Photodetachment of H^- at the GBAR Experiment

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Motivation for GBAR Experiment

Our understanding of gravity is incomplete.

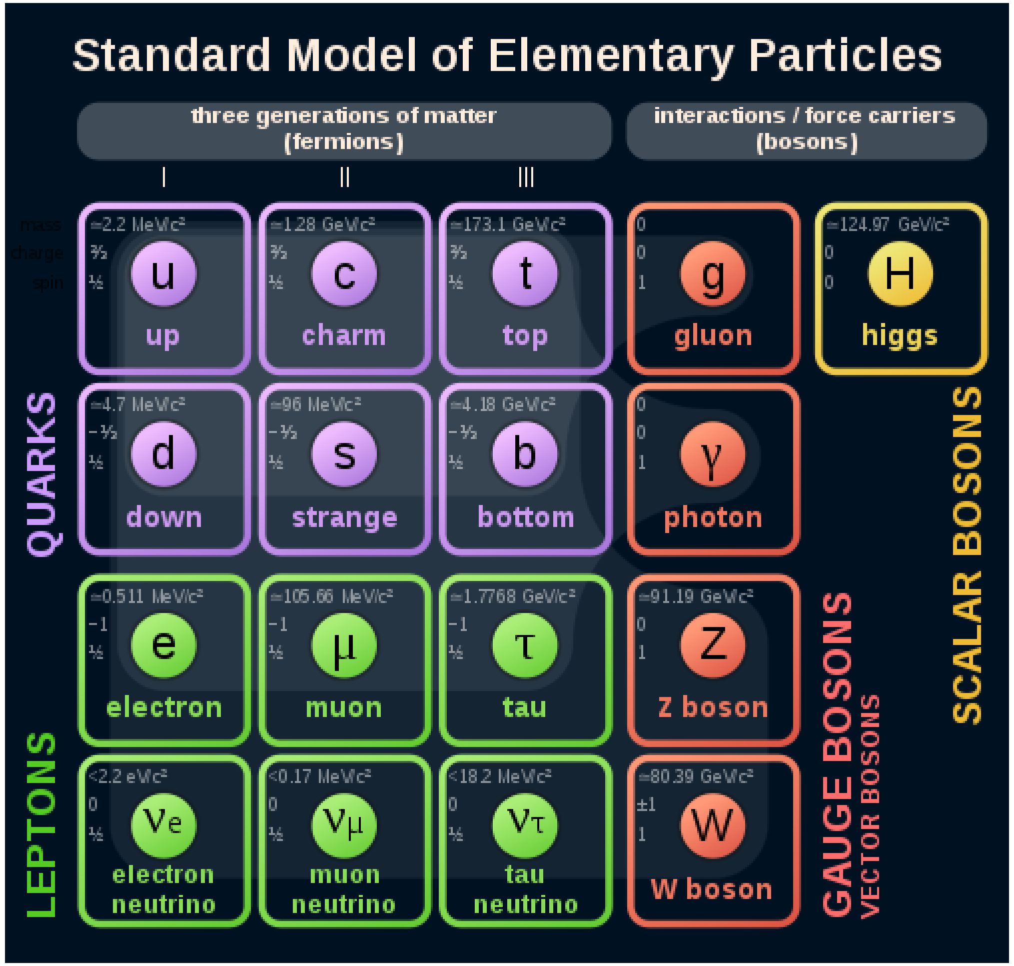
- **Quantum Field Theory says nothing about gravity**
- **Dark Energy and Dark Matter linger**

Test the Weak Equivalence Principle with antimatter.

- **No (meaningful) direct measurement of the interaction of gravity on antimatter exists.**
  - Best and only direct result from free fall: $-65g < \bar{g} < 110g$ from ALPHA

Require a stable, neutral particle for freefall.

- **Cannot use antineutrons, positronium…**
- **Next simplest particle: antihydrogen!**



Wikipedia

GBAR / Project Overview

Excited positronium reacts with slow antiprotons.

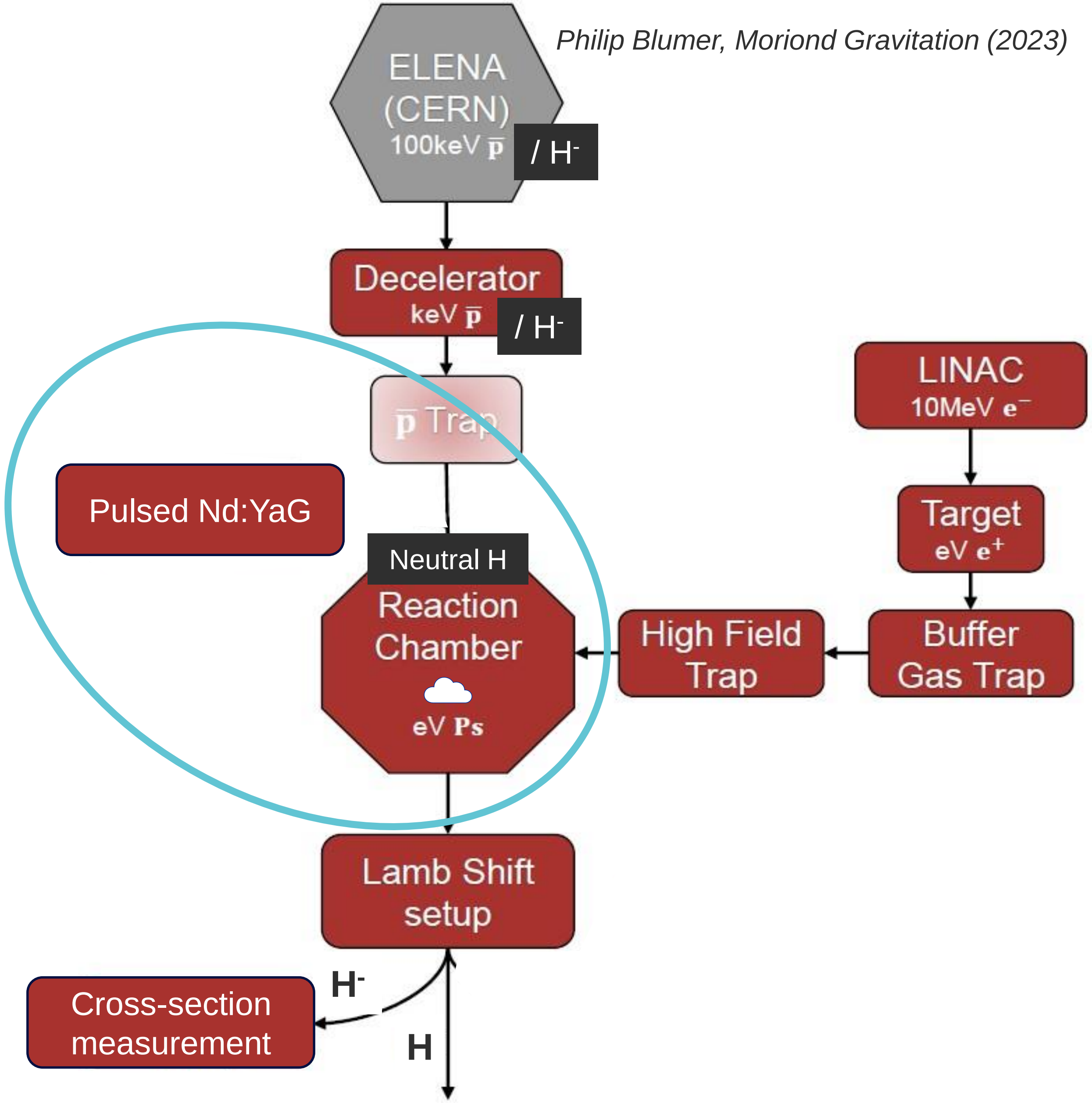
- Antihydrogen ions are produced and are directed based on their charge

Landmark goal: Cross-section measurement of $\bar{\mathrm{H}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}}^{+} + e^{-}$.

- **Can use hydrogen as a proxy for antihydrogen: $\mathrm{H} + Ps \rightarrow \mathrm{H}^{-} + e^{+}$**
  - **To study this process, we must produce H in-line!**

Have access to H$^-$ beam from ELENA.

- **Photodetach H$^-$ upon entering reaction chamber to form neutral H.**
- **H will also be used for beam alignment.**

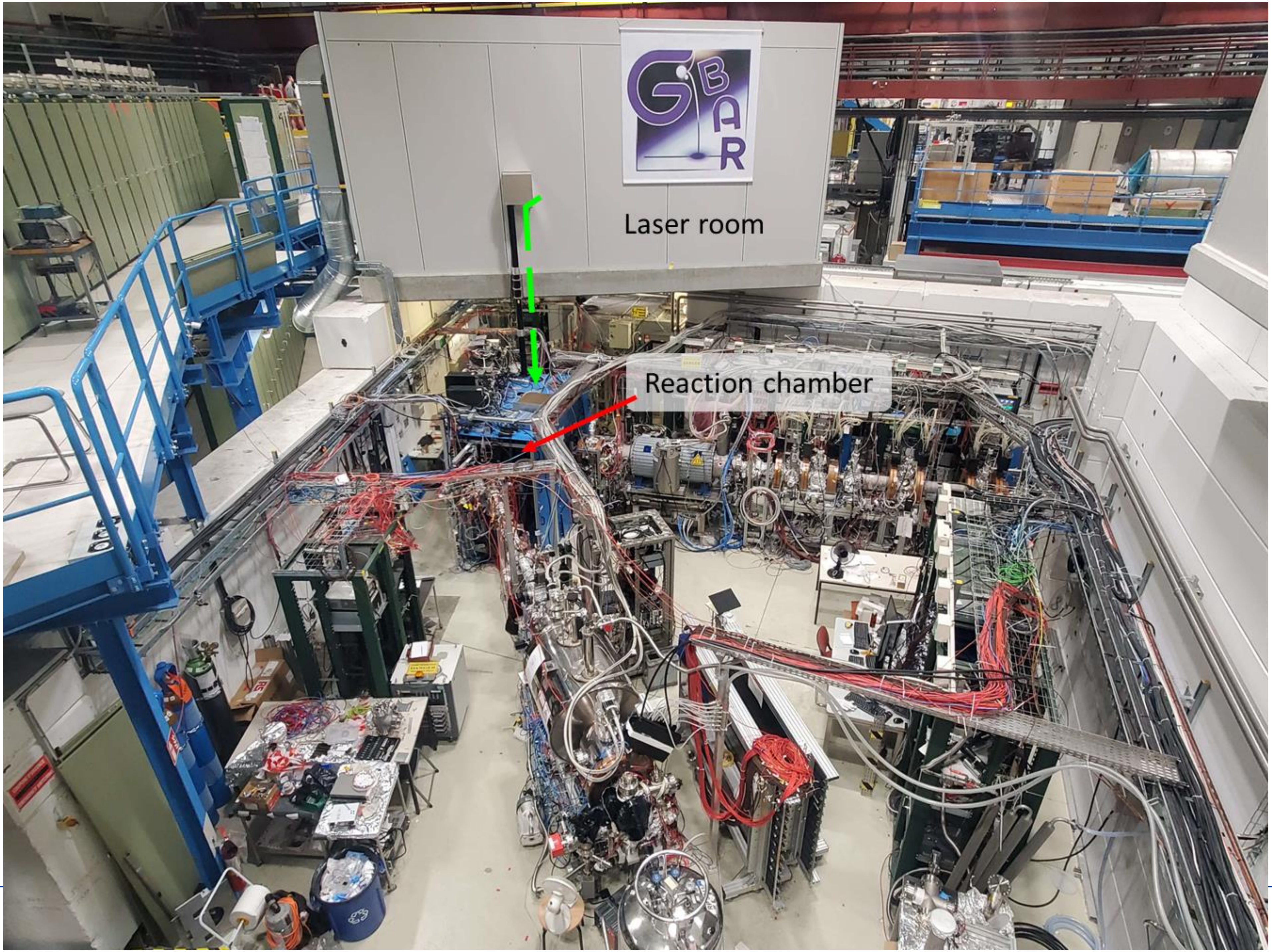


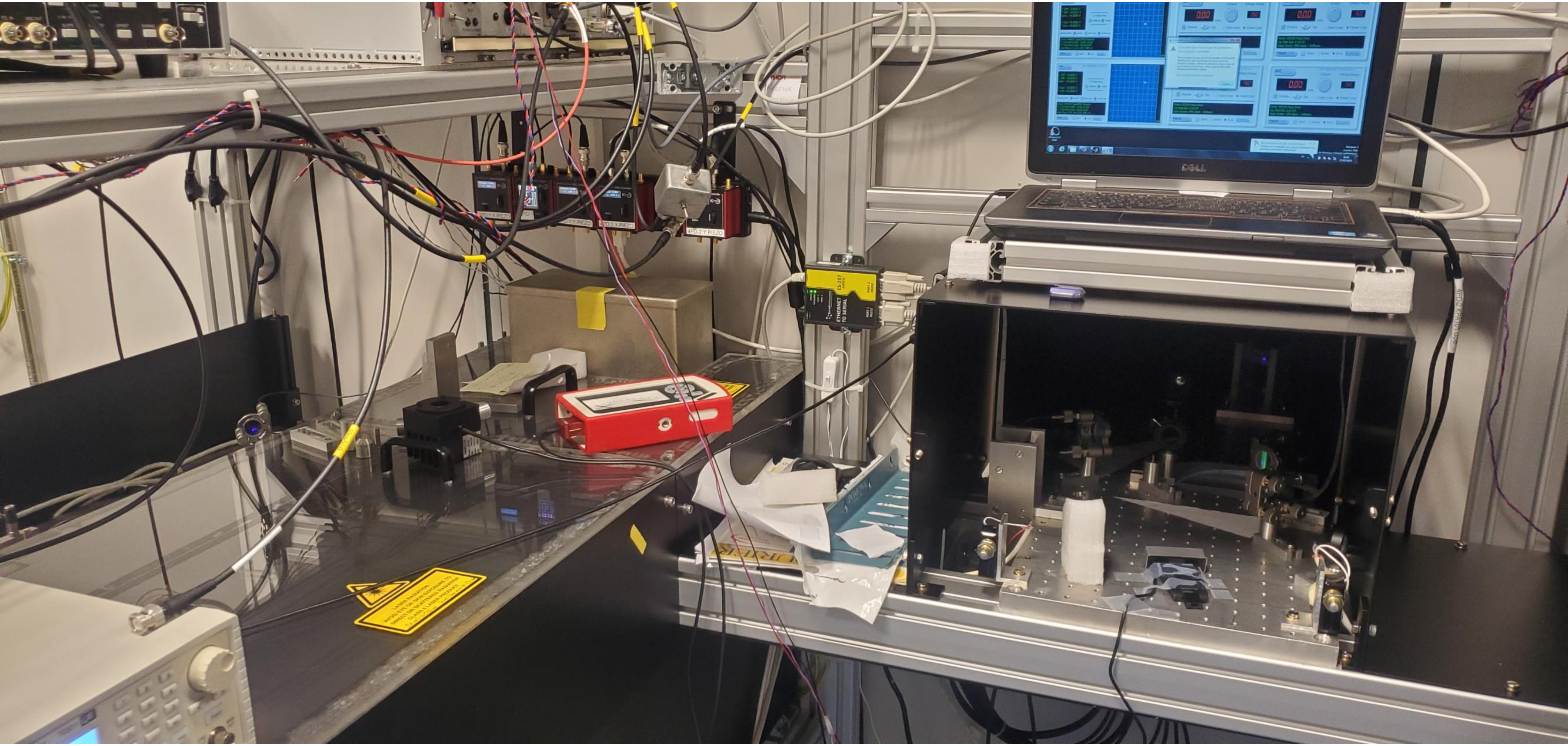
Philip Blumer, Moriond Gravitation (2023)

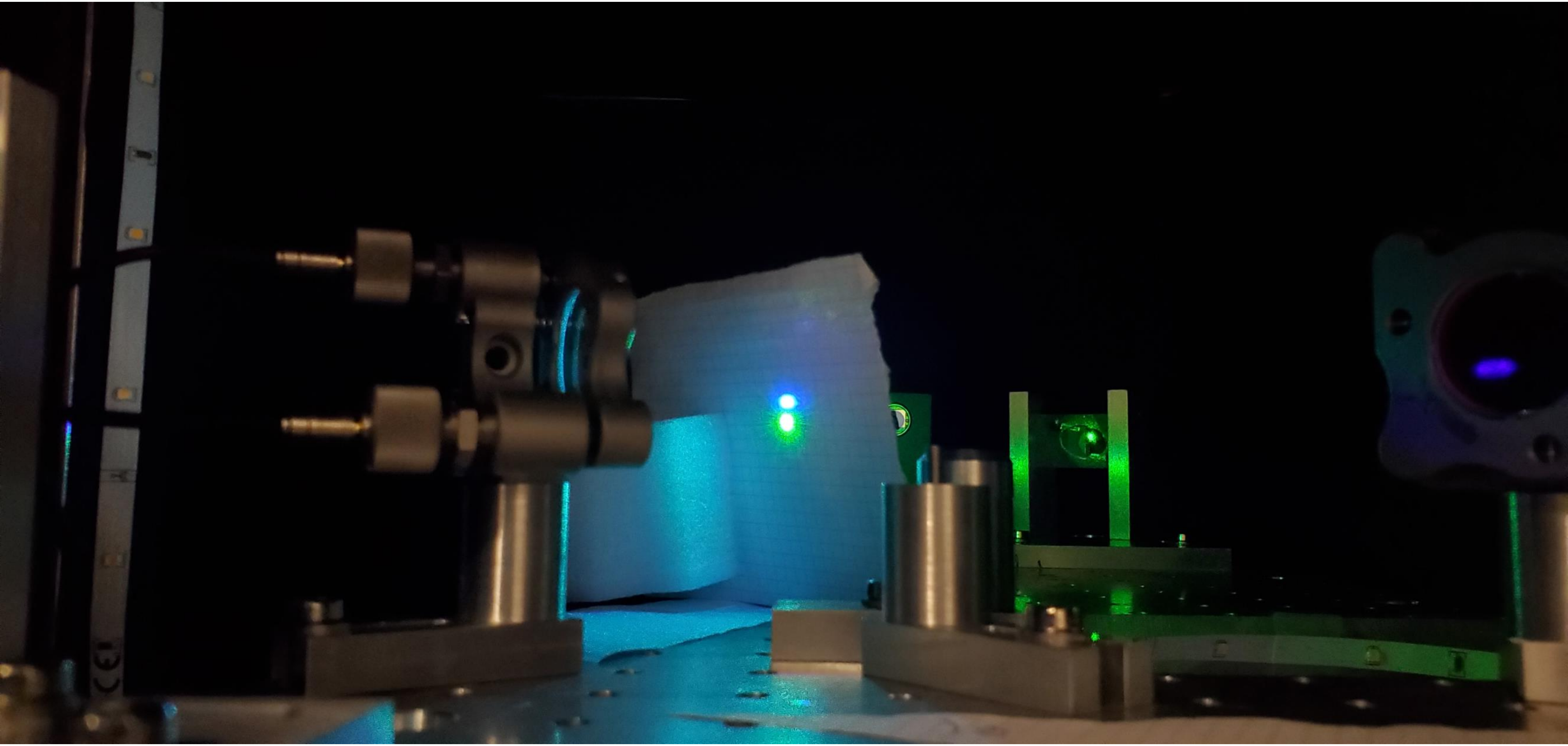
1: Alignment of Beam into Reaction Chamber

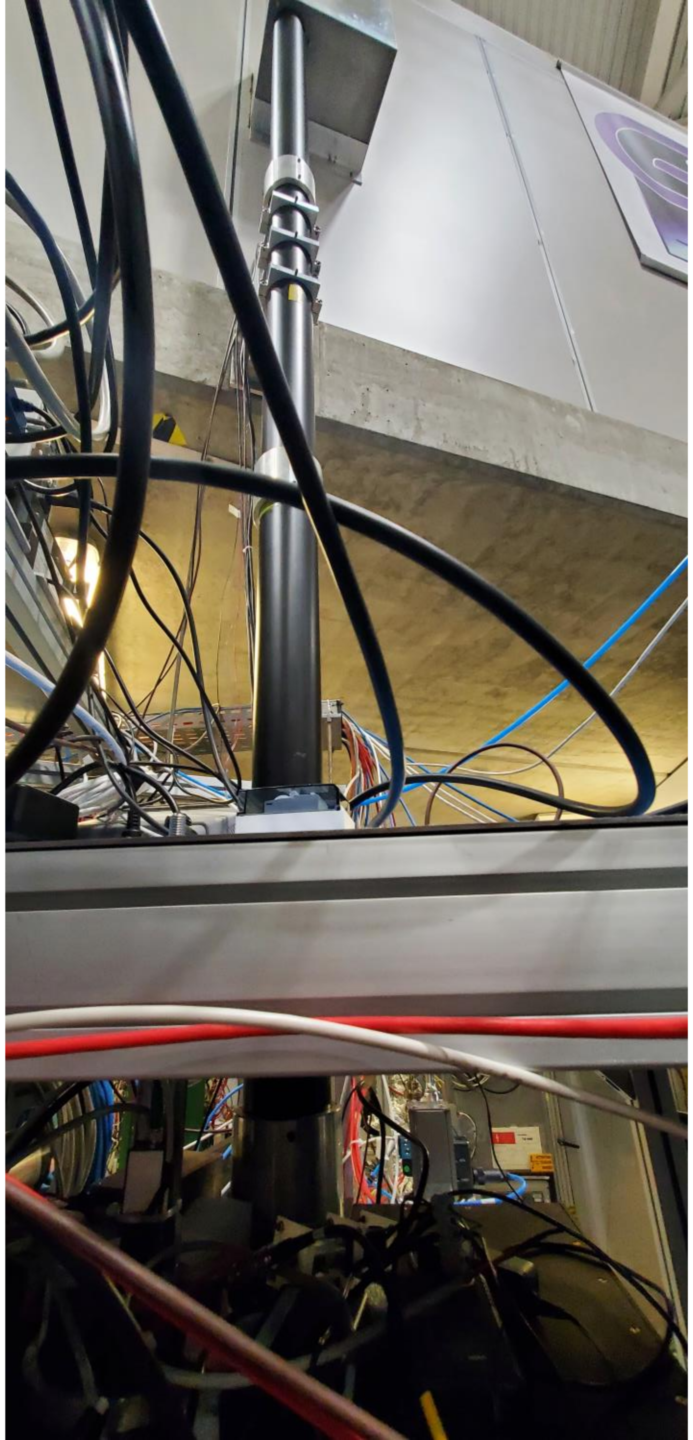
- **Objective: Align photodetachment beam from laser room into reaction chamber**
  - Use low-powered diode lasers as to not blind myself during alignment
  - Then align high-powered beam to low-powered diode.

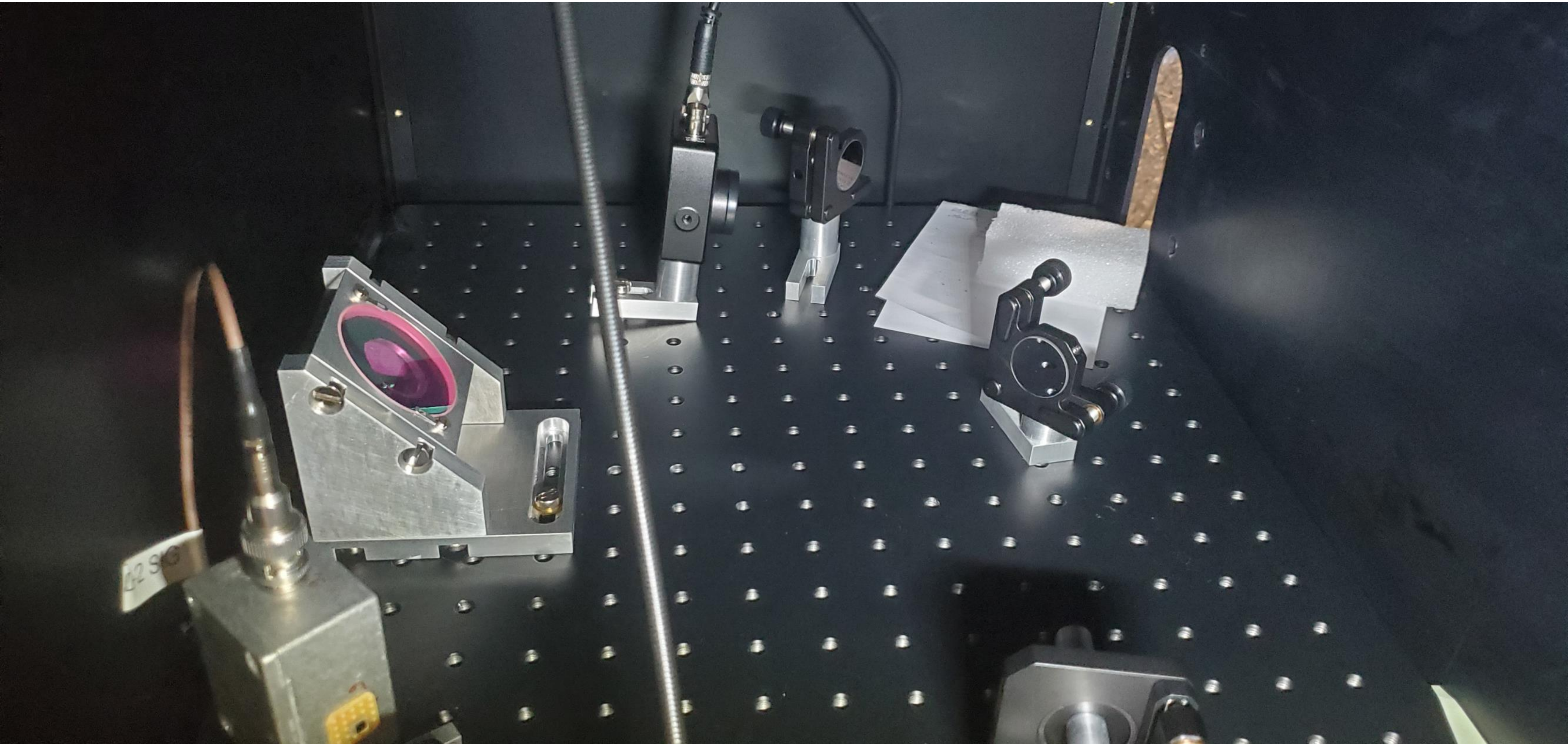
- **Turned out to be much more challenging than initially anticipated…**

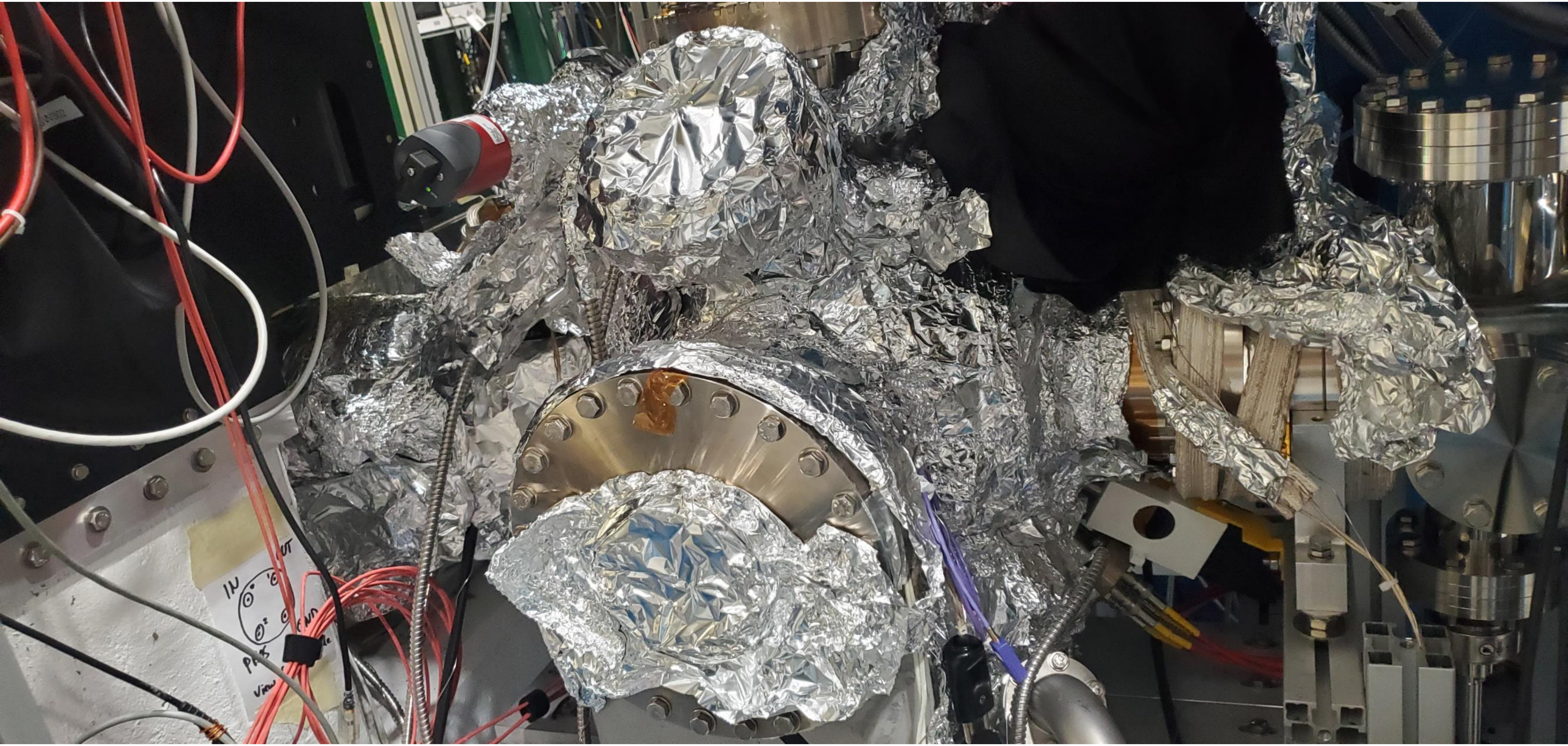

GBAR
Laser room
Reaction chamber

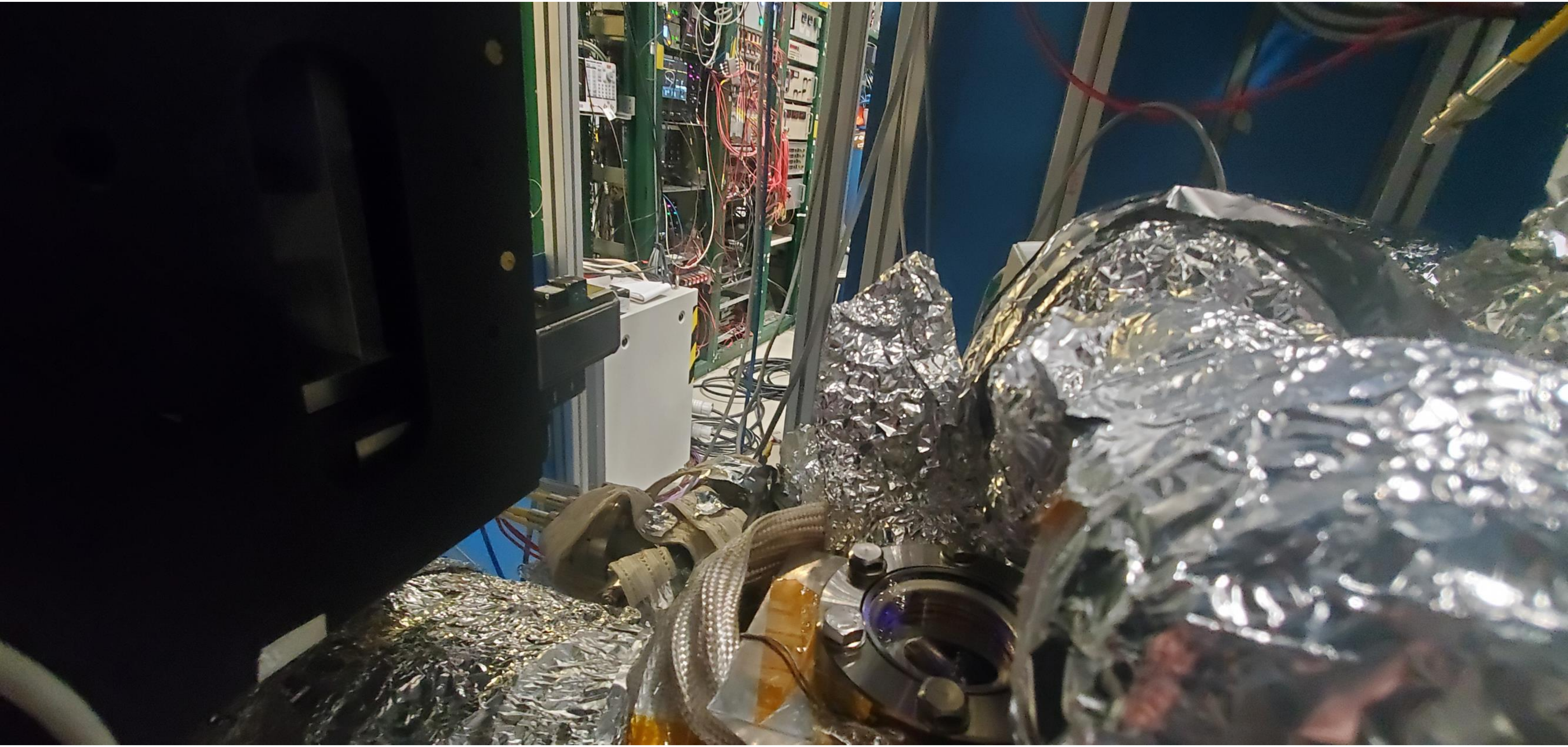

4PD-2 X PIEZO
4PD-2 Y PIEZO
ES-257
ETHERNET TO SERIAL
DELL

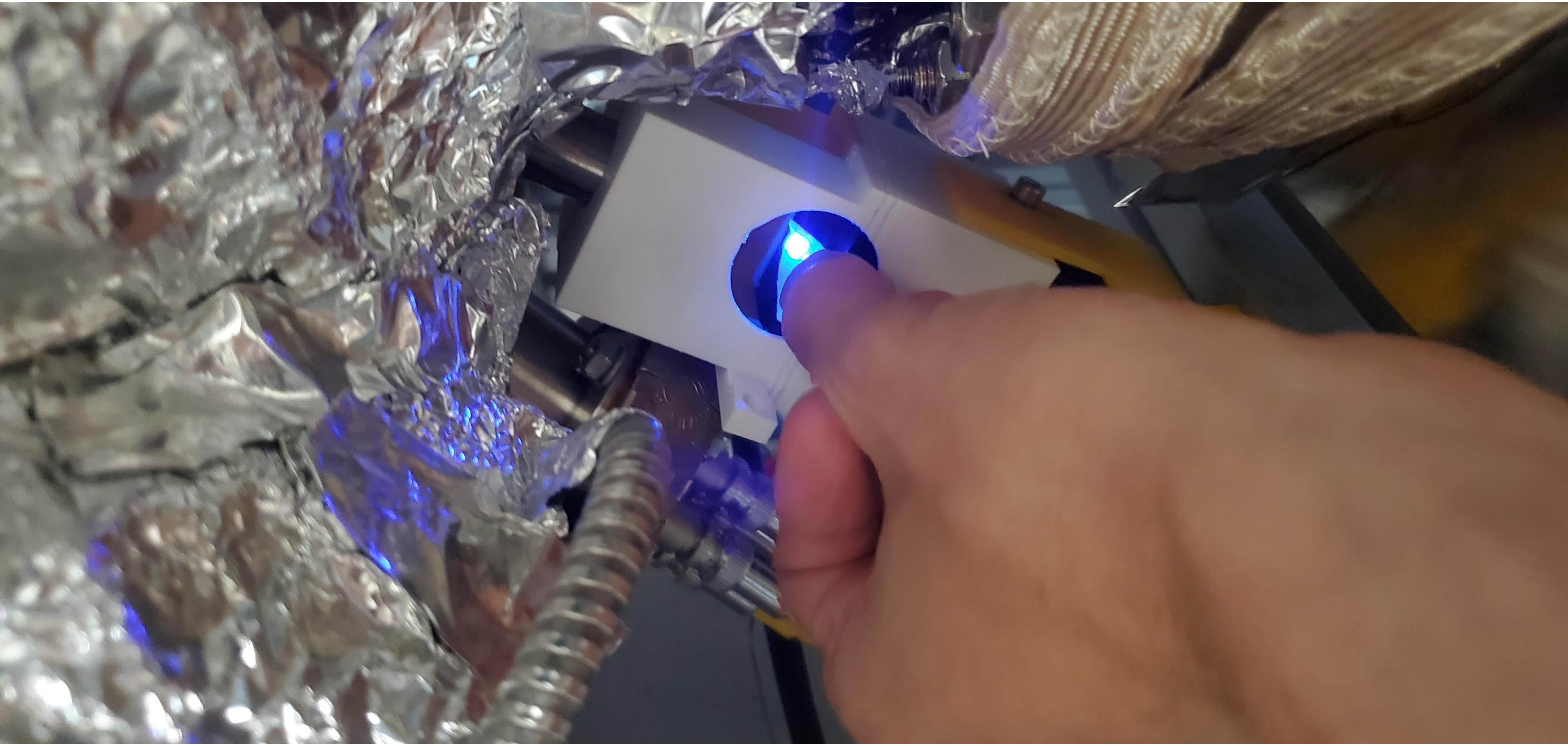





Q2 SIG


IN
OUT
GND
View

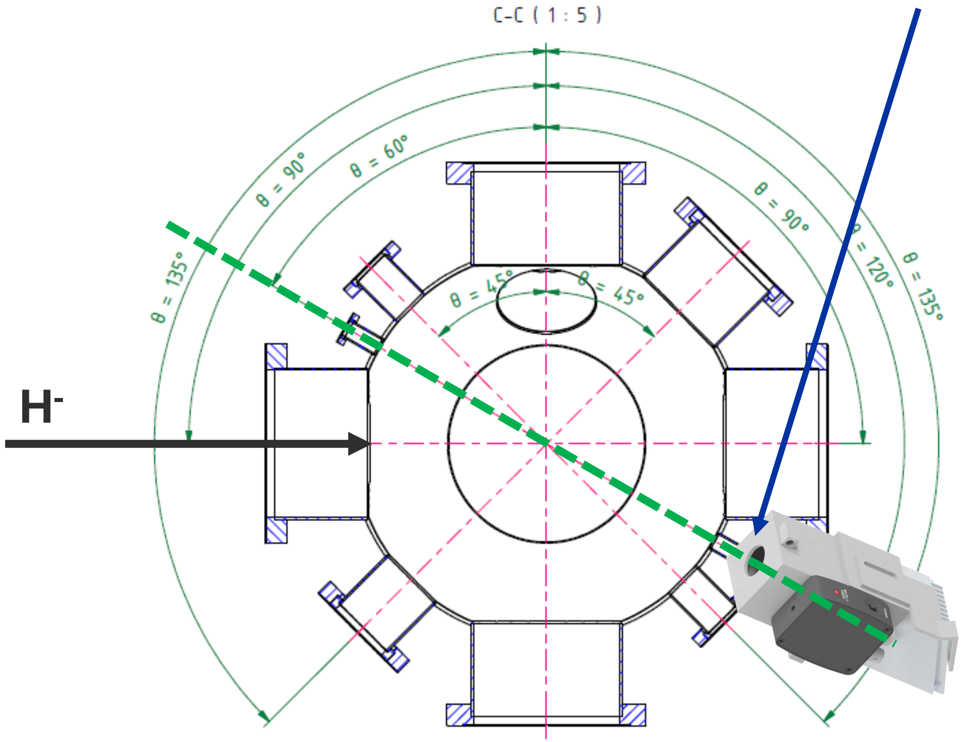




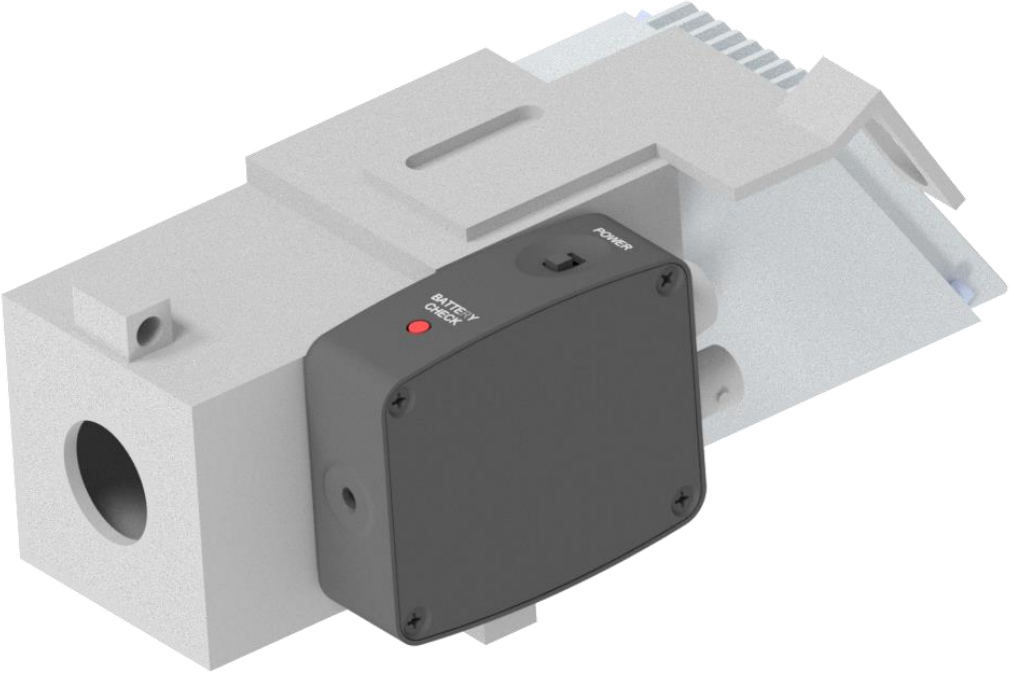
2: Designing Diagnostics for Laser

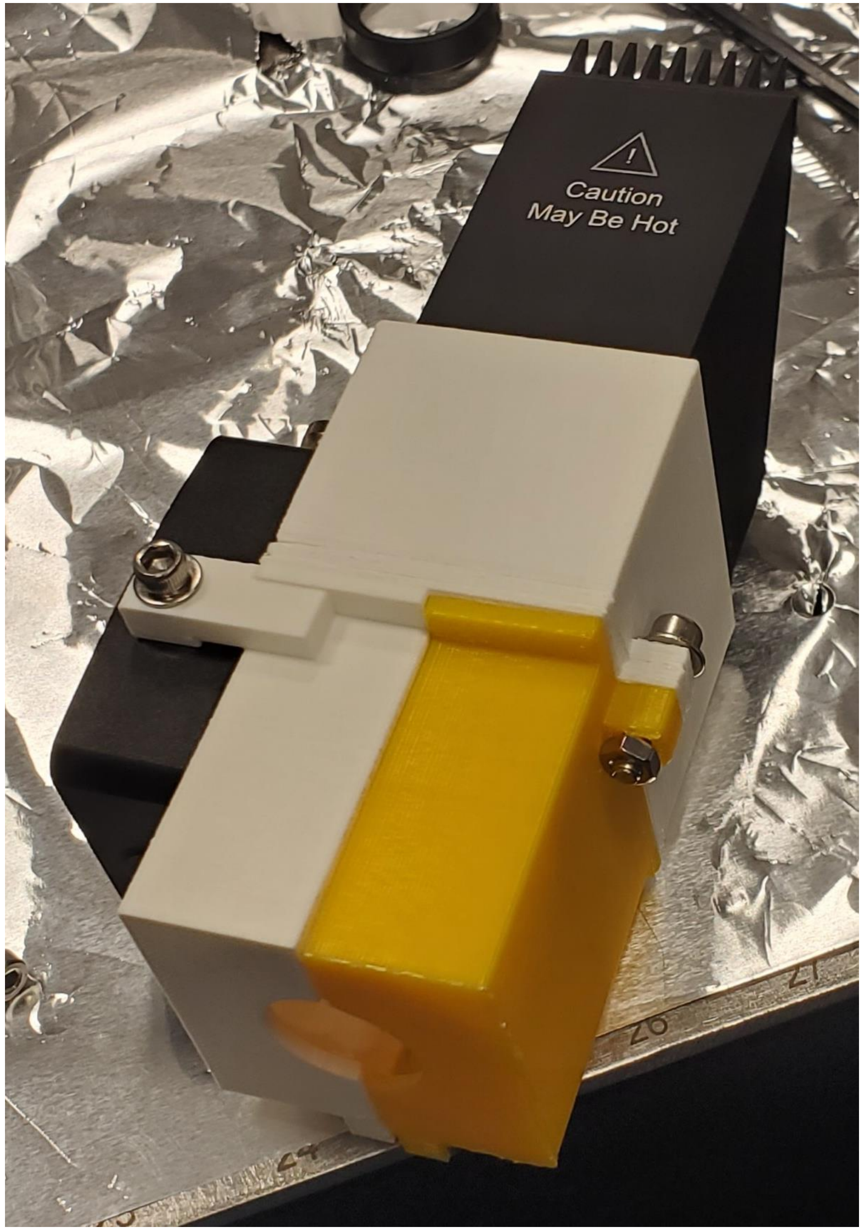
- **Objective: safely measure transmission of high-powered laser beam into reaction chamber.**

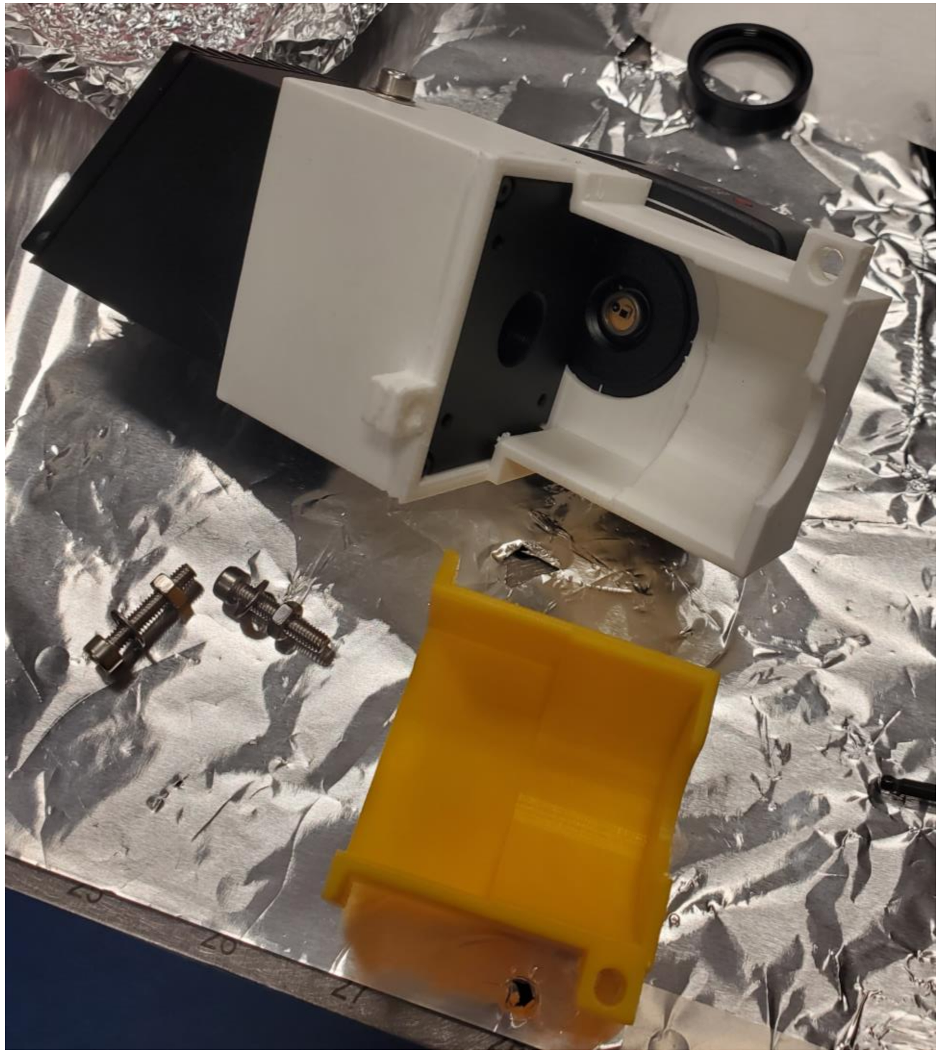
Detect transmission and block beam here.

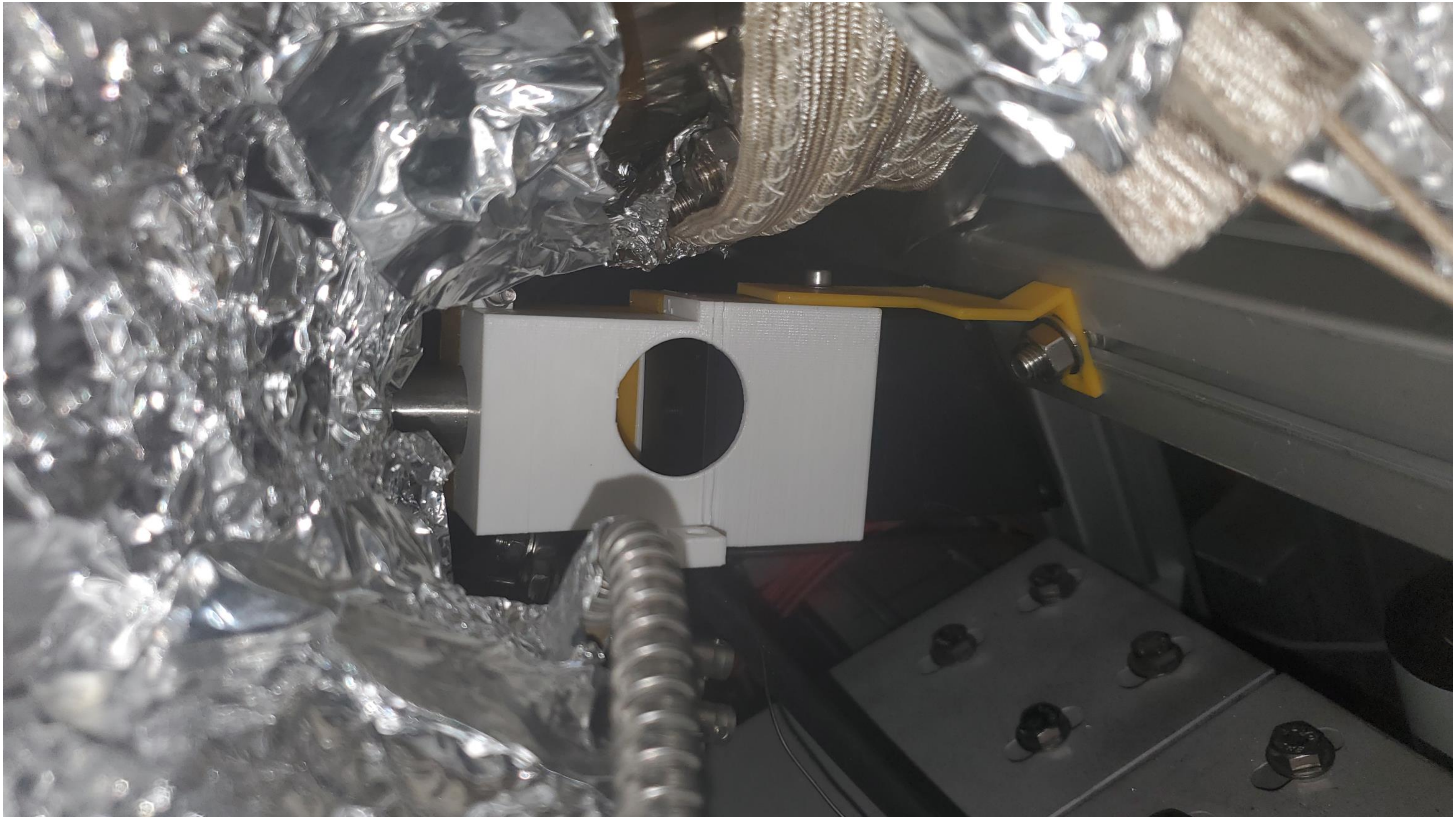


CAD Design




Caution
May Be Hot

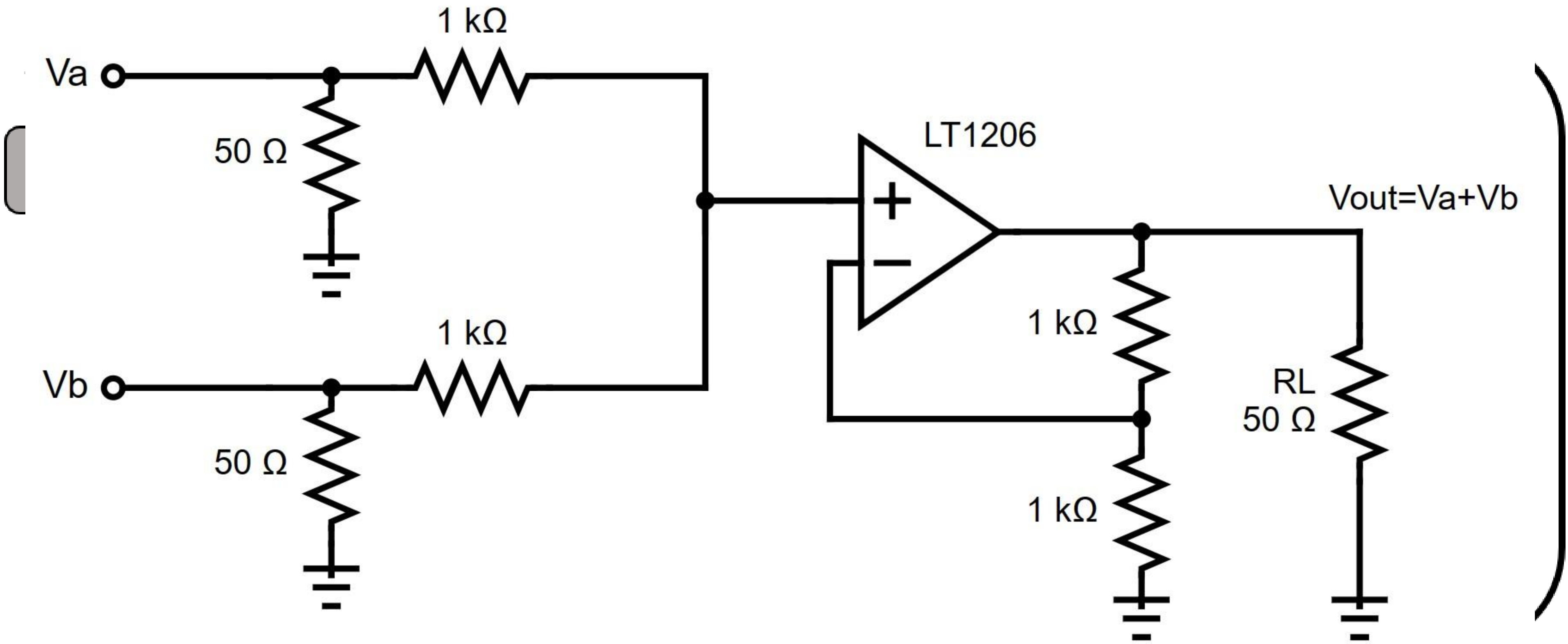


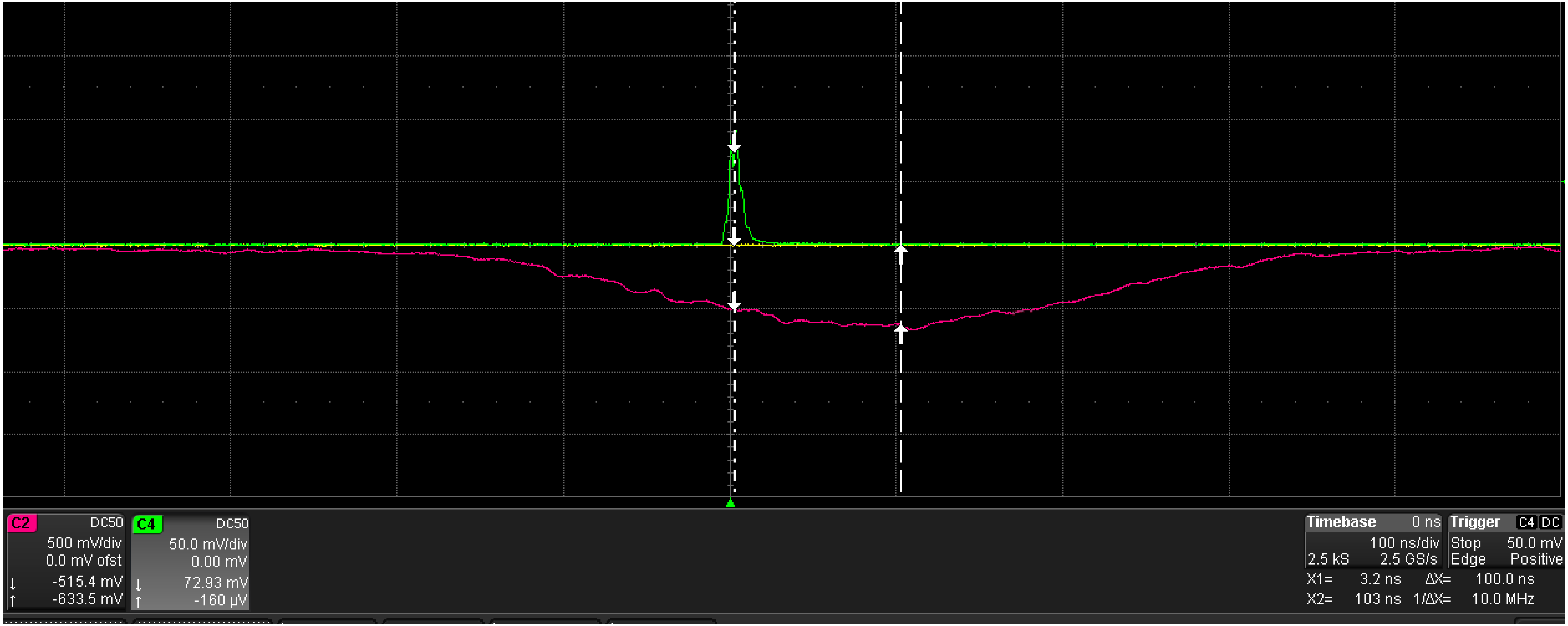


3: Pulsed Laser Trigger Timing

Objective: Time laser pulse so that beam pulse arrives on H^- ions as they enter the reaction chamber.

- Receive two triggers from beamline: -3s, and -1ms.
  - Need to shape, delay, and (possibly) sum both before triggering laser flashlamp and Q-switch.





C2 DC50
500 mV/div
0.0 mV ofst
↓ -515.4 mV
↑ -633.5 mV

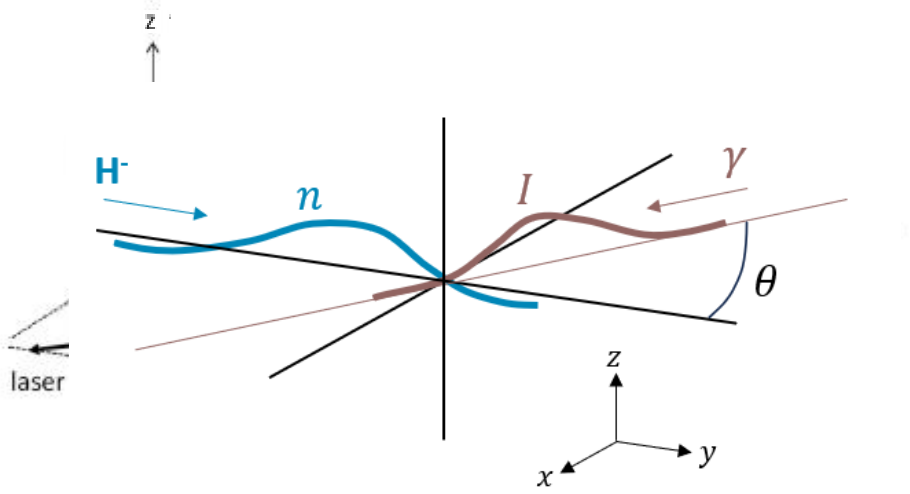
C4 DC50
50.0 mV/div
0.00 mV
↓ 72.93 mV
↑ -160 µV

Timebase 0 ns
100 ns/div
2.5 kS 2.5 GS/s

Trigger C4 DC
Stop 50.0 mV
Edge Positive

X1= 3.2 ns ΔX= 100.0 ns
X2= 103 ns 1/ΔX= 10.0 MHz

4: Simulation of Photodetachment Process



- **Objective: Simulate photodetachment rates of H- via process $\mathbf{H^- + \gamma \rightarrow H + e^-}$.**

- **Model via differential equation**

$$\frac{\partial n(x,y,z,t)}{\partial t} = -\frac{\partial n}{\partial y} v_H - n\sigma \frac{I(x,y,z,t)}{E_\gamma}$$

- **Number of photodetached $\mathbf{H^-}$ given by** $N_{\text{photodetached}} = N - \lim_{t\to\infty} \int n \, dV$

- **Formal solution via method of characteristics:**

$$N_{\text{photodetached}} = \int N_0(x,y,z) \left(1 - \exp \int -\sigma \frac{I(x, y + v_H t, z, t)}{E_\gamma} \, dt \right) dV$$

Mathematica Numerics

$$N_{\text{photodetached}} = \int N_0(x,y,z)\underbrace{\left(1-\exp\int -\boldsymbol{\sigma}\frac{\boldsymbol{I}(\boldsymbol{x},\boldsymbol{y}+\boldsymbol{v_H t},\boldsymbol{z},\boldsymbol{t})}{\boldsymbol{E_\gamma}}\,dt\right)}_{\text{Can no longer compute } N_{\text{photodetached}} \text{ numerically.}}dV$$

But $\boldsymbol{I}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z},\boldsymbol{t})$ is Gaussian, so we can (in principle) compute the innermost integral analytically.

Then we compute the rest numerically.

Work in mm, mJ, ns.

```
In[•]:= wLaser0 = 6.12;
        lLaser0 = 1.9*^3;
        ϕ0 = Pi / 3;
        λ0 = 532*^-6;
        σPhoto0 = 3.1*^-15;
        Ntot0 = 5*^6;
        wIon0 = 5.1;
        lIon0 = 262;
        vH0 = 1.072;
        hConst0 = 6.626*^-22;
        cConst0 = 299.8;

In[•]:= N0[x_, y_, z_] := (2 / Pi) ^ (3 / 2) * Ntot0 / (wIon0^2 * lIon0) * Exp[-2 * (x^2 + z^2) / wIon0^2] * Exp[-2 * y^2 / lIon0^2]

In[•]:= Ntotcheck = NIntegrate[N0[x, y, z], {x, -∞, ∞}, {y, -∞, ∞}, {z, -∞, ∞}]
```

Out[•]= $5.\times 10^{6}$

```
In[•]:= ExponentTerm[x_, y_, z_, t_, cConst_, wLaser_, lLaser_, ϕ_] :=
         -2 * ((x * Sin[ϕ] + y * Cos[ϕ]) ^2 + z^2) / wLaser^2 - 2 * ((x * Cos[ϕ] - y * Sin[ϕ]) - cConst * t) ^2 / lLaser^2

In[•]:= tCoeffs = Map[Simplify, Table[Coefficient[Collect[ExponentTerm[x, y + vH * t, z, t, cConst, wLaser, lLaser, ϕ], t], t, i], {i, 0, 2}]]
```

Out[•]=
$$\left\{-\frac{2\left(\left(\text{wLaser}^2 x^2+\text{lLaser}^2 y^2\right)\text{Cos}[\phi]^2-2\,\text{wLaser}^2\,x\,y\,\text{Cos}[\phi]\,\text{Sin}[\phi]+\left(\text{lLaser}^2 x^2+\text{wLaser}^2 y^2\right)\text{Sin}[\phi]^2+\text{lLaser}^2\left(z^2+x\,y\,\text{Sin}[2\phi]\right)\right)}{\text{lLaser}^2\,\text{wLaser}^2},\right.$$
$$-\frac{4\left(-\text{cConst}\,\text{wLaser}^2\,x\,\text{Cos}[\phi]+\text{lLaser}^2\,\text{vH}\,y\,\text{Cos}[\phi]^2+\text{vH}\left(\text{lLaser}^2-\text{wLaser}^2\right)x\,\text{Cos}[\phi]\,\text{Sin}[\phi]+\text{wLaser}^2\,y\,\text{Sin}[\phi]\left(\text{cConst}+\text{vH}\,\text{Sin}[\phi]\right)\right)}{\text{lLaser}^2\,\text{wLaser}^2},$$
$$\left.-\frac{2\left(\text{lLaser}^2\,\text{vH}^2\,\text{Cos}[\phi]^2+\text{wLaser}^2\left(\text{cConst}+\text{vH}\,\text{Sin}[\phi]\right)^2\right)}{\text{lLaser}^2\,\text{wLaser}^2}\right\}$$

```
In[•]:= GeneralIntegral[a2_, a1_, a0_] := Evaluate[Integrate[Exp[a2 * t^2 + a1 * t + a0], {t, -∞, +∞}, Assumptions → {a2 < 0, a1 ∈ ℝ, a0 ∈ ℝ}]]

In[•]:= GeneralIntegral[a2, a1, a0]
```

Out[•]=
$$\frac{e^{\text{a0}-\frac{\text{a1}^2}{4\,\text{a2}}}\sqrt{\pi}}{\sqrt{-\text{a2}}}$$

```
In[•]:= IntegratedIntensity[x_, y_, z_, Epulse_, vH_, cConst_, wLaser_, lLaser_, ϕ_] := Evaluate[(2 / Pi) ^ (3 / 2) * cConst / (wLaser^2 * lLaser) * Epulse *
            (GeneralIntegral @@ Reverse[tCoeffs])]
```

Out[•]= IntegratedIntensity[x_, y_, z_, Epulse_, vH_, cConst_, wLaser_, lLaser_, ϕ_] :=
$$\left(2\,\text{cConst}\;e^{\frac{2\left(-\text{cConst}\,\text{wLaser}^2\,x\,\text{Cos}[\phi]+\text{lLaser}^2\,\text{vH}\,y\,\text{Cos}[\phi]^2+\text{vH}\left(\text{lLaser}^2-\text{wLaser}^2\right)x\,\text{Cos}[\phi]\,\text{Sin}[\phi]+\text{wLaser}^2\,y\,\text{Sin}[\phi]\left(\text{cConst}+\text{vH}\,\text{Sin}[\phi]\right)\right)^2}{\text{lLaser}^2\,\text{wLaser}^2\left(\text{lLaser}^2\,\text{vH}^2\,\text{Cos}[\phi]^2+\text{wLaser}^2\left(\text{cConst}+\text{vH}\,\text{Sin}[\phi]\right)^2\right)}-\frac{2\left(\left(\text{wLaser}^2 x^2+\text{lLaser}^2 y^2\right)\text{Cos}[\phi]^2-2\,\text{wLaser}^2\,x\,y\,\text{Cos}[\phi]\,\text{Sin}[\phi]+\left(\text{lLaser}^2 x^2+\text{wLaser}^2 y^2\right)\right.}{\text{lLaser}^2\,\text{wLaser}^2}}\;\text{Epulse}\right)\Big/\left(\text{lLaser}\,\pi\,\text{wLaser}^2\sqrt{\frac{\text{lLaser}^2\,\text{vH}^2\,\text{Cos}[\phi]^2+\text{wLaser}^2\left(\text{cConst}+\text{vH}\,\text{Sin}[\phi]\right)^2}{\text{lLaser}^2\,\text{wLaser}^2}}\right)$$

```
In[•]:= η[x_, y_, z_, Epulse_] := 1 - Exp[-IntegratedIntensity[x, y, z, Epulse, vH0, cConst0, wLaser0, lLaser0, ϕ0] * σPhoto0 / (hConst0 * cConst0 / λ0)]

In[•]:= NPhotodetach[Epulse_] := NIntegrate[N0[x, y, z] * η[x, y, z, Epulse], {x, -∞, ∞}, {y, -∞, ∞}, {z, -∞, ∞}]
```

Simulation Results

($N = 5 \cdot 10^6$ H- per pulse)