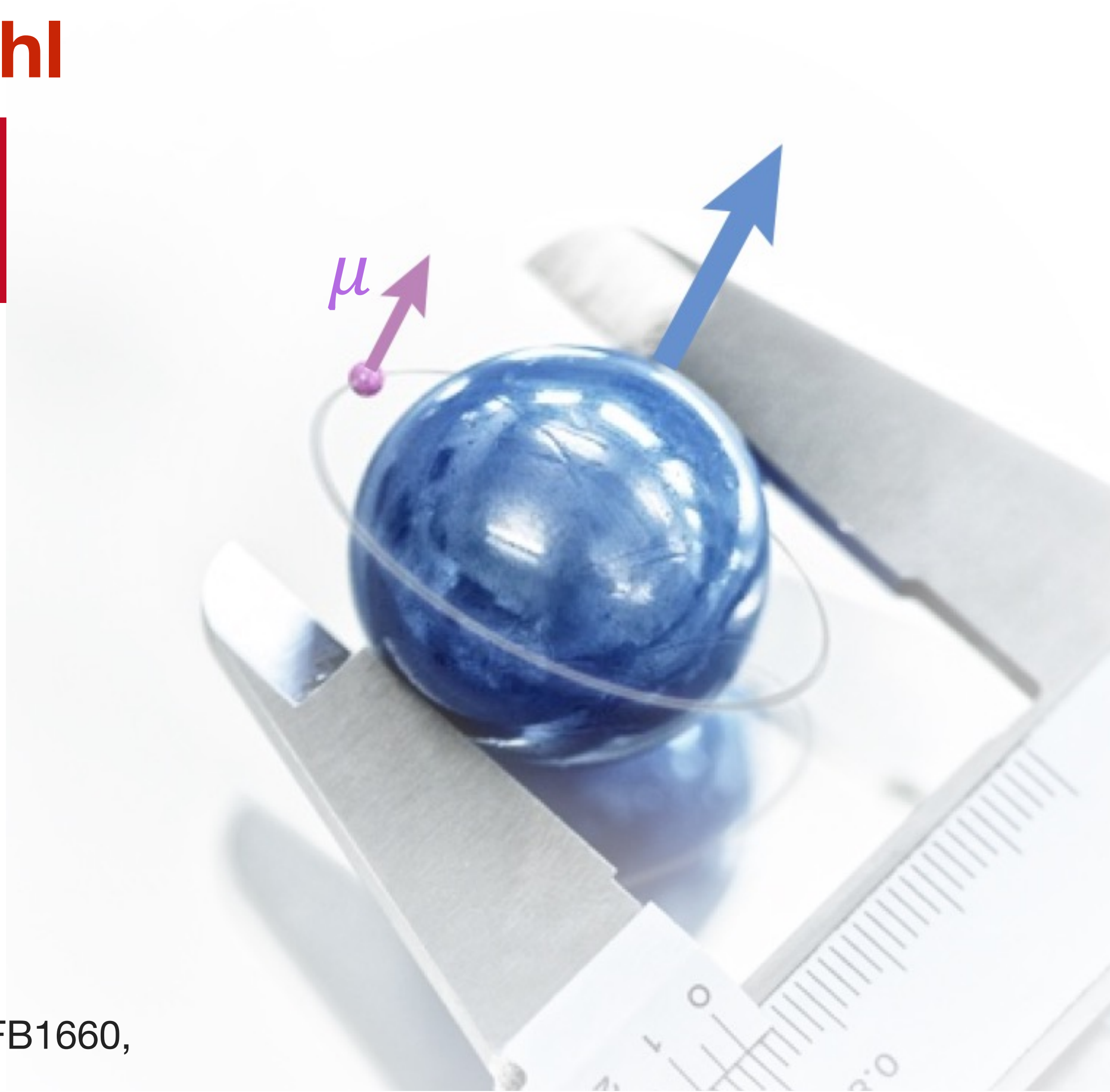
The muonic hydrogen hyperfine splitting experiment at PSI

AG Pohl

JG|U

CREMA

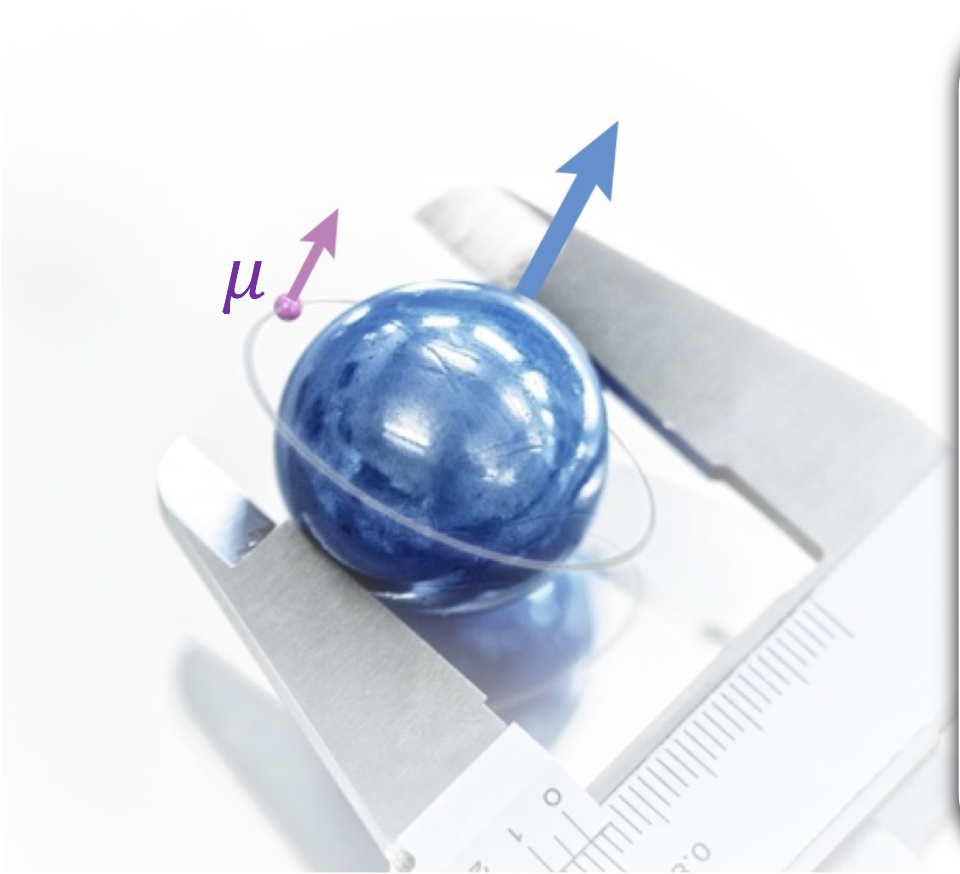
PSI

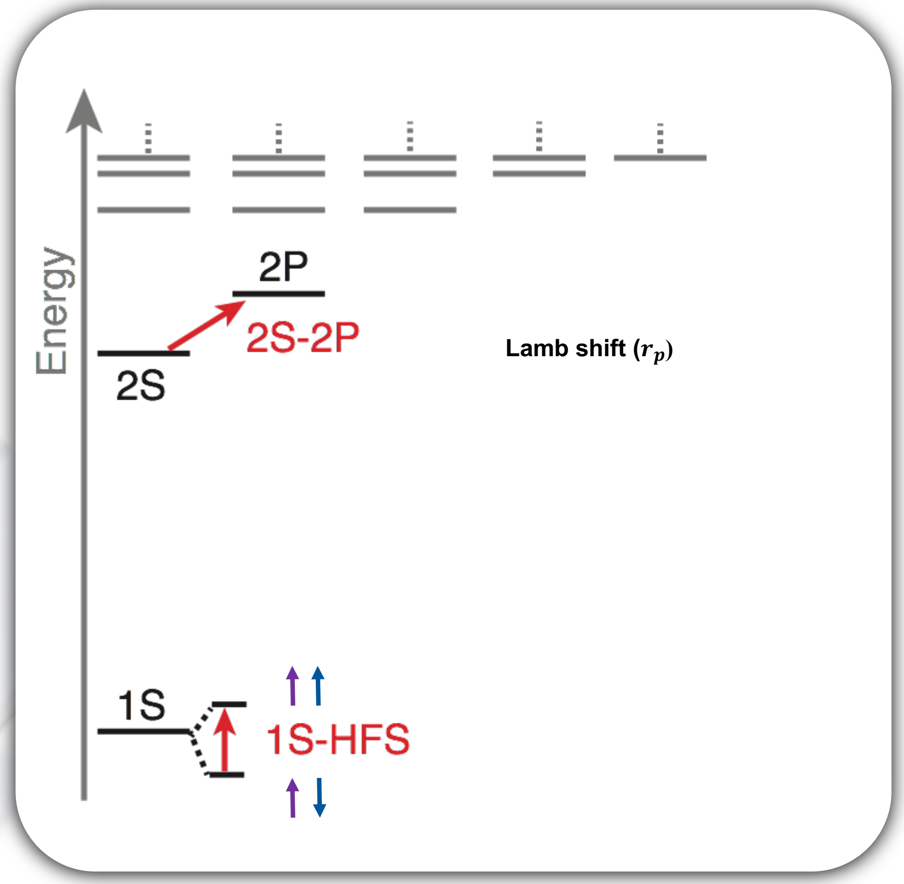


ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
FONDAZIONE BRUNO KESSLER

Supported by SFB1660,
ERC, SNF, DFG

Goal

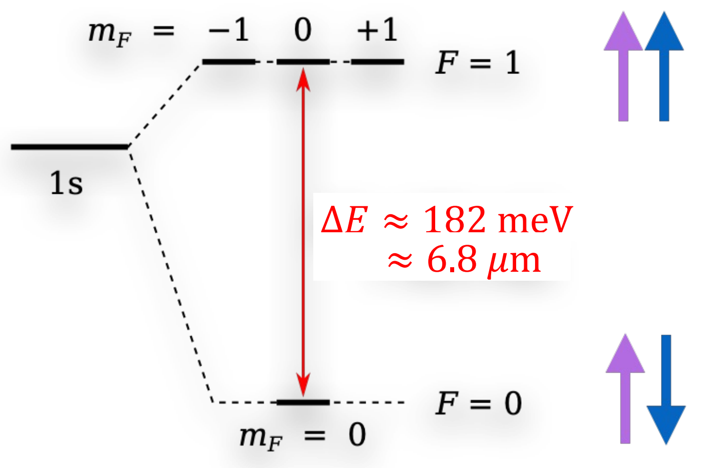


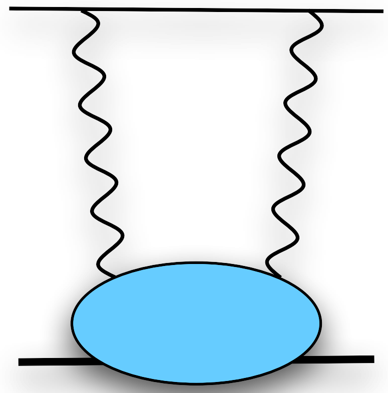


Measure the 1s-HFS in μp with a relative accuracy $\delta \approx 1\times 10^{-6}$

1S hyperfine splitting in muonic hydrogen

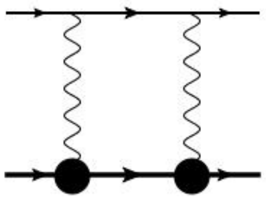
$$E_{1S-HFS}(\mu p) = \Big[\underbrace{182.443}_{E_F} + \underbrace{1.3496}_{\text{QED + weak}} + \underbrace{0.0035}_{\text{hVP}} - \underbrace{1.30670(17)\left(\frac{r_z}{\text{fm}}\right) + E_F\left(1.01656(4)\Delta_{\text{recoil}} + 1.00402\Delta_{\text{pol}}\right)}_{2\gamma + \text{rad} - \text{corrections}}\Big]\ \text{meV}$$



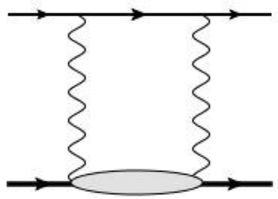


Extract the nuclear structure contribution with $\approx 1 \times 10^{-4}$ relative accuracy

Proton structure dependent contributions



$$E^{\langle 2\gamma\rangle}_{nS\text{-HFS}} = \frac{E_F}{n^3}\left(\Delta_Z + \Delta_{\text{recoil}} + \Delta_{\text{pol}}\right).$$



Zemach

$$\Delta_Z = -2Z\alpha m_r r_Z \qquad r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[\frac{G_E(Q^2)G_M(Q^2)}{1+\kappa_N} - 1\right].$$

$$\Delta_Z(\mu\text{H}) = -7403^{+21}_{-16}\ \text{ppm}$$

Lin, Yong-Hui, Hammer, Meißner (2022)

Recoil

$$\Delta_{\text{recoil}} = \frac{Z\alpha}{\pi(1+\kappa)}\int_0^\infty \frac{dQ}{Q}\left\{\frac{8mM}{v_l+v}\frac{G_M(Q^2)}{Q^2}\left(2F_1(Q^2) + \frac{F_1(Q^2)+3F_2(Q^2)}{(v_l+1)(v+1)}\right) - \frac{8m_r G_M(Q^2)G_E(Q^2)}{Q} - \frac{m}{M}\frac{5+4v_l}{(1+v_l)^2}F_2^2(Q^2)\right\}.$$

$$\Delta_{\text{recoil}} = 837.6^{+2.8}_{-1.0}\ \text{ppm}$$

Antognini, Yong-Hui, Hammer, Meißner(2022)

Polarizability

$$\Delta_{\text{pol}} = \Delta_1 + \Delta_2 \equiv \frac{Z\alpha m}{2\pi(1+\kappa_N)M}\left[\delta_1 + \delta_2\right],$$

$$\delta_1 = 18\int_0^\infty \frac{dQ}{Q}\kappa_0(Q^2)\,I_1^{(\text{pol})}(Q^2) + 16M^4\int_0^\infty \frac{dQ}{Q^3}\int_0^{x_0} dx\,\kappa_1(x,Q^2)\,g_1(x,Q^2),$$

$$\delta_2 = 96M^2\int_0^\infty \frac{dQ}{Q^3}\int_0^{x_0} dx\,\kappa_2(x,Q^2)\,g_2(x,Q^2),$$

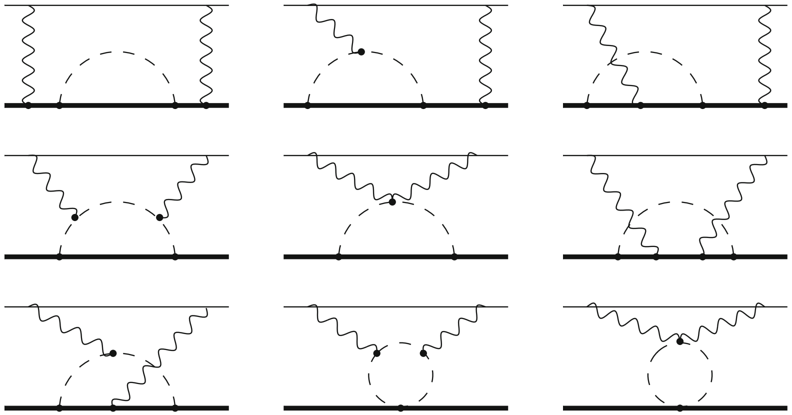
$$\Delta_{\text{pol}} = 200.6(54.0)\ \text{ppm}$$

Ruth et al. 2024

Proton polarizability

$$E_{1S-HFS}(\mu p) = \Big[\underbrace{182.443}_{E_F} + \underbrace{1.3496}_{\text{QED + weak}} + \underbrace{0.0035}_{\text{hVP}} \underbrace{- 1.30670(17)\left(\frac{r_z}{\text{fm}}\right) + E_F\left(1.01656(4)\Delta_{\text{recoil}} + 1.00402\Delta_{\text{pol}}\right)}_{2\gamma + \text{rad} - \text{corrections}}\Big]\ \text{meV}$$

Chiral Perturbation theory



$\Delta_{pol} = 38(62)$ ppm

Hagelstein, Pascalutsa (2023)

Dispersive analysis Data driven

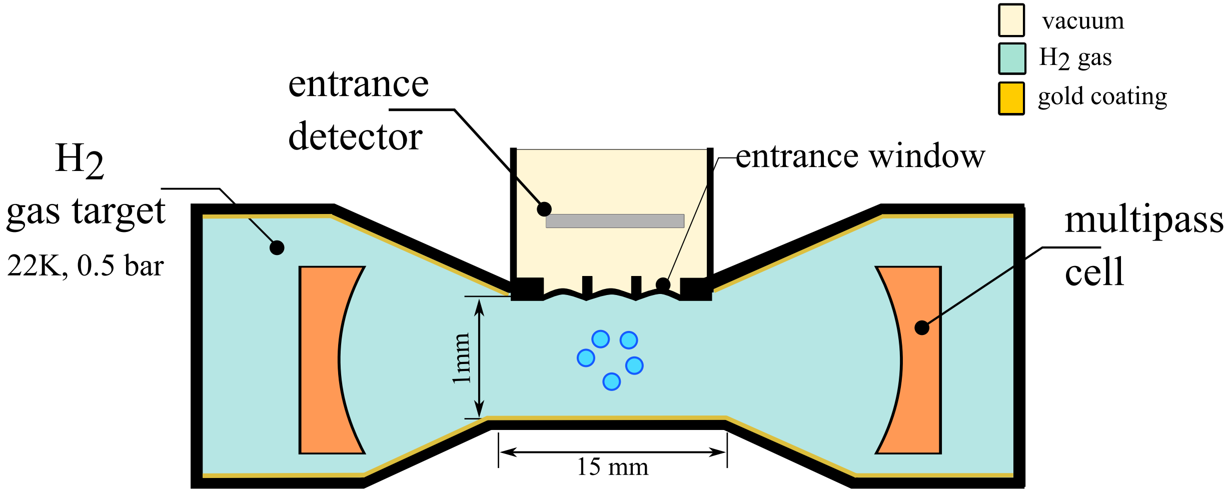
Structure functions, Form factors

$g_1(x,Q^2)$, $g_2(x,Q^2)$, F_2 …

$\Delta_{pol} = 200.6(54.0)$ ppm

Ruth et al. 2024

The principle of the experiment

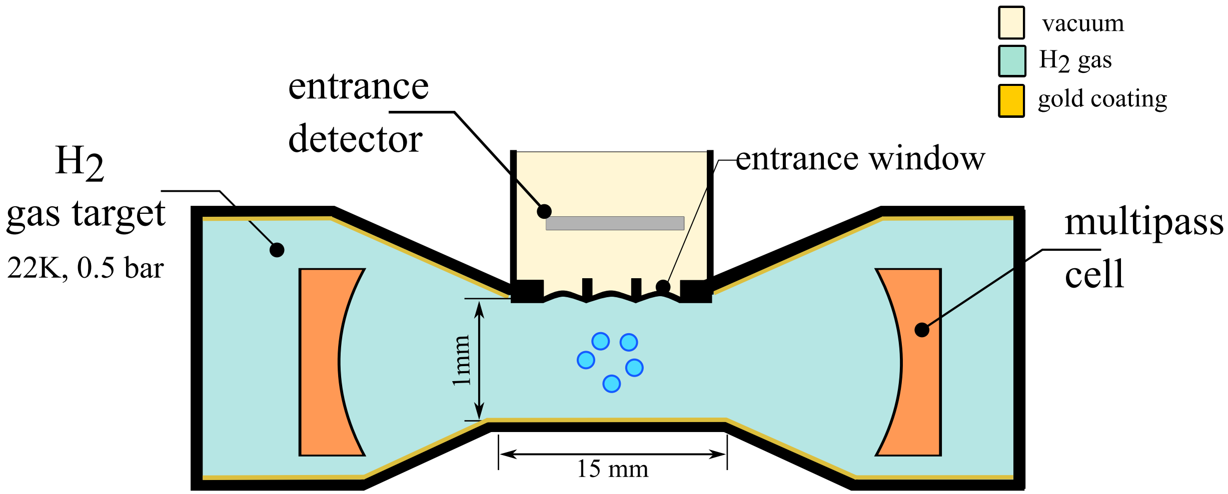


The principle of the experiment

Measurement sequence

t = 0 µs

1. μp formation
2. Thermalization
3. Laser excitation
4. De-excitation
5. Diffusion to wall
6. X-ray detection



Laser requirements

The principle of the experiment

Measurement sequence

$t = 0$ **μs**

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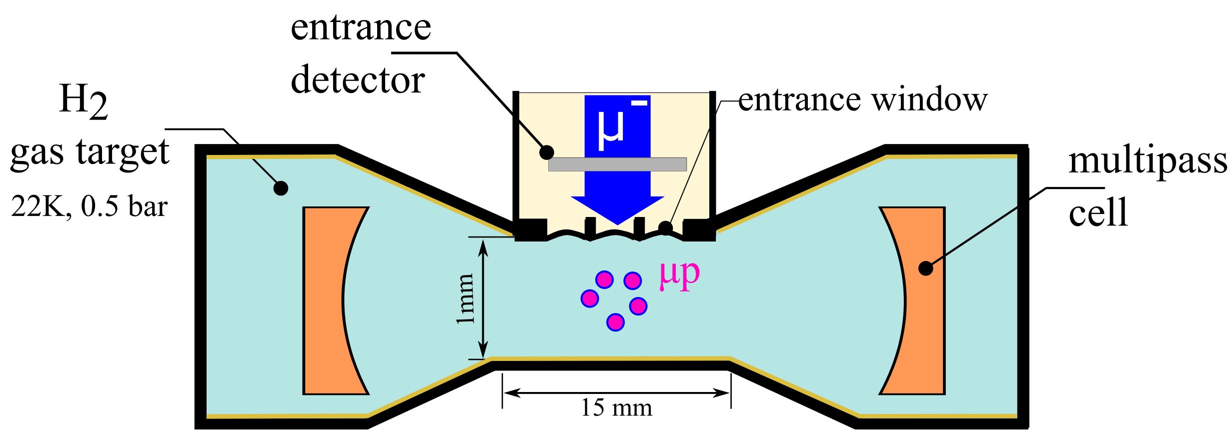
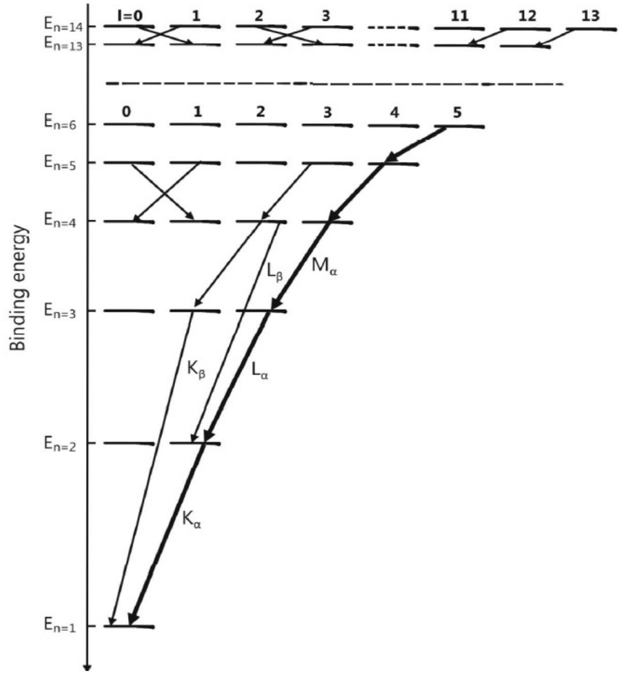


Laser requirements

1. Stochastic triggering



The principle of the experiment

Measurement sequence

$t\ =\ 0$ **μs**

1. μp formation
2. Thermalization
3. Laser excitation
4. De-excitation
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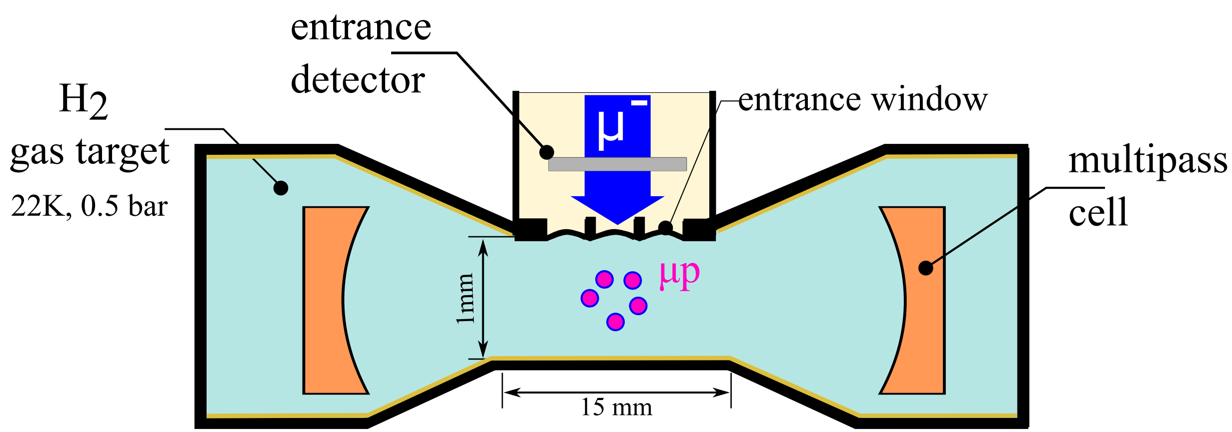
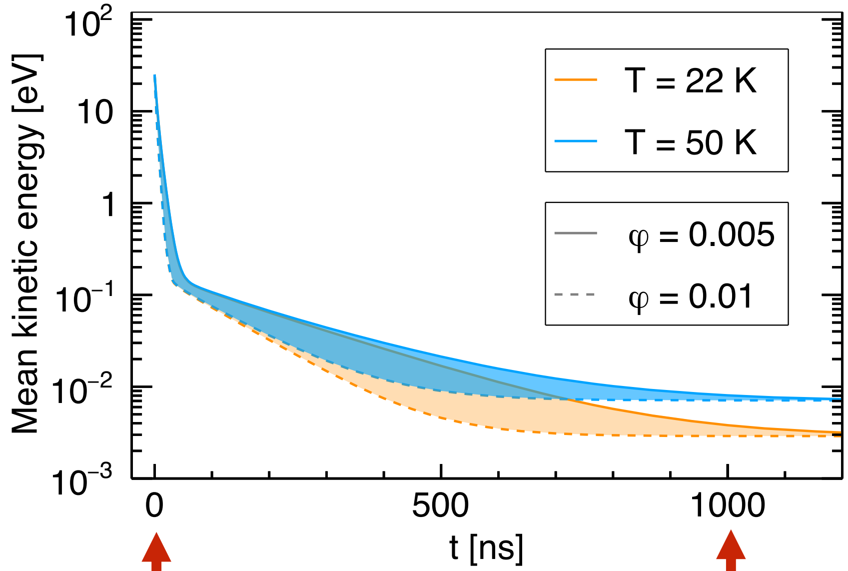
6. X-ray detection

Laser requirements

1. Stochastic triggering
2. Response time 1 μs





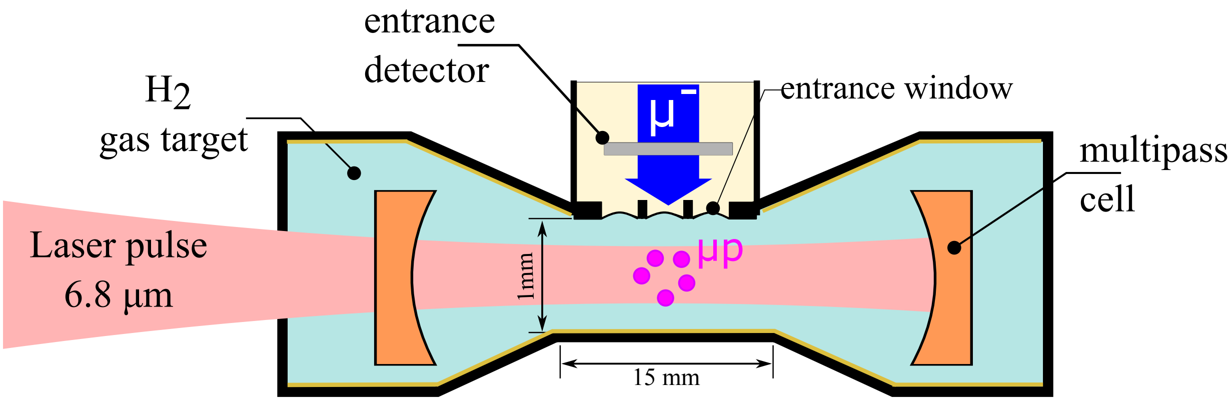
μp formation

Laser excitation

The principle of the experiment

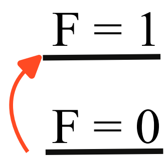
Measurement sequence

1. μp formation — $t = 0$ **µs**
2. Thermalization
3. Laser excitation — $t = 1$ **µs**
4. De-excitation
5. Diffusion to wall
6. X-ray detection



Laser requirements

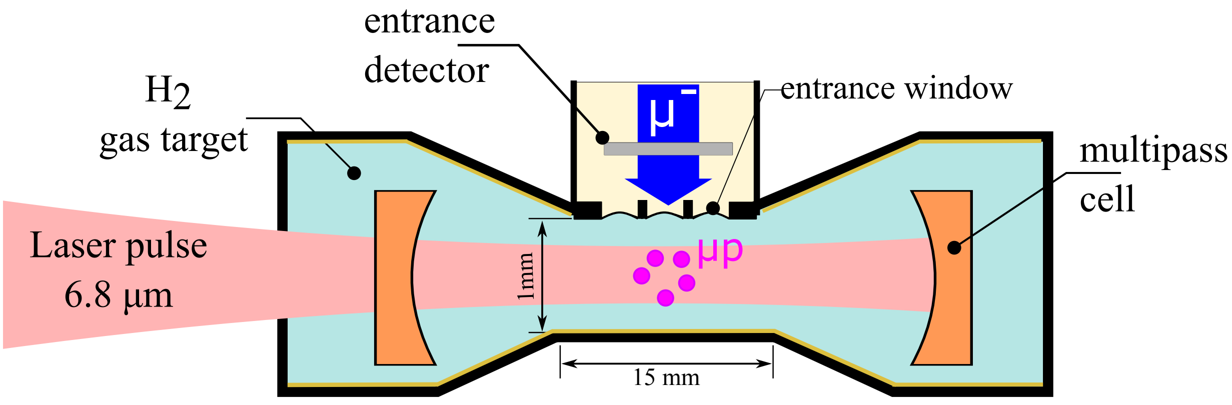
1. Stochastic triggering
2. Response time 1 µs
3. 3mJ @ 6.8 µm
4. Beam quality $M^2 \approx 1$



The principle of the experiment

Measurement sequence

1.	μp formation	$t = 0$ μs
2.	Thermalization	
3.	Laser excitation	$t = 1$ μs
4.	De-excitation	
5.	Diffusion to wall	
6.	X-ray detection	



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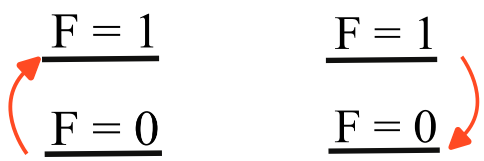
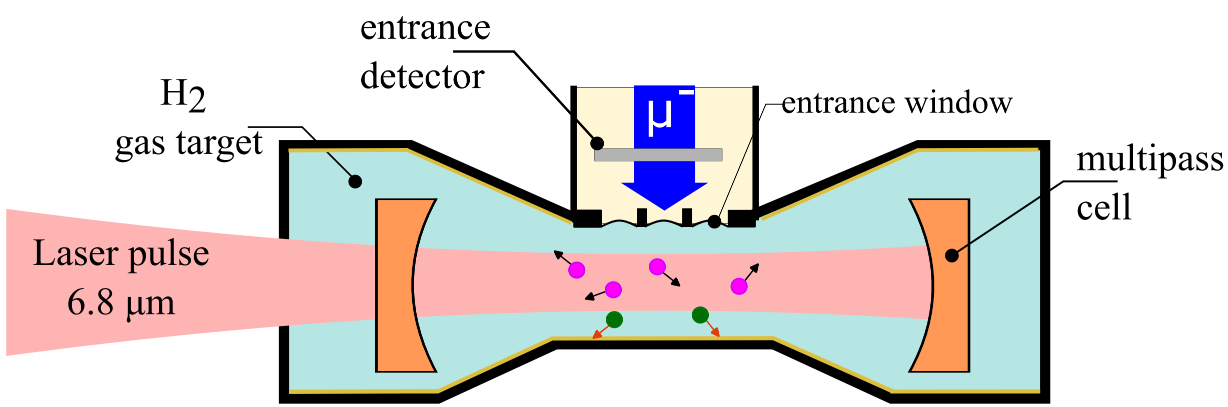


$$H_2 + \mu p^{F=1} \rightarrow H_2 + \mu p^{F=0} + E_{kin}$$

The principle of the experiment

Measurement sequence

1. μp formation — $t = 0$ μs
2. Thermalization
3. Laser excitation — $t = 1$ μs
4. De-excitation
5. Diffusion to wall
6. X-ray detection



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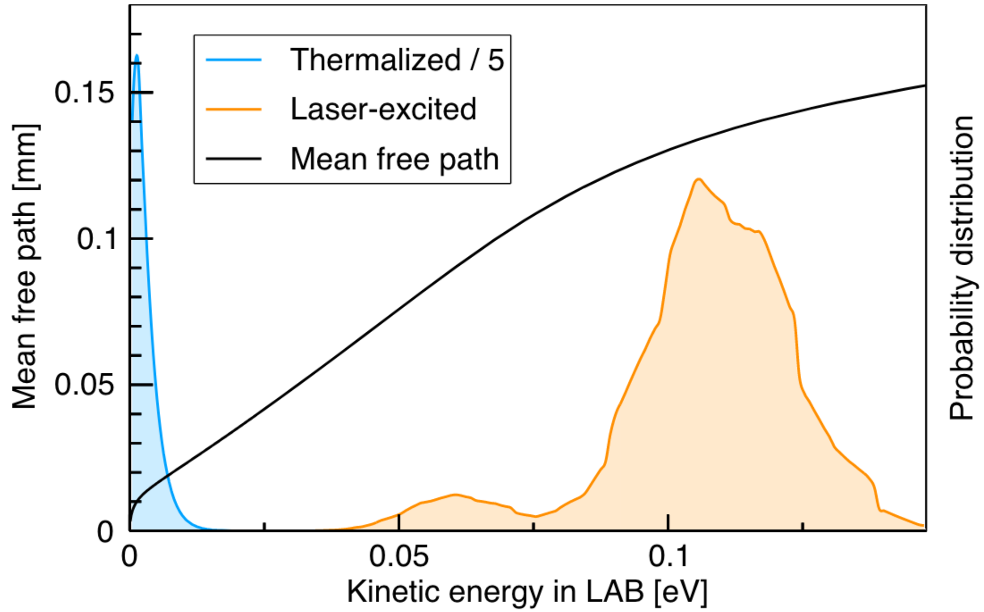
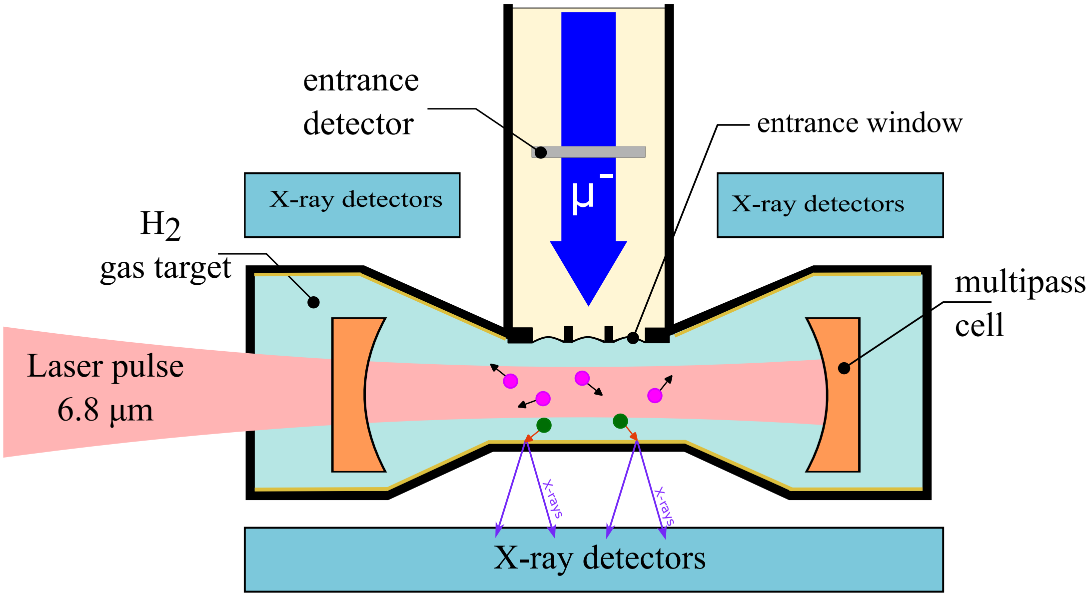


The principle of the experiment

Measurement sequence

1.	μp formation	$t = 0$ µs
2.	Thermalization	
3.	Laser excitation	$t = 1$ µs
4.	De-excitation	
5.	Diffusion to wall	
6.	X-ray detection	$t \approx 1.2$ µs



Laser requirements

1. Stochastic triggering
2. Response time 1 µs
3. 3mJ @ 6.8 µm
4. Beam quality $M^2 \approx 1$

$$\mu p + Au \to (\mu Au)^* + p$$
$$(\mu Au)^* \to \mu Au + \text{X-rays}$$

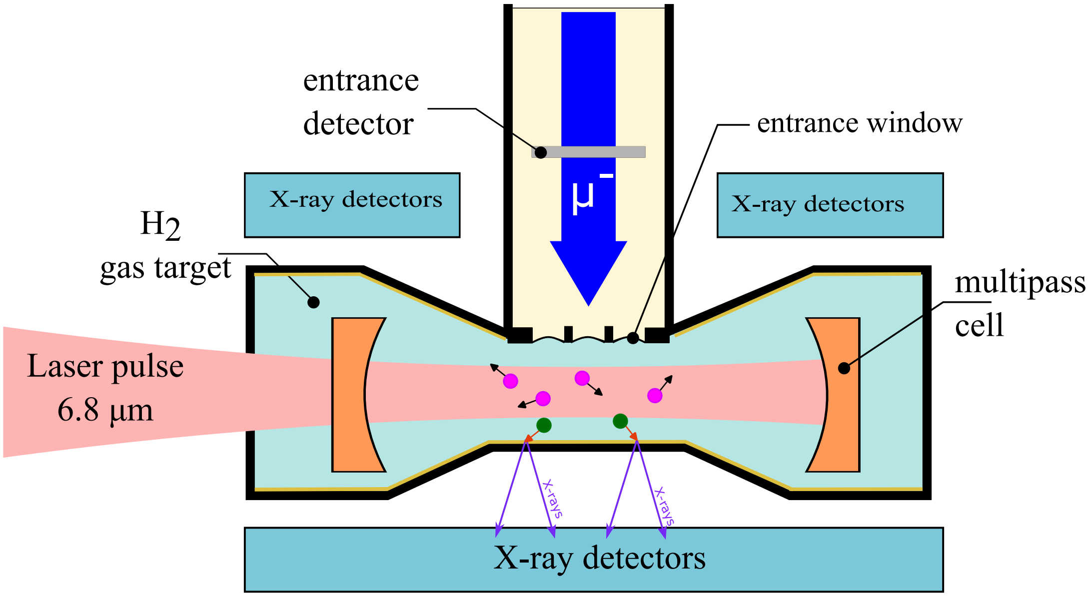
The principle of the experiment

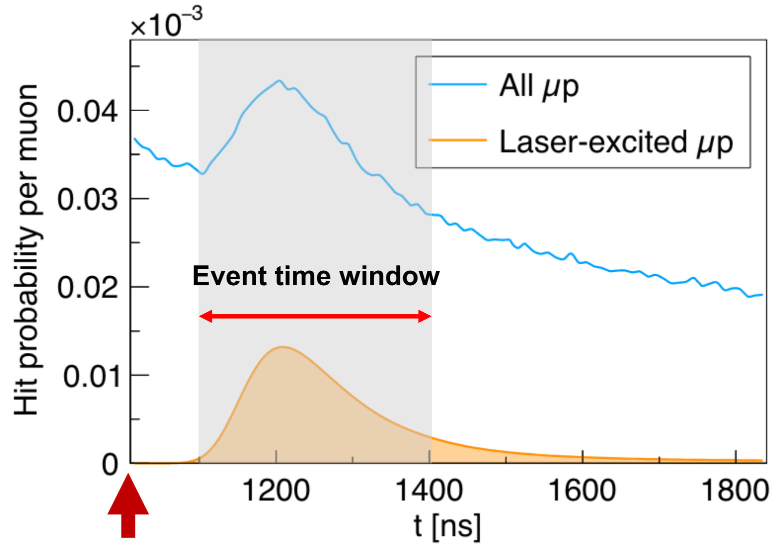
Measurement sequence

1.	μp formation	t = 0 µs
2.	Thermalization	
3.	Laser excitation	t = 1 µs
4.	De-excitation	
5.	Diffusion to wall	
6.	X-ray detection	t ≈ 1.2 µs

Laser requirements

1. Stochastic triggering
2. Response time 1 µs
3. 3mJ @ 6.8 µm
4. Beam quality $M^2 \approx 1$
5. ≲ 100 MHz laser bandwidth





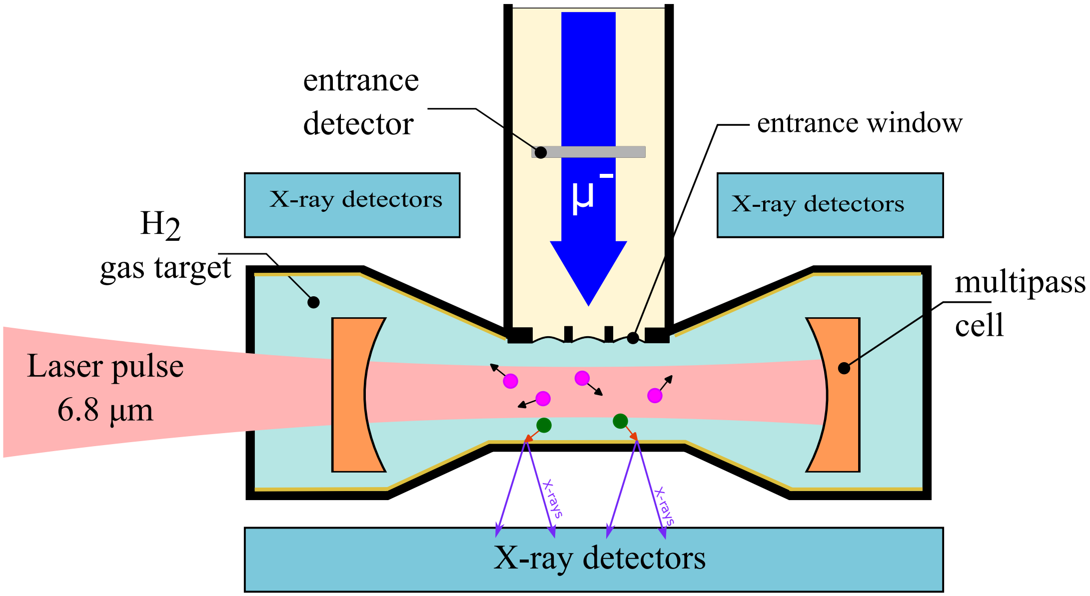
The principle of the experiment

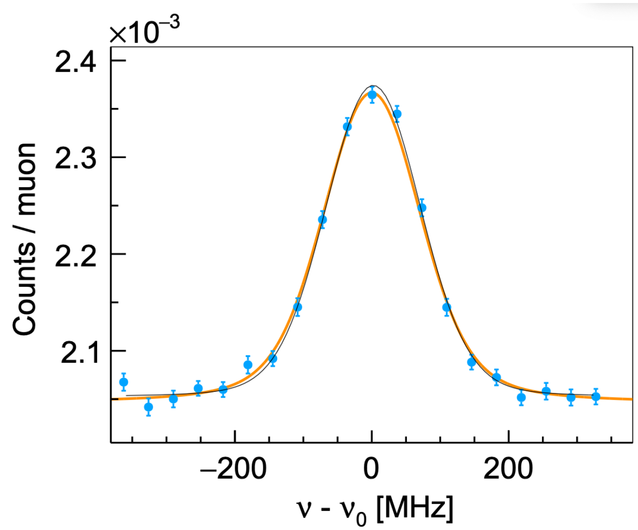
Measurement sequence

1.	μp formation	t = 0 µs
2.	Thermalization	
3.	Laser excitation	t = 1 µs
4.	De-excitation	
5.	Diffusion to wall	
6.	X-ray detection	$t \approx 1.2$ µs

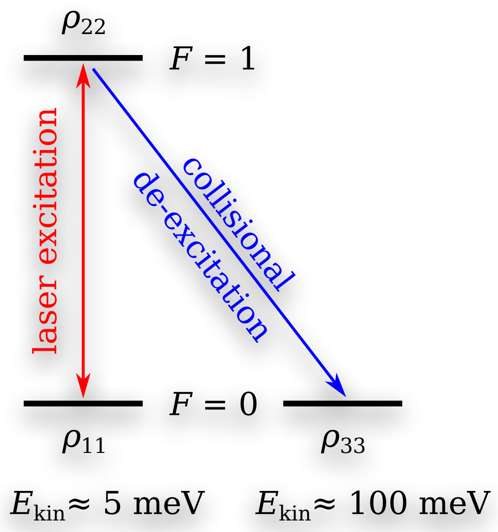
Laser requirements

1. Stochastic triggering
2. Response time 1 µs
3. 3mJ @ 6.8 µm
4. Beam quality $M^2 \approx 1$
5. $\lesssim$ 100 MHz laser bandwidth
6. Widely tunable (50 GHz)





Laser excitation modeled including collision

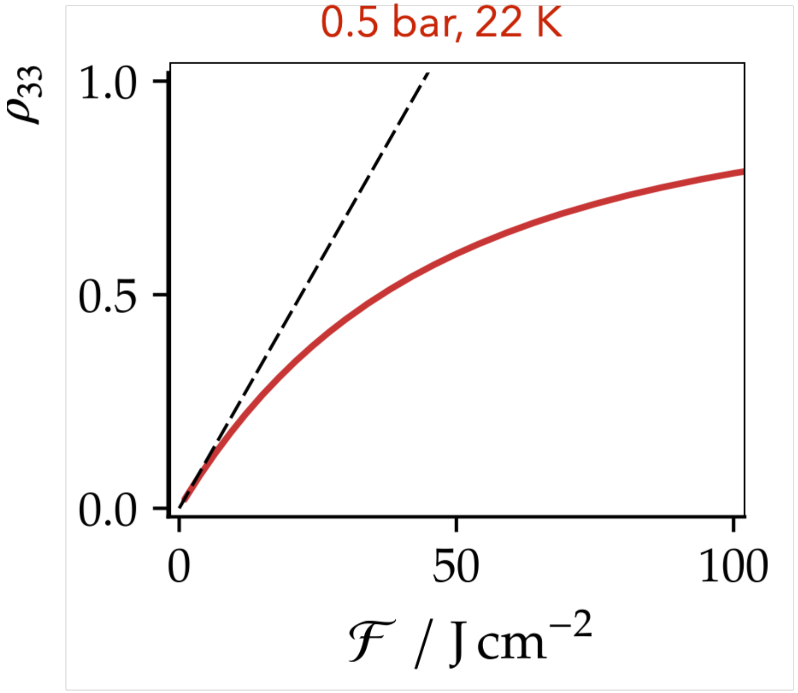


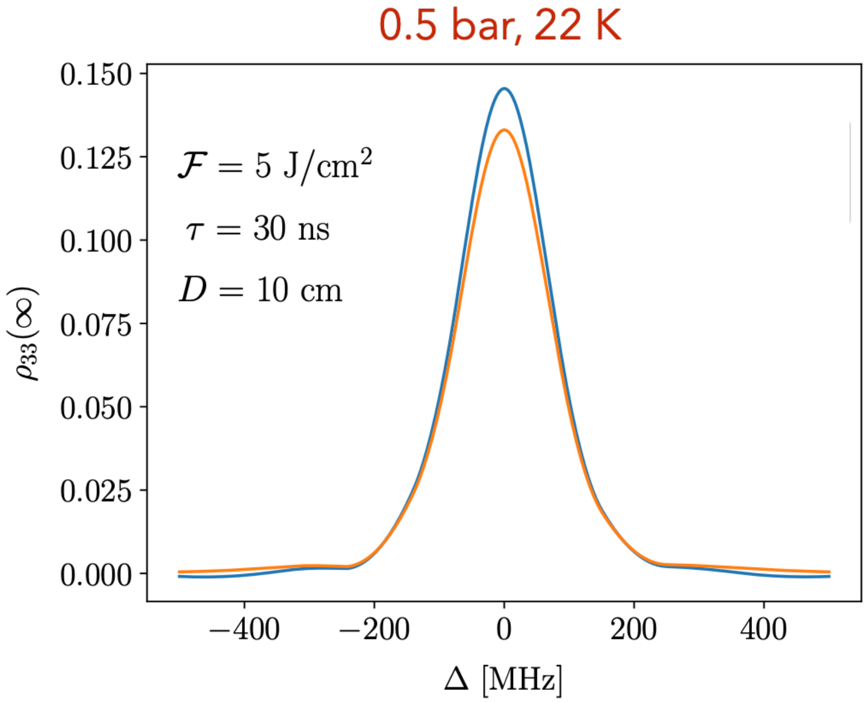
$$\begin{aligned}
\frac{d\rho_{11}}{dt}(t) &= -\mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) + \Gamma_{\mathrm{sp}}\rho_{22}\,, \\
\frac{d\rho_{22}}{dt}(t) &= \mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) - (\Gamma_i + \Gamma_{\mathrm{sp}})\rho_{22}\,, \\
\frac{d\rho_{12}}{dt}(t) &= \frac{i\Omega^*}{2}(\rho_{11} - \rho_{22})e^{-i\Delta t} - \frac{\Gamma_c}{2}\rho_{12}\,, \\
\frac{d\rho_{33}}{dt}(t) &= \Gamma_i\rho_{22}\,,
\end{aligned}$$

- ✓ Inelastic collisions
- ✓ Elastic collisions
- ✓ Laser bandwidth
- ✓ Doppler broadening

P.Amaro et al. (scipost 2022)

Saturation fluence and linewidth



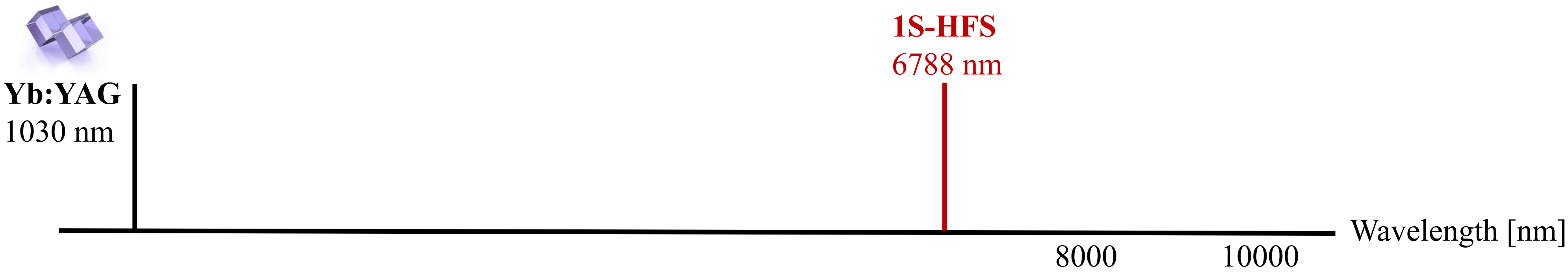


Transition	Linewidth	Saturation fluence
2S-2P	20 GHz	0.016 J/cm^2
HFS	200 MHz	44 J/cm^2

Laser system requirements

1. Stochastic triggering
2. Response time 1 μs
3. 3mJ @ 6.8 μm
4. Beam quality $M^2 \approx 1$
5. $\lesssim$ 100 MHz laser bandwidth
6. Widely tunable (50 GHz)

The laser system



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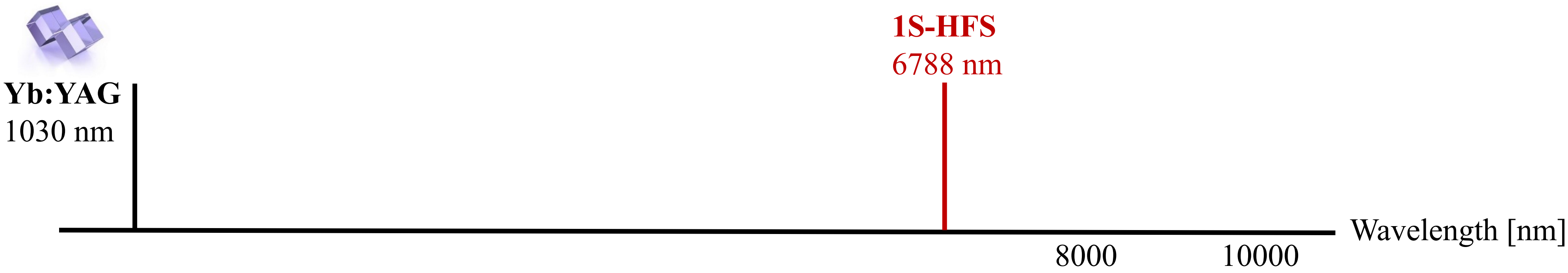
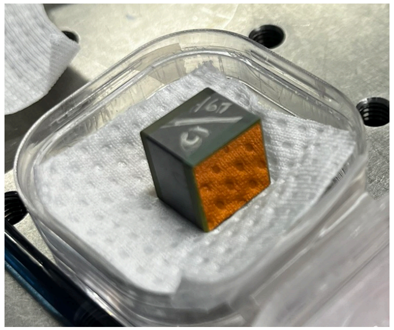
Down-conversion





ZGP

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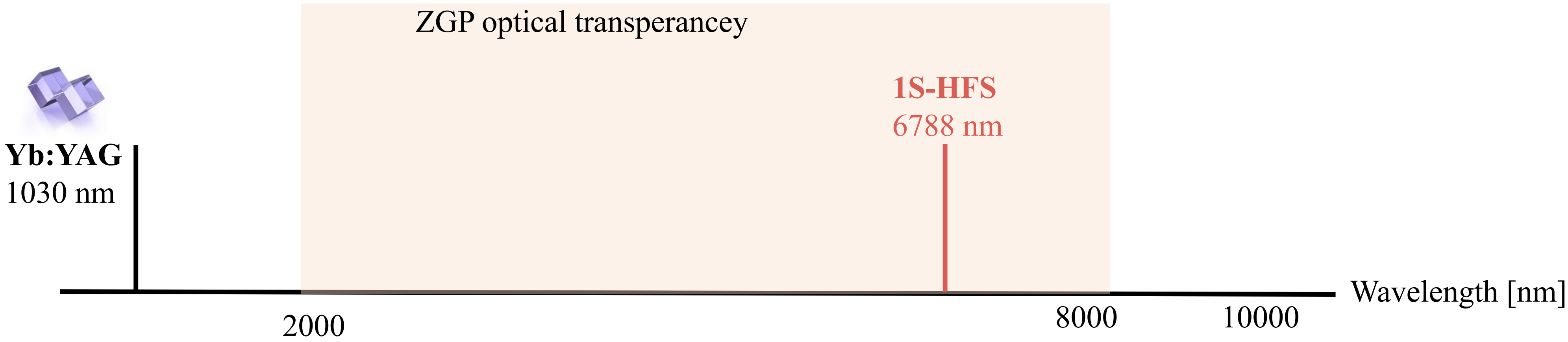

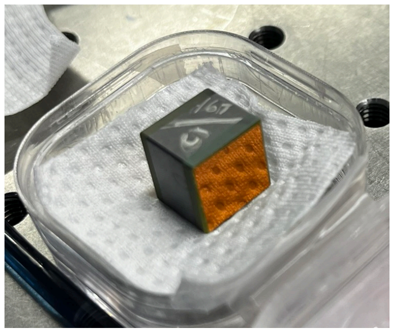

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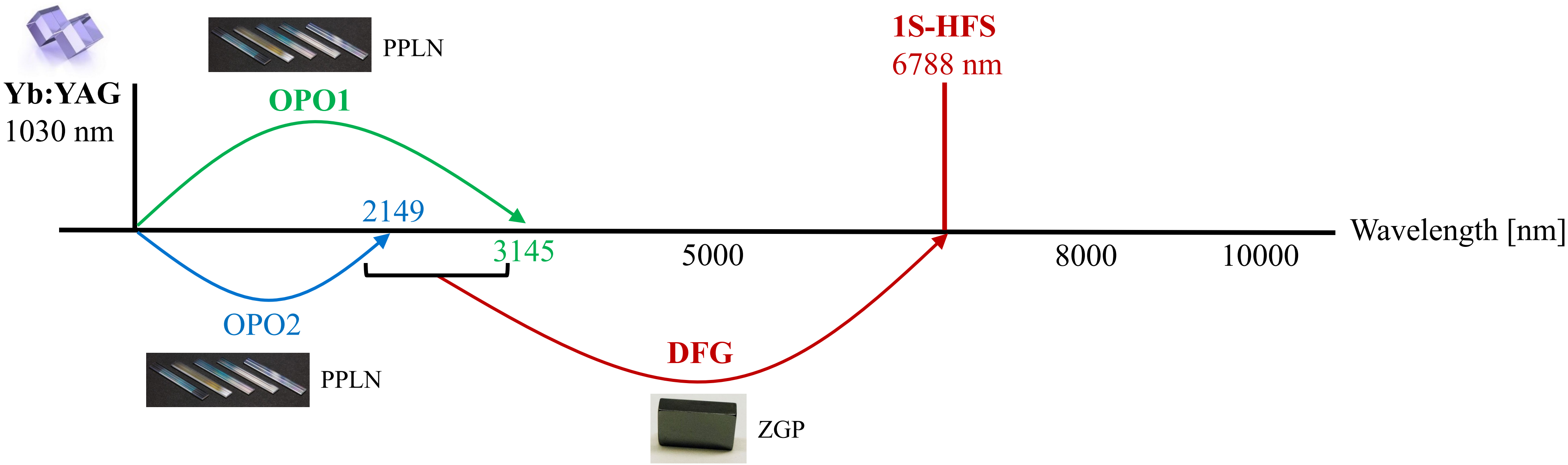
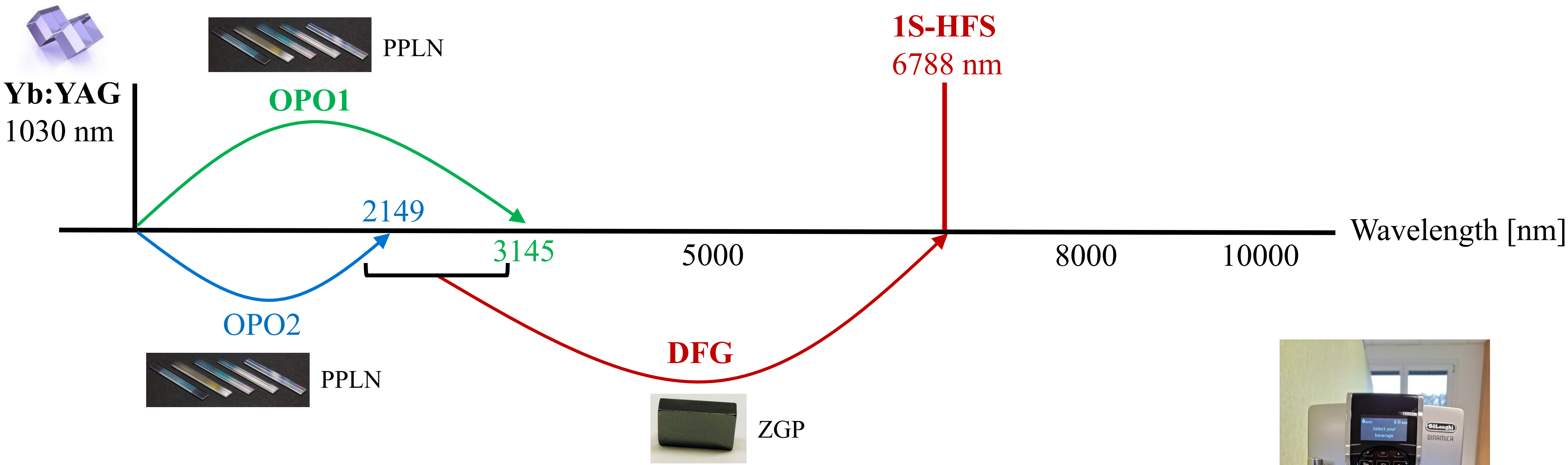
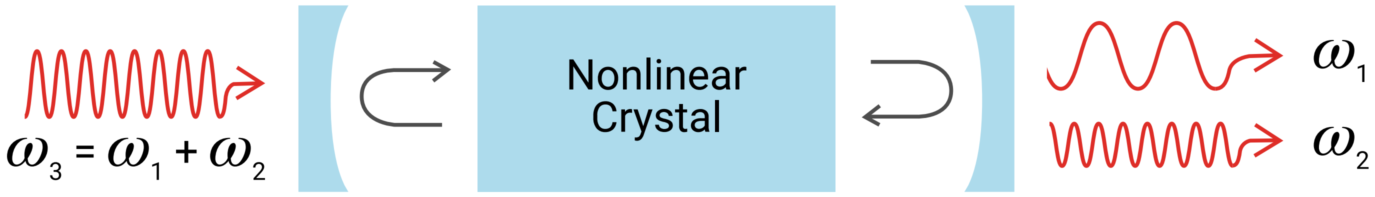


Down-conversion

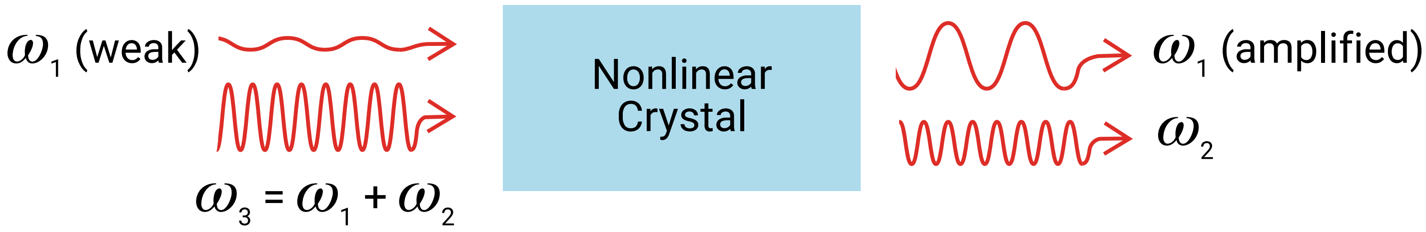


OPO/OPA/DFG

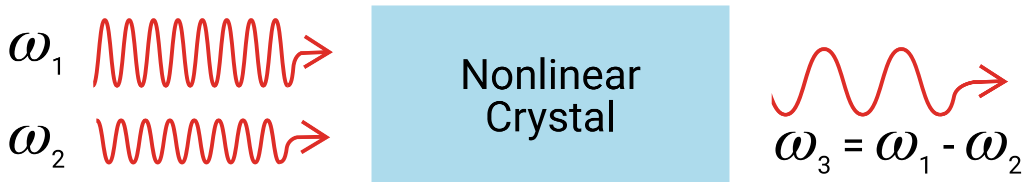
Optical Parametric Oscillation (OPO)



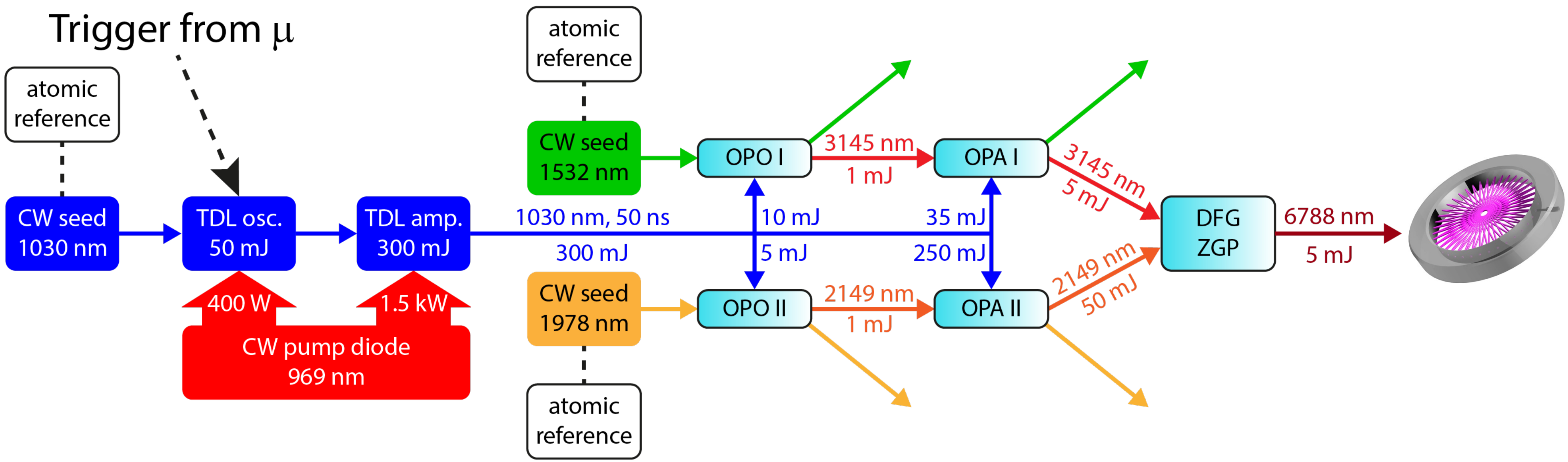
Optical Parametric Amplification (OPA)



Difference Frequency Generation (DFG)

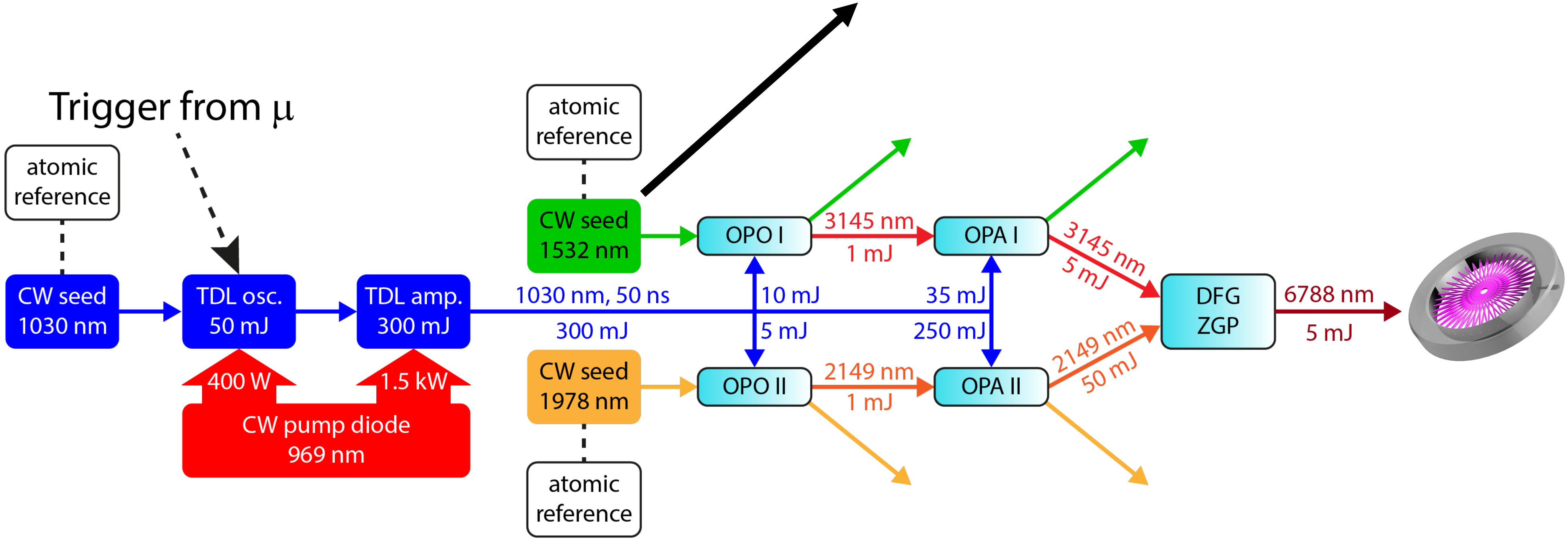


The laser system

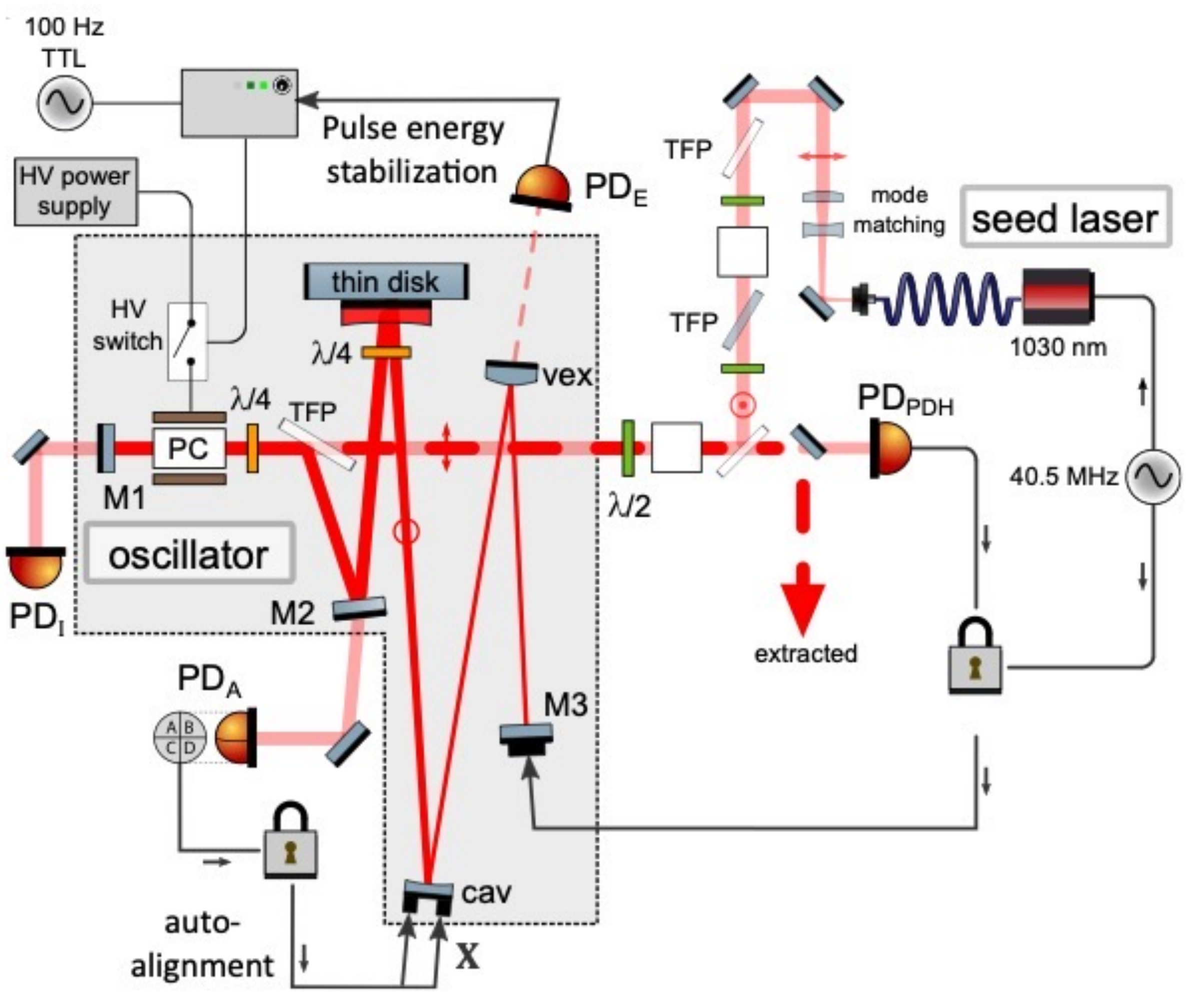


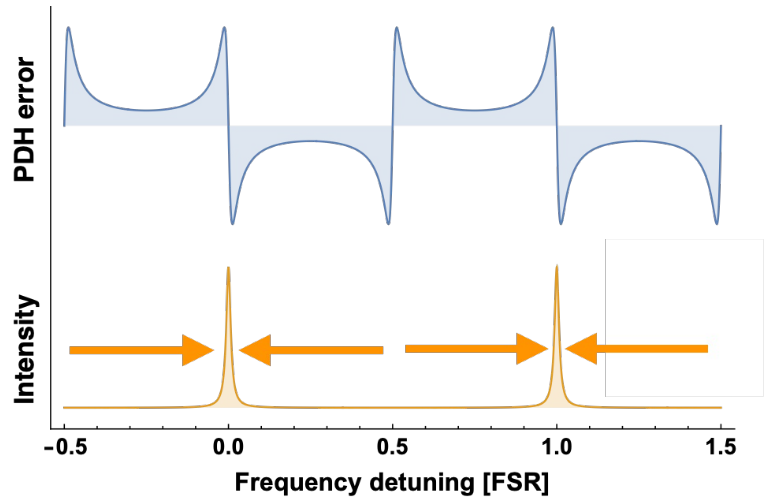
Frequency control

$$\nu_{67XX} = \nu_{2149} - \nu_{31XX} = \nu_{15XX} - \nu_{1979}$$



Thin-disk oscillator



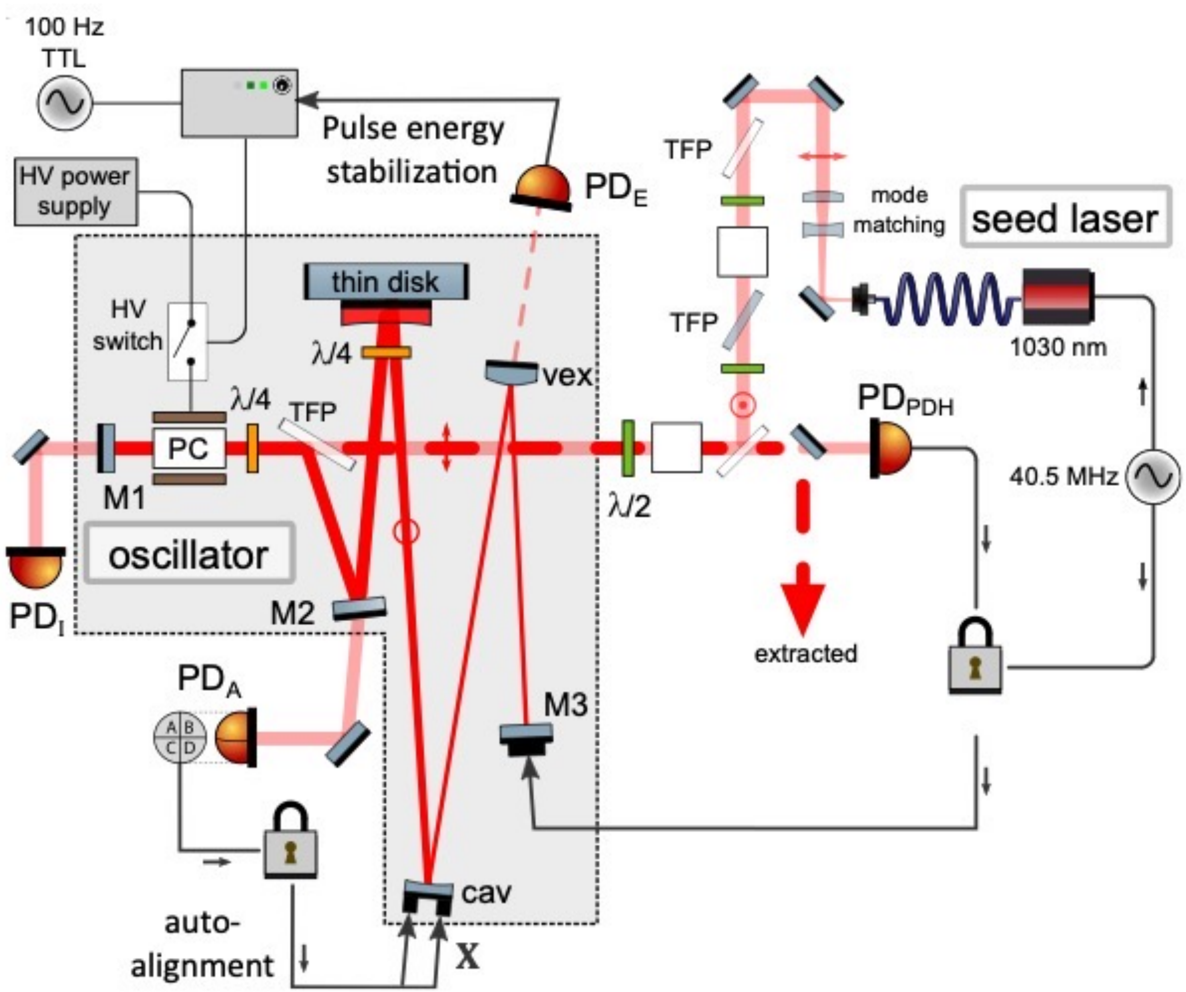


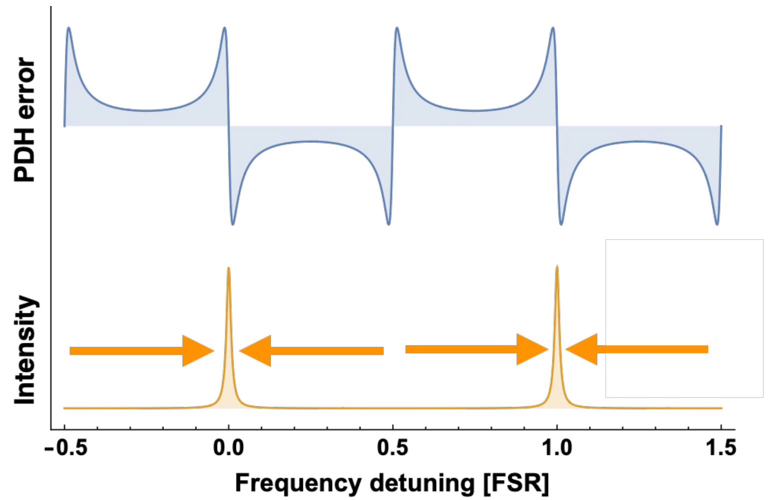
Zeyen, Manuel, et al. review of scientific instruments 2023.

Zeyen, Manuel, et al. Optics express, 2023.

- ✓ Delay: 700 ns
- ✓ Energy: 50 mJ
- ✓ Pulse-to-pulse stability: <0.5% (rms)
- ✓ Single-frequency operation
- ✓ Laser chirp < 2 MHz
- ✓ PDH lock scheme with infinite dynamic range

Thin-disk oscillator





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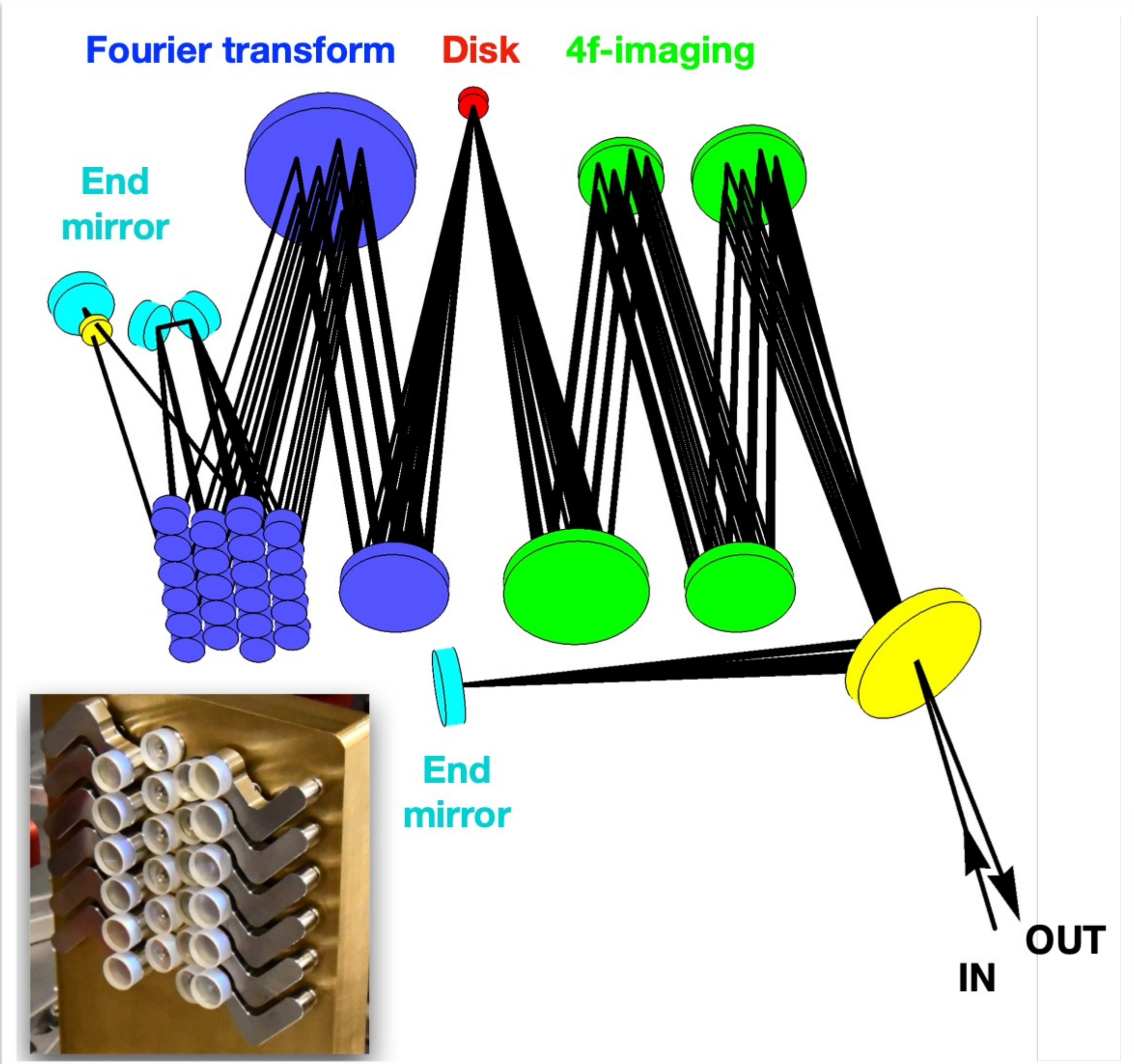
Multipass amplifier

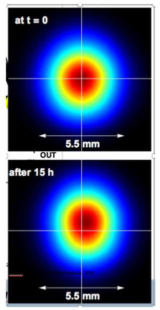
Sequence
4f
amplification
Fourier transform
amplfication
4f
4f
amplification
Fourier transform
amplfication
4f
4f
amplification
Fourier transform
amplfication
4f
4f
.
.
.



Zeyen, Manuel, et al. 2019

K. Schuhmann et al., Appl. Opt. 57, 10323-10333 (2018)

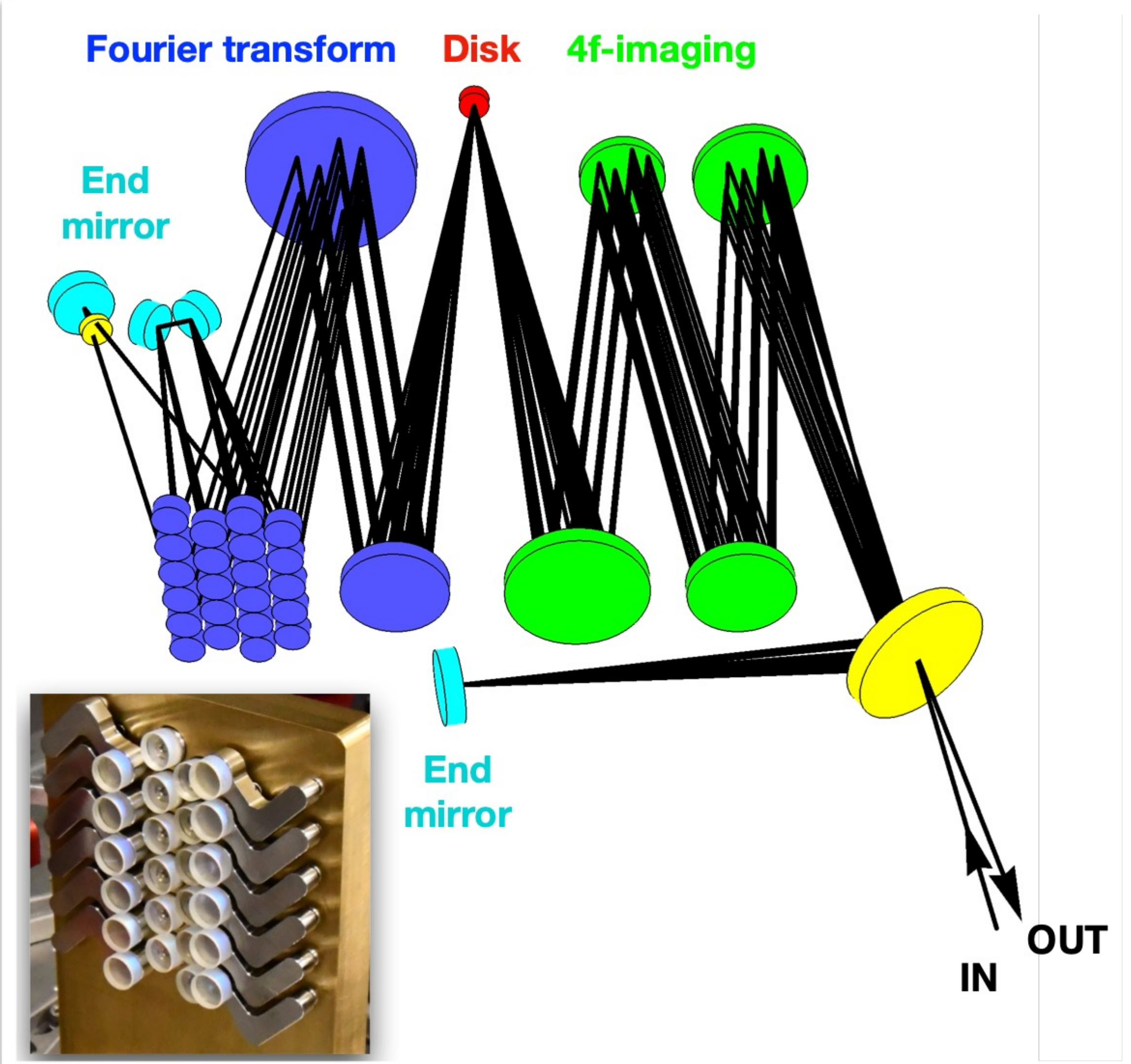
- ✓ **Insensitive to thermal lensing**
- ✓ **Energy: 330 mJ**
- ✓ **M2 < 1.17**
- ✓ **Pointing stability**



Zeyen, Manuel, et al. Optics express, 2024.

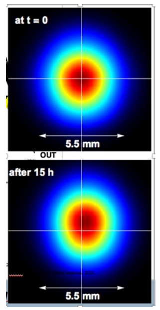
Multipass amplifier

Sequence
4f
amplification
Fourier transform
amplfication
4f
4f
amplification
Fourier transform
amplfication
4f
4f
amplification
Fourier transform
amplfication
4f
4f
.
.
.



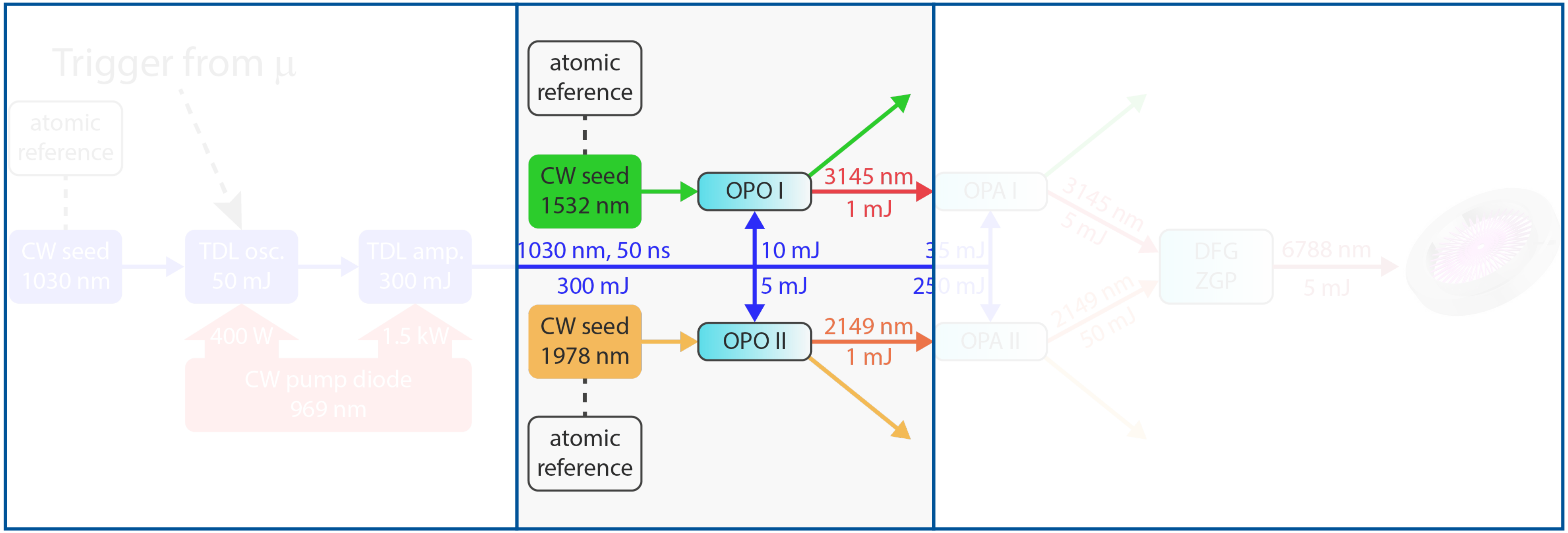
Zeyen, Manuel, et al. 2019
K. Schuhmann et al., Appl. Opt. 57, 10323-10333 (2018)

- ✓ Insensitive to thermal lensing
- ✓ Energy: 330 mJ
- ✓ M2 < 1.17
- ✓ Pointing stability

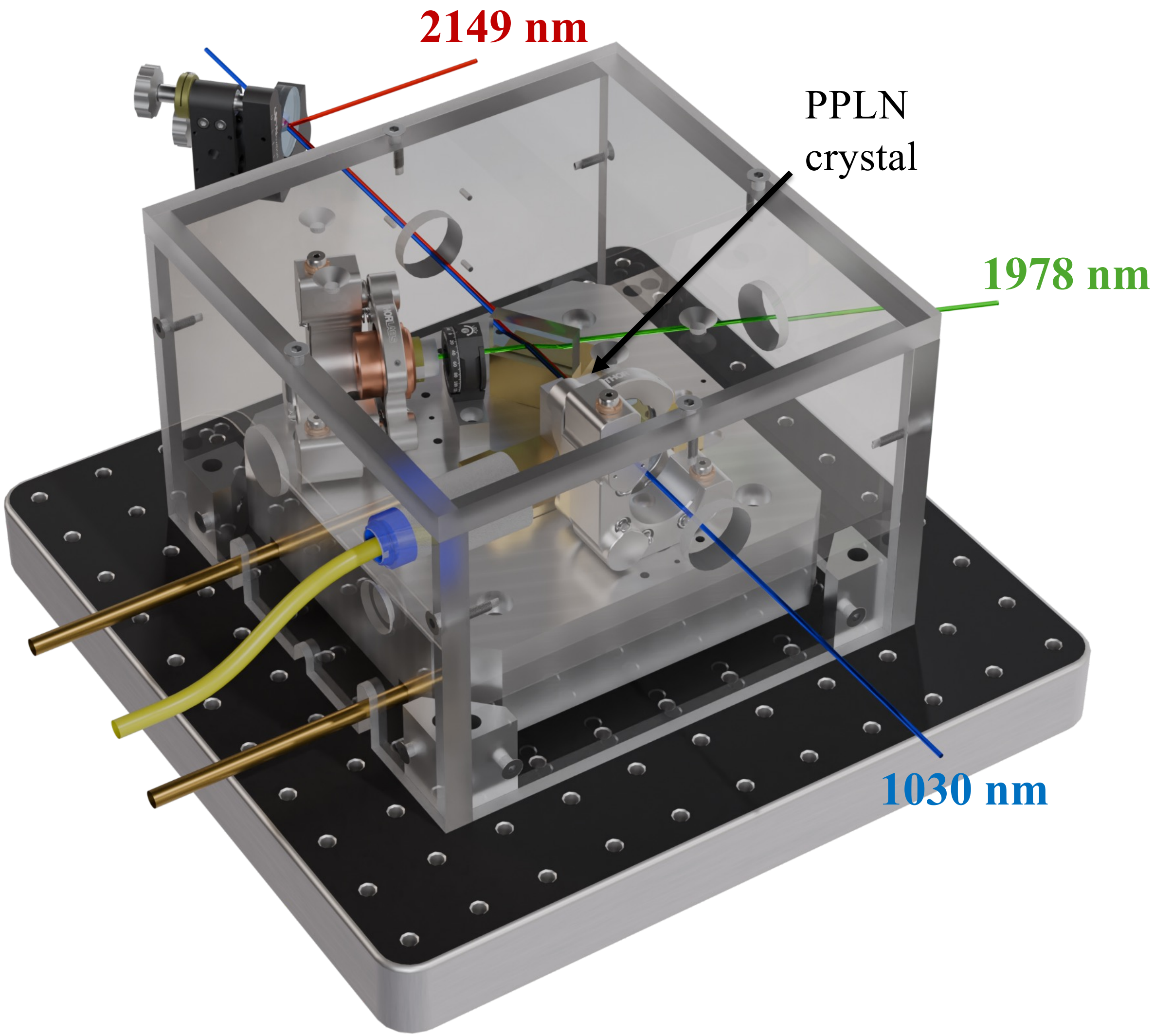


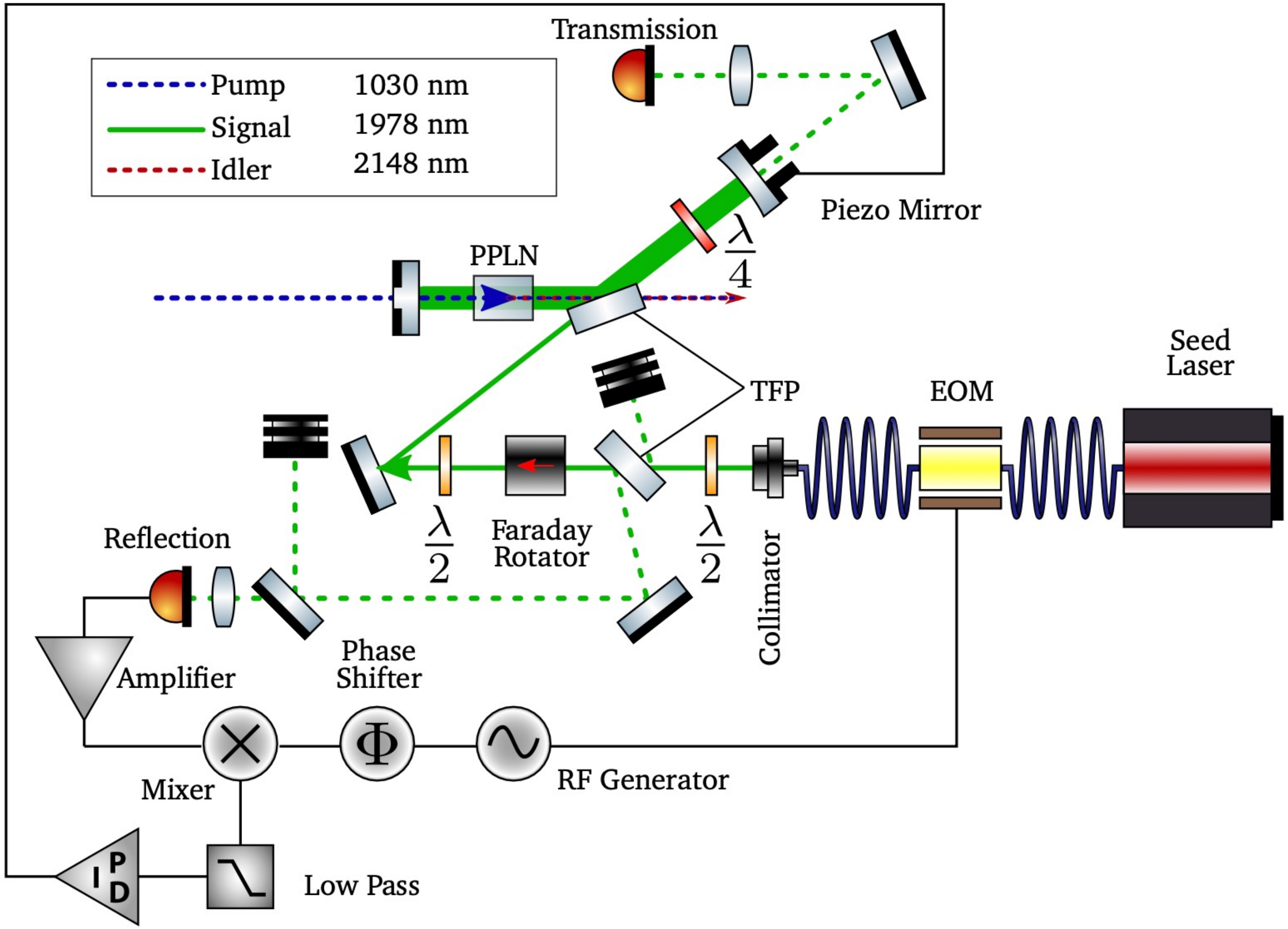
Zeyen, Manuel, et al. Optics express, 2024.

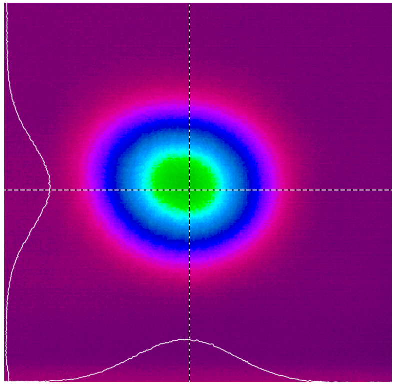
OPOs at 3 μm and 2 μm



OPO 2 μm

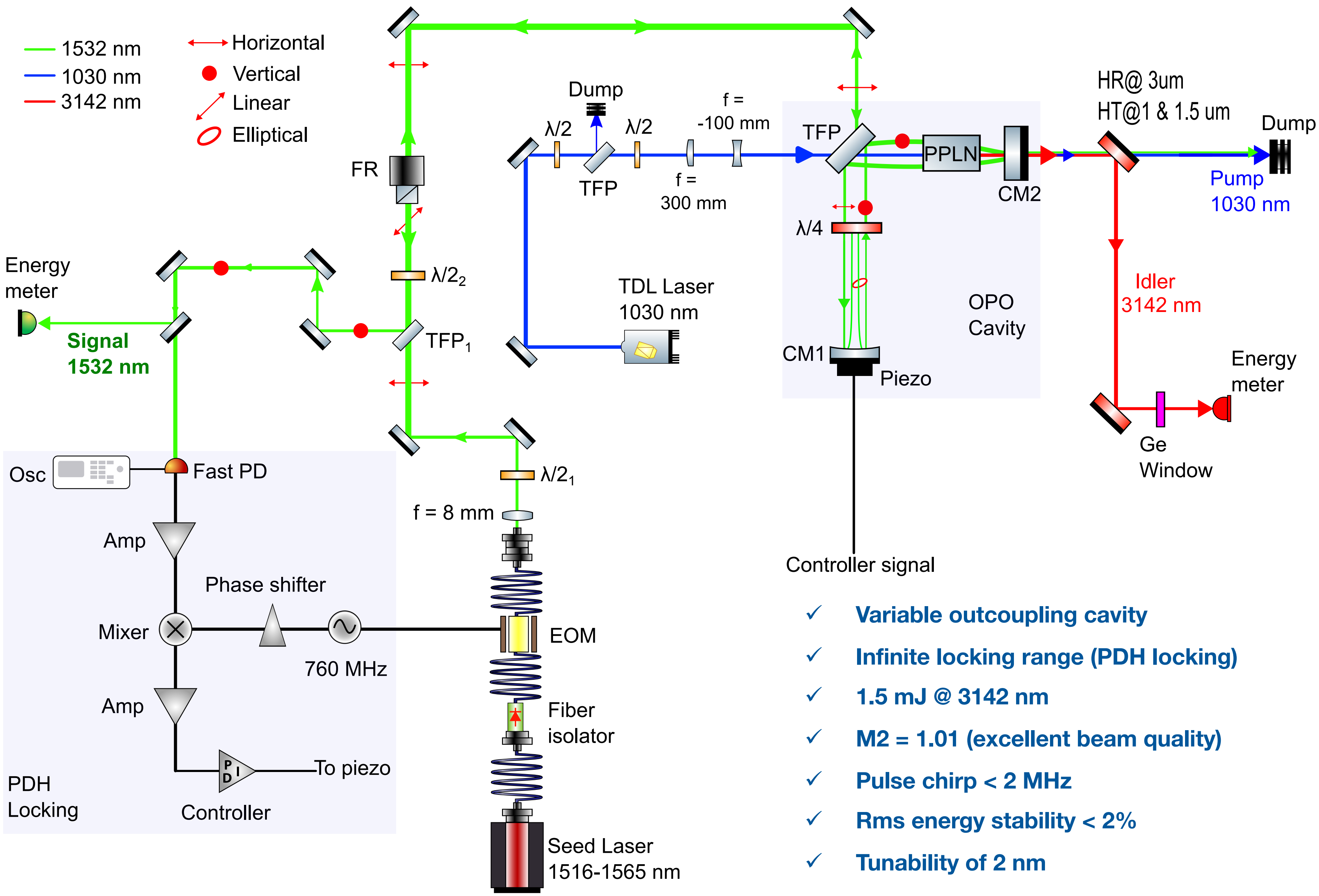






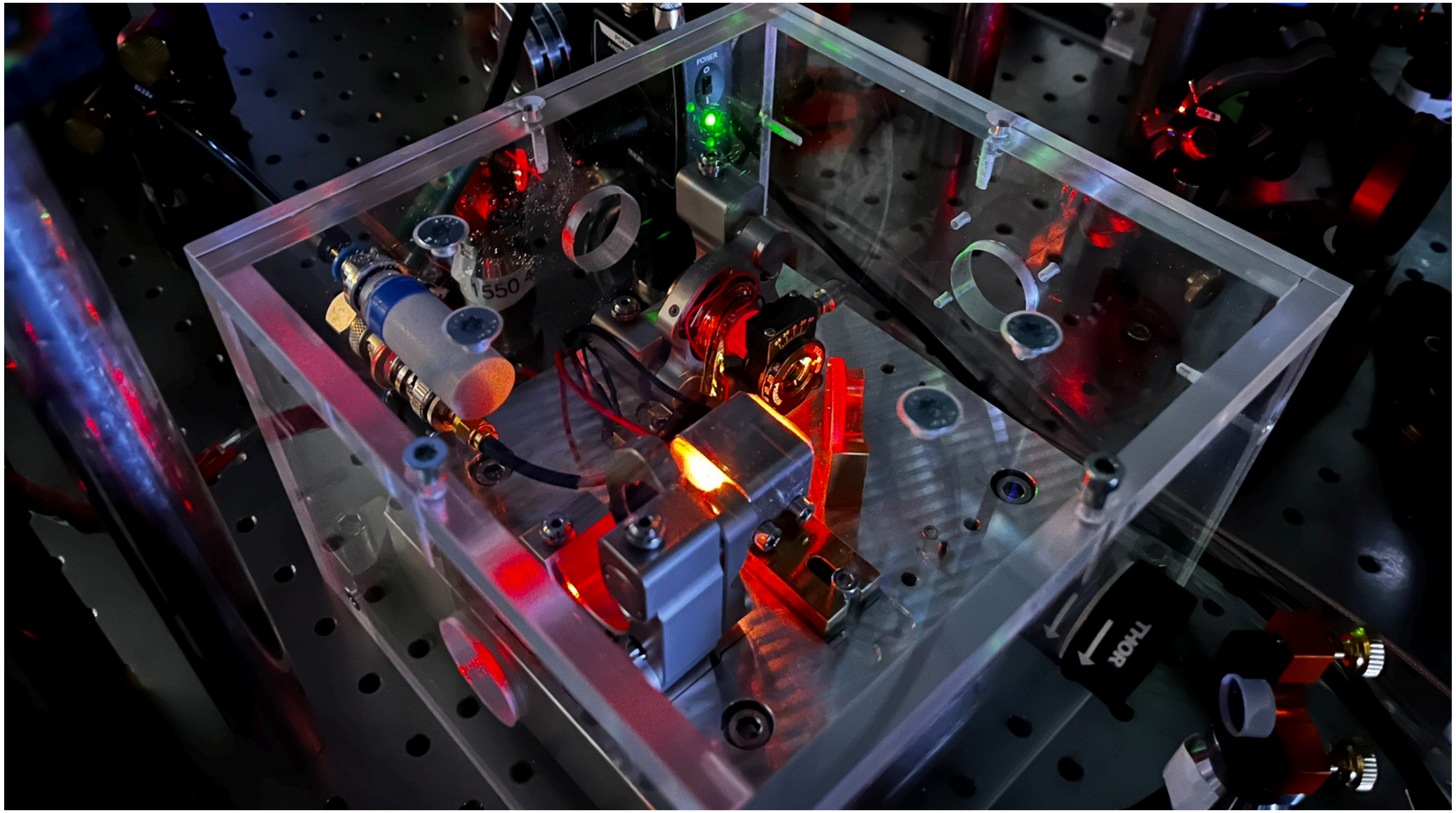
- ✓ 1.5 mJ @ 2149 nm
- ✓ Efficiency 50 %
- ✓ excellent beam quality

OPO at 3 μm



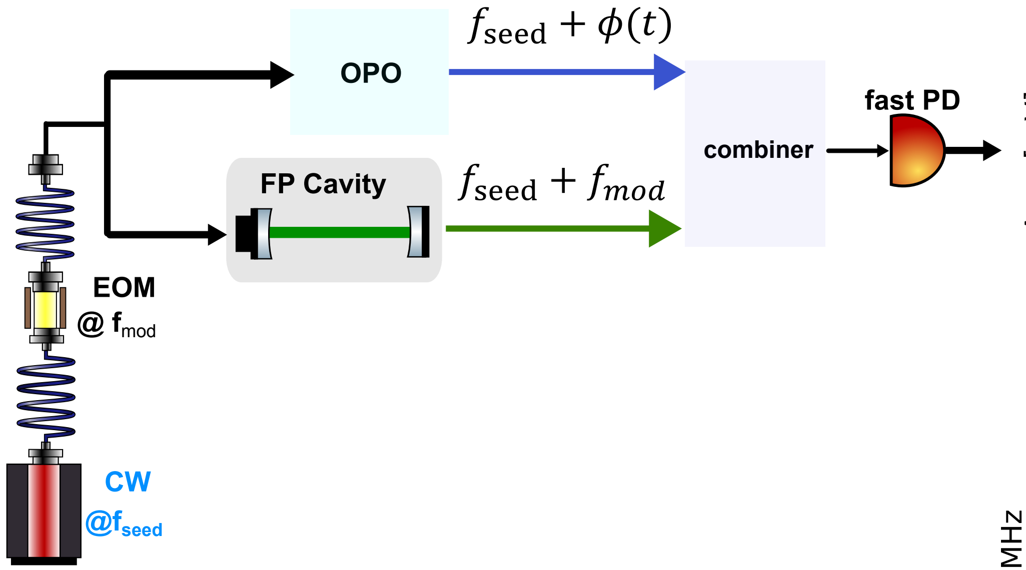
- ✓ **Variable outcoupling cavity**
- ✓ **Infinite locking range (PDH locking)**
- ✓ **1.5 mJ @ 3142 nm**
- ✓ **M2 = 1.01 (excellent beam quality)**
- ✓ **Pulse chirp < 2 MHz**
- ✓ **Rms energy stability < 2%**
- ✓ **Tunability of 2 nm**

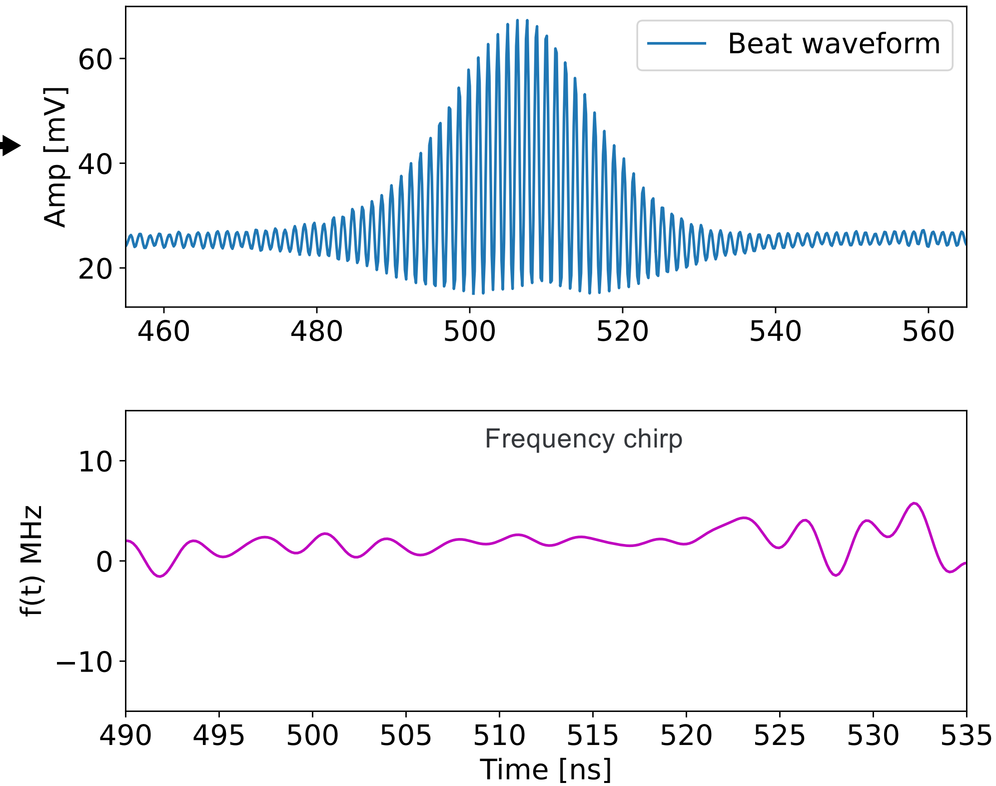
OPO at 3 μm



OPO instantaneous frequency

- Beat the OPO pulses with a CW from the seed laser
- $f(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt}$





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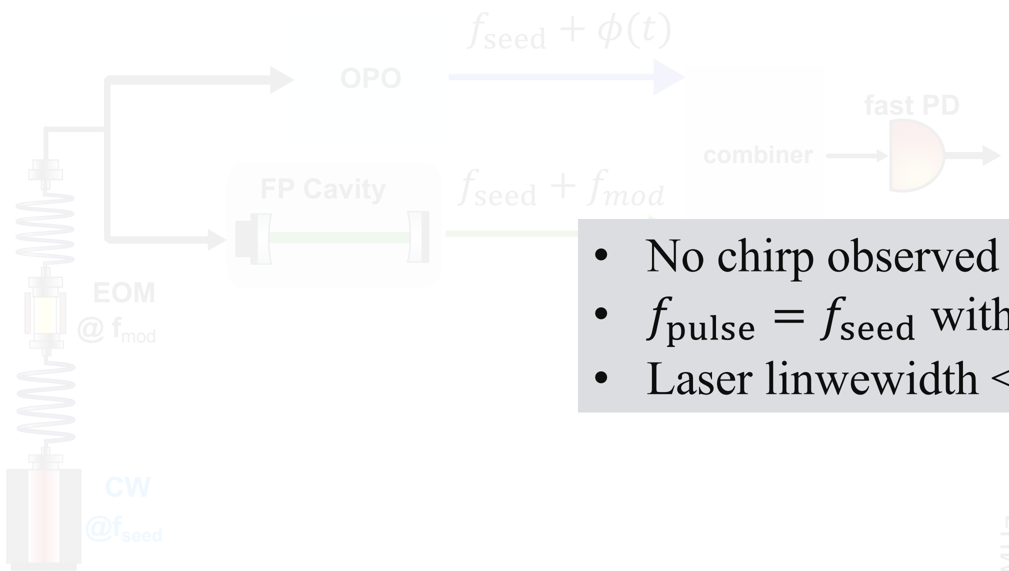

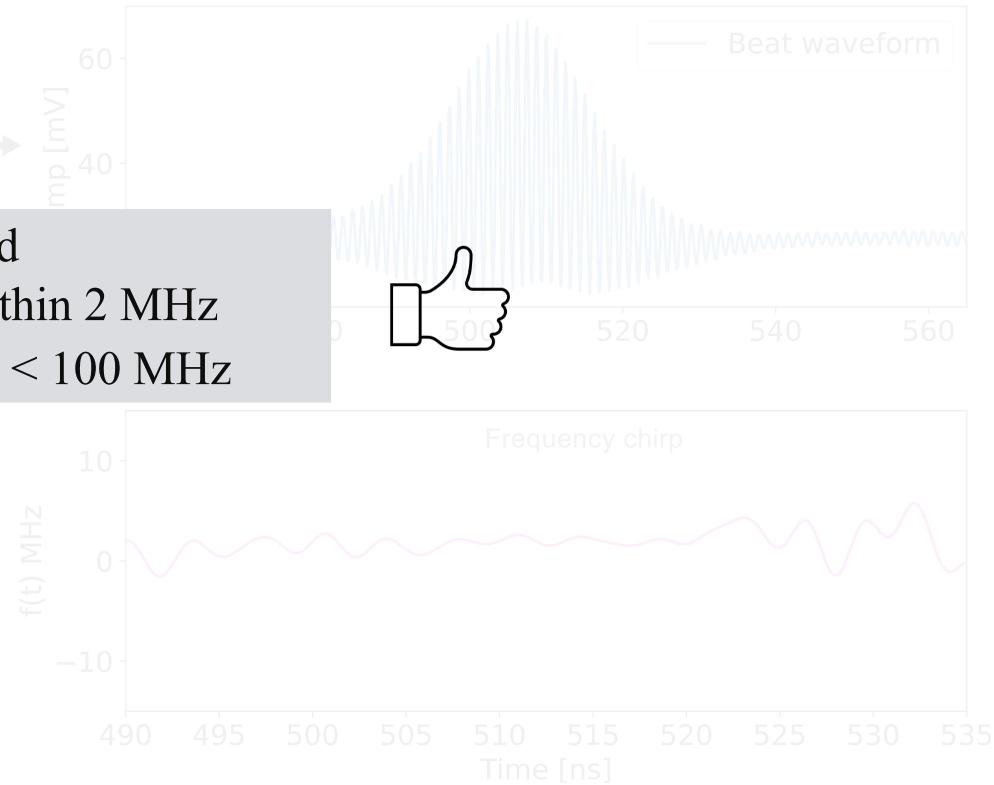

- No chirp observed
- $f_{pulse} = f_{seed}$ within 2 MHz
- Laser linwewidth < 100 MHz

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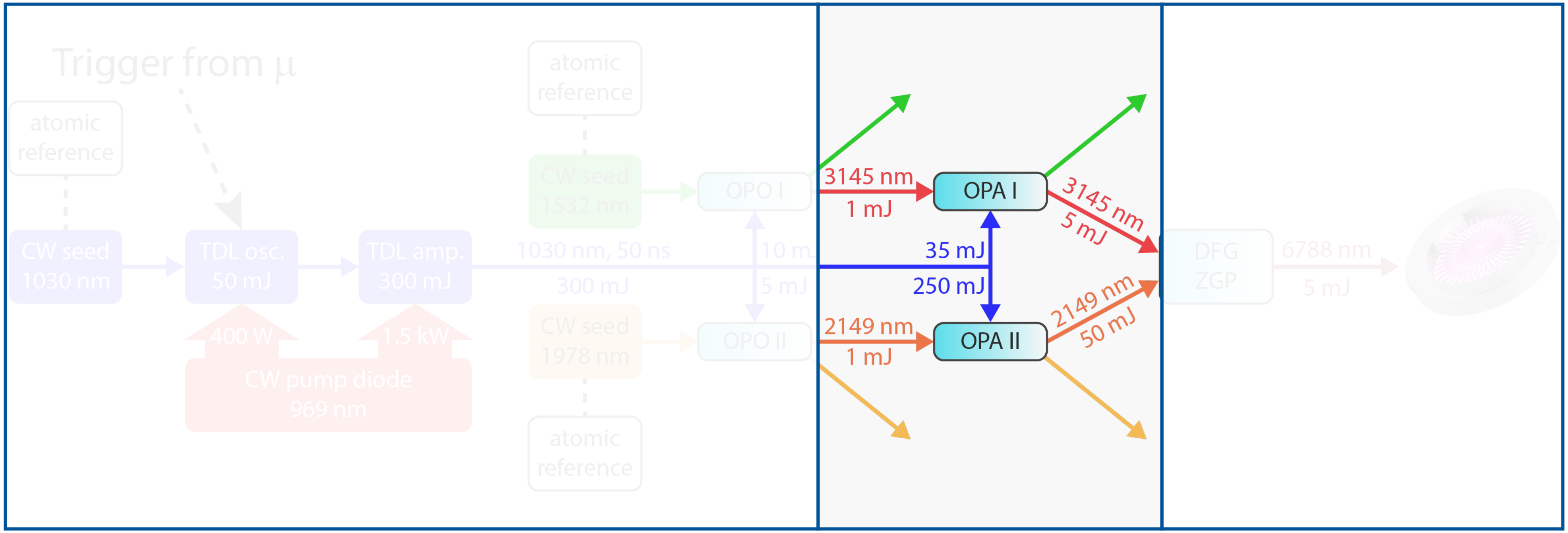
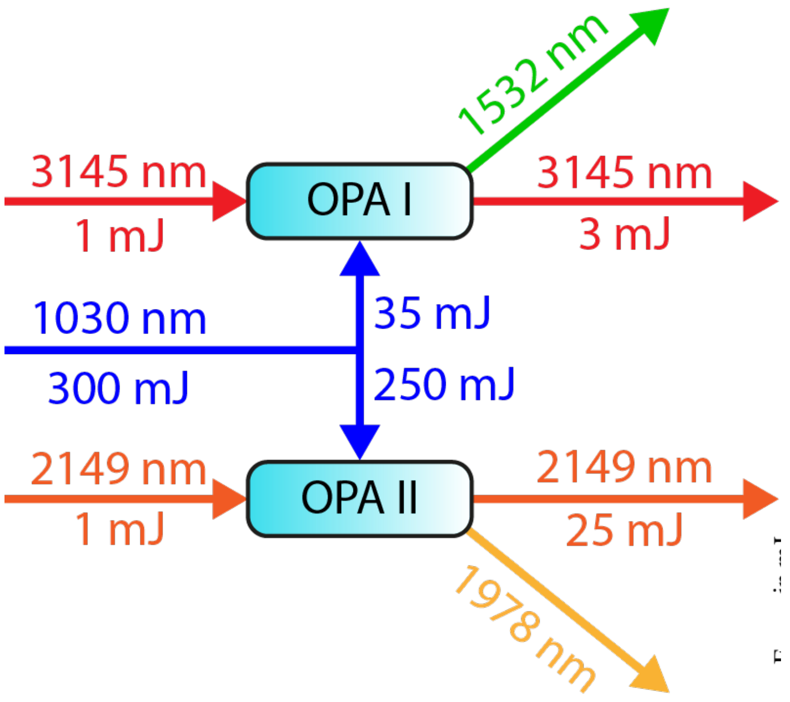
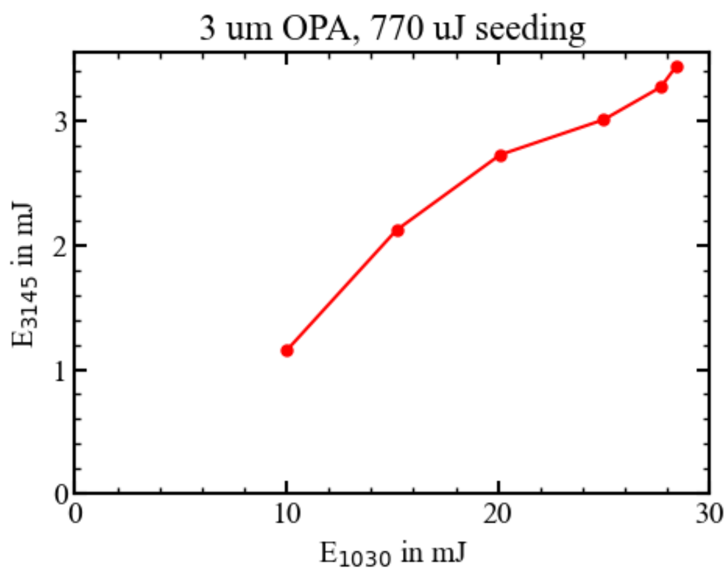
OPAs at 3 μm and 2 μm

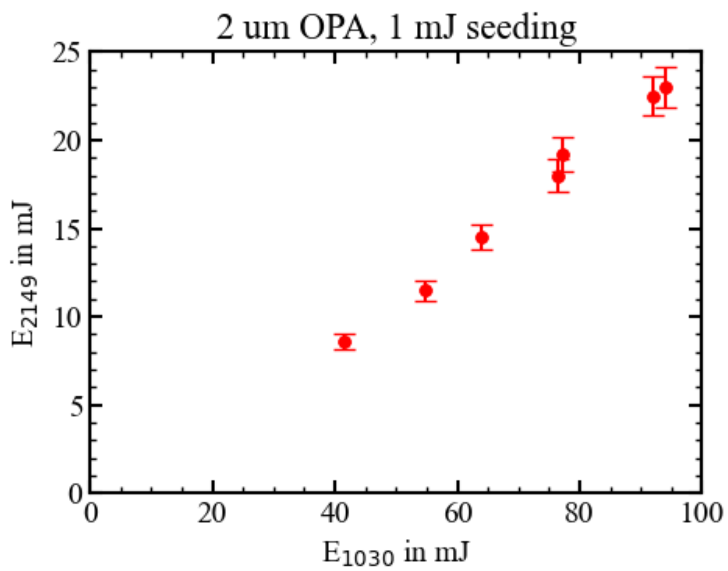


OPAs at 3 μm and 2 μm



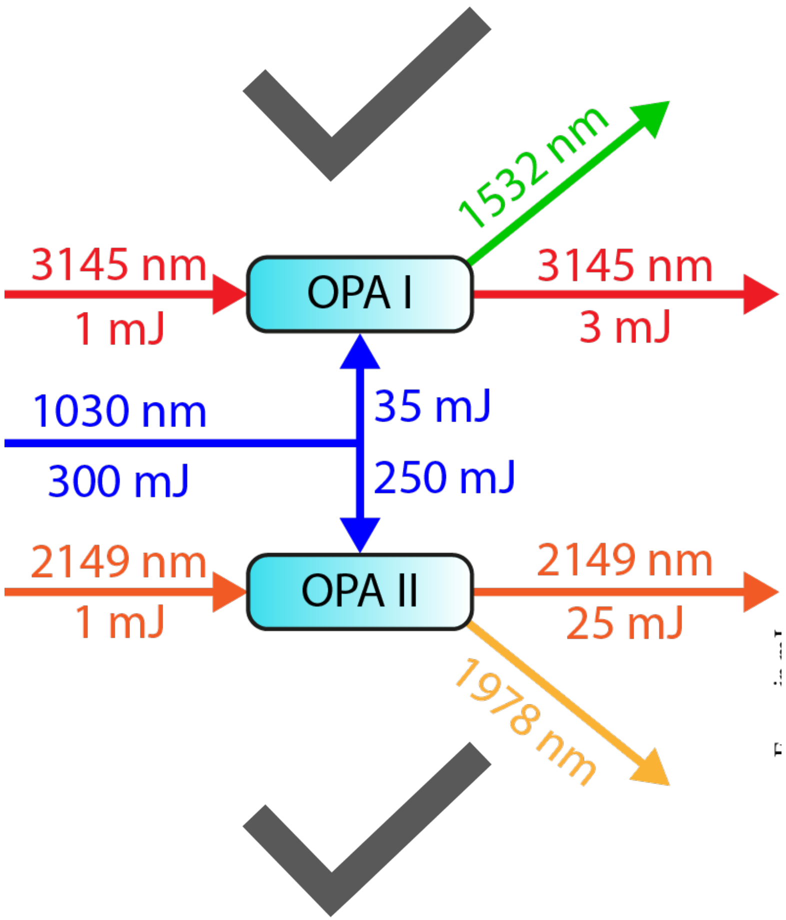


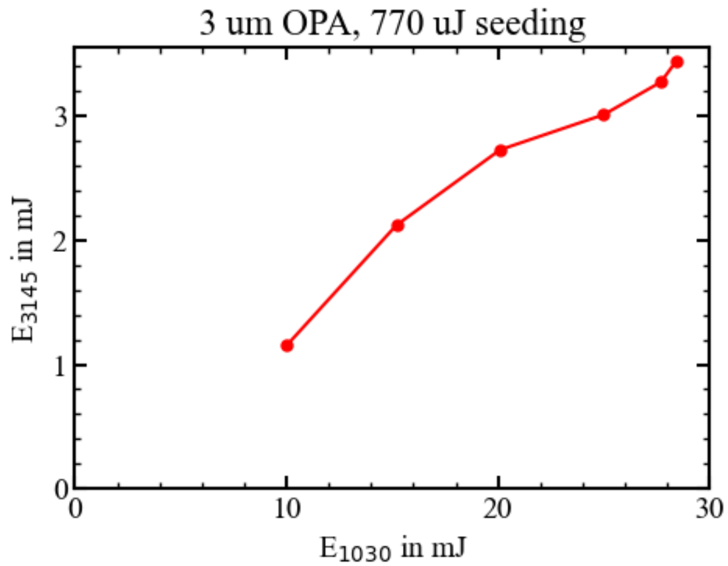
- ✓ **3.4 mJ**
- ✓ **M2 = 1.3**



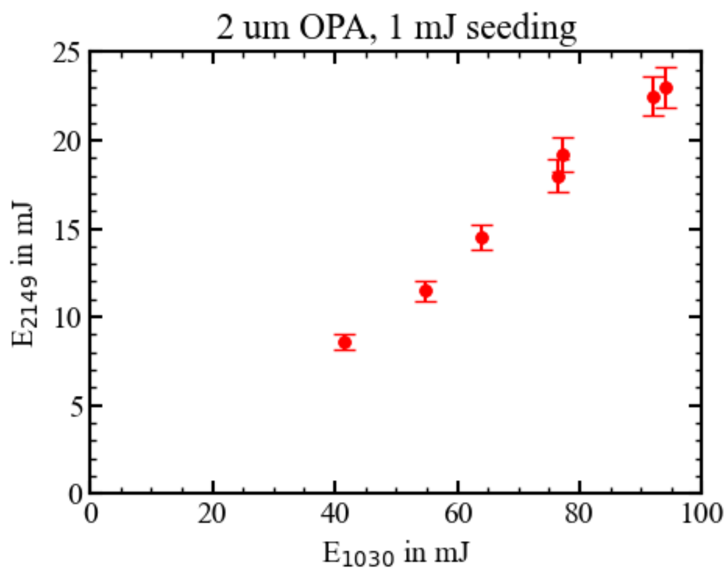
- ✓ **23 mJ**
- ✓ **M2 = 1.5**

OPAs at 3 μm and 2 μm



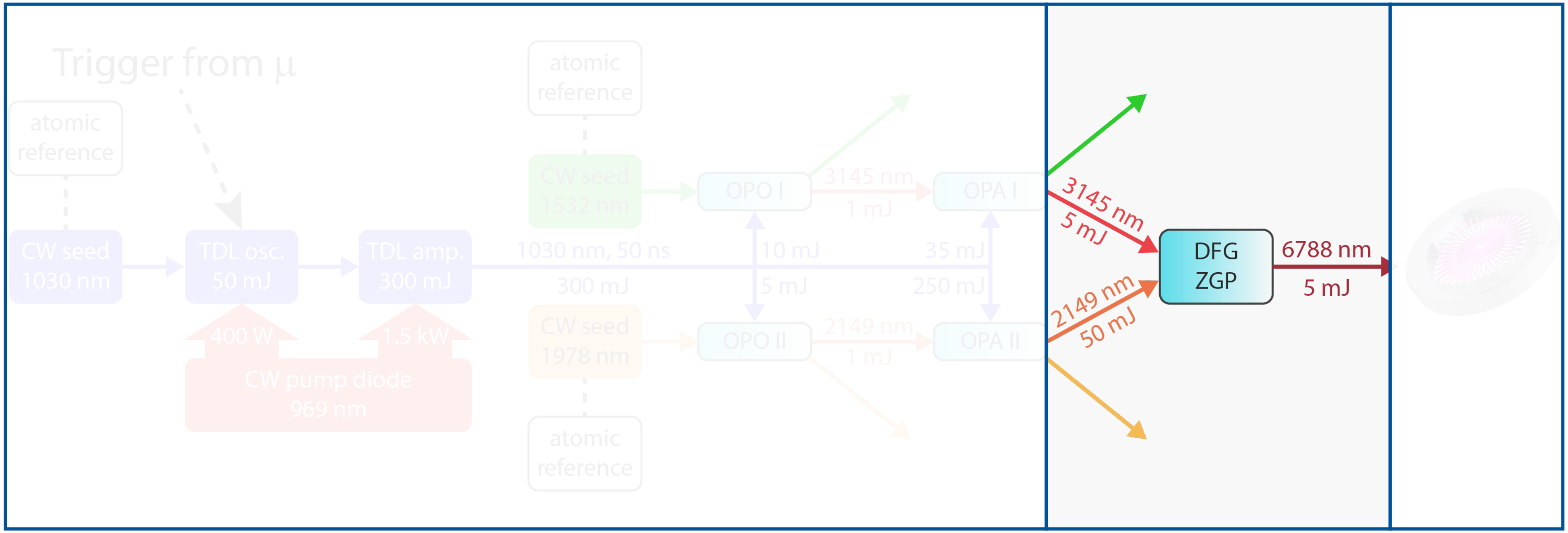


- ✓ **3.4 mJ**
- ✓ **M2 = 1.3**



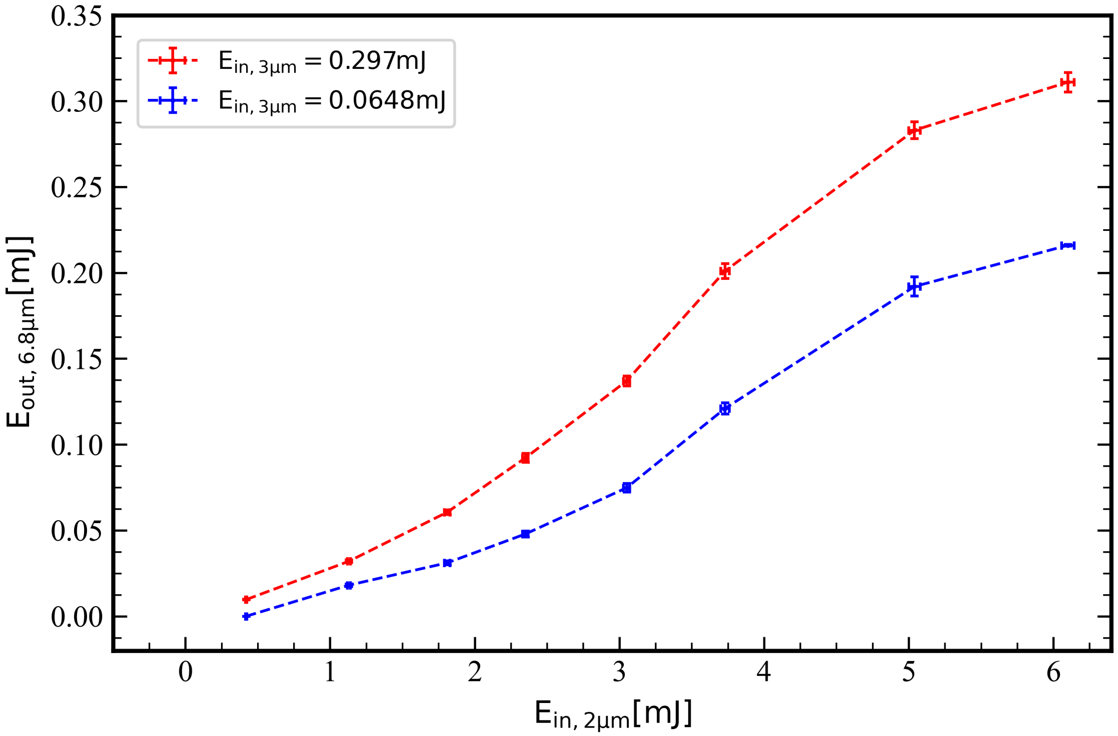
- ✓ **23 mJ**
- ✓ **M2 = 1.5**

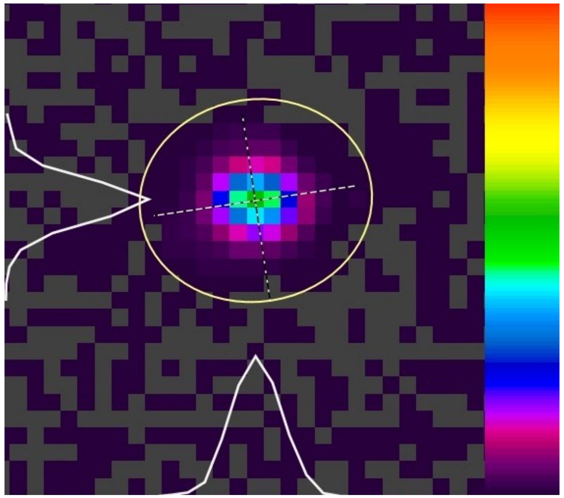
DFG at 6.8 μm


Trigger from μ
atomic reference
CW seed 1030 nm
TDL osc. 50 mJ
TDL amp. 300 mJ
400 W
1.5 kW
CW pump diode 969 nm
1030 nm, 50 ns
300 mJ
atomic reference
CW seed 1532 nm
OPO I
3145 nm
1 mJ
OPA I
10 mJ
5 mJ
35 mJ
250 mJ
CW seed 1978 nm
OPO II
2149 nm
1 mJ
OPA II
atomic reference
3145 nm
5 mJ
2149 nm
50 mJ
DFG ZGP
6788 nm
5 mJ

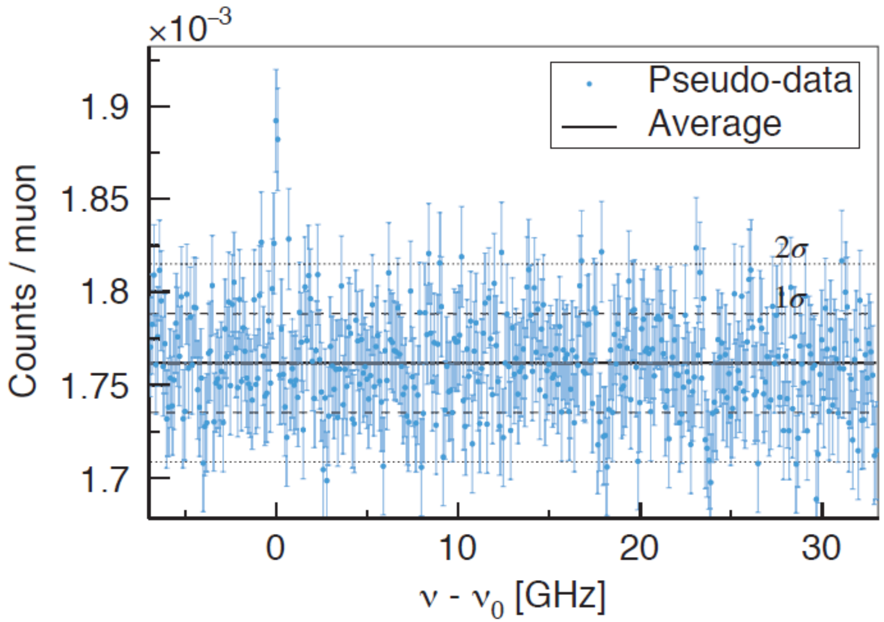
DFG at 6.8 μm

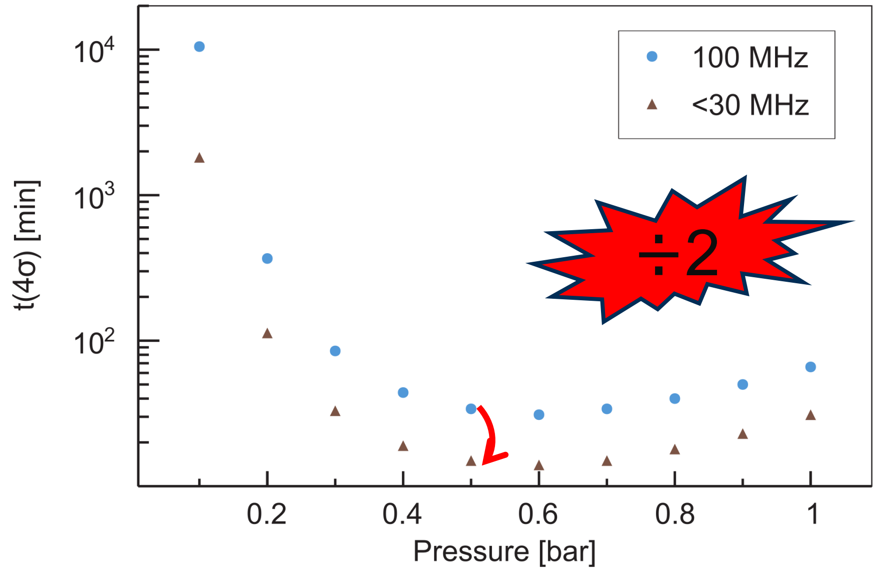
- ✓ **Generated 0.4 mJ @ 6.8 μm**
- ✓ **Round beam**





Time needed to search for the resonance

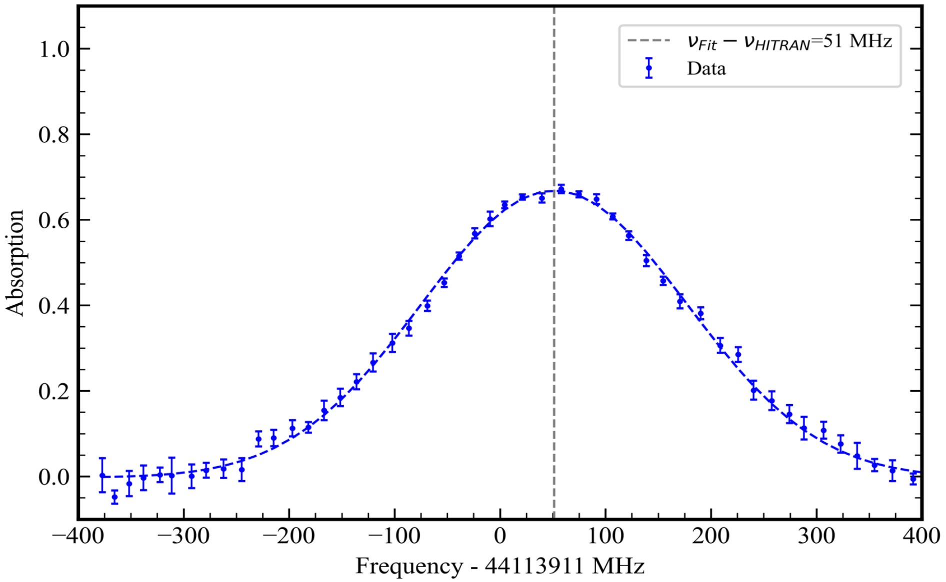


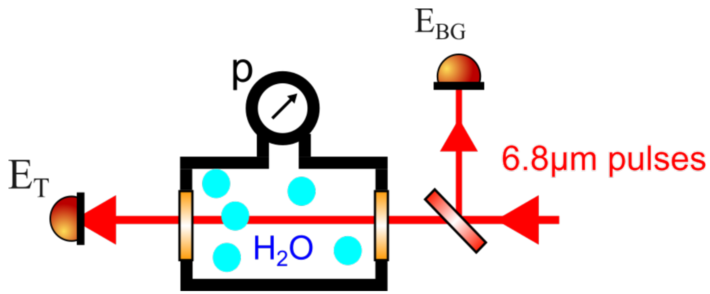


[Nuber PhD Thesis]

Frequency calibration of the laser system

- **Estimation of laser-bandwidth**
- **Absolute laser frequency**





Frequency calibration of the laser system

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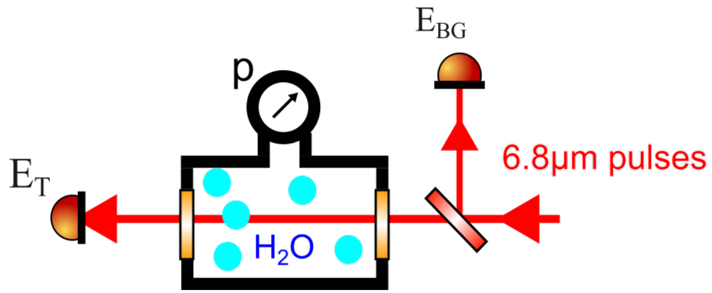
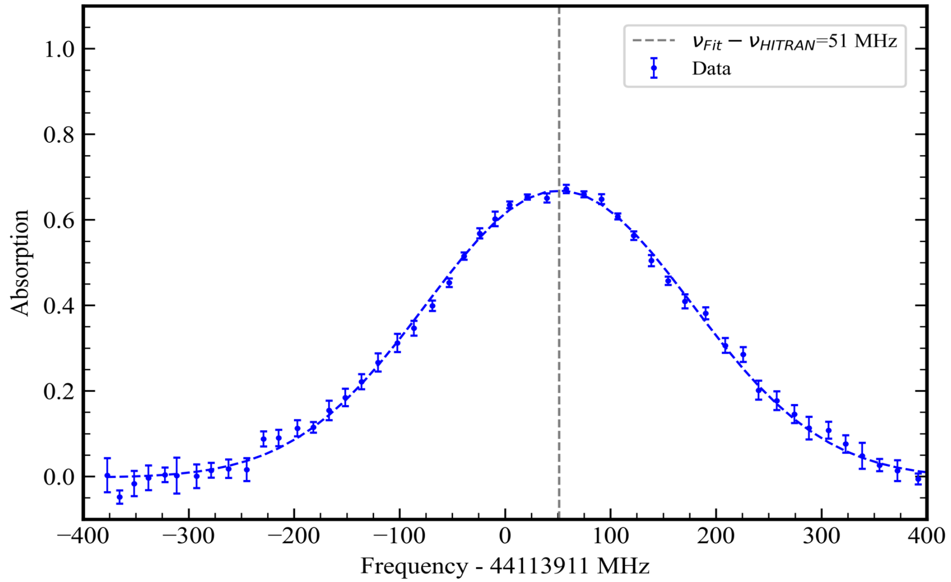
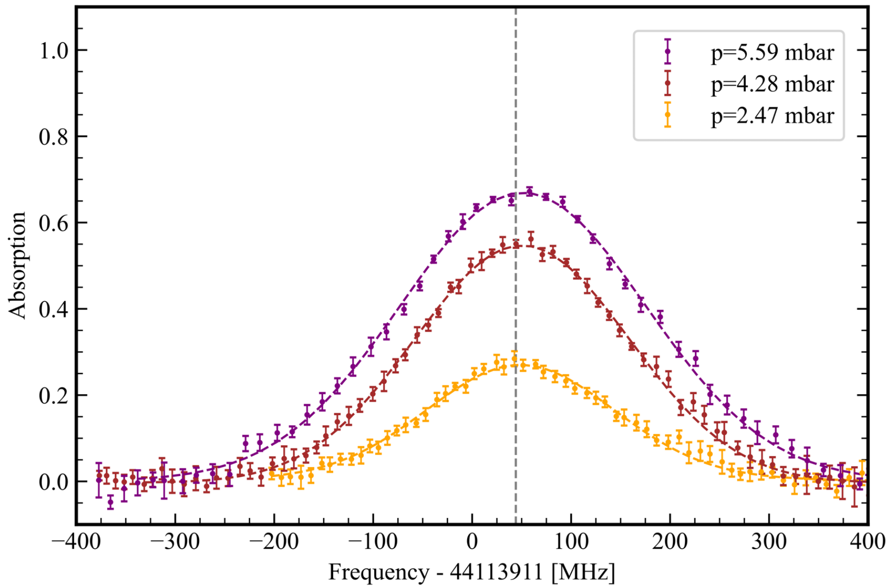


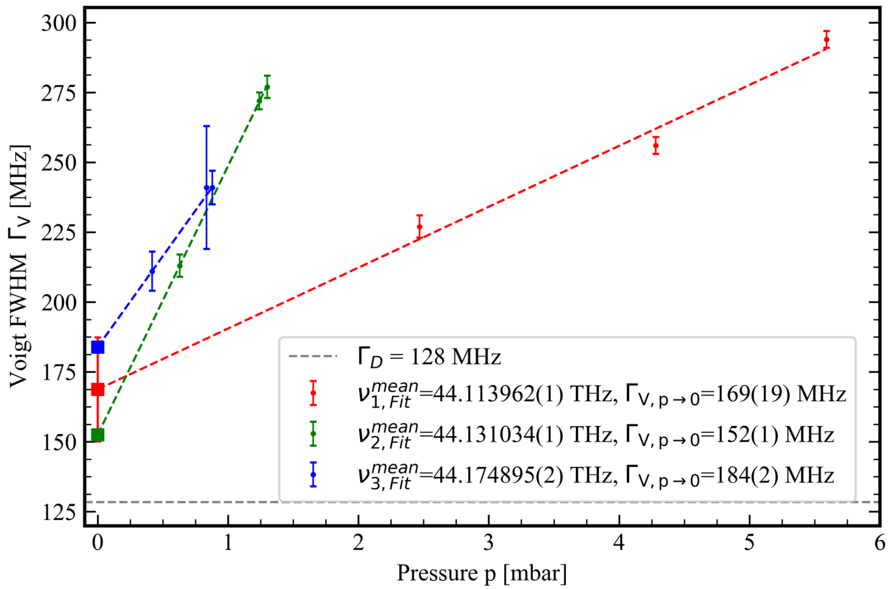


Natural Linewidth	<0.1MHz
Pressure Broadening	$\Gamma_P \propto p$
Doppler broadening	$\Gamma_D = \frac{1}{c}\sqrt{\frac{8k_BT}{M}}\nu_0$
Power broadening	Γ_I depends on I
Laser Bandwidth	Γ_L =???

Frequency calibration of the laser system

- ✓ **Absolute laser frequency**
- ✓ **Laser linewidth estimation < 100 MHz**

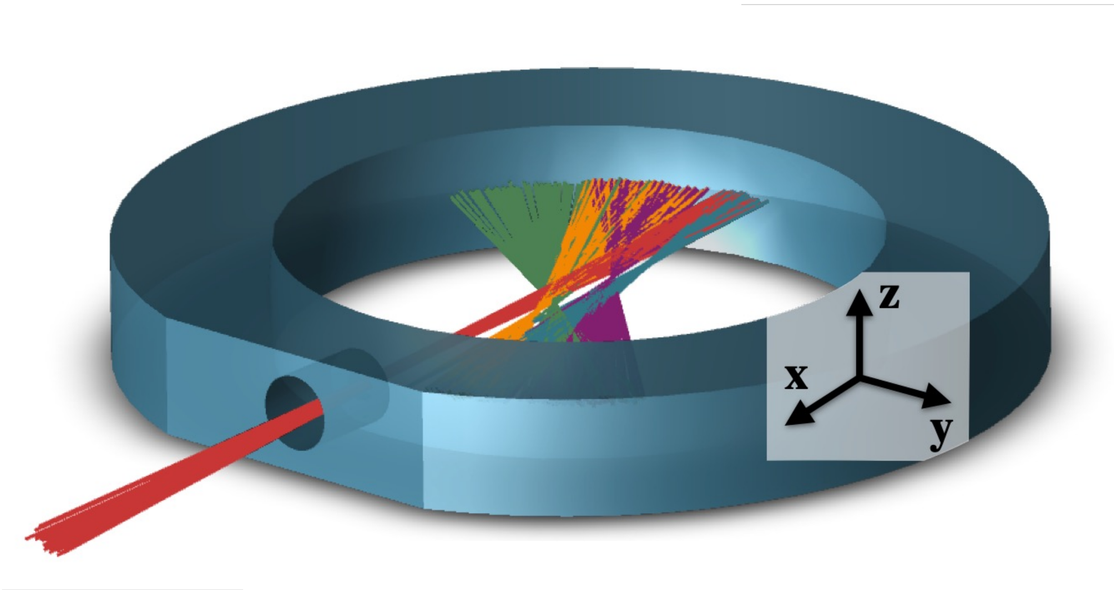


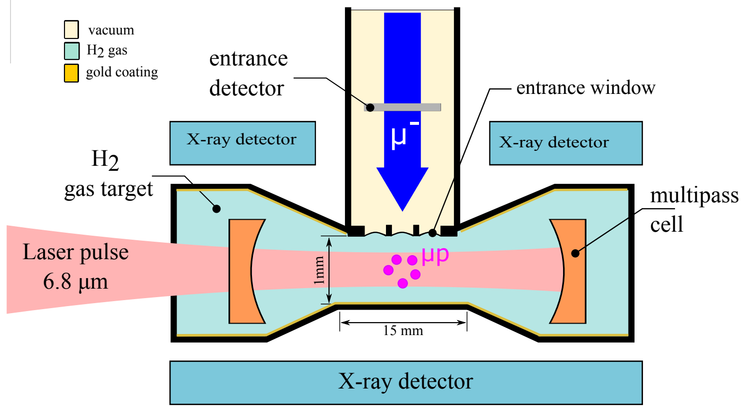


$$\Gamma_D = \frac{1}{c}\sqrt{\frac{8k_BT}{M}} = 128\,\text{MHz}$$

$$\Gamma_L^{Max} = \sqrt{\Gamma^2_{V,p\to0} - \Gamma^2_D} = 110(6)\,\text{MHz}$$

Enhancement cavity

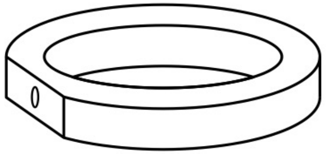




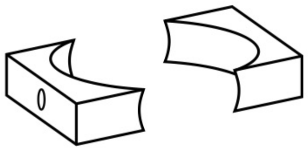
M. Marszalek et.al , arXiv:2402.07223

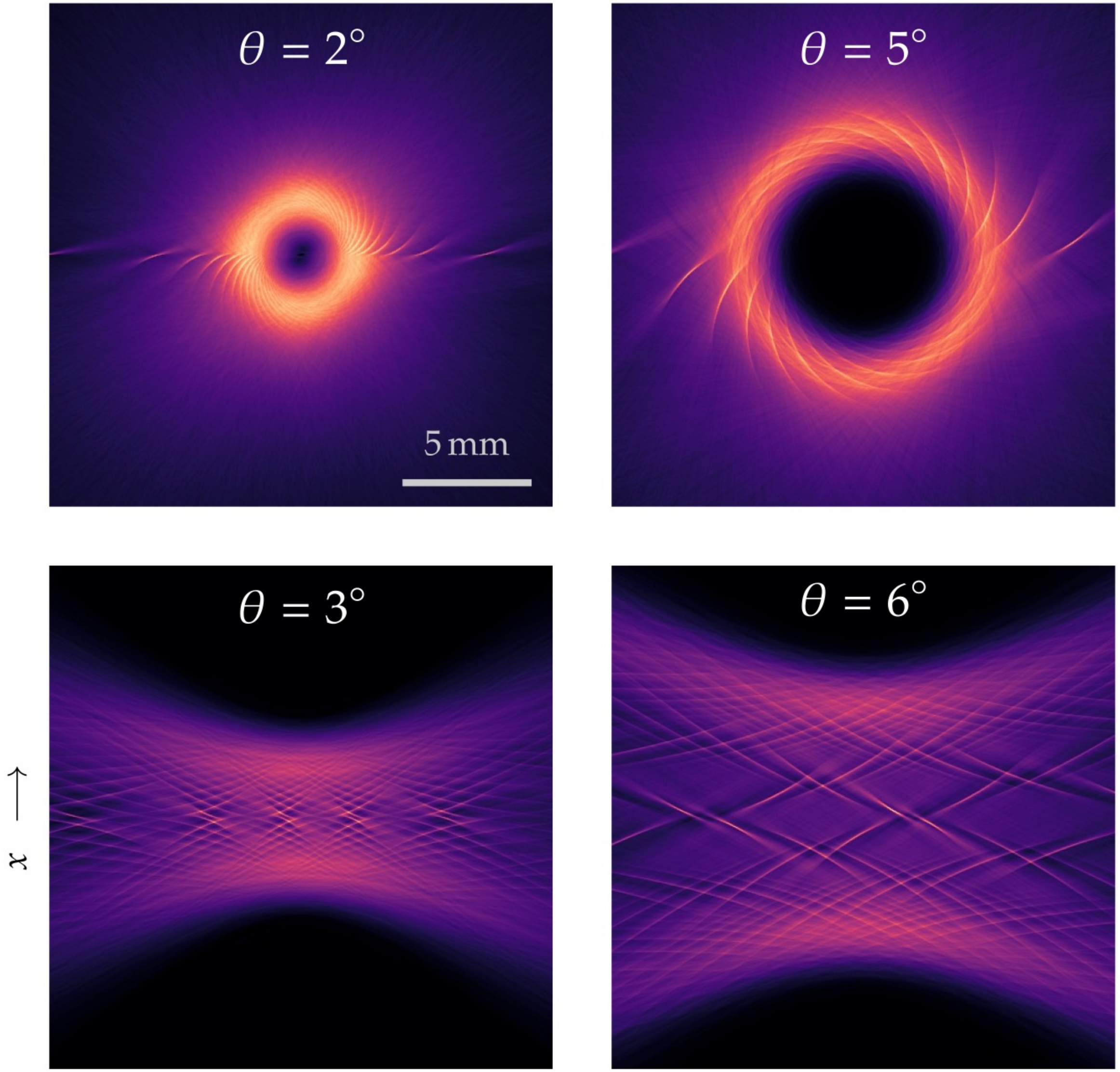
Two different configurations

- Resonant vertically
- Unstable horizontally



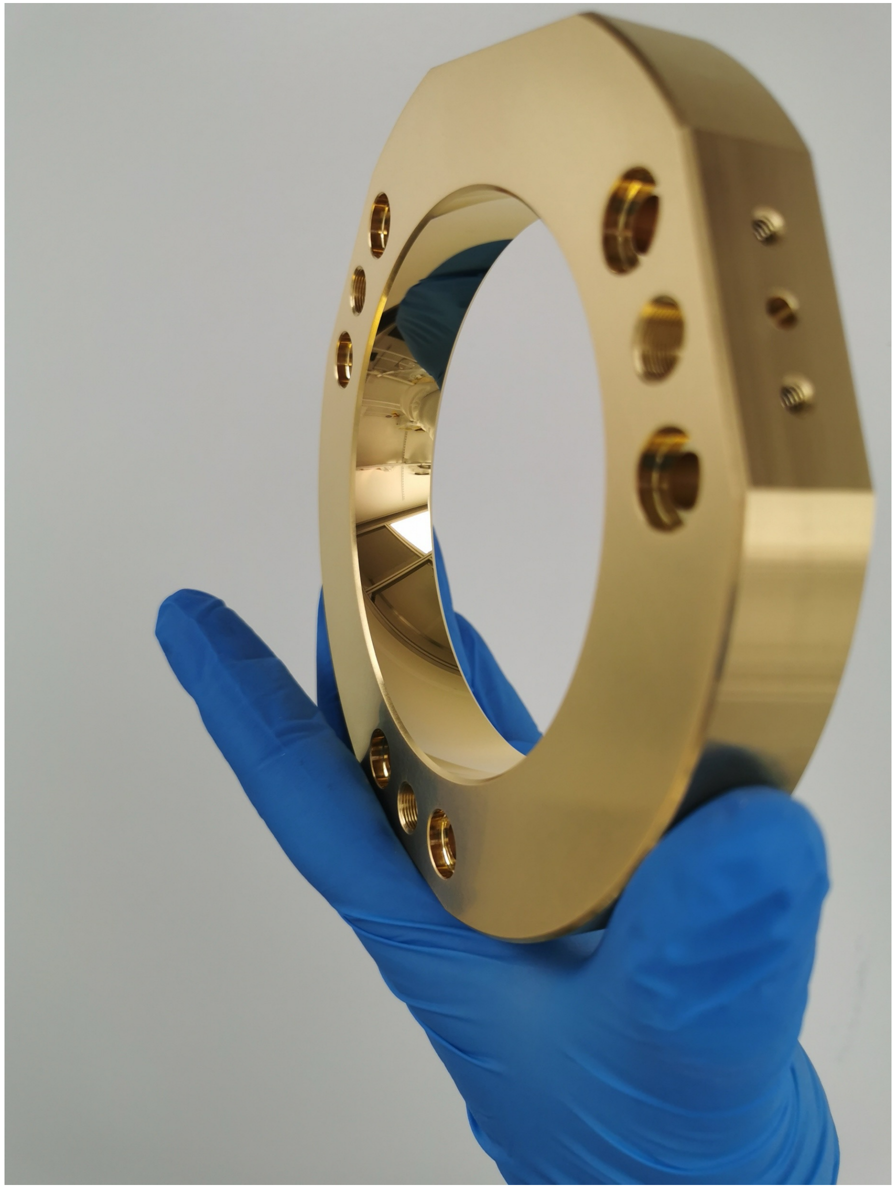
- Resonant vertically
- Stable horizontally





M. Marszalek , PhD Thesis, ETH 2022

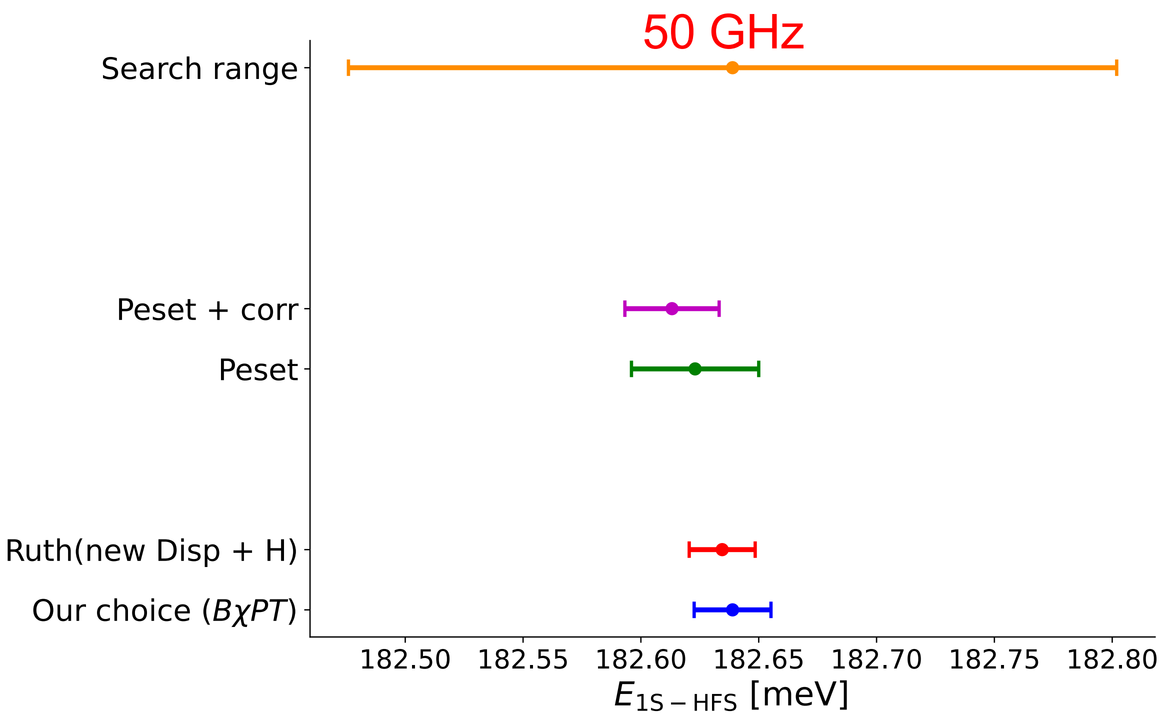
Enhancement cavity



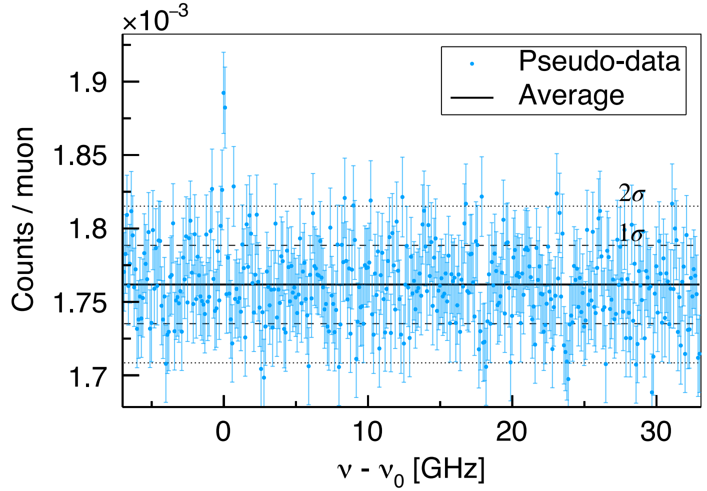
✓ **Reflectivity of 99.0 %**

M. Marszalek et.al , arXiv:2402.07223

Search for the resonance



- ***Simulation of the search for resonance***

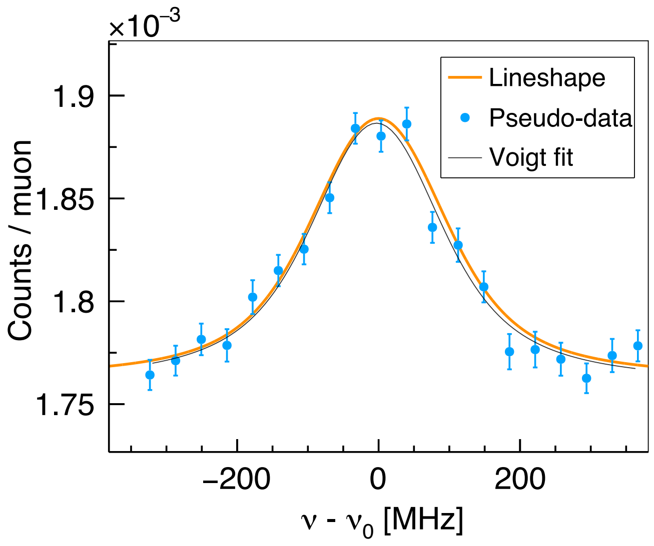


- **Steps to search for resonance**
- Measure 1.4 h at fixed wavelength to expose a 4 σ effect over background
- 1 h to change the laser frequency in steps of 100 MHz

Simulated resonance

Assuming the resonance has been found and given:

- Laser pulse 1mJ
- Target length 1.2 mm
- Cavity R = 99.2%
- Laser linewidth < 100 MHz
- Detection system: $\epsilon_{\text{Au}} = 70\%$, $\epsilon_{\text{Au-false}} = 9\%$



Determine resonance position with

$$\sigma = 4\ \text{MHz}\ (1.6 \times 10^{-8}\ \text{eV})$$

$$\frac{\sigma}{E_{\text{HFS}}} = \frac{4\ \text{MHz}}{44\ \text{THz}} = 1 \times 10^{-7}$$

Collaboration

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L. Sustelo

A. Adamczak

M. Abdou-Ahmed, T. Graf

F.D. Amaro, L.M.P. Fernandes,
C. Henriques, C.M.B. Monteiro,
J.M.F. dos Santos, P. Silva

Our lab at PSI

Thank you !