A cavity-enhanced hydrated electron sensor for real-time, tissue-equivalent measurement of individual clinical radiation pulses

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Quantum Optics
& Sensing Lab

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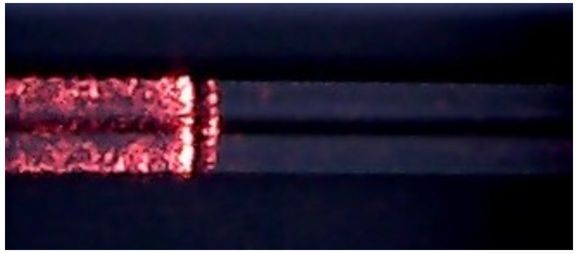
What? **Develop an *in vivo* water-based radiation dosimeter as tiny as a human hair**

For conventional and ultrahigh dose rate EBRT

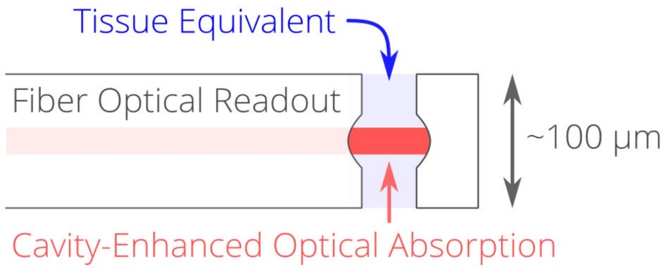


Why? Use quantum optics skills to address dosimetry limitations

Measuring the reference quantity for radiotherapy D_w:

- 10 cm long ionization chamber
  - Ionization current
  - Average dose in the air cavity
  - Dose in water in one point

- Micron-scale optical fiber cavity
- Tissue equivalent (water) detection
- Real-time sub-mGy readout
- *In situ* dosimetry



How? **Monitor the concentration of hydrated electrons (e^{-}_{aq}) using cavity-enhanced absorption spectroscopy**

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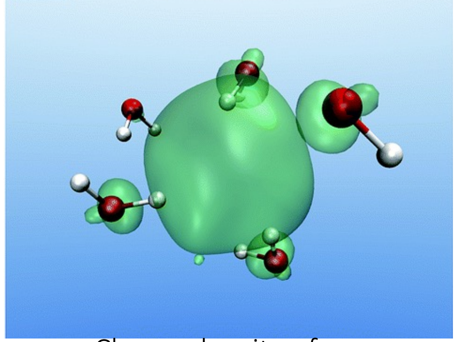
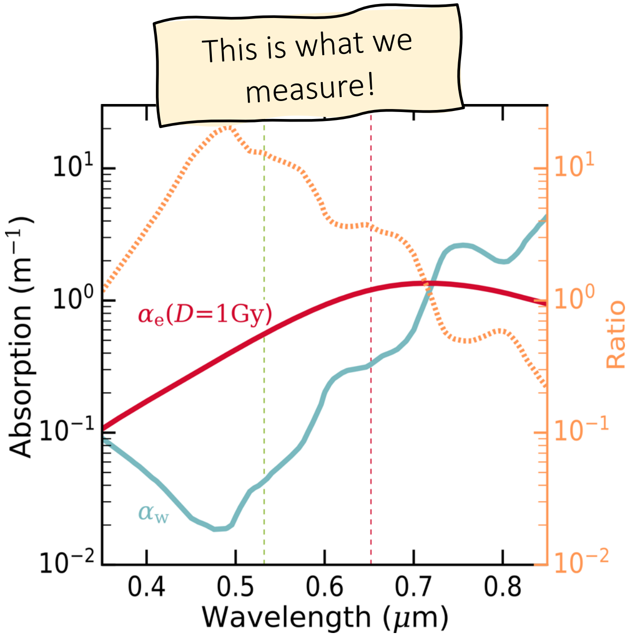
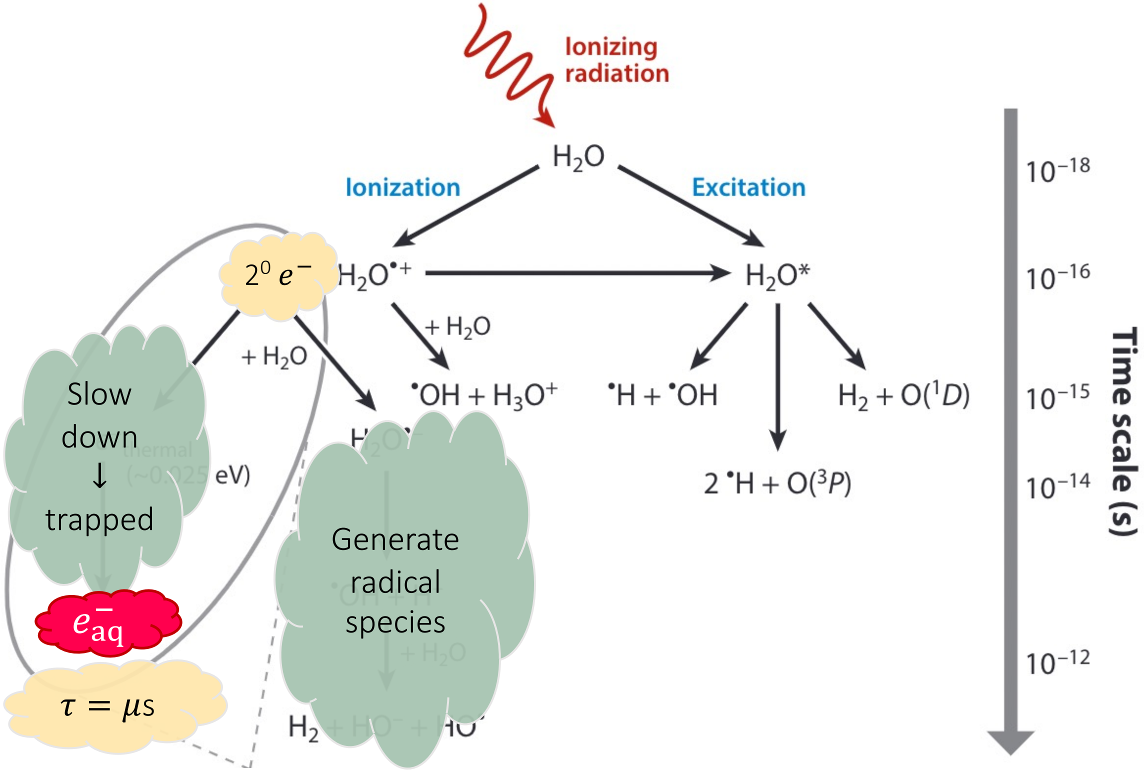
How? Determine dose by monitoring the concentration of **hydrated electrons (e^-_{aq})** using fast cavity-enhanced absorption spectroscopy



Charge density of e^-_{aq}.
(Pizzochero *et al.*, 2019)





(Herbert and Coons, *Annu. Rev. Phys. Chem. 2017*)

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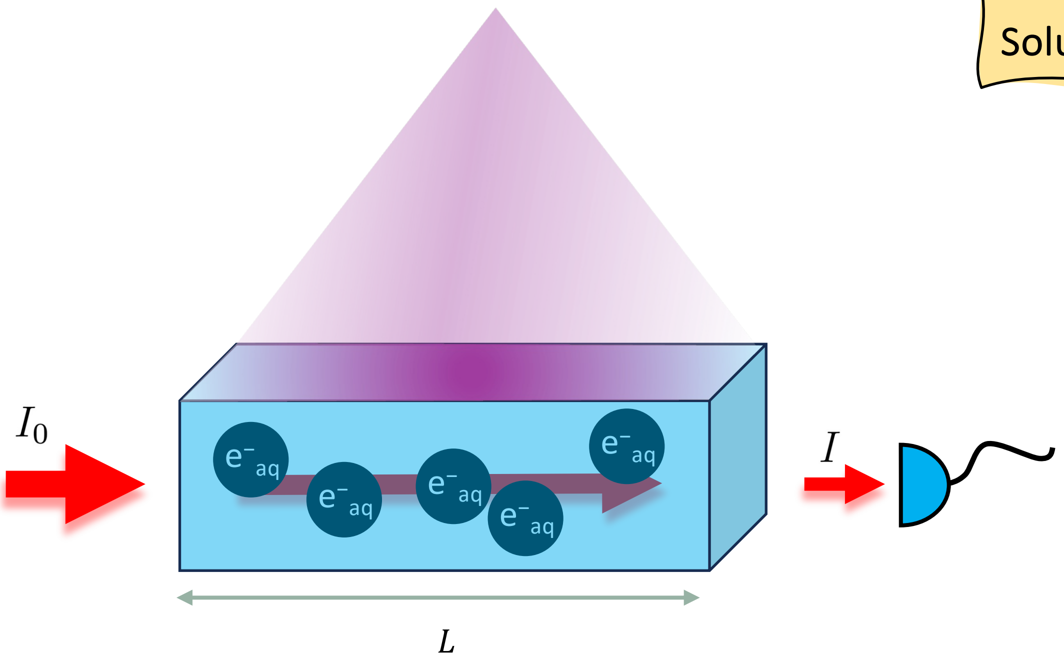
How? Determine dose by monitoring the concentration of **hydrated electrons (e^-_{aq})** using fast cavity-enhanced **absorption spectroscopy**

$$I = I_0 e^{-\alpha L}$$

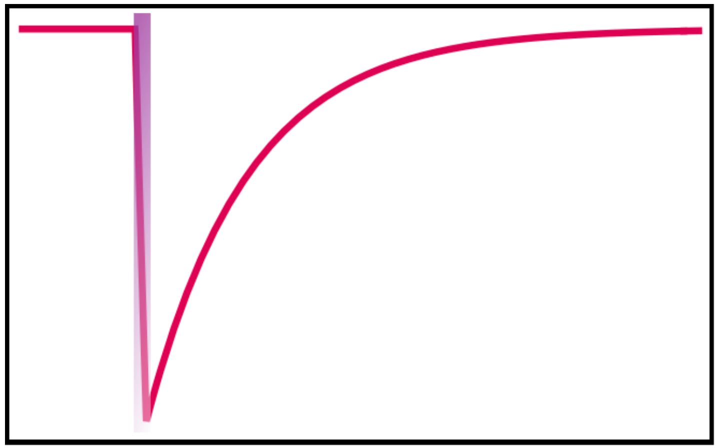
$\alpha \propto$ Dose



Super big, useless device

Problem: long optical path (or absurd pulse) is required for a detectable signal ($\propto 1\text{m}$)

Solution: **optical cavity enhancement**



Absurd pulse

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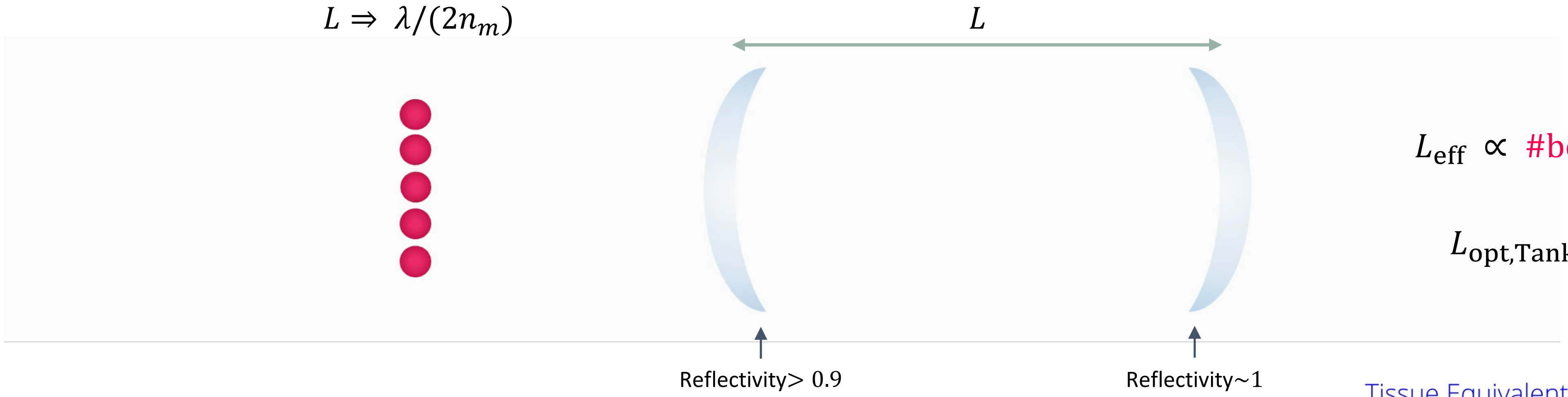
How? Determine dose by monitoring the concentration of **hydrated electrons (e^-_{aq})** using fast **cavity-enhanced absorption spectroscopy**

Optical cavity:

"Folds" meter-long paths to sub-millimeter → enhances interaction with sample

Small sensor sensitive to tiny absorption signals

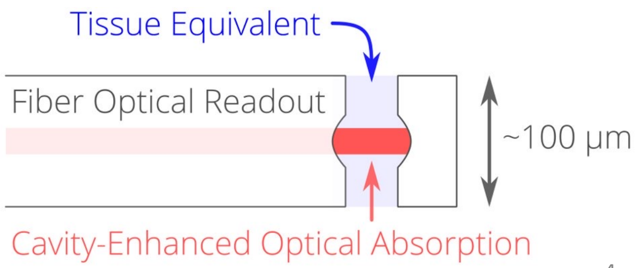


$$L_{\mathrm{eff}} \propto \#\mathrm{bounces} \cdot L \propto \frac{L}{\mathrm{losses}}$$

$$L_{\mathrm{opt,Tank}} \approx 3m \Rightarrow 100\mu m$$

With optimal parameters
→ **single pulse doses ~ 10 µGy**

~ **1%** of conv pulse!



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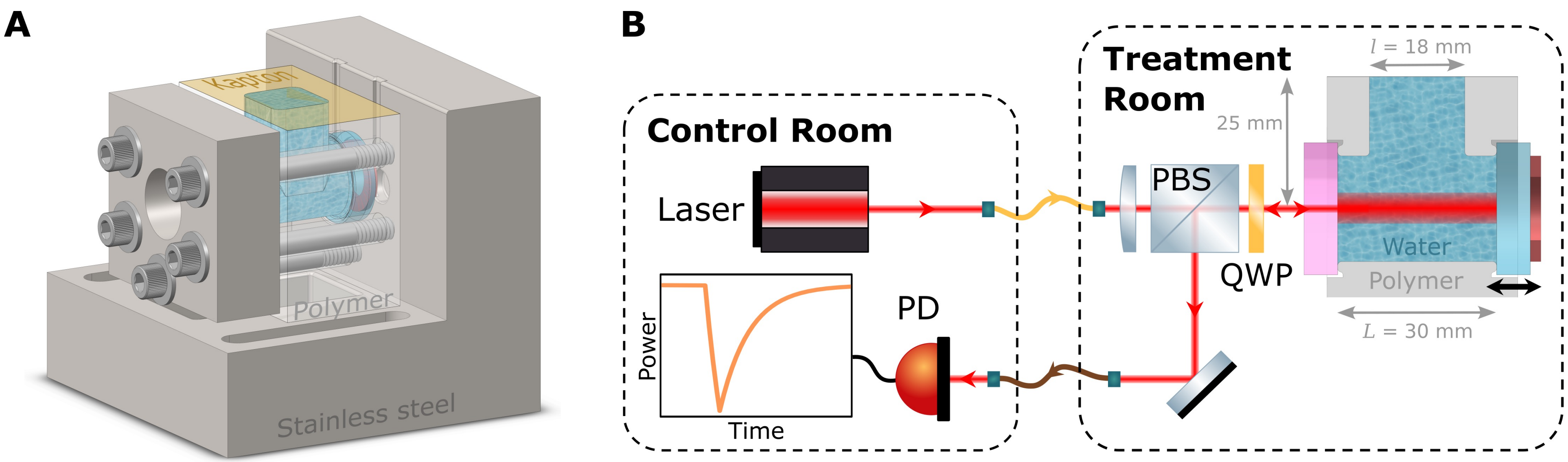
Currently: performing tests in a 3-cm proof-of-concept cavity → CONV photon & e^- therapy



$$L = 3\ cm$$
$$L_{\text{eff}} \approx 1.3\ m$$

Resonance condition kept with a Pound-Drever-Hall locking scheme feeding back to a piezo transducer on the back mirror

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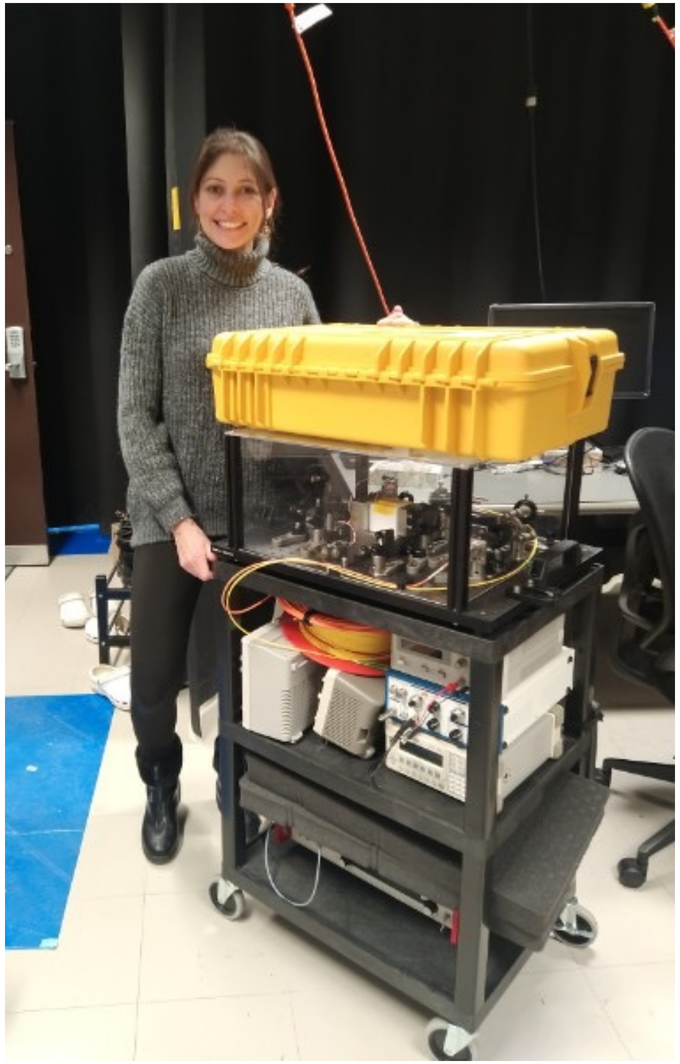

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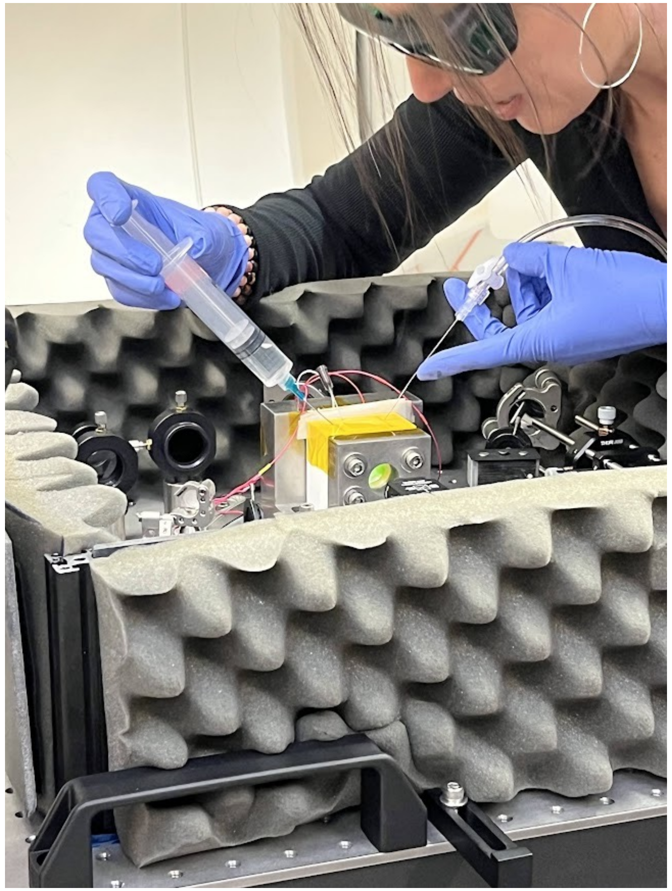

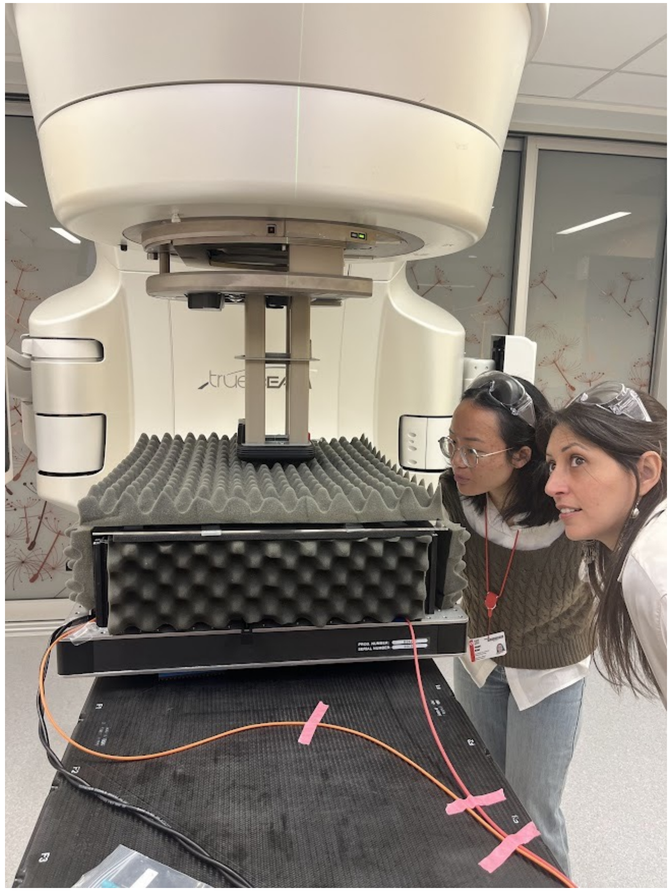

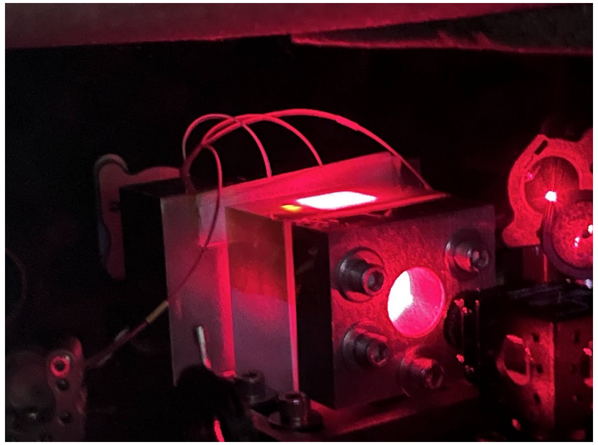

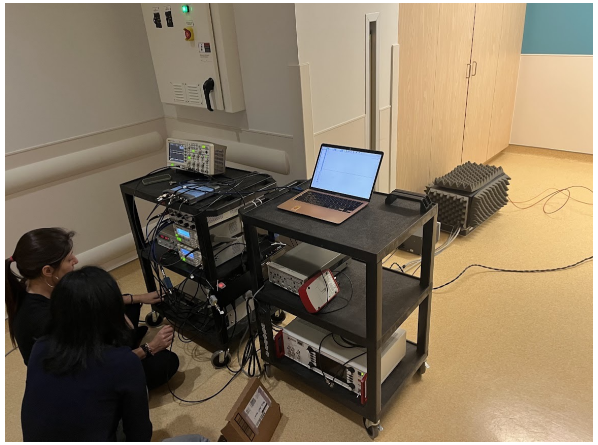

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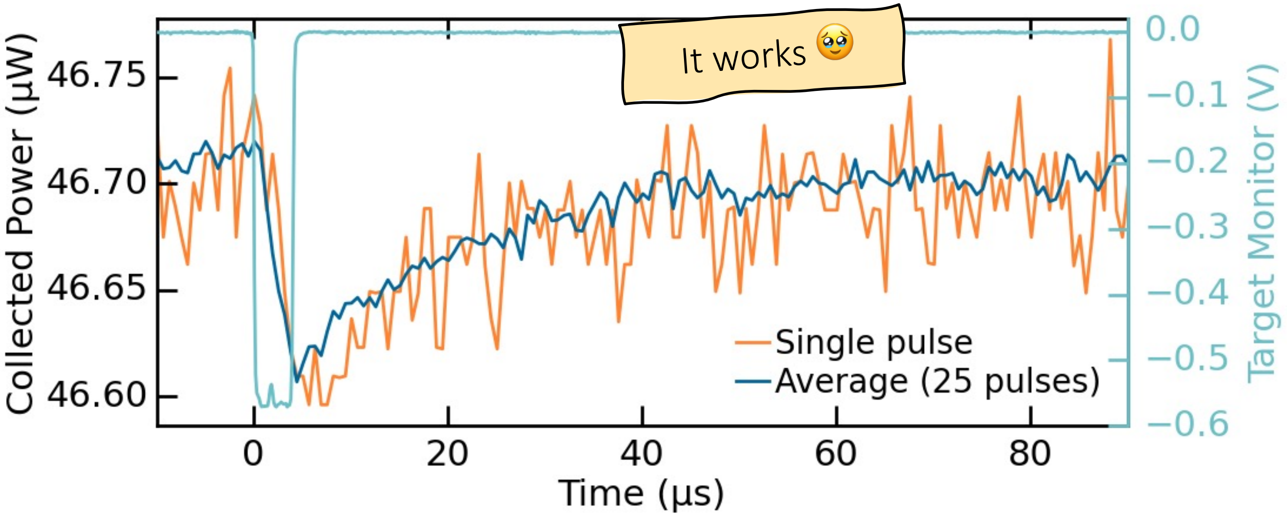

$$P_{\text{out}} \approx P_{\text{in}} \left(\eta R + 1 - \eta\right)$$

$$R \approx \left(\frac{\mathcal{L}_0 + \mathcal{L}_{\text{rad}}(t) - T_1}{\mathcal{L}_0 + \mathcal{L}_{\text{rad}}(t) + T_1} \right)^2$$

$$\mathcal{L}_{\text{rad}} = 2\alpha_{\text{e}} l$$

$$\alpha(t) = \ln(10) \underbrace{\mathcal{E}}_{\text{molar absorption coeff } [1/(\text{M}\cdot\text{m})]} \overbrace{n_e(t)}^{\text{molar concentration } [\text{M}=\text{mol/L}]}$$

$$\frac{dn_e}{dt} = \underbrace{\rho G_e d(t)}_{\text{creation}} - \underbrace{\frac{1}{\tau} n_e(t)}_{\text{decay}} \approx \rho G_e \frac{\mathcal{D}}{\Delta t} - \frac{1}{\tau} n_e(t)$$

Rate eq for e^-_{aq} number density

$$n_{\text{e}}(t) = \rho G_{\text{e}} \frac{\mathcal{D}}{\Delta t} \tau \begin{cases} 0 & t < 0 \\ 1 - e^{-t/\tau} & 0 \le t \le \Delta t \\ \left(e^{\Delta t/\tau} - 1\right) e^{-t/\tau} & t > \Delta t \end{cases}$$

Problem to solve: getting the value of the quantity from the instrument output

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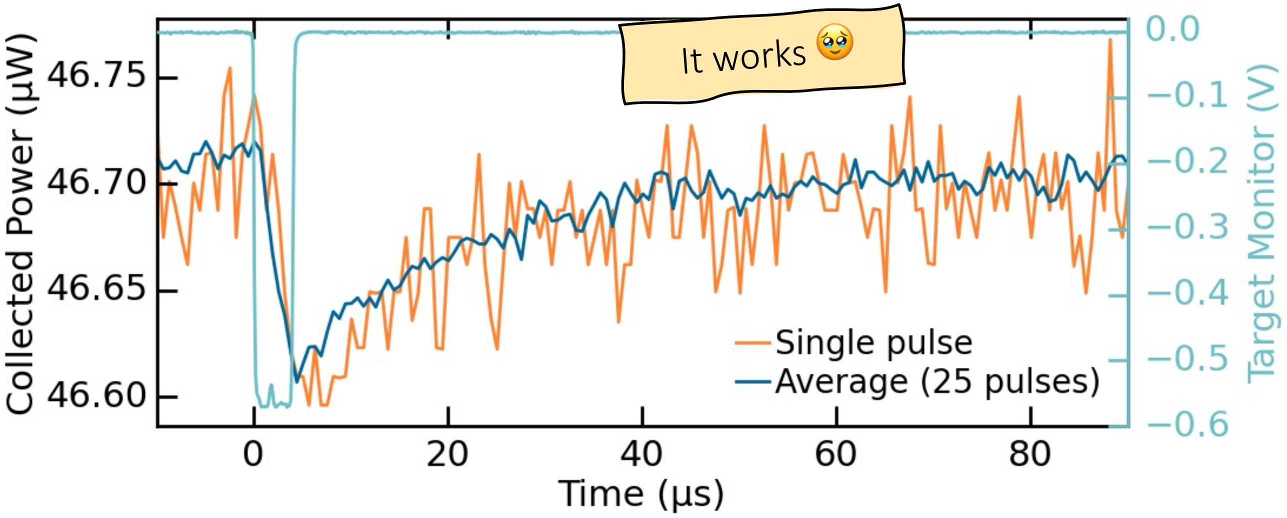

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$$\frac{\text{\# particles}}{\text{radiation energy}}$$

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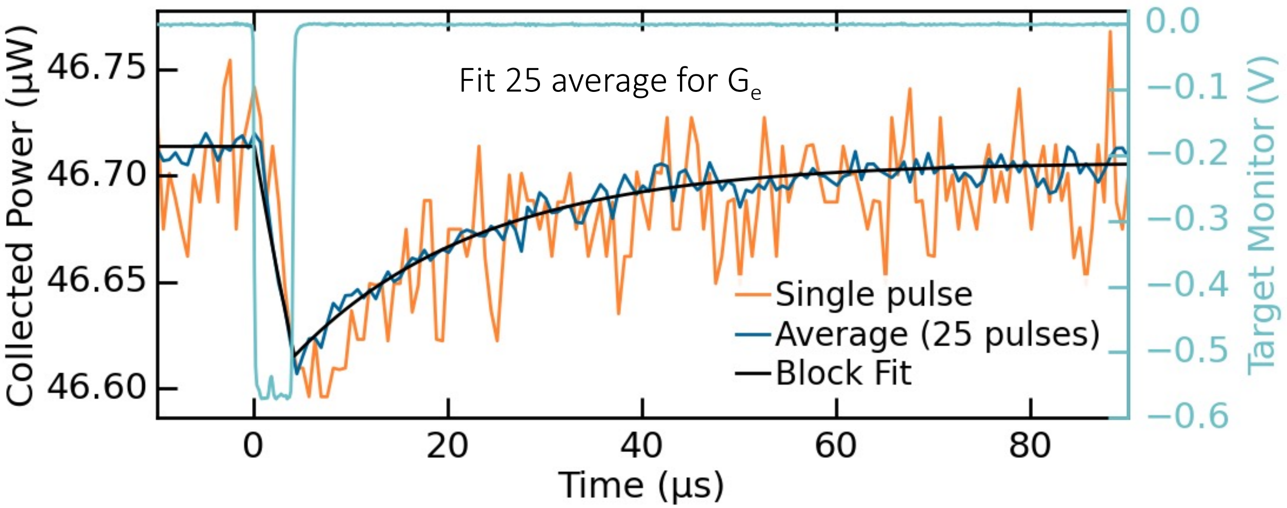

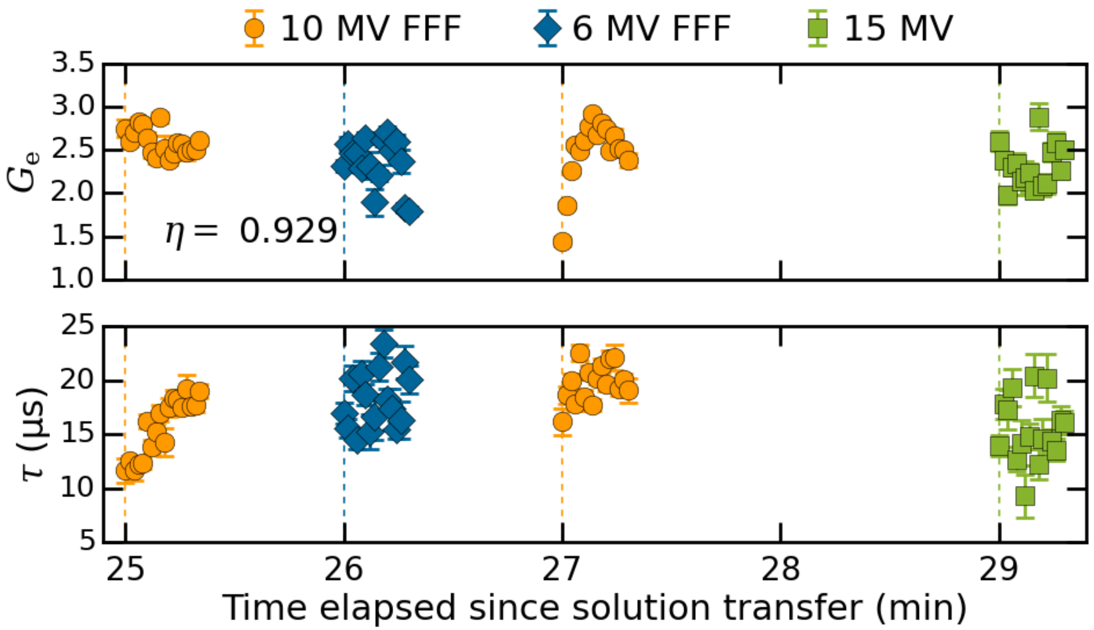

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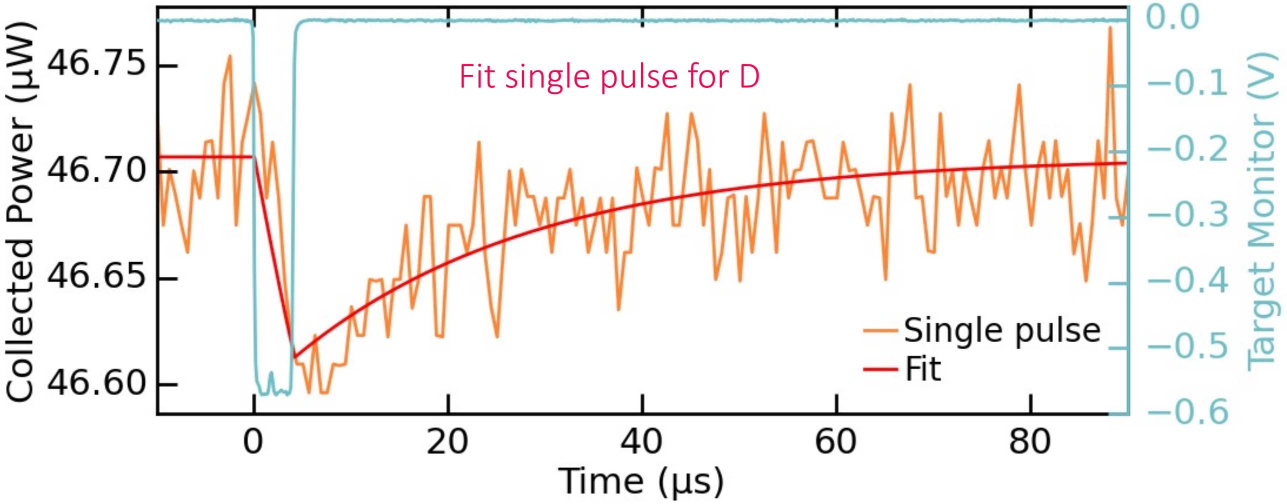

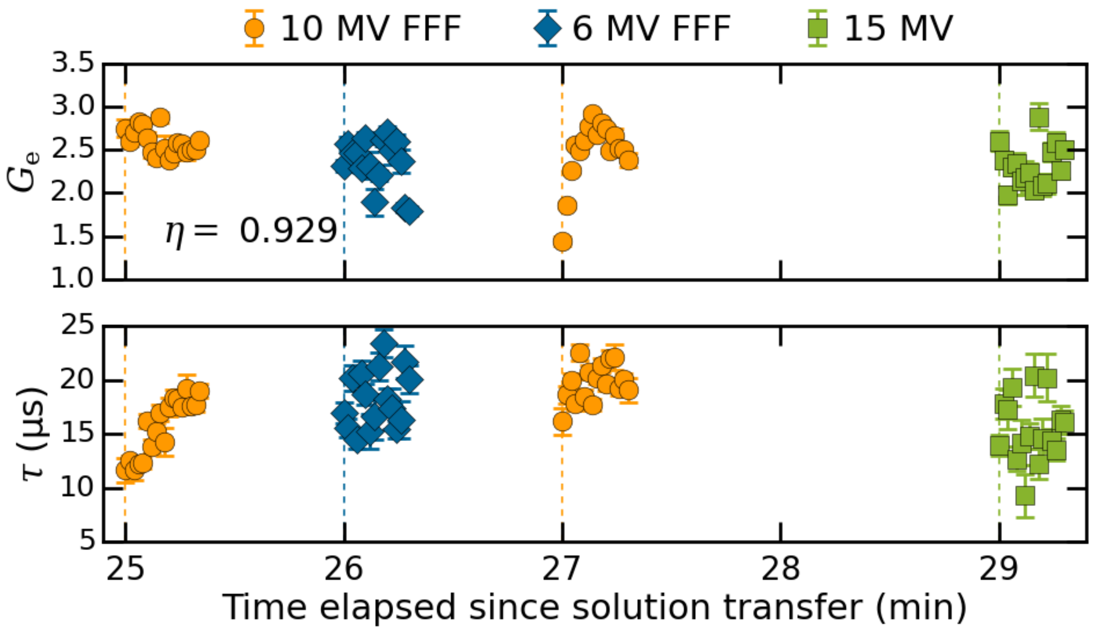

Min detectable D ≈ 150 μGy

Pulse Dose ≈ 2 mGy

Pulse length ≈ 4 μs

➔ Instantaneous dose rate ≈ 500 Gy/s

Beam size = 2x2 cm^2

$$n_e(t) = \rho G_e \frac{\mathcal{D}}{\Delta t} \tau \begin{cases} 0 & t < 0 \\ 1 - e^{-t/\tau} & 0 \leq t \leq \Delta t \\ \left(e^{\Delta t/\tau} - 1\right) e^{-t/\tau} & t > \Delta t \end{cases}$$

$$G_e = \frac{\text{\# particles}}{\text{radiation energy}}$$

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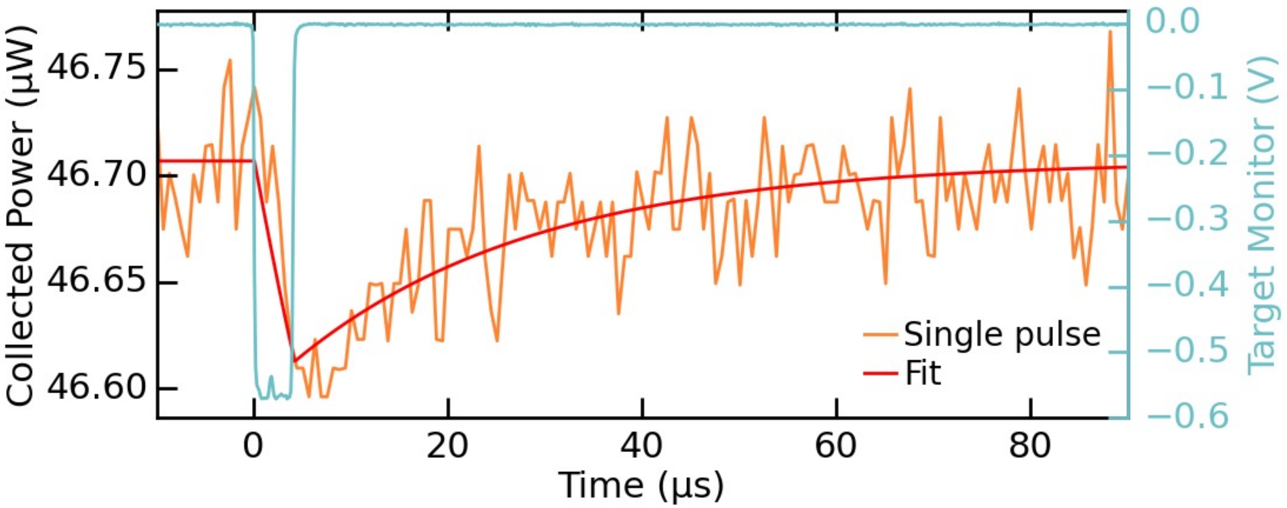

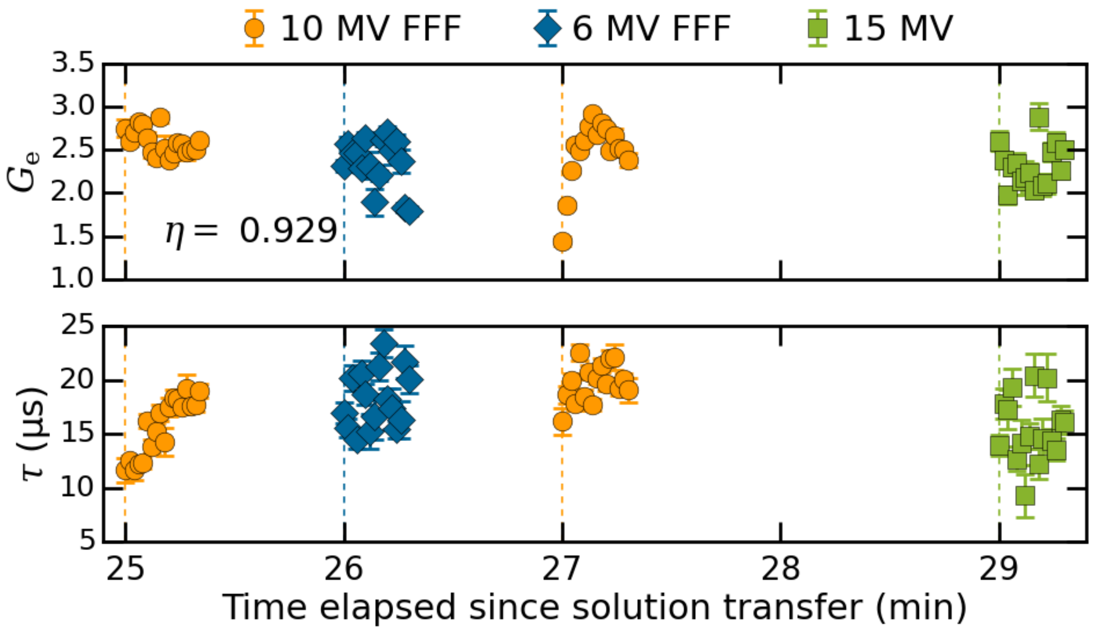

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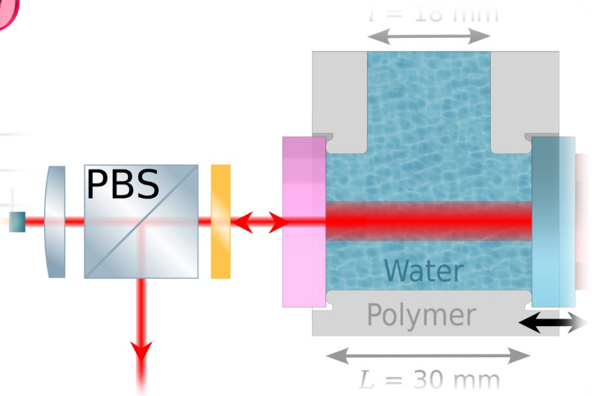

Drifts in mode coupling η due to thermal refractive-index variations

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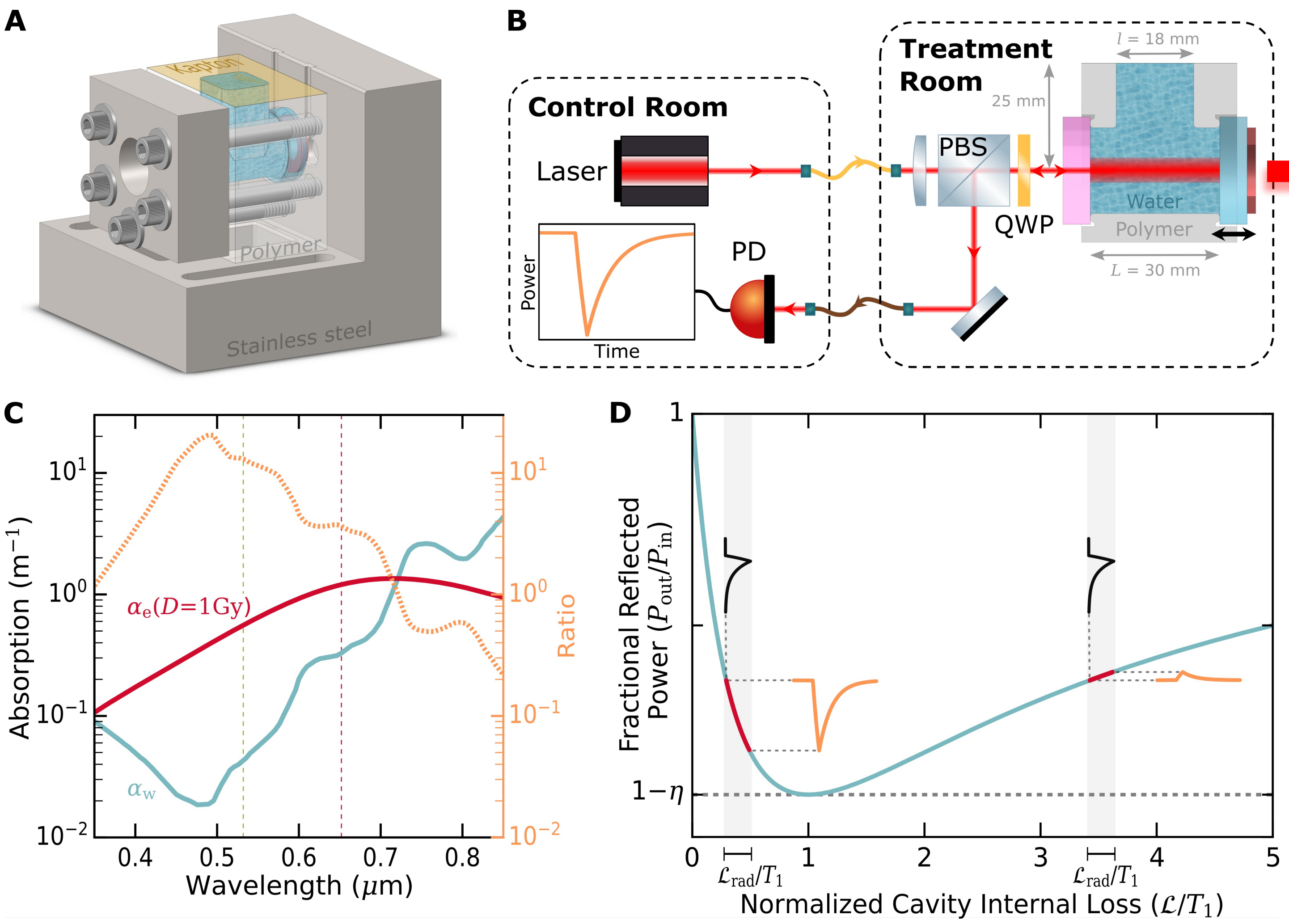
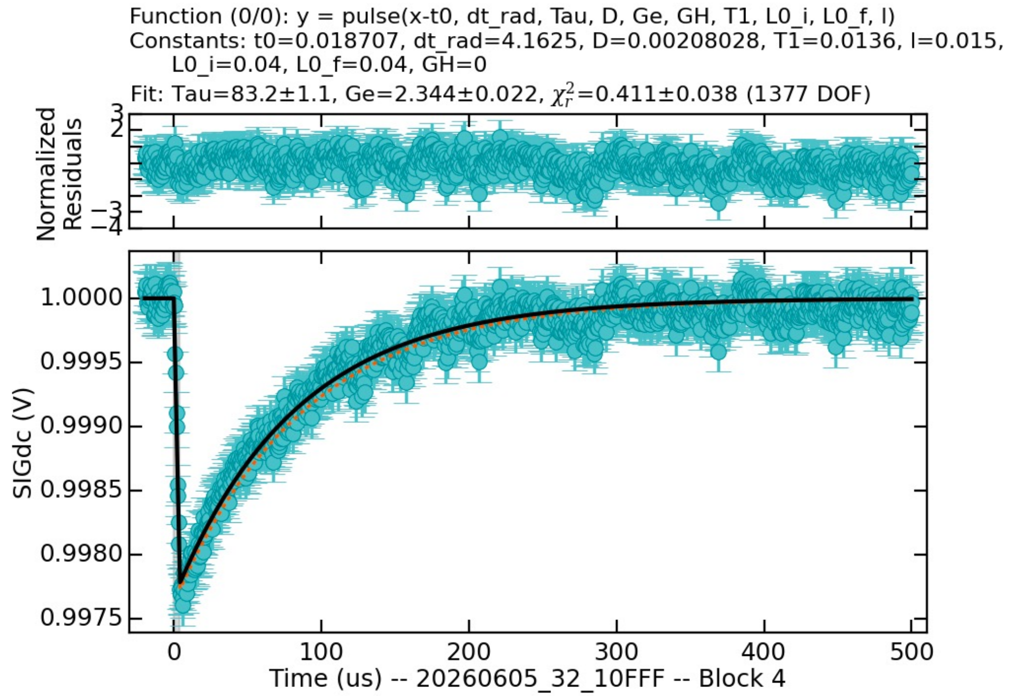
Solution: transmission measurement



Collect T

No interferences!



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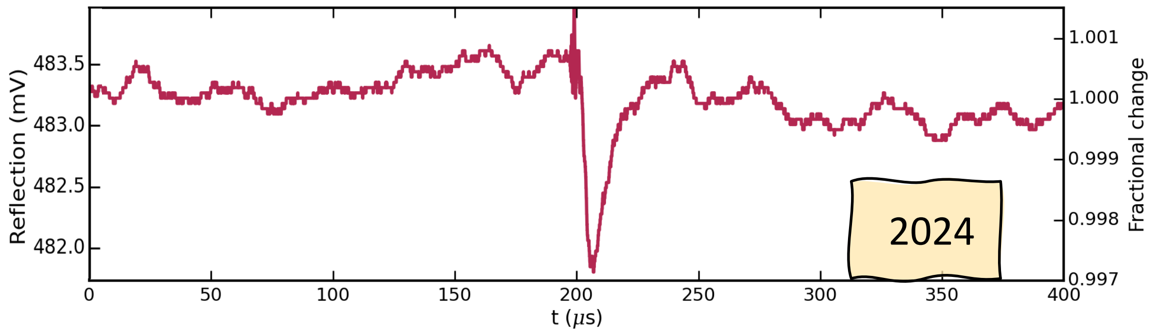

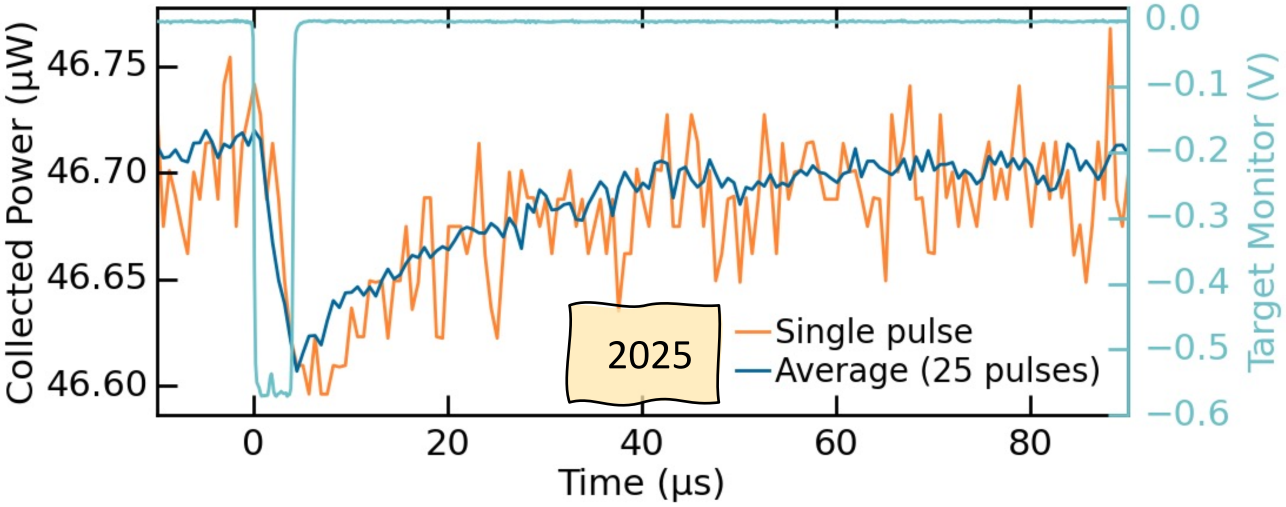

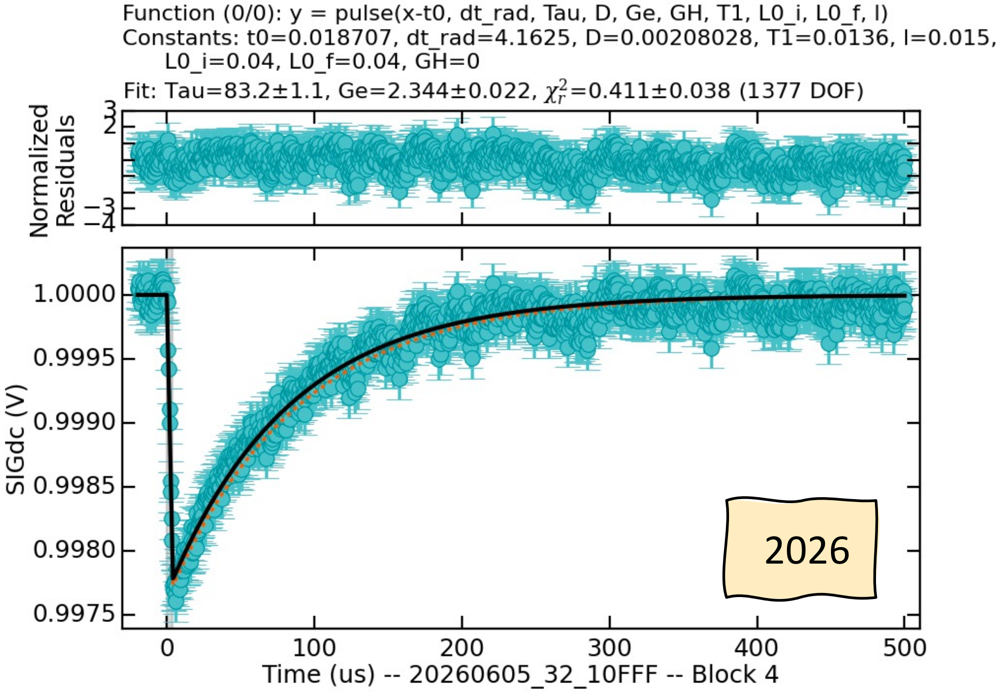

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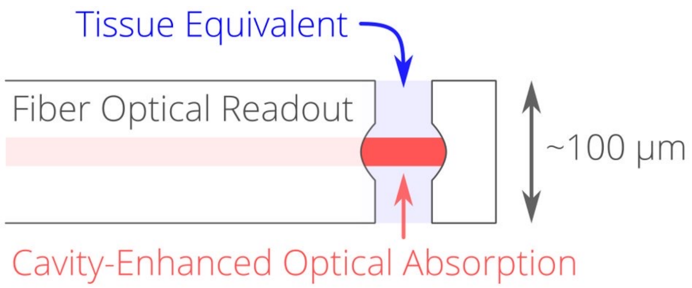
So, what, why and how?

A new sensor

- **Water medium** → independence on dose rate and beam energy
- **Absolute measurement** of absorbed dose



1. cm-scale devices

- Tissue-equivalent, absolute dosimeters (linac QA)
- Sub-mGy sensitivity
- Works well with small fields
- Can handle dose rates > 400 Gy/s

2. water-filled microcavities

- Detect **dose to a point** with excellent sensitivity
- *In vivo, in situ* dosimetry with instantaneous readout

Thank you!!

Acknowledgments:

Kate Szabo, Jingyi Bian, Julien Megroureche, Simon Bernard, Tanner Connell, Hamed Bekerat, Robert Hopewell, Lilian Childress, Shirin Enger, Jack Sankey

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