria has worked in startups and companies in wide ranging areas, from productizing machine learning applications for cybersecurity to consumer brands at LVMH. Victoria studied art and design at Central St. Martins before working in finance as an equity market strategist and investment analyst.

Victoria's current focus is on creating more open routes to commercialization and effective product design for emerging technology. Victoria is the co-founder and exec director of Quantum Village.

Who are we

Mark is a mathematician and Quantum Hacker. Working at the bleeding edge of technology for two decades, he has presented on an array of topics stemming from his work on quantum computation, machine learning, cryptography and cybersecurity data science.

Mark is a former professional violinist, thereminist and is a logician with a PhD in computability theory and tilings, Mark is the co-founder and CTO of Quantum Village.

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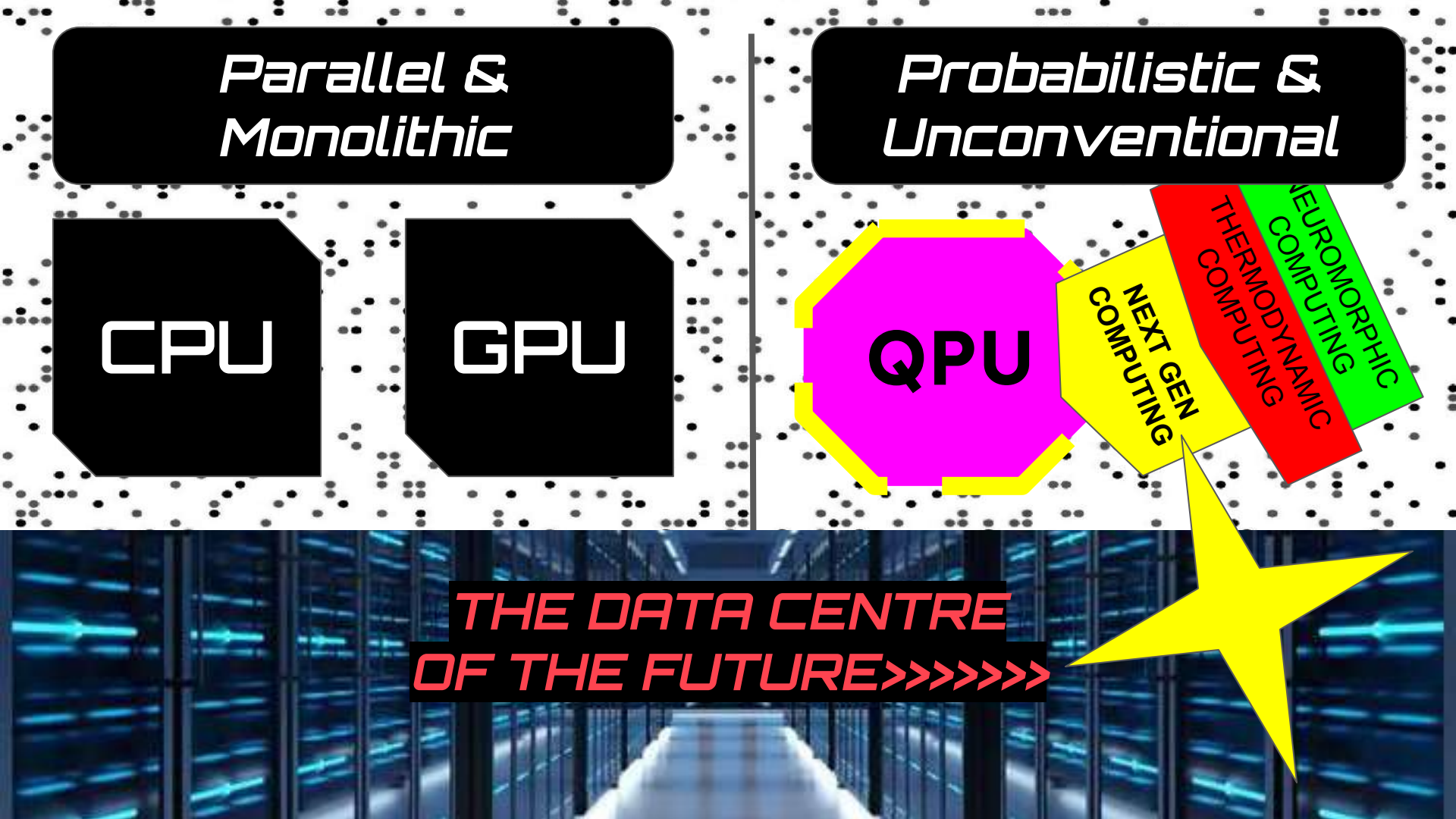
Harnessing Creative Misuse

…for better quantum tech!


Parallel &
Monolithic
Probabilistic &
Unconventional
CPU
GPU
QPU
NEXT GEN COMPUTING
THERMODYNAMIC COMPUTING
NEUROMORPHIC COMPUTING
THE DATA CENTRE
OF THE FUTURE>>>>>>>

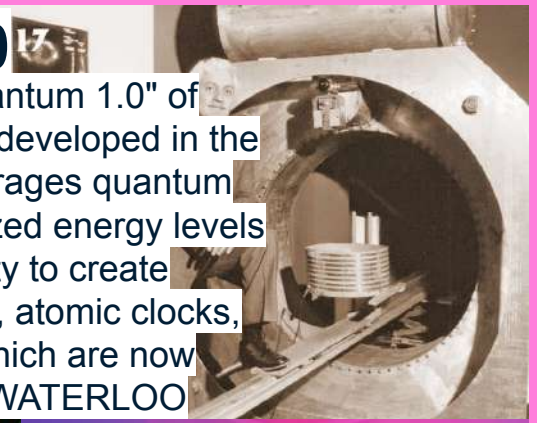
WHAT ABOUT QUANTUM TECHNOLOGY?

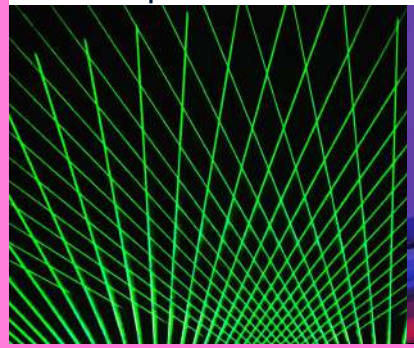
IT'S NOT ALL about Quantum Computing...

Why does it matter? Promises and Future Impacts

Quantum 1.0

The "first wave" or "Quantum 1.0" of quantum technologies, developed in the early 20th century, leverages quantum phenomena like quantized energy levels and wave-particle duality to create technologies like lasers, atomic clocks, and semiconductors, which are now commonplace. - U OF WATERLOO





Quantum 2.0

£1.7m funding for wearable brain imaging system closer to patient use

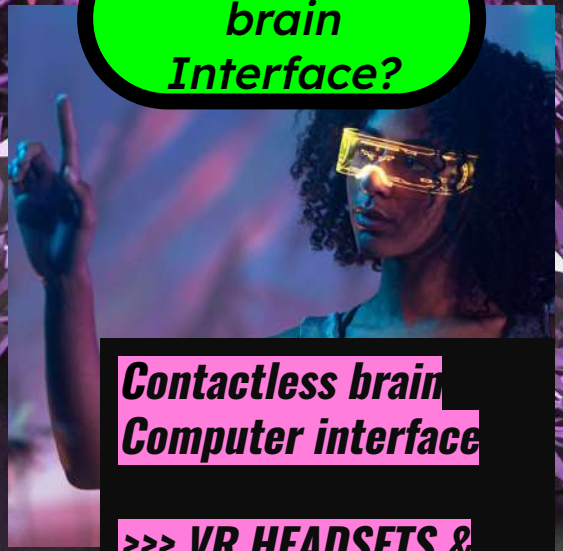
Tuesday, 21 February 2023

Tomorrow's Market: Where might NVC Diamond Sensing take us?

Robotics & Industrials

Sensors for Extreme Environments....

Consumer brain Interface?



Contactless brain Computer interface

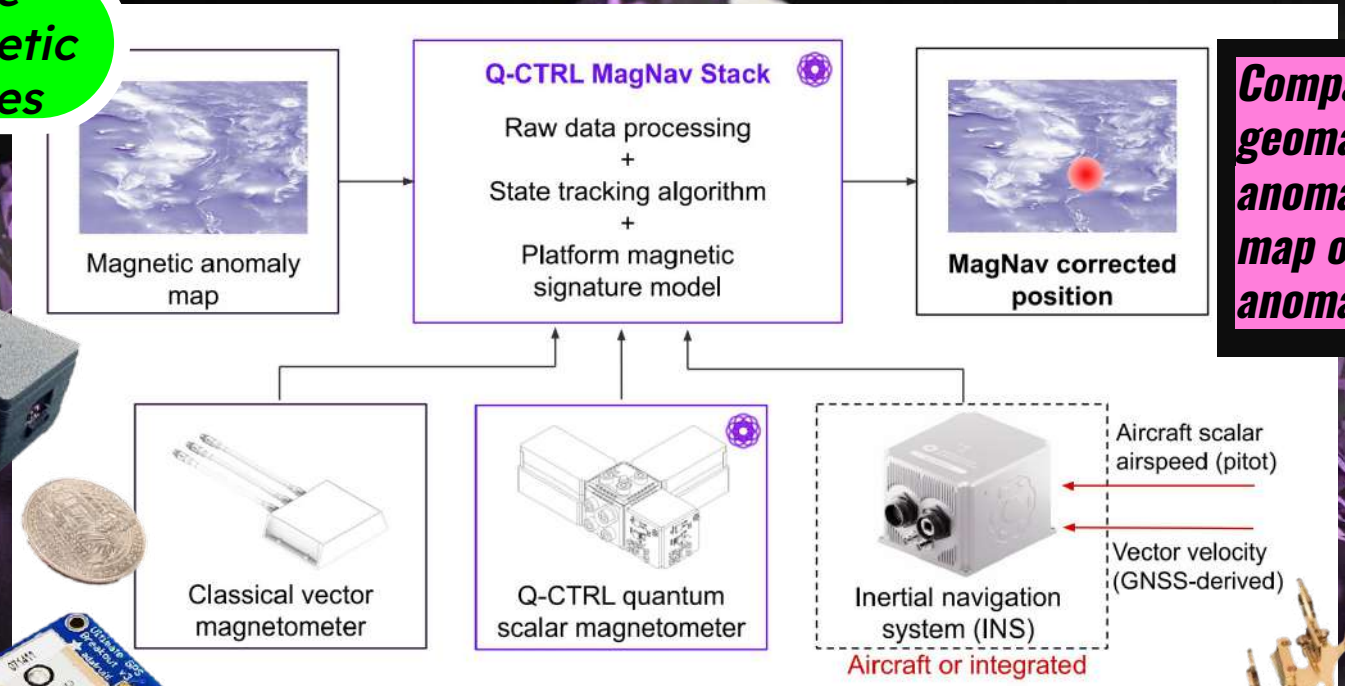
>>> VR HEADSETS & SMART GLASSES?

Medical Diagnostics?

Shieldless Diagnostics...

Dealing with GPS Jamming: Magnetometry as PNT

Measure Geomagnetic Anomalies



Compare detected geomagnetic anomalies with the map of known anomalies...

GPS > Quantum > Sextant...

Source: https://arxiv.org/pdf/2504.08167


WHO ELSE IS INTO DIAMONDS?

Diamonds with Defects in other Quantum Technologies

QUANTUM COMPUTING

room temp quantum computers powered by diamonds?? 💎 💎 💎 💎 💎

The first mobile Quantum Computer?

INTERCONNECTS QUANTUM NETWORKING COMMS

Sources:
https://www.lightsynq.com/
.org/2025/03/12/qia-researchers-create-first-operating-system-for-quantum-networks/
https://quantumbrilliance.com/
https://www.nature.com/articles/s41565-025-01704-w
https://www.saxonq.com/en/

Uncut Gem - Key Design Philosophy:

1. Aim to create a platform for exploration.
2. Use Consumer Off-the-shelf (COTS) components as much as possible.
3. Create a hardware stack that allows as many aspects of the sensing process to be ‘software problems’ as possible.
4. Where assembly is required, simplify!

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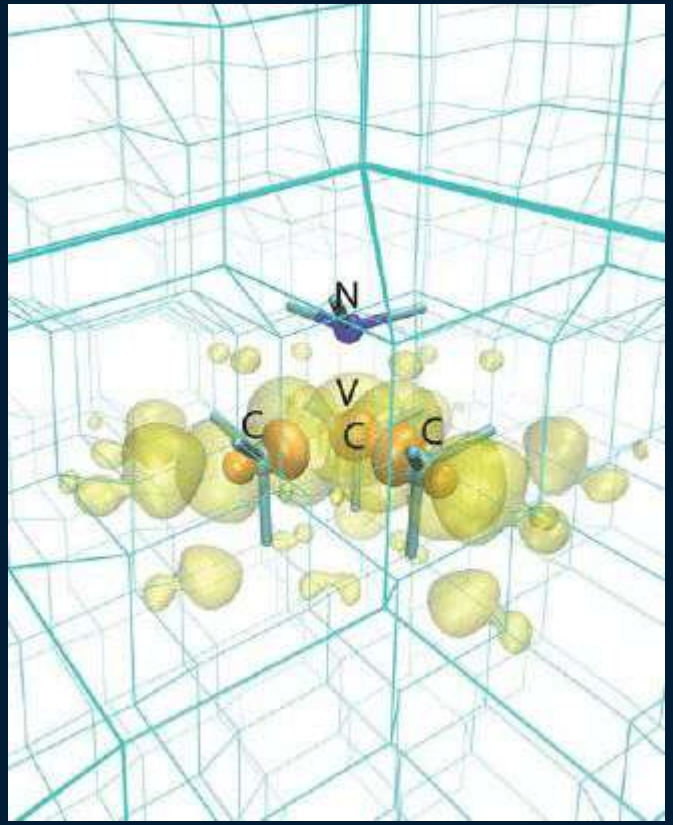
NVC Diamond Magnetometr y

A Full Overview of the physics, hardware/firmware and technology we are releasing



Iso-probabilistic spin-density surface,
Source: https://doi.org/10.1557/mrs.2013.18

The Hamiltonian for the NV Center

Source: https://doi.org/10.1088/1361-6404/acbe7c

$$\mathcal{H} = hDS_z^2 + hE(S_y^2 - S_x^2) + g\mu_B \mathbf{B} \cdot \mathbf{S}$$

The Hamiltonian for the NV Center

Source: https://doi.org/10.1088/1361-6404/acbe7c

The Energy of the System

$$\mathcal{H} = hDS_z^2 + hE(S_y^2 - S_x^2) + g\mu_B \mathbf{B} \cdot \mathbf{S}$$

The Hamiltonian for the NV Center

Source: https://doi.org/10.1088/1361-6404/acbe7c

The Energy of the System

$$\mathcal{H} = hDS_z^2 + hE(S_y^2 - S_x^2) + g\mu_B \mathbf{B} \cdot \mathbf{S}$$

Energy from Light and Microwaves

The Hamiltonian for the NV Center

Source: https://doi.org/10.1088/1361-6404/acbe7c

The Energy of the System

$$\mathcal{H} = hDS_z^2 + hE(S_y^2 - S_x^2) + g\mu_B \mathbf{B} \cdot \mathbf{S}$$

Energy from Light and Microwaves

Magnetic Field Tensor

The Hamiltonian for the NV Center

Source: https://doi.org/10.1088/1361-6404/acbe7c

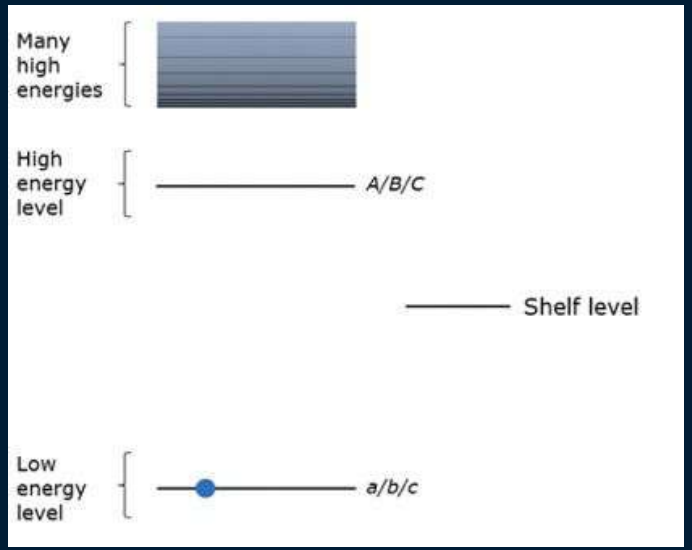
The Energy of the System

Stress Tensor

$$\mathcal{H} = hDS_z^2 + hE(S_y^2 - S_x^2) + g\mu_B \mathbf{B} \cdot \mathbf{S}$$

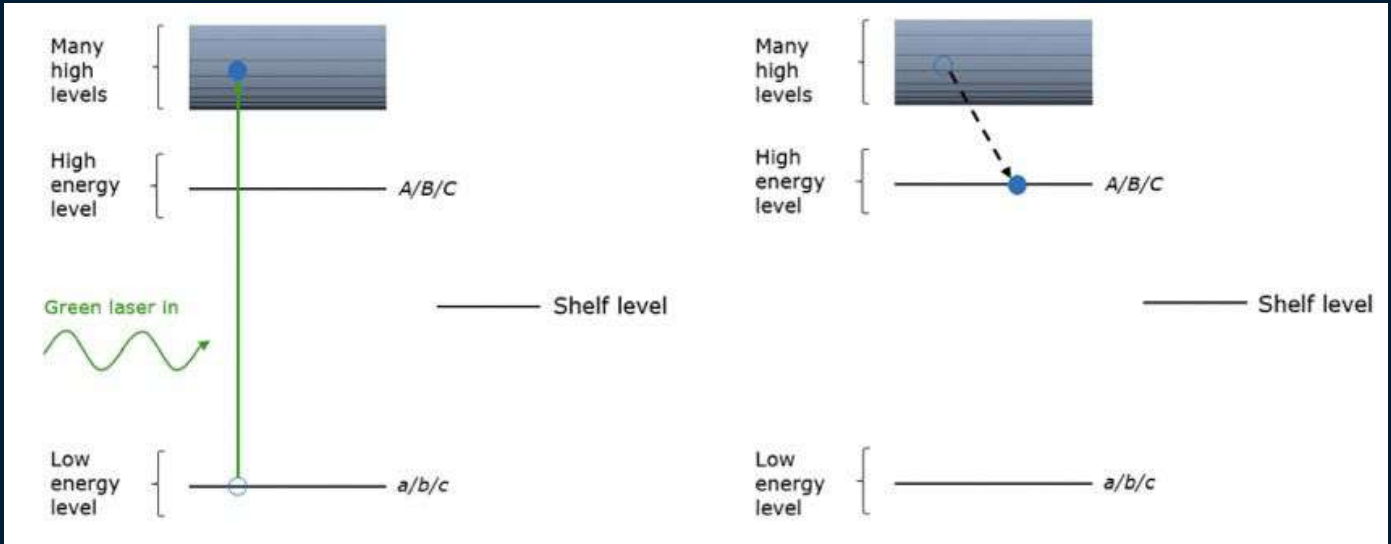
Energy from Light and Microwaves

Magnetic Field Tensor



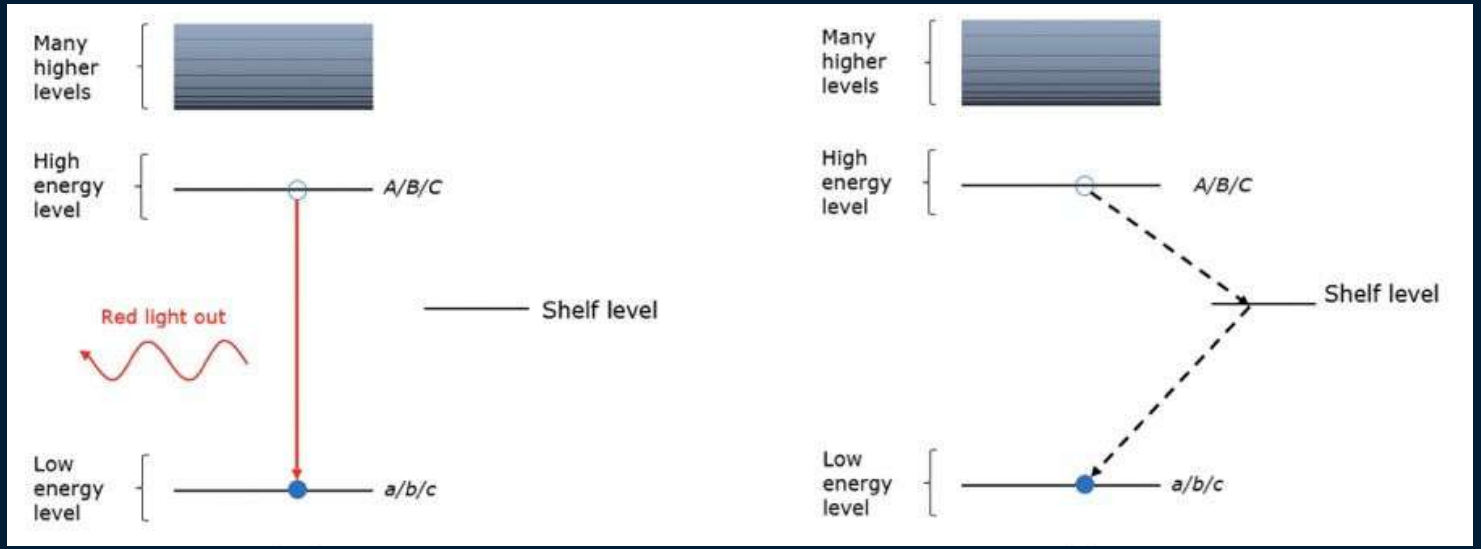
Energy Level Structure of NVC in Diamond

Source: https://quantum-journal.org/views/qv-2018-07-17-10/



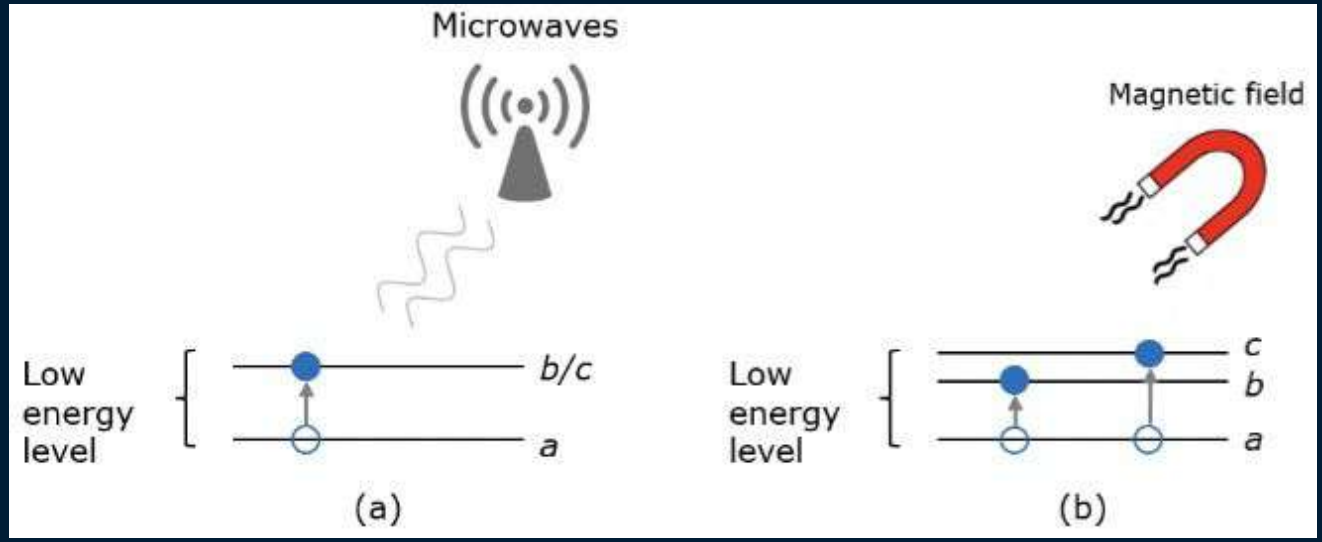
515-525nm charging of NVC

Source: https://quantum-journal.org/views/qv-2018-07-17-10/



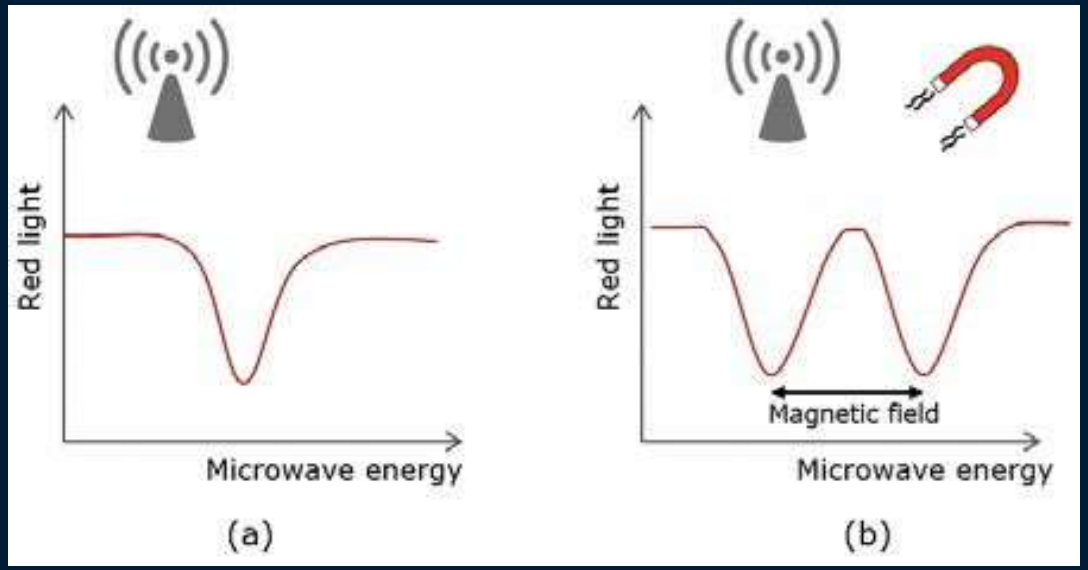
~620nm Discharge of NVC

Source: https://quantum-journal.org/views/qv-2018-07-17-10/



Hyperfine energy levels from microwave sweep + magnetic fields

Source: https://quantum-journal.org/views/qv-2018-07-17-10/

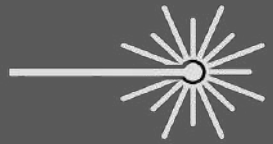


uW only; b/c (one of) state. uW + H gives b and c state

Source: https://quantum-journal.org/views/qv-2018-07-17-10/

The Sensor

4 things are required for NVC Diamond Magnetometry:



Light Source

Microwave Source

Photodetector

Magnet Field

The Sensor - core parts

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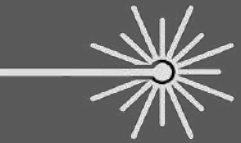
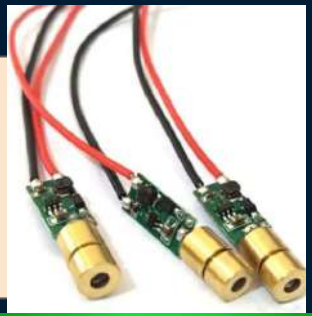
Magnet Field

Provided by the user/use case.



Light Source

Green Laser Modules are widely used…



HOWEVER… The Hamiltonian doesn't care about phase, so bright 525nm LEDS work fine!

The Sensor - core parts

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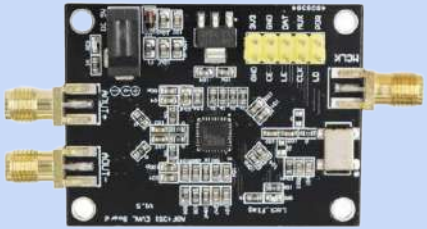
Microwave Source

Lots of widely available options - we chose to use ADF4351 based solutions…



ADF4351 uW Generator

~40dB RF Amplifier

The Sensor - core parts

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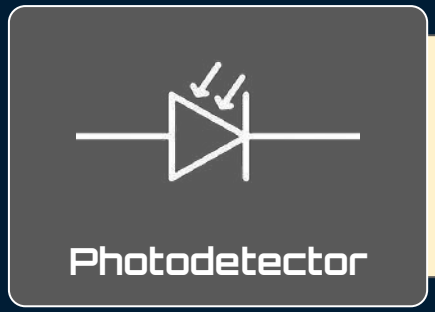


We need to measure light! Lots of options already exist, but most of them had some issues;

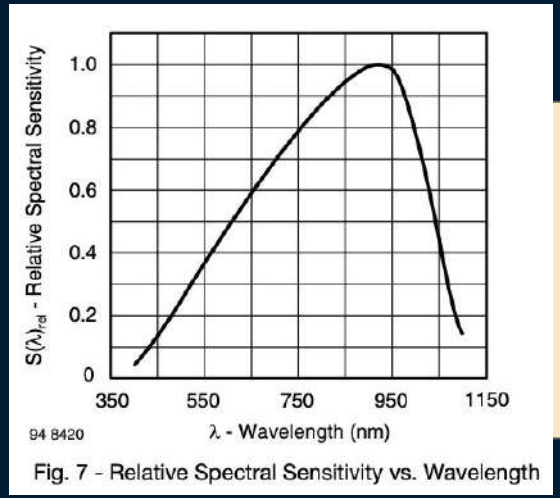


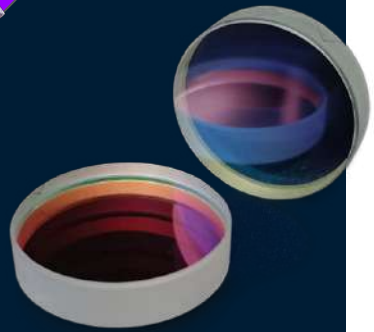
Fig. 7 - Relative Spectral Sensitivity vs. Wavelength

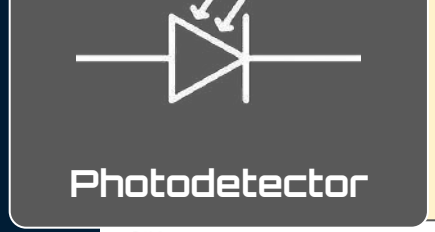
BPW34 Photodiode:

- Great sensitivity in Red and near-IR
- Low cost and widely available
- Large detection surface 3 x 3mm

The Sensor - core parts

QUANTUM VILLAGE





Challenge 1: Red Filtering

- Normally you would use a dichroic mirror
  - But these can be expensive, heavy, and add complexity.
- Stegemann et al. found a very elegant solution; red light filter gels!

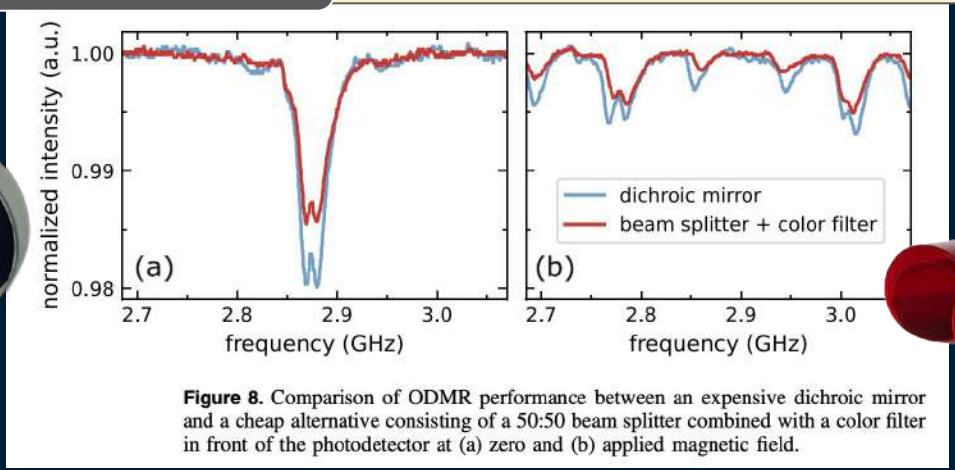
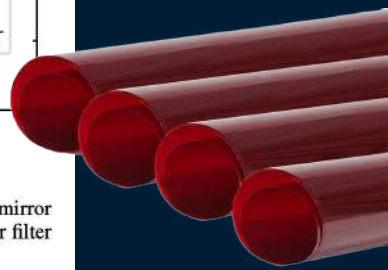


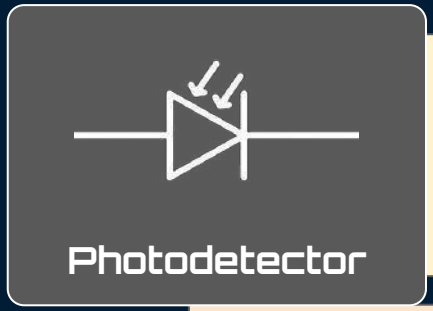
Figure 8. Comparison of ODMR performance between an expensive dichroic mirror and a cheap alternative consisting of a 50:50 beam splitter combined with a color filter in front of the photodetector at (a) zero and (b) applied magnetic field.



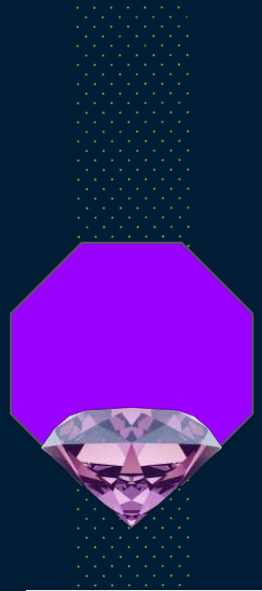
Source: https://doi.org/10.1088/1361-6404

The Sensor - core parts

QUANTUM VILLAGE

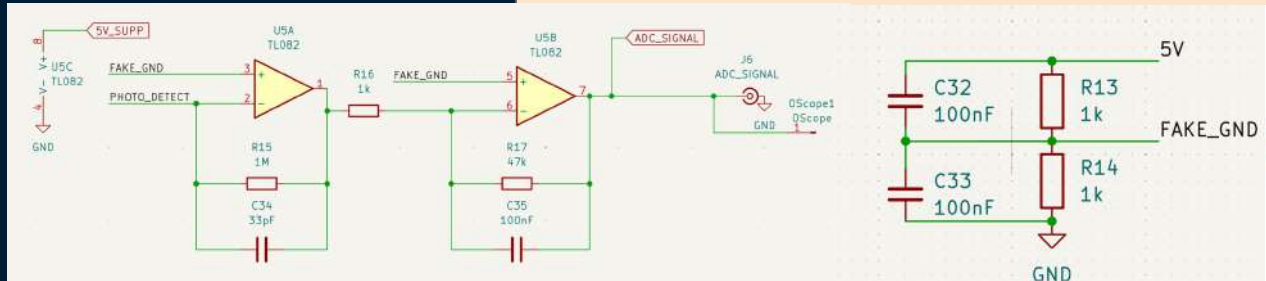


Challenge 2: Transimpedence Amplifiers
Wide variety of candidates in different papers, but none were particularly useful here, or they were too expensive (e.g. Thor Labs)



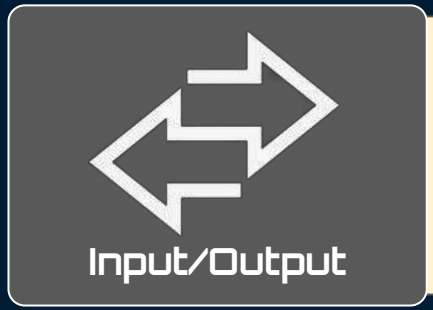
Create a custom design:

- Flexible design that has optional capacitor pads for integrator mode.
- Usage of voltage divider to create ‘fake GND’ at 2.5V -
  - Acts as signal GND for OpAmp non-inv. input
  - Reduces output Voltage to 2.5V for uC for free
- Probably took the most time and work to do…



The Sensor - core parts

QUANTUM VILLAGE



Modern microcontrollers and hobbyist electronics stores have a wealth of options for measuring the output and presenting the data from our sensor.

ESP32 Microcontroller functions:

- Send SPI control messages to ADF4351
- On-board 3V ADC to measure signal from PD
- Do initial signal processing
- Has onboard WiFi and Bluetooth for connectivity
- Compatible with Arduino IDE
- Cheap, and easy to procure, with a broad, helpful community of developers.

OLED Screen - added to expose I2C and for data viz…

The Sensor - core parts

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uC Firmware

We chose to use Arduino IDE as the base for our firmware.

ARDUINO

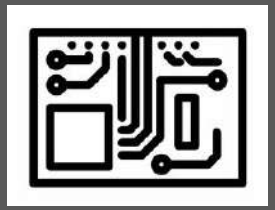
Arduino IDE Features we like:

- Supports a vast number of different boards and architectures
- Very sleek, well defined, and widely ported hardware abstraction layer (Wire.h, Serial, SPI.h, etc)
  - Same code can run on ESP32 as RPi Pico, Arduino Uno/Nano, etc.
- Very broad developer support, HUGE community of already-familiar developers and hobbyists
- Future-proofs and broadens appeal of our code!

```
1  #include <SPI.h>
2  #include <ADF4350.h>
3
4  #define LED_PIN 2
5
6  #include <Wire.h>
7  #include <Adafruit_GFX.h>
8  #include <Adafruit_SH110X.h>
9  #define i2c_Address 0x3c
10 #define SCREEN_WIDTH 128 // OLED display width
11 #define SCREEN_HEIGHT 64 // OLED display heigh
12 #define OLED_RESET -1   //   QT-PY / XIAO
13 Adafruit_SH1106G display = Adafruit_SH1106G(SC
14
15 #define COM_PIN 26 //32 // sets pin 26 to be t
16 #define ADC_PIN 34
17 ADF4350 PLL(COM_PIN, ADC_PIN); // declares obj
18
19 int MINVAL ADC = 1750;
20 Not connected. Select a board and a port to connect automatically.
21 int VAL_DIV = 11;
22 int CALIBRATION_COUNT = 10;
```

The Sensor - core parts

QUANTUM VILLAGE



PCB - v1

Our first PCB was designed to be hand assembled, and carries the various development modules.

PCB v1 Design Considerations:

- Carries the various development modules as daughter boards, secured by regular PCB brass mounts.
- We mount boards on the back and front to minimize space.
- A COTS short RF connector cable joins the two sides.

The Sensor - core parts

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The Diamond

In sourcing our diamond material, we are VERY grateful to our partner in this endeavor!

elementsix™ DE BEERS GROUP

ADÁMAS nano

Procuring NVC Diamond Material:

- Not a highly controlled material - EAR99 in the US, etc.
- We met E6, and Dr. Matthew Markham has been incredibly helpful in supplying test materials!

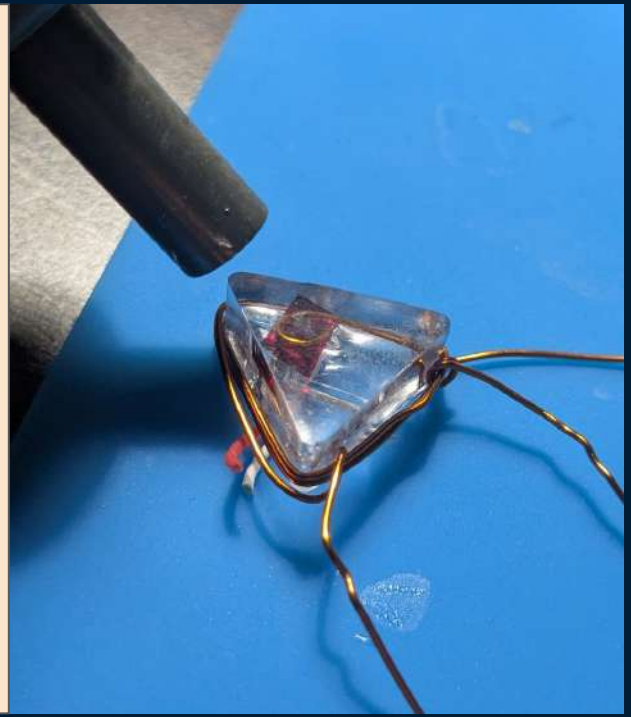
The Sensor - creating the epoxy 'prism'

Rough Plan:

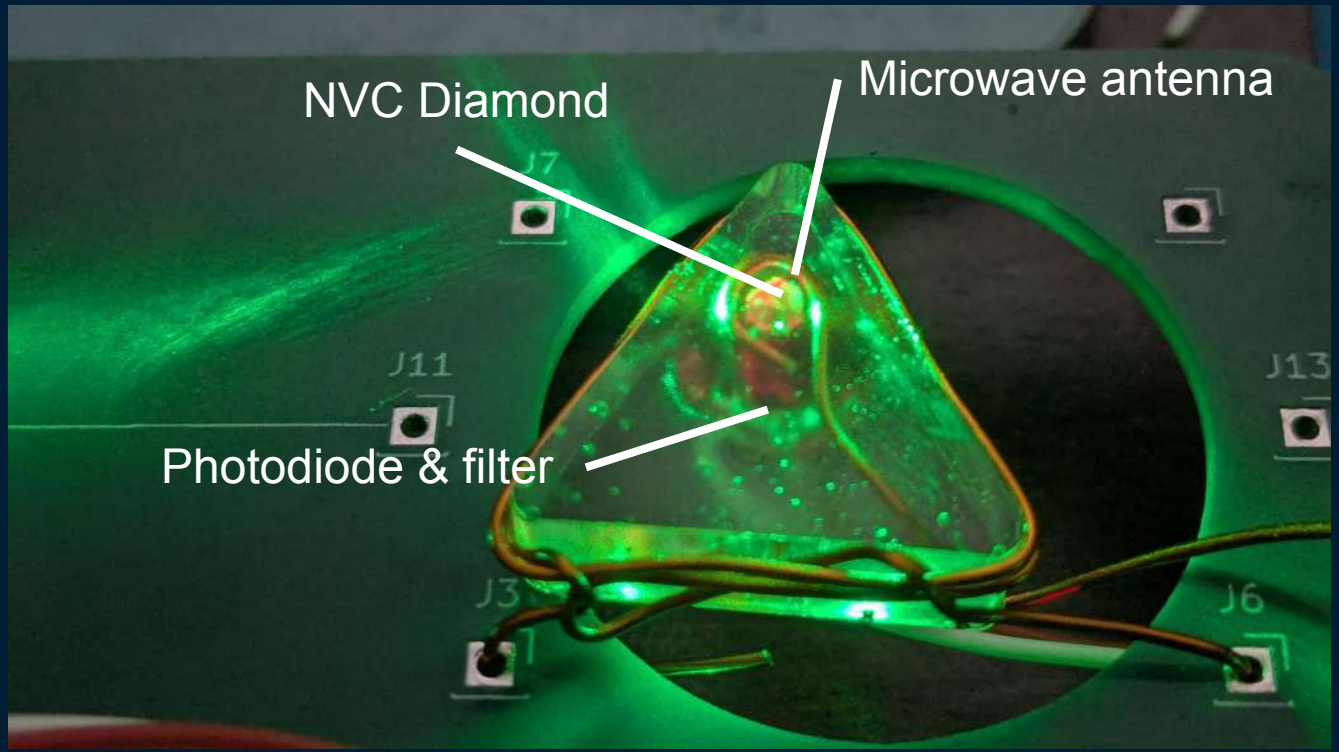
- Encase everything in Epoxy!
- Epoxy fixes the filter to the PD and holds the diamond in place above
- Use signal copper enameled wire as uW antenna and structural ties
- We use fast UV curing epoxy in small epoxy jewellery moulds (Amazon)

Things to Consider:

- Diamond density - it sinks! So use a multi-layer build process
- Prepare antenna and PD beforehand
- If you need to start again, only the diamond can be rescued.

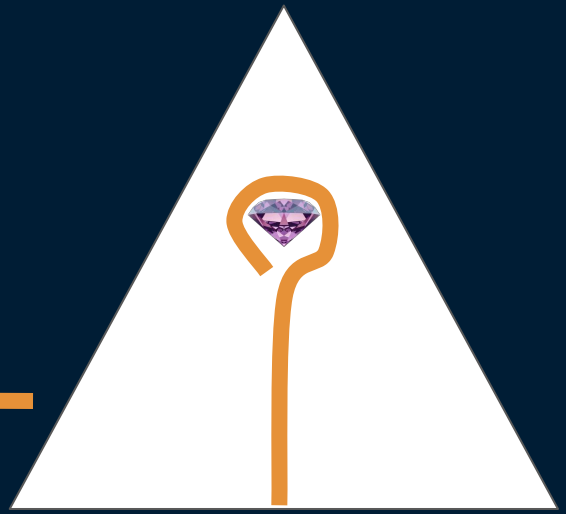


The Sensor - creating the epoxy 'prism'



The Sensor - creating the epoxy 'prism'

Side View



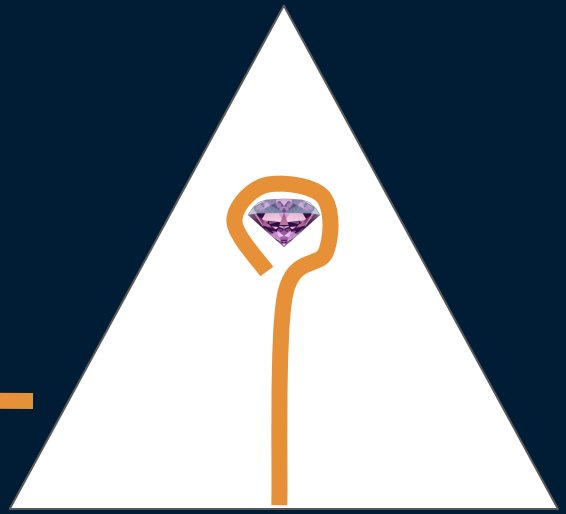
Top View

Layer 1 - base layer and antenna/diamond

- Using 24SWG (0.56mm) wire, make a loop and sand the end for soldering.
- Place things carefully - slightly under-cure the epoxy to keep it sticky

The Sensor - creating the epoxy 'prism'

Side View

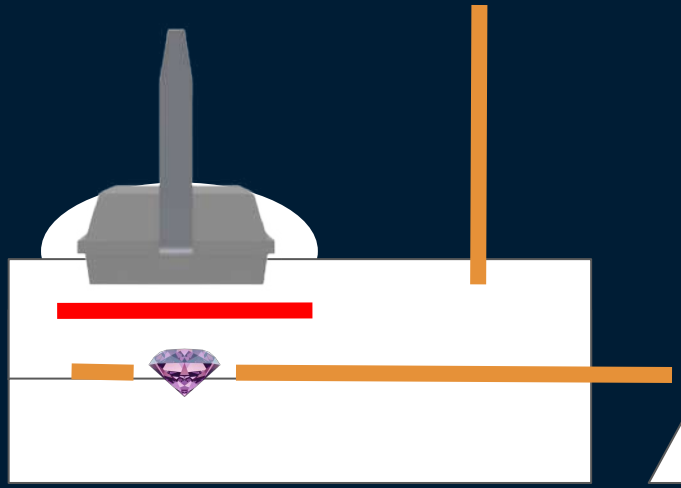


Top View

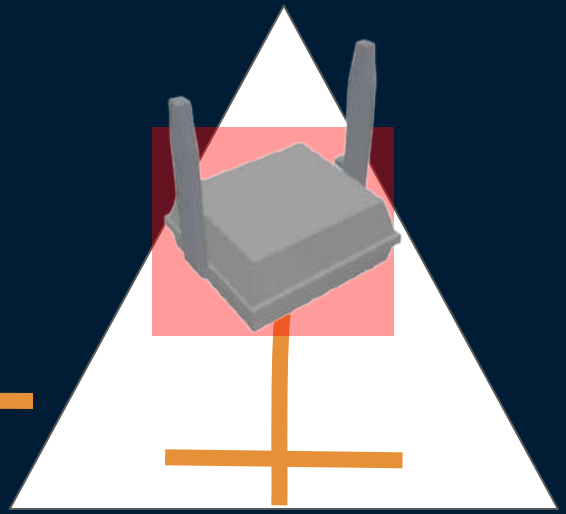
Layer 2 - secure diamond and antenna:

- Fill the epoxy over the top and cure
- This holds the diamond in place ahead of placing the red filter and photodiode in the next step.

The Sensor - creating the epoxy 'prism'



Side View

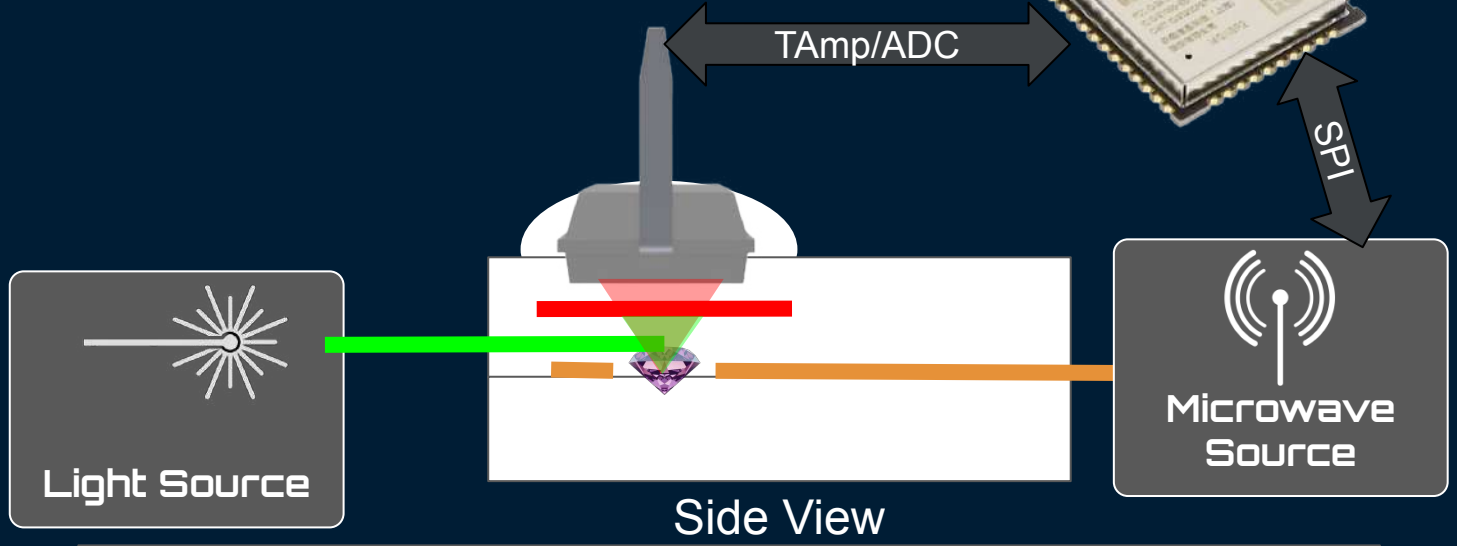


Top View

Layer 3 - red filter and BPW34:

- Place the red filter gel, cut out to fit the 5x5mm face of the BPW34
- With a small amount of epoxy, place the BPW34
- Don't forget to include any copper wire supports!

The Sensor - Energizing and Reading the Diamond



Operation:

- The ESP32 will control the microwave source, with the laser module powered from the 5V USB supply
- The PD is wired into the transimpedance amp and then to the ESP32's ADC

The Sensor - Bill of Materials

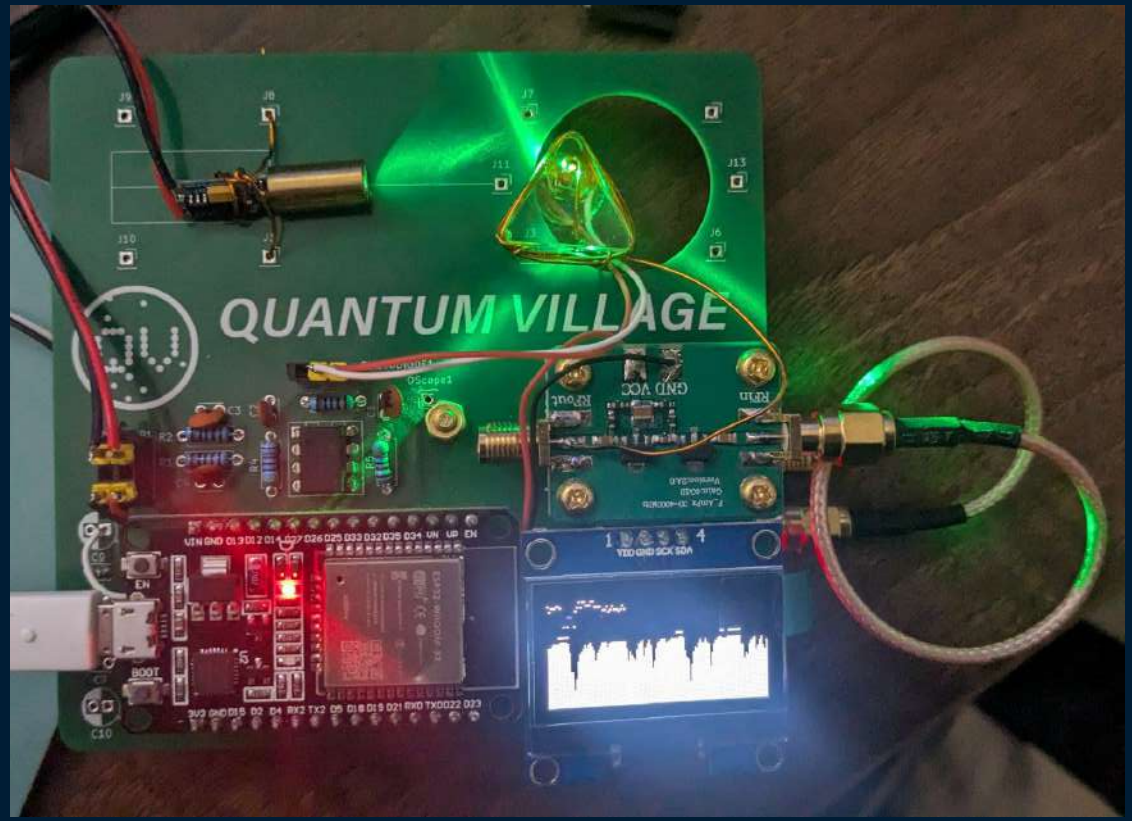
Bill of Materials:

We have managed to to keep the cost down to around ~$160 all in.

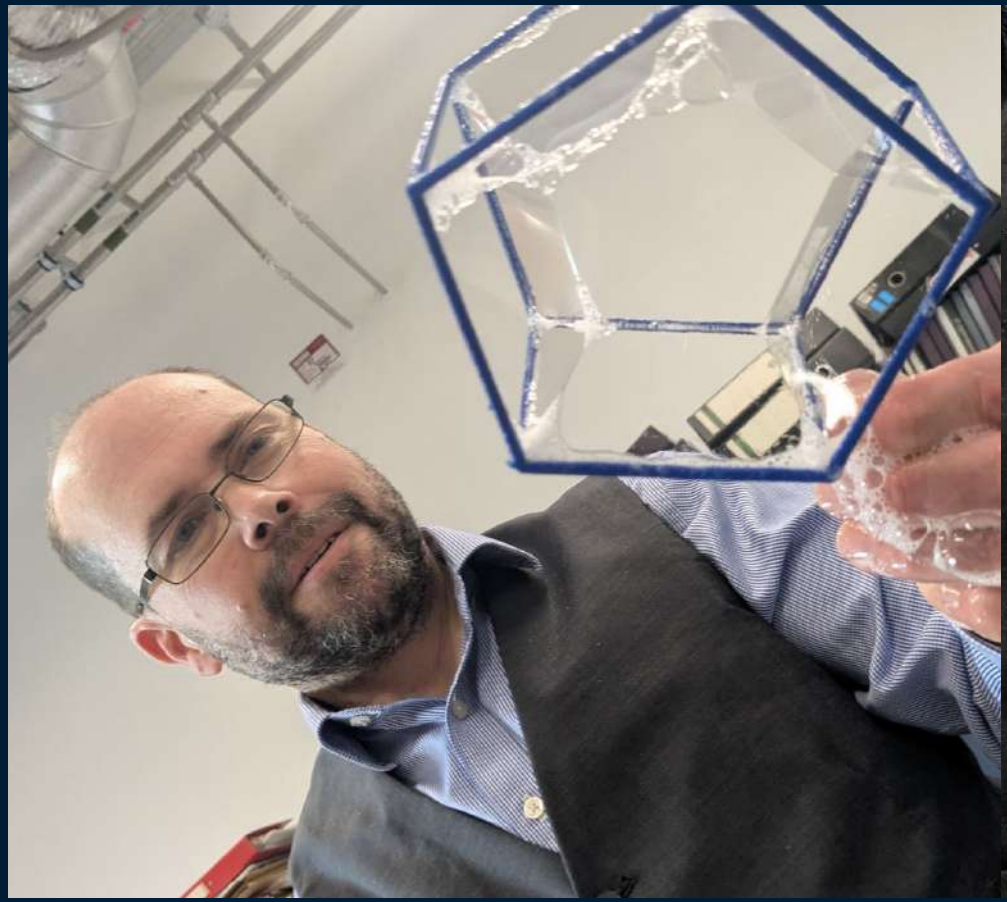
In future versions, the BOM cost per device has gone down dramatically, mainly owing to the move towards a single board which we have designed to carry many of the components directly, without the need for daughter boards.

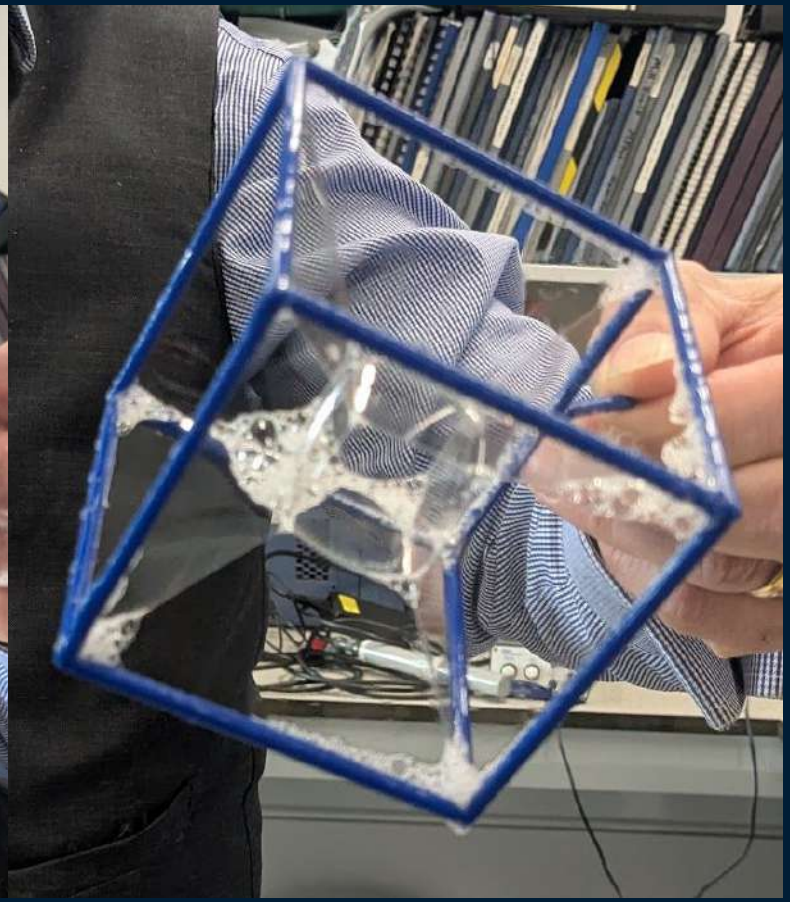
Item	Number	Cost
Battery pack	1	Free - $10
OpAmp + electronics	1	up to $10
Laser Module	1	~$10-20
ADF4350/1 MW Generator	1	$20-35
MW Gain (40dB) + BNC	1	~$15
PCB (unit from run)	1	~$7
OLED Screen	1	$10
ESP32 board	1	~$10
NV Center Diamond	1	~$15
Epoxy and Cu Wire	1 ea.	~$25
	TOTAL	**~$160**

The Sensor - V1 (Beta)



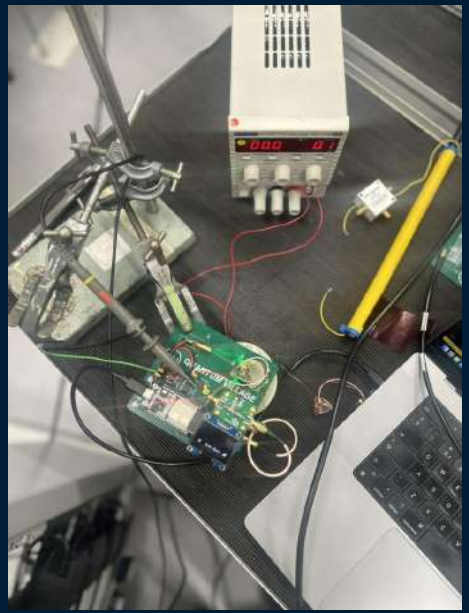
Prof. Ben Varcoe

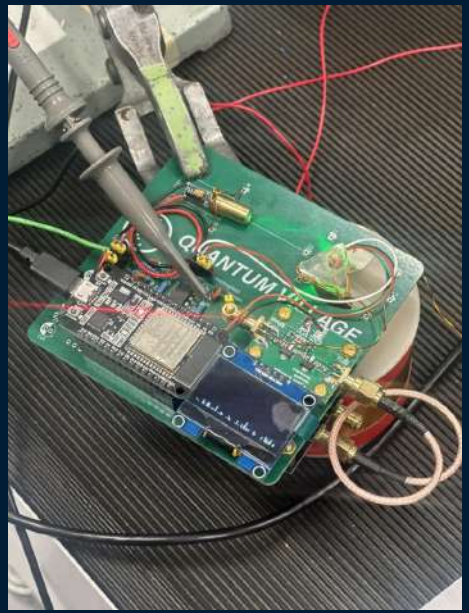


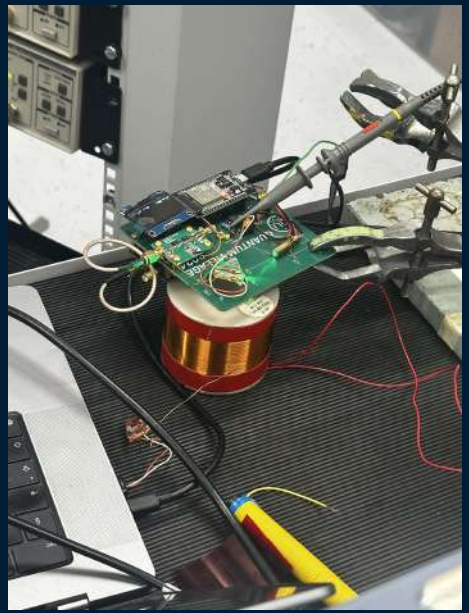


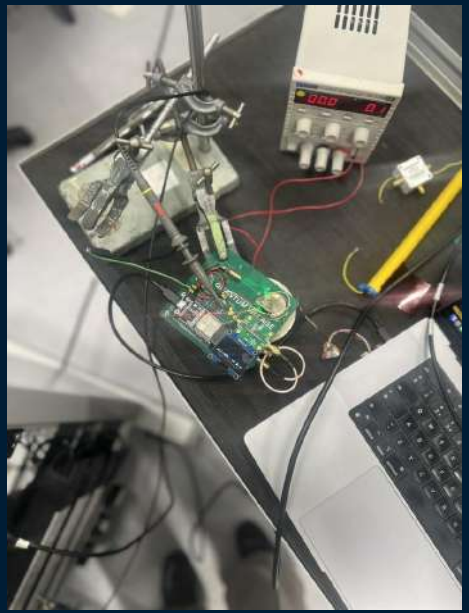
Lab Test @ University of Leeds...

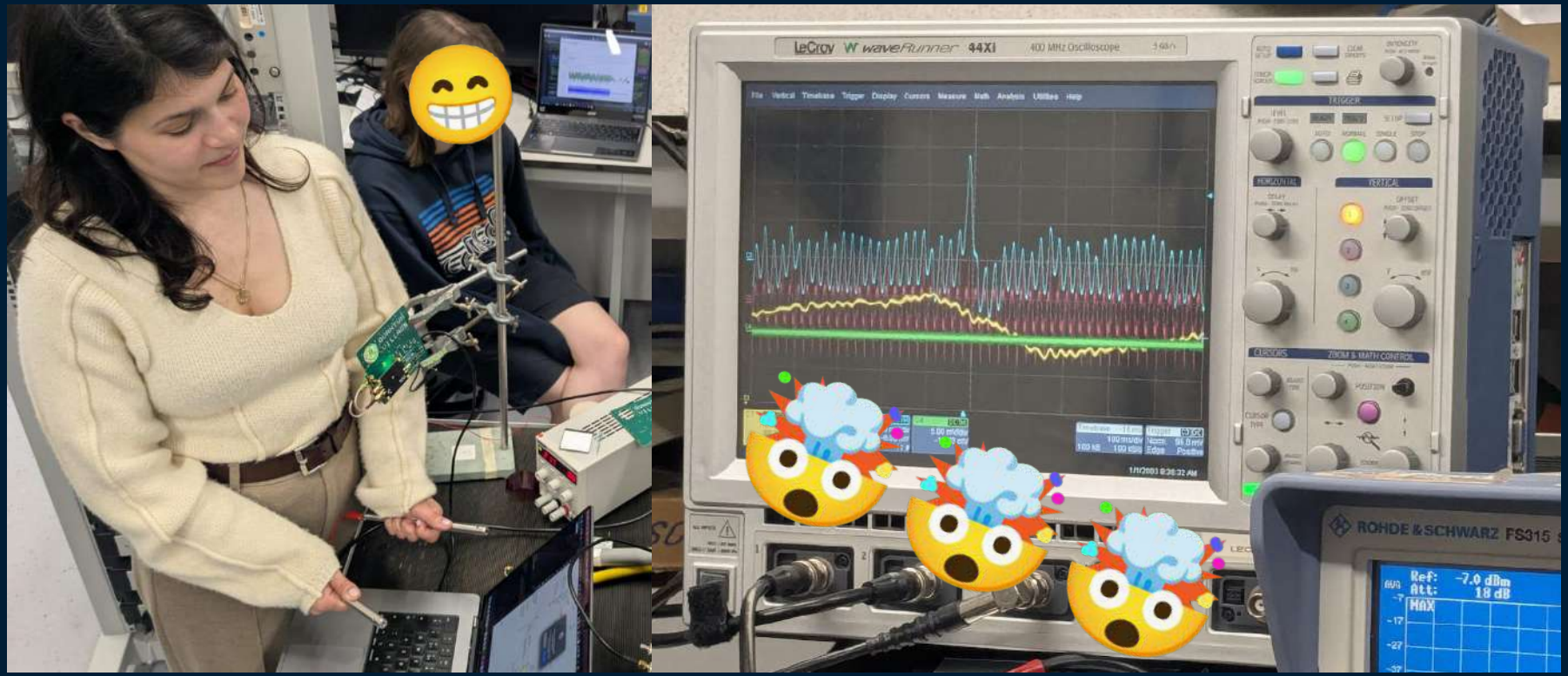
QUANTUM VILLAGE

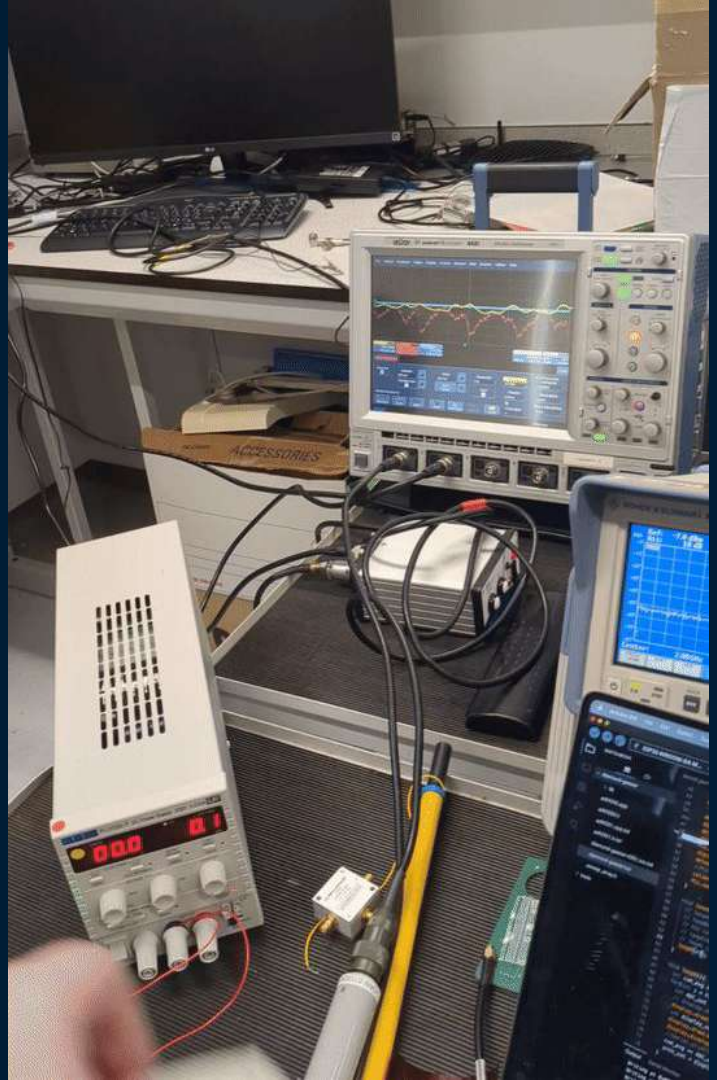









LeCroy WaveRunner 44Xi 400 MHz Oscilloscope
ROHDE&SCHWARZ FS315
Ref: -7.0 dBm
Att: 18 dB
MAX



Magnetometer Showdown:

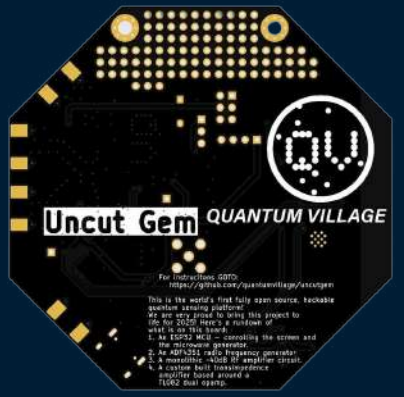
The red trace is a reference lab magnetometer.

The yellow trace is the amplified signal from the photodiode.

The yellow trace moves contrary to red because of the integrator mode of the opamp in use on that previous design.

QUANTUM VILLAGE

The Sensor - PCB v2

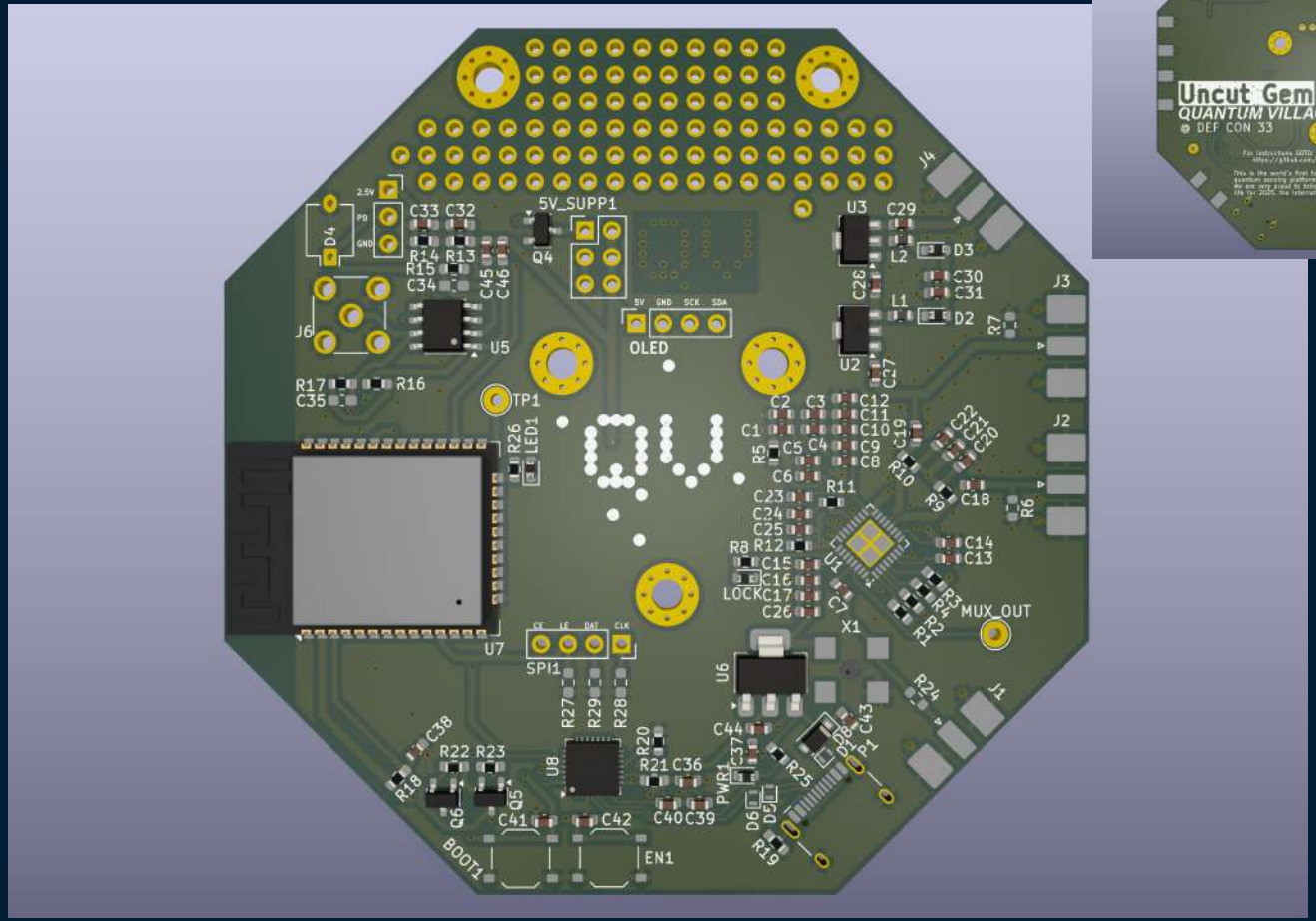


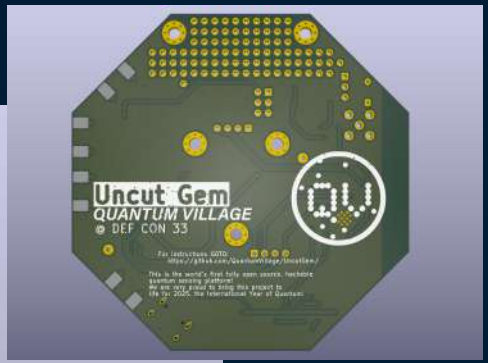
A New Design:

- All-in-one PCB!
  - Reduce cost and footprint
  - Remove lots of parasitics
- Make it more ‘hackable’!
  - Add prototyping area
  - Expose more pinouts
  - Use wider pads
- Make it easy to manufacture
  - Single side SMD placement
  - COTS connectors and parts

RELEASED FOR DEF CON 33!!

PCB v2 Prototype:





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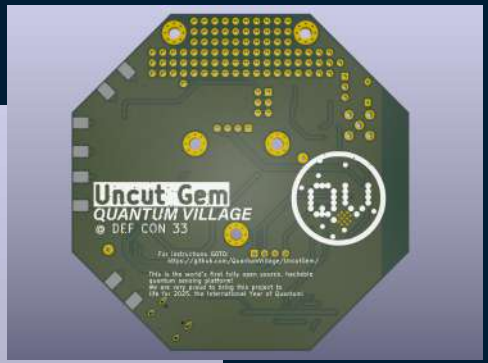

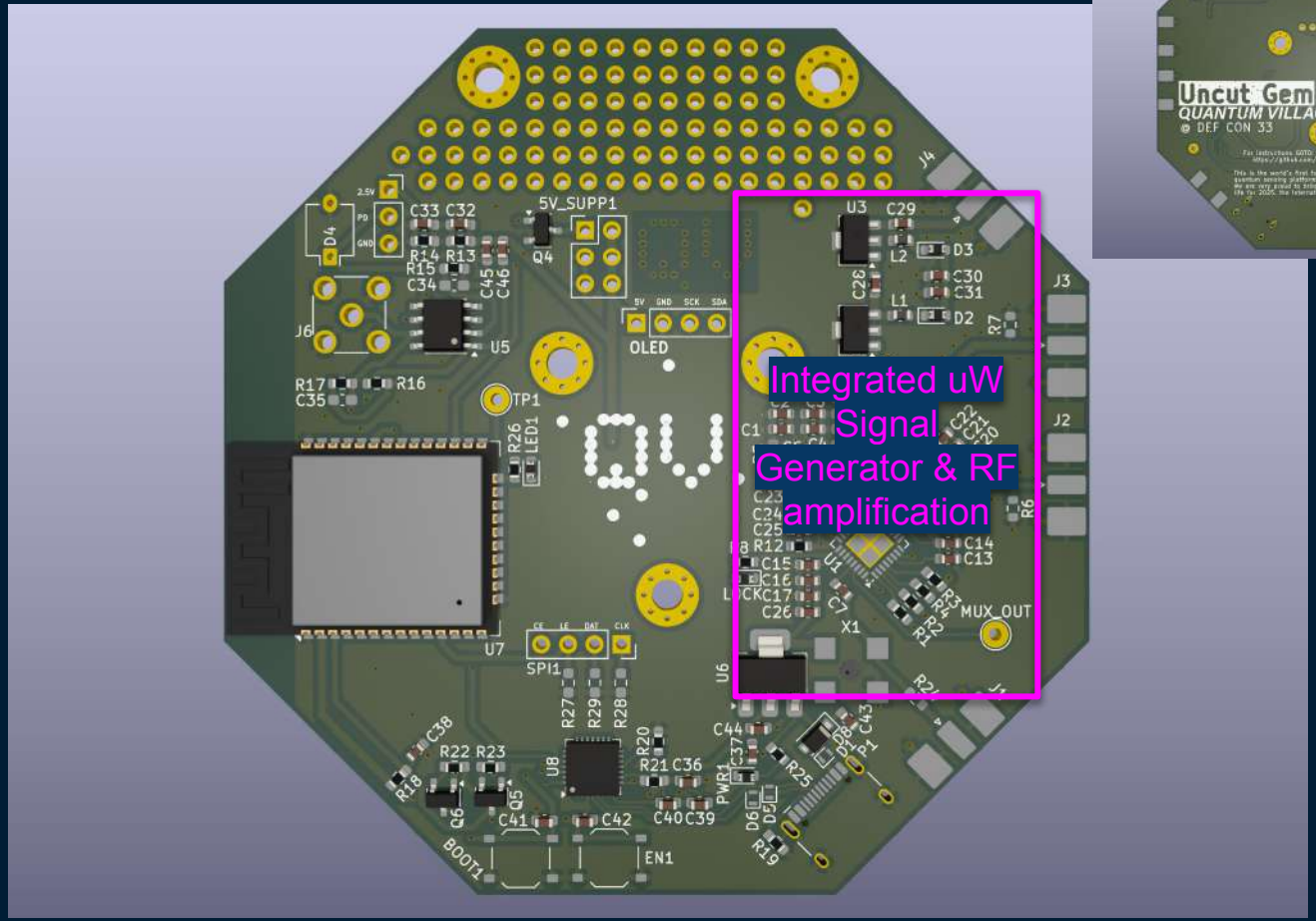

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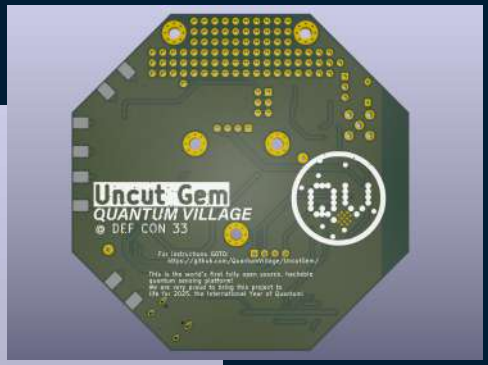

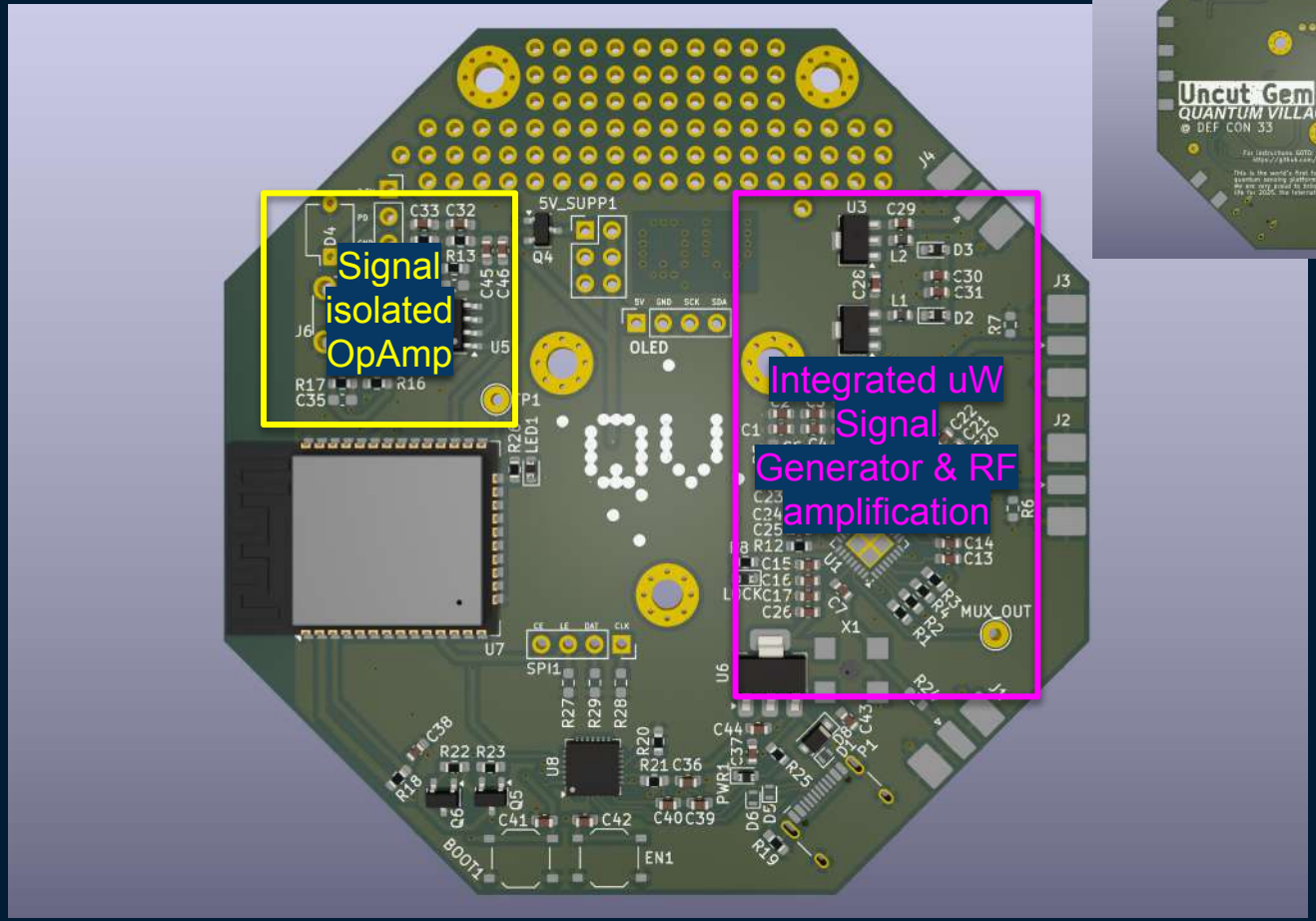

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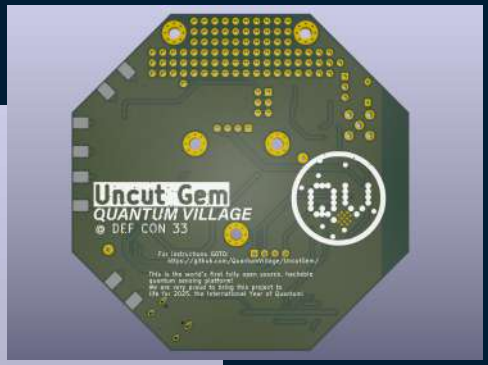

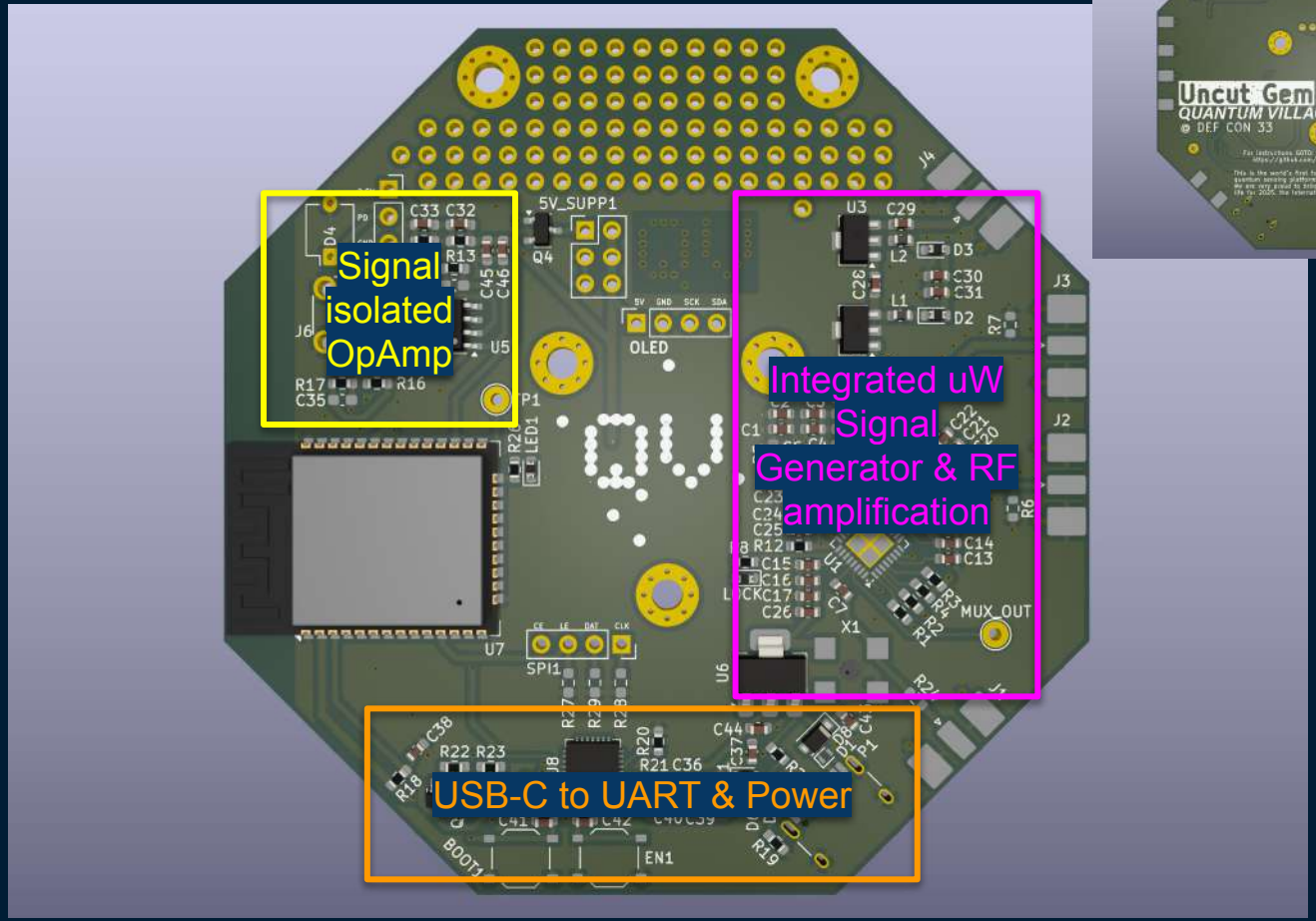

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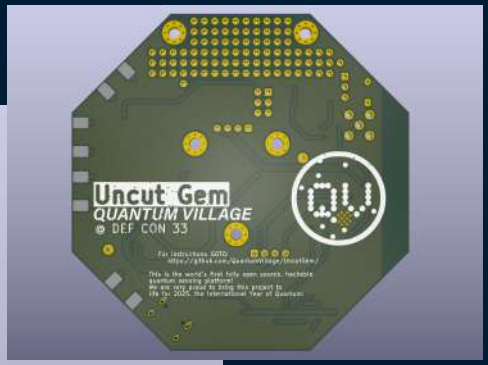

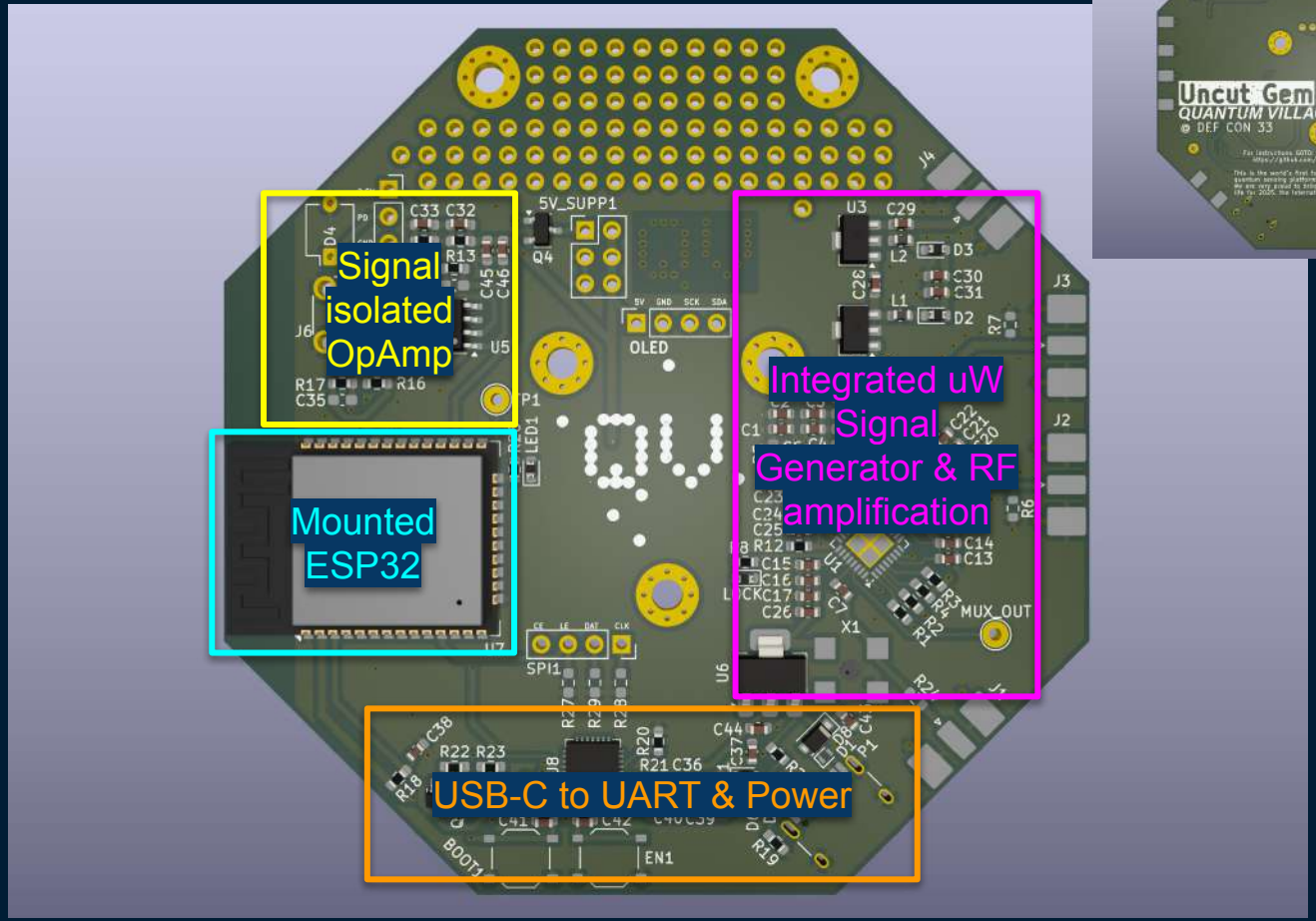

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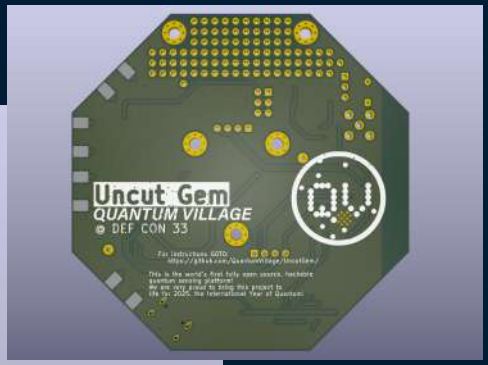

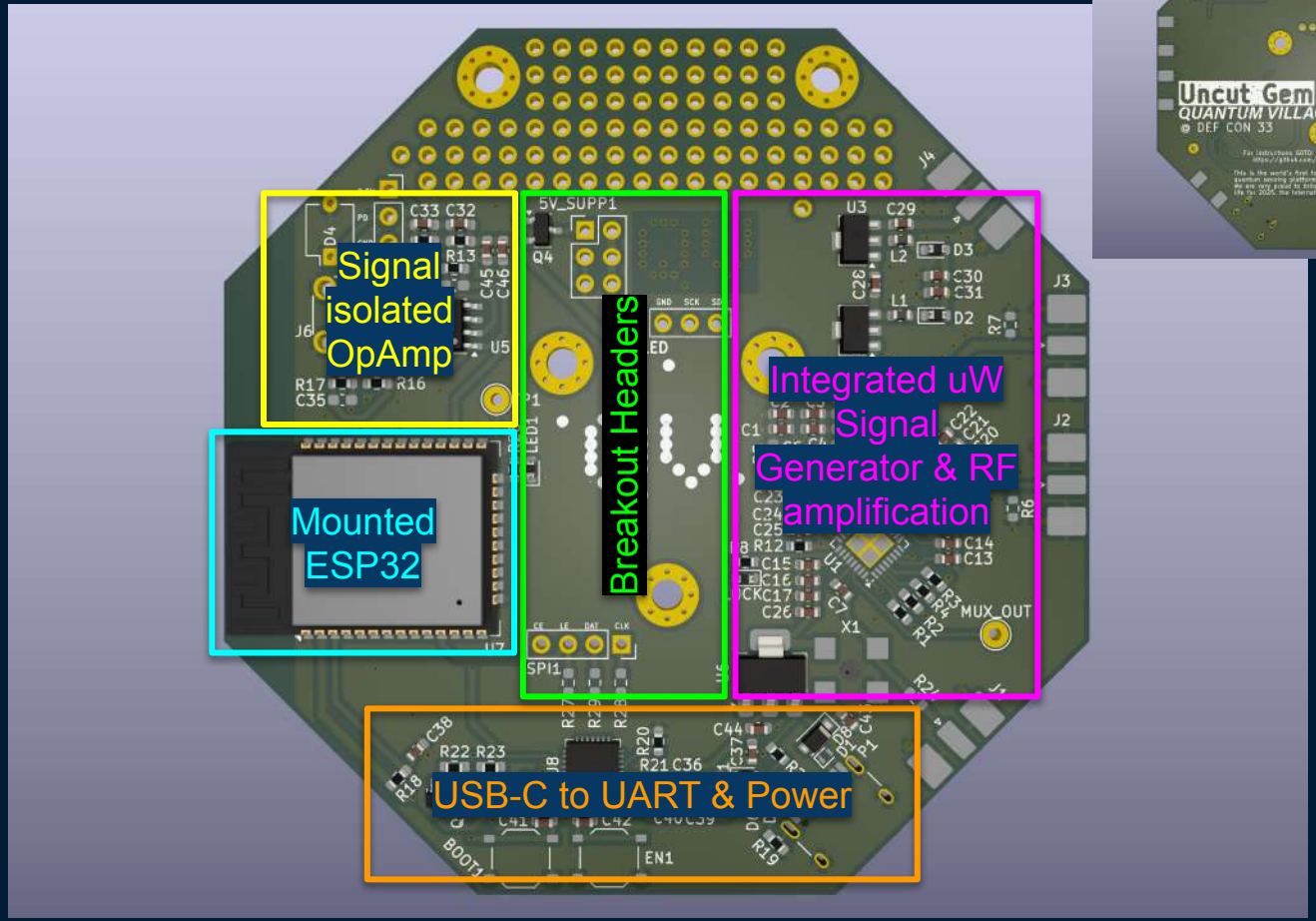

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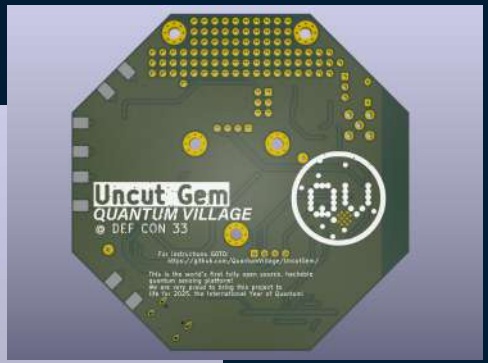
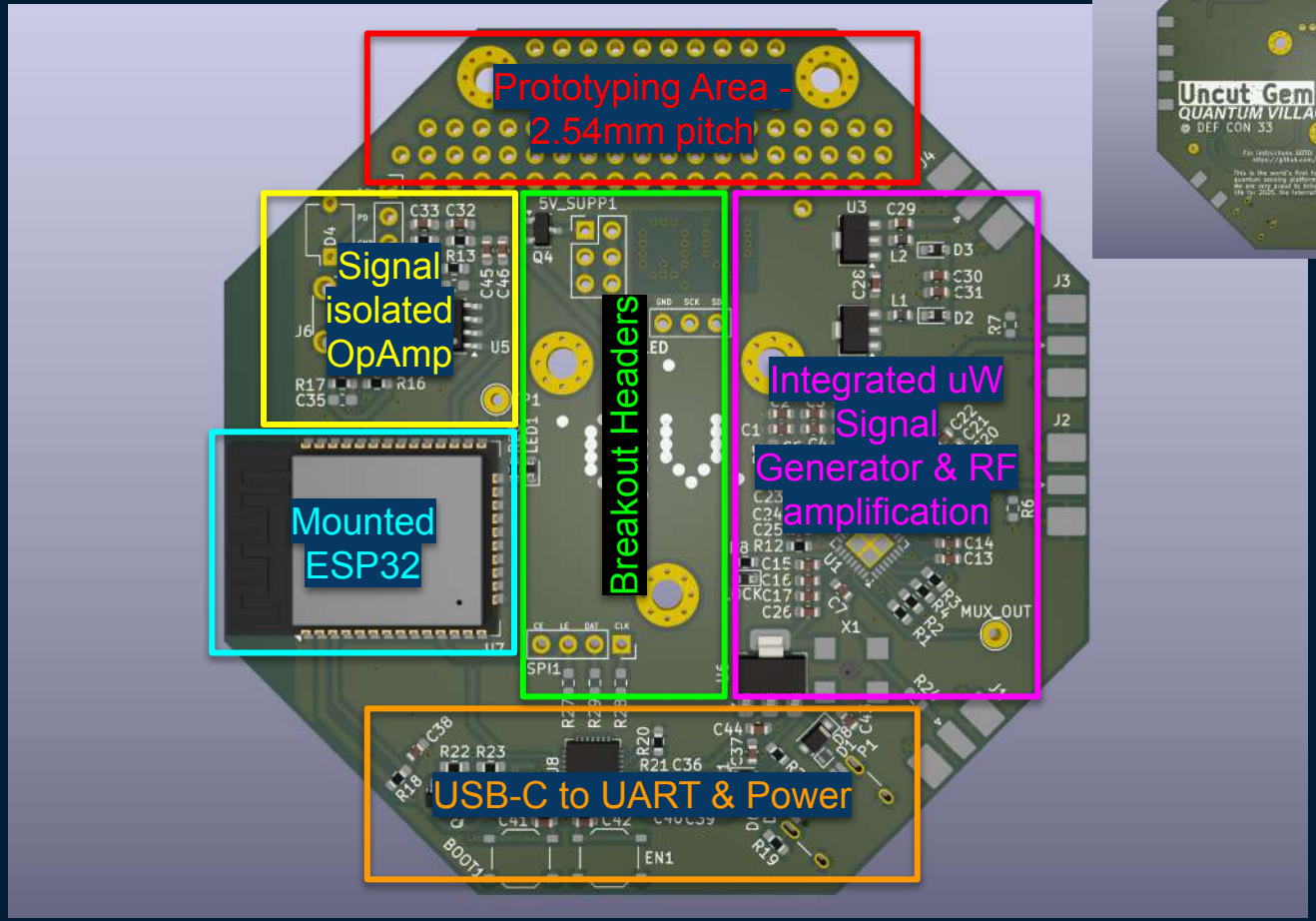
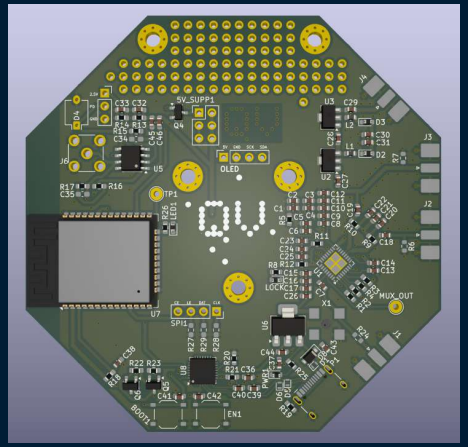
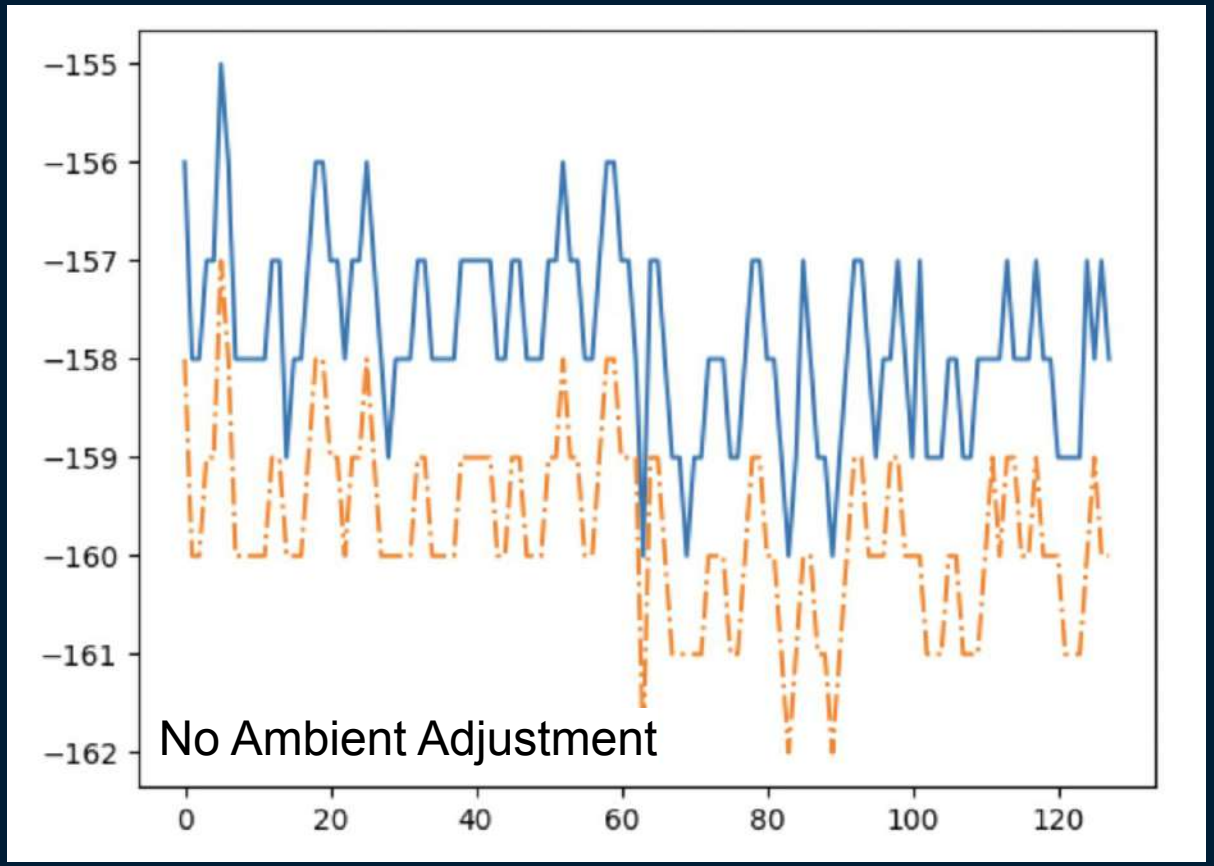




PCB v2 Prototype: Results





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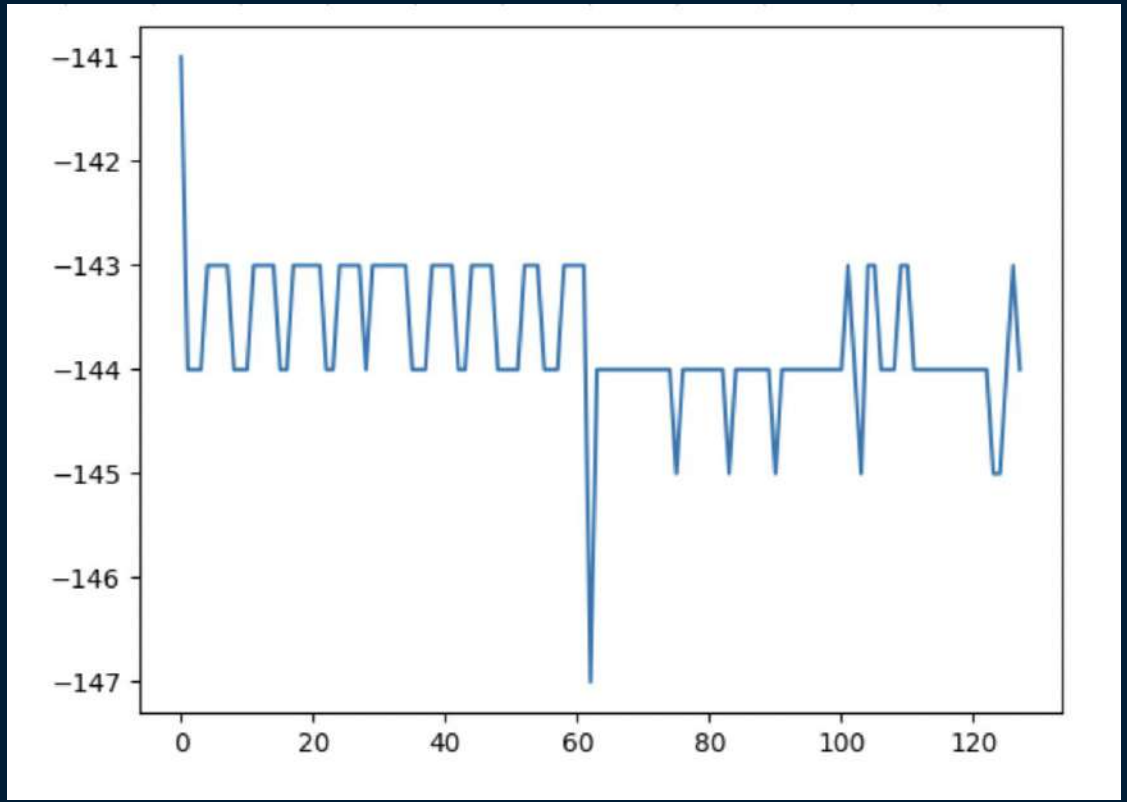
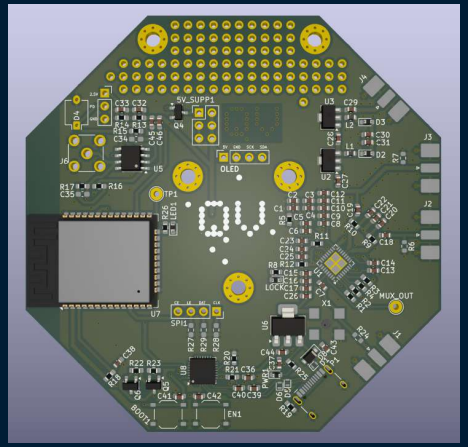
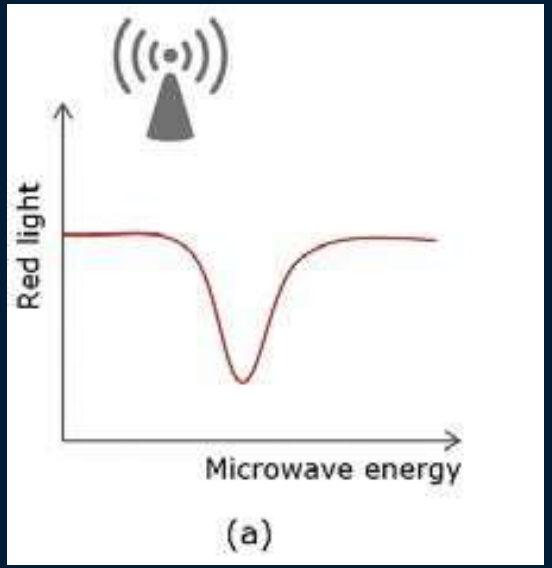
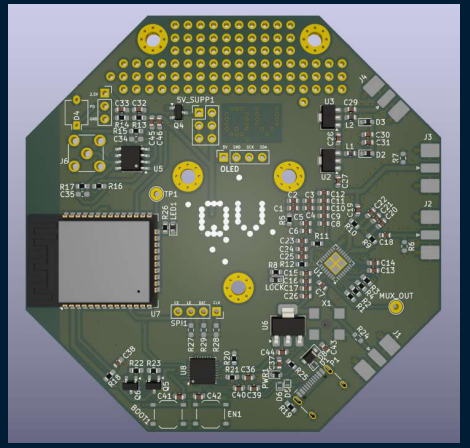
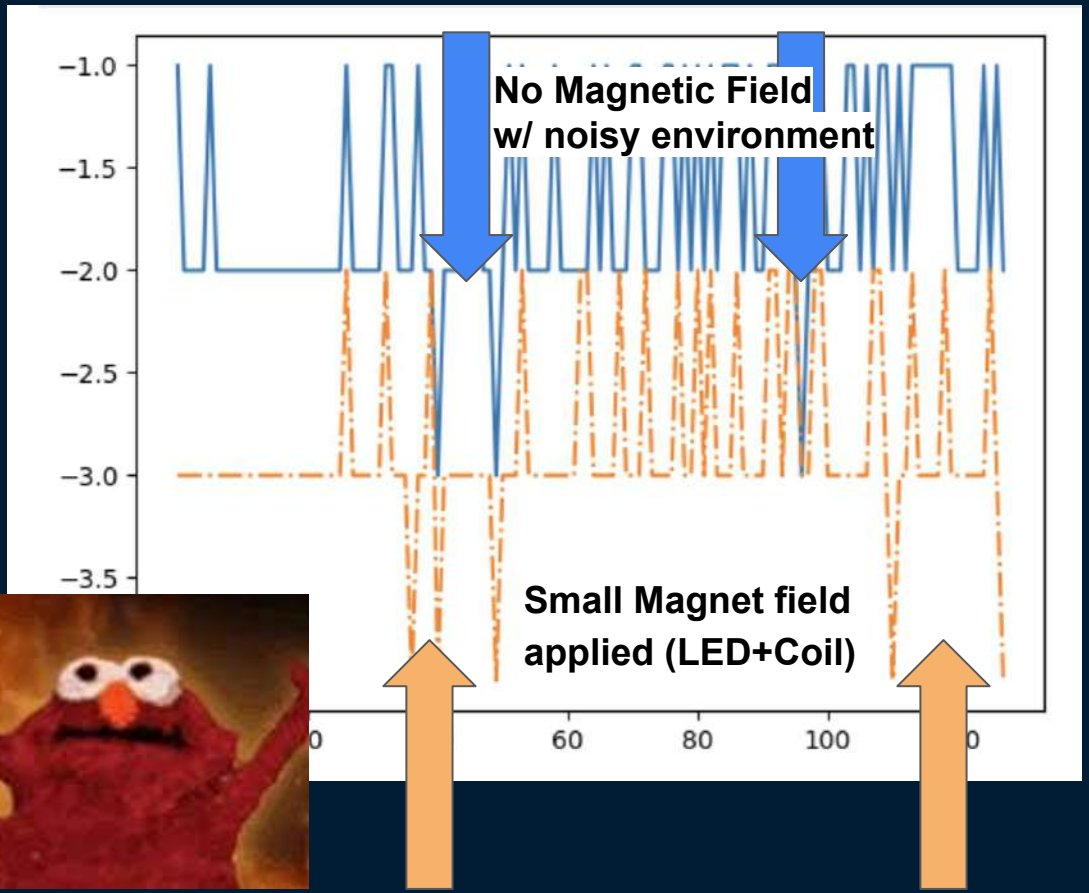


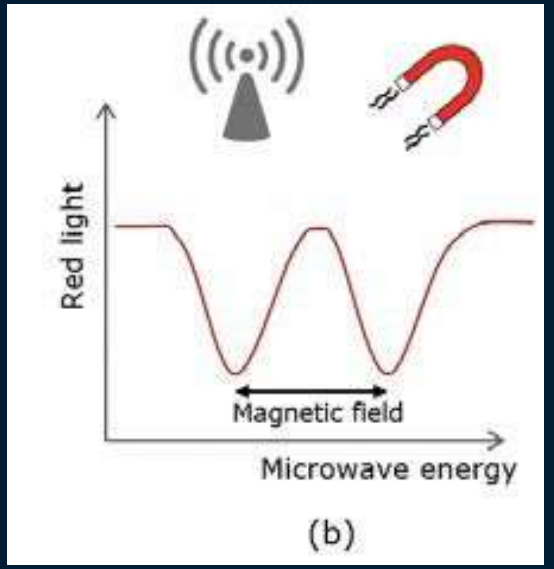




PCB v2 Prototype: Results







Version 2 Launched

WIRED

NEWSLETTERS SUBSCRIBE

A Special Diamond Is the Key to a Fully Open Source Quantum Sensor

Quantum sensors can be used in medical technologies, navigation systems, and more, but they're too expensive for most people. That's where the Uncut Gem open source project comes in.

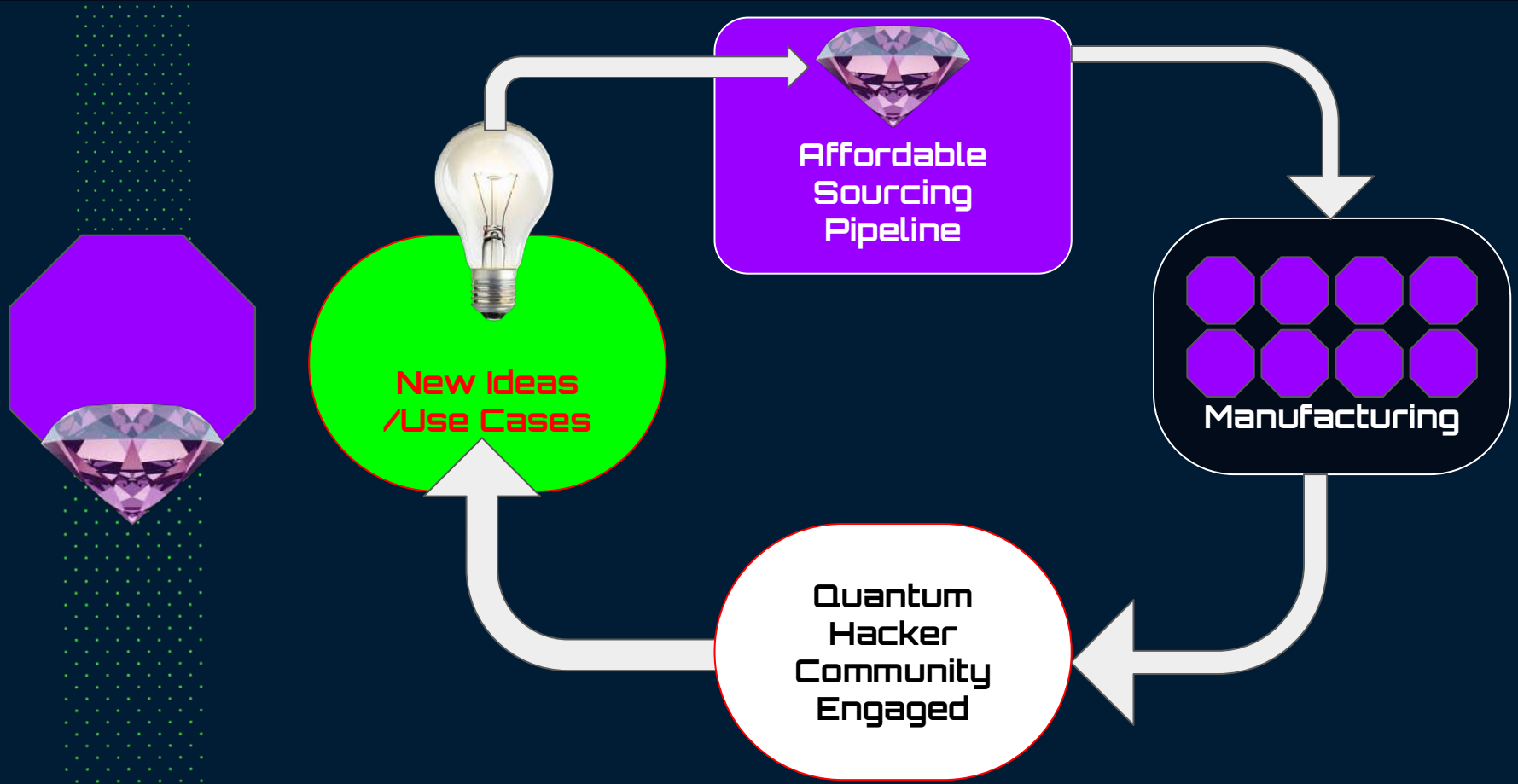
ILLUSTRATION: WIRED STAFF/QUANTUM VILLAGE

QUANTUM VILLAGE

DEFCON

Building a pipeline and design flywheel

QUANTUM VILLAGE



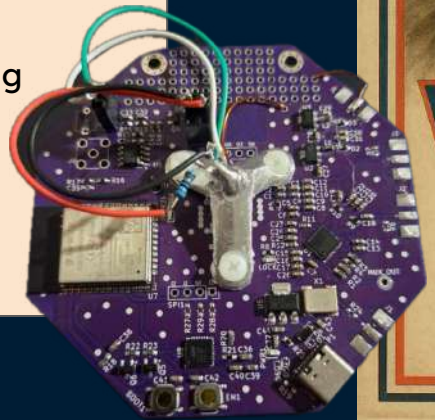
QUANTUM VILLAGE

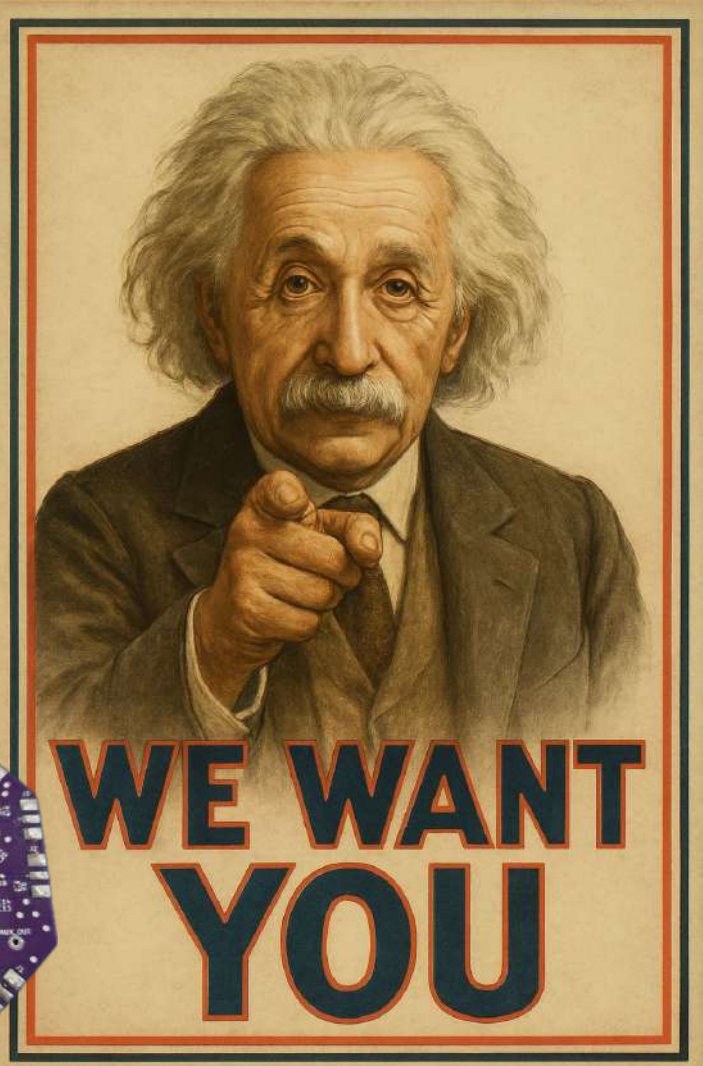
What's Next for Uncut Gem?

Call All Would-be Quantum Hackers!

Now that we've released everything, we really want your help!

- Improving the amplifier
- Improving the RF plane
- More ideas for the encapsulation of the diamond/LED/PD
- More use cases…
- 3 Academic partnerships and growing





ACCESS ALL ATOMS

Acknowledgements

QUANTUM VILLAGE

Victoria Kumaran - Prototyping, design and conceptualisation, and project contextualisation.

Mark Carney - Prototyping, initial designs for hardware/firmware.

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Rick Altherr - Design and engineering expertise and support.

David Bengtson - RF expertise and electronics support.

Prof. Ben Varcoe - testing support and physics expertise/advisory.

Dr. Brian McDermott - Expert Advisor.