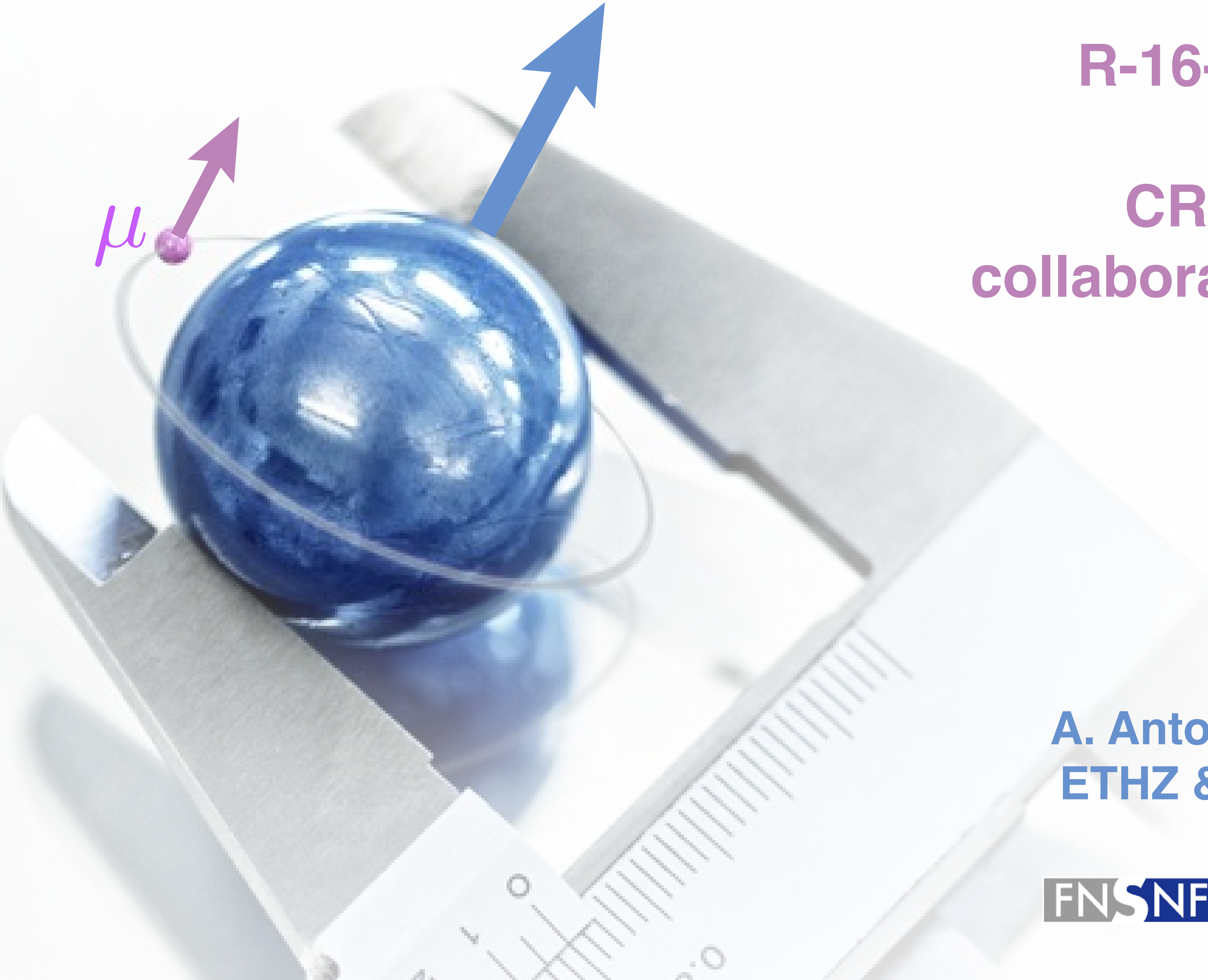
Hyperfine Splitting in Muonic Hydrogen



R-16-02.1

CREMA collaboration

A. Antognini
ETHZ & PSI

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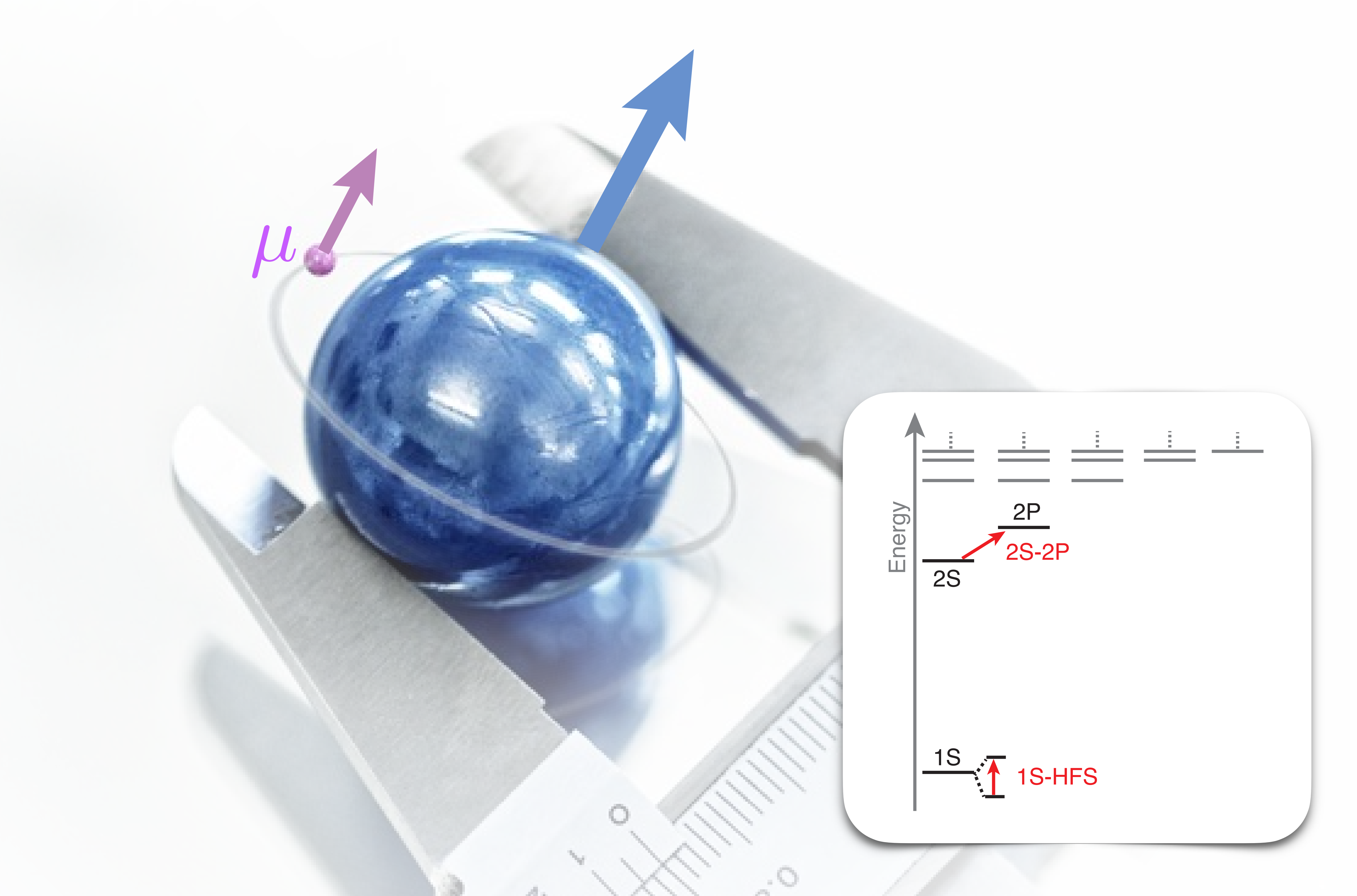
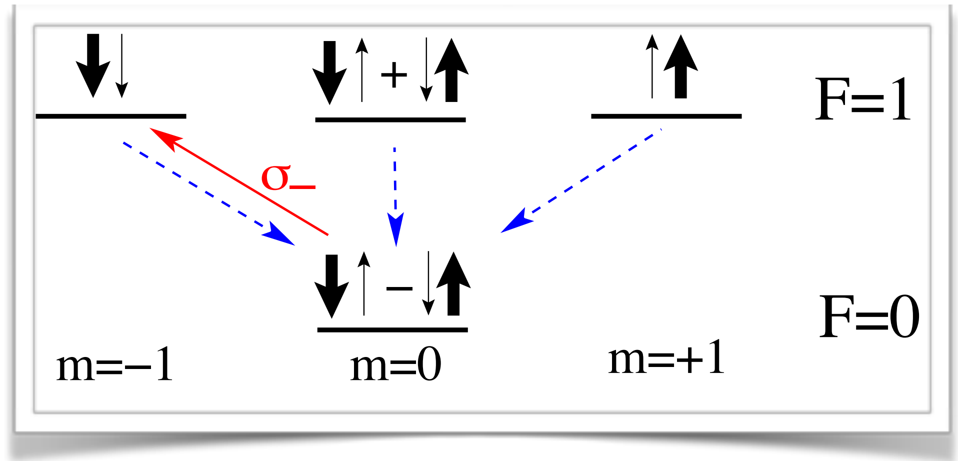
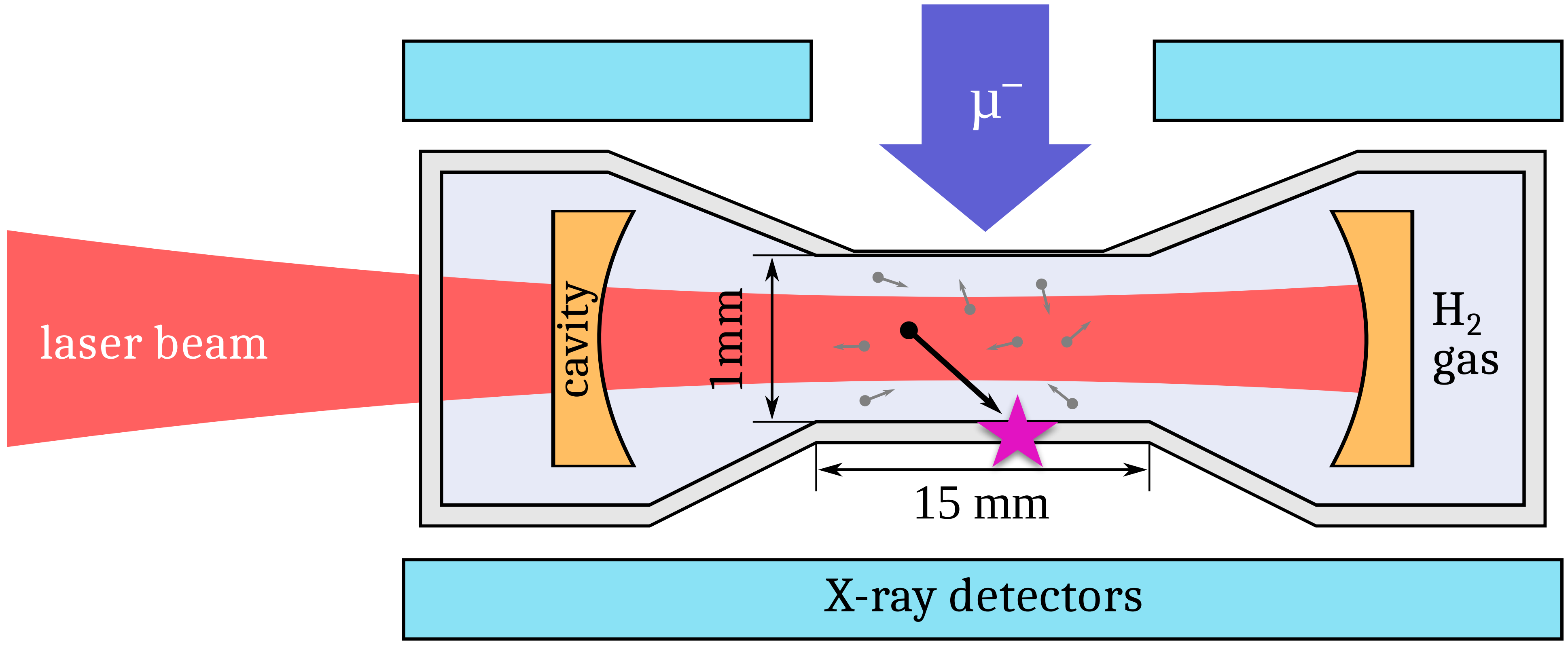


The principle of the μp HFS experiment

- Stop muon beam in 1 mm H_2 gas target at 40 K
- Wait until *μ*p atoms de-excite and thermalize
- Laser pulse: *μ*p(F=0) + γ → *μ*p(F=1)
- De-excitation: *μ*p(F=1) + H_2→*μ*p(F=0) + H_2 + E_{kin}
- *μ*p diffuses to Au-coated target walls
- formed *μ*Au* de-excites producing X-rays
- Plot number of X-ray events vs laser frequency





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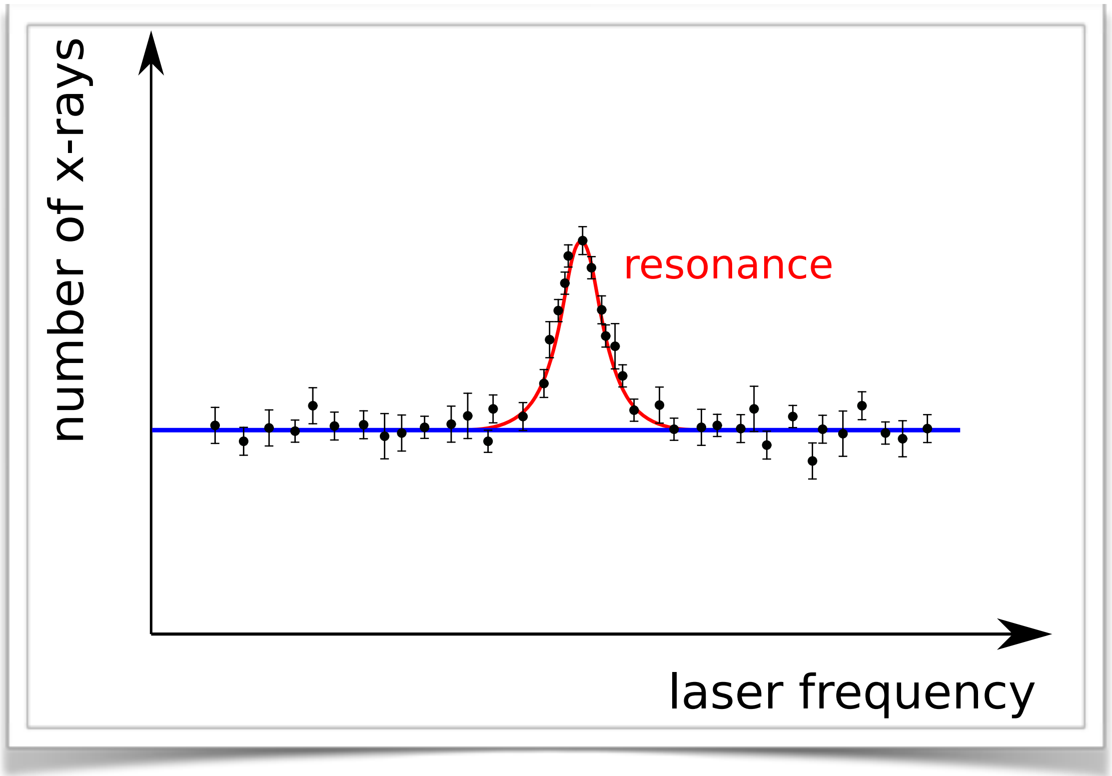
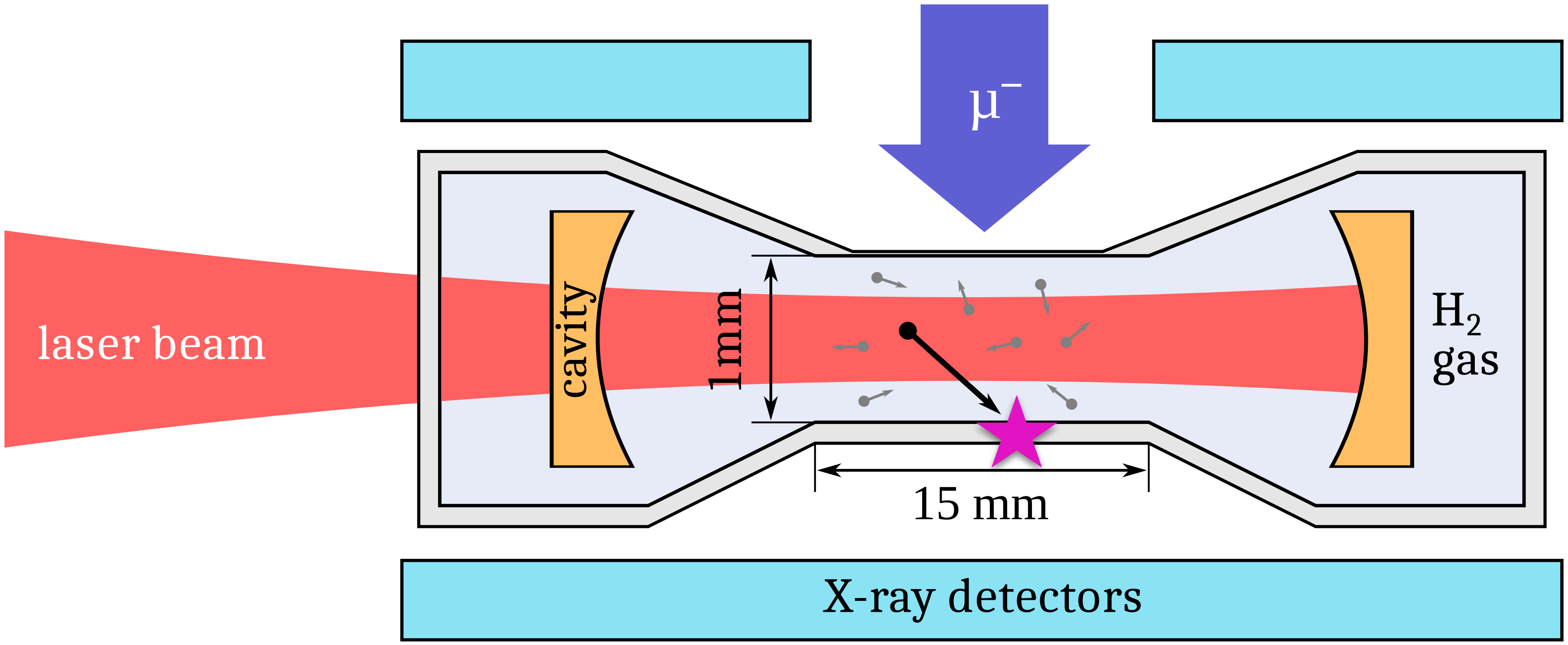
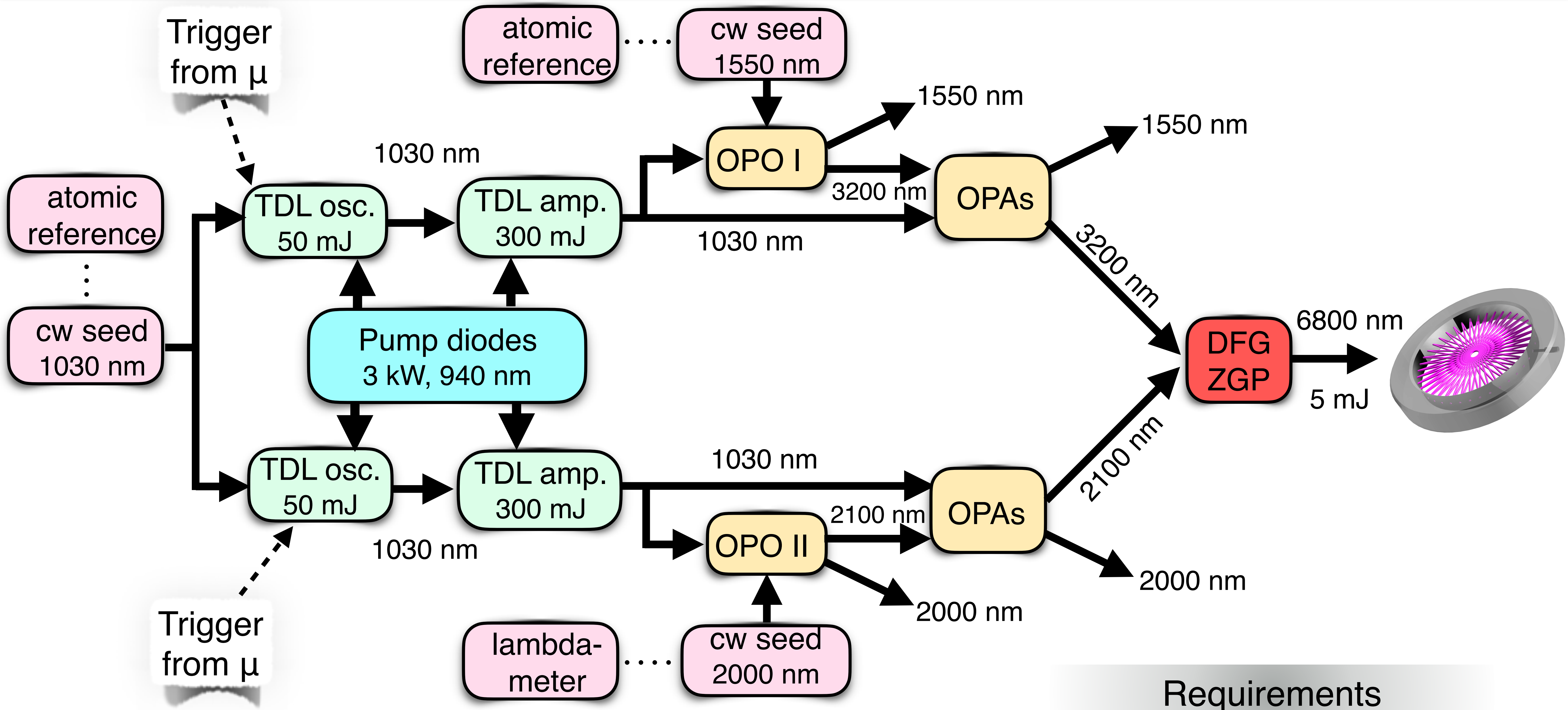




The laser system

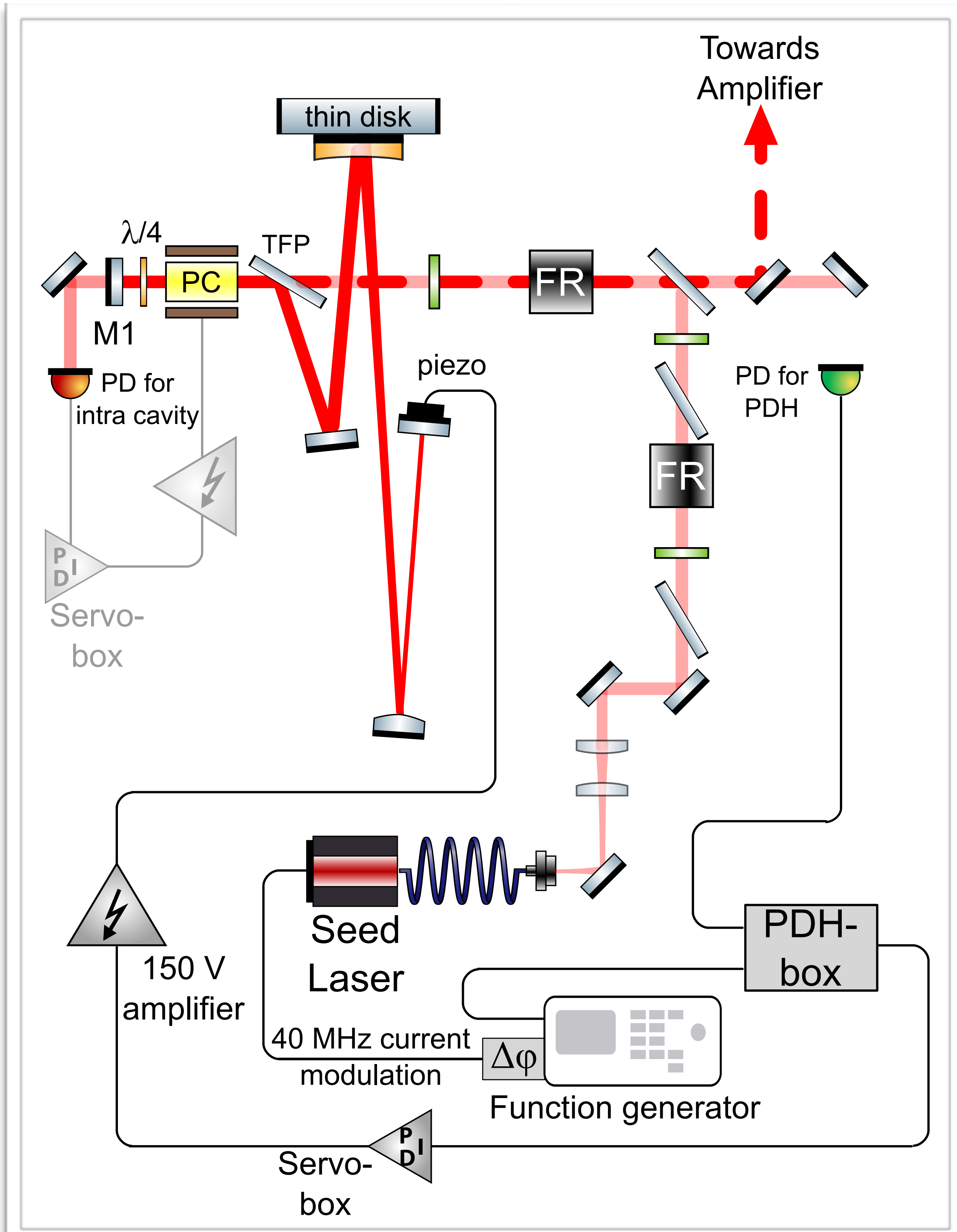


Other schemes for the down-conversion are investigated

Requirements

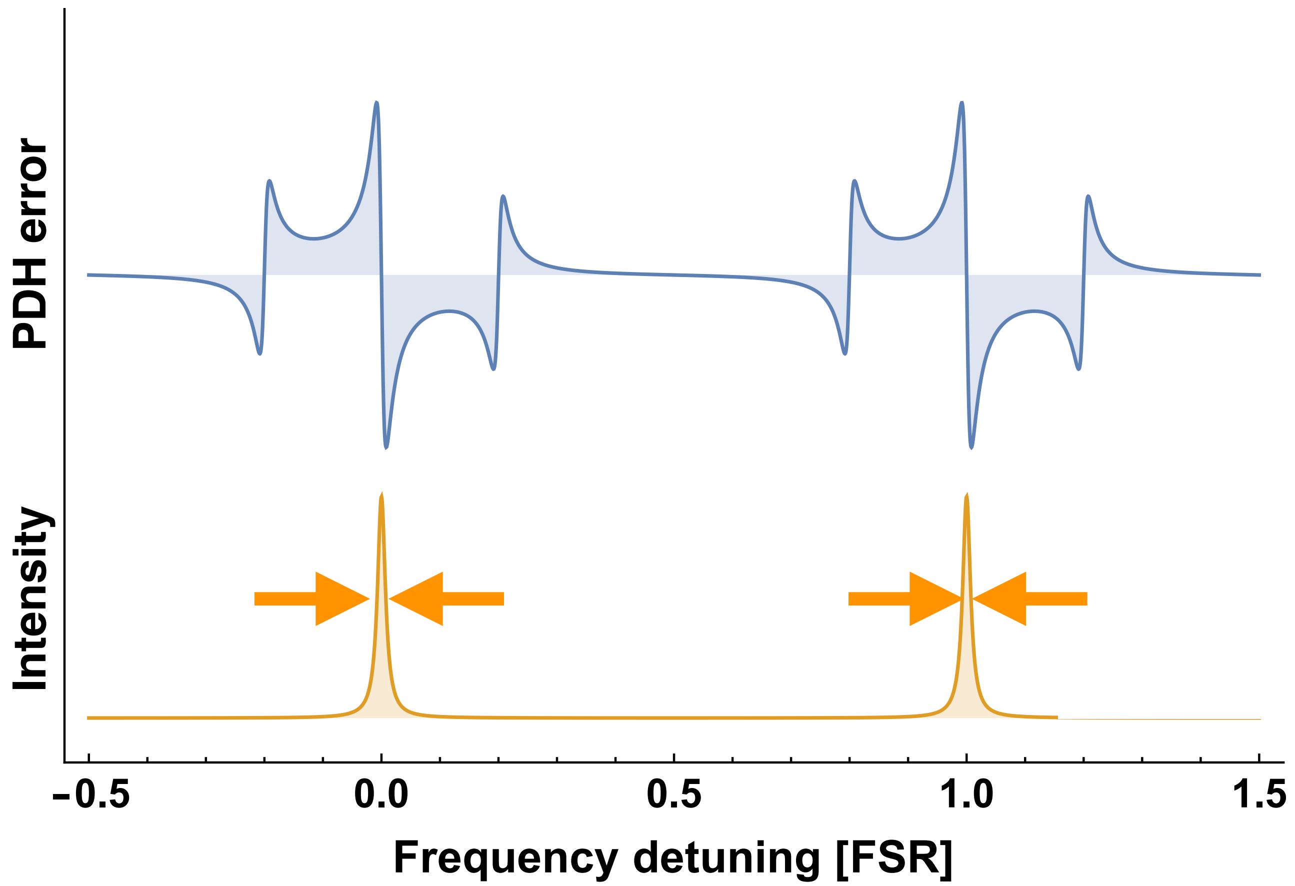
- delay time: 1 μs
- stochastic trigger
- energy: 5 mJ
- repetition rate: 200 1/s
- wavelength: 6.8 μm
- bandwidth: < 100 MHz

The single-frequency thin-disk oscillator



Injection seeding challenged by

- vibrations from water jet cooling
- gain narrowing
- re-locking over the whole FSR



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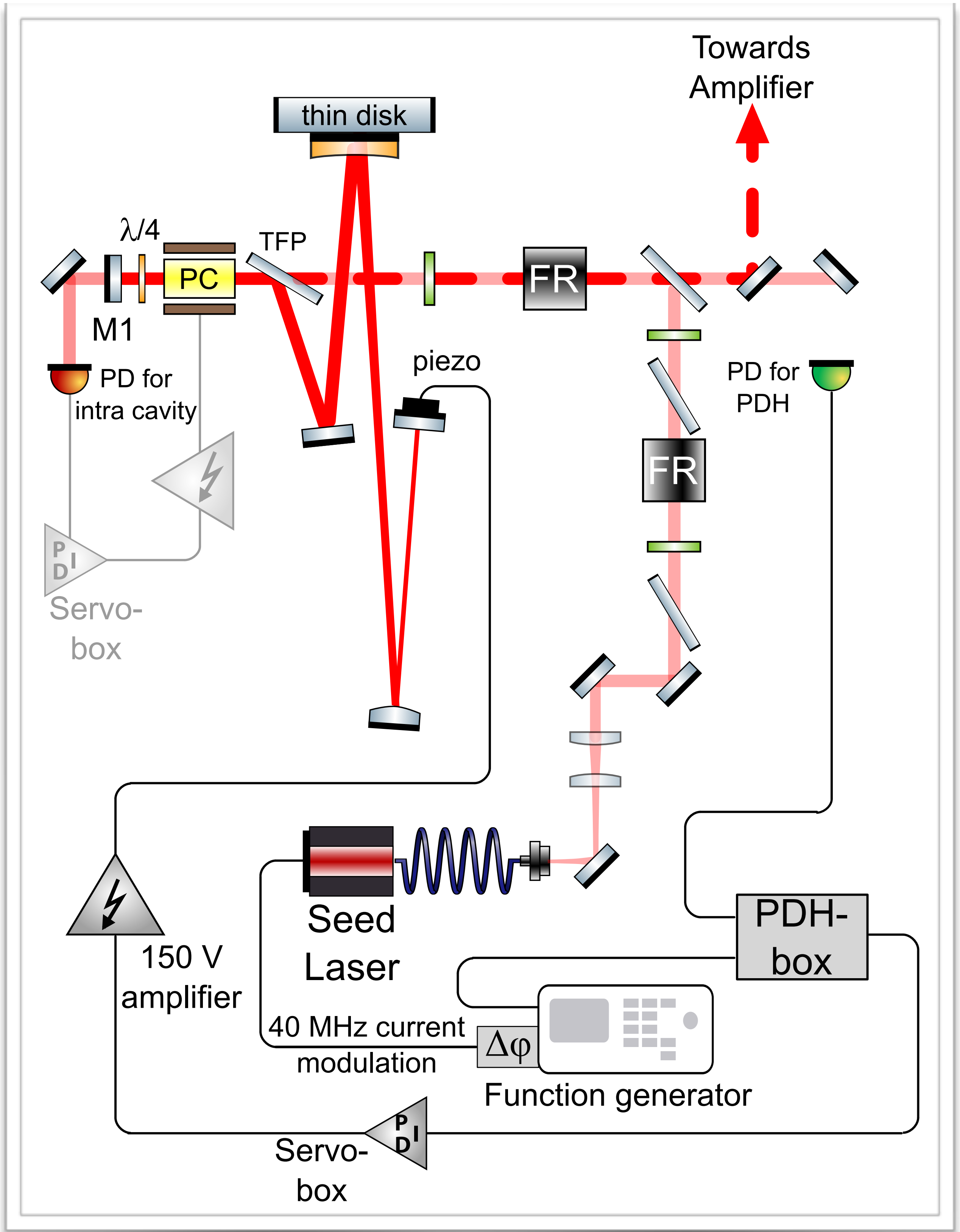

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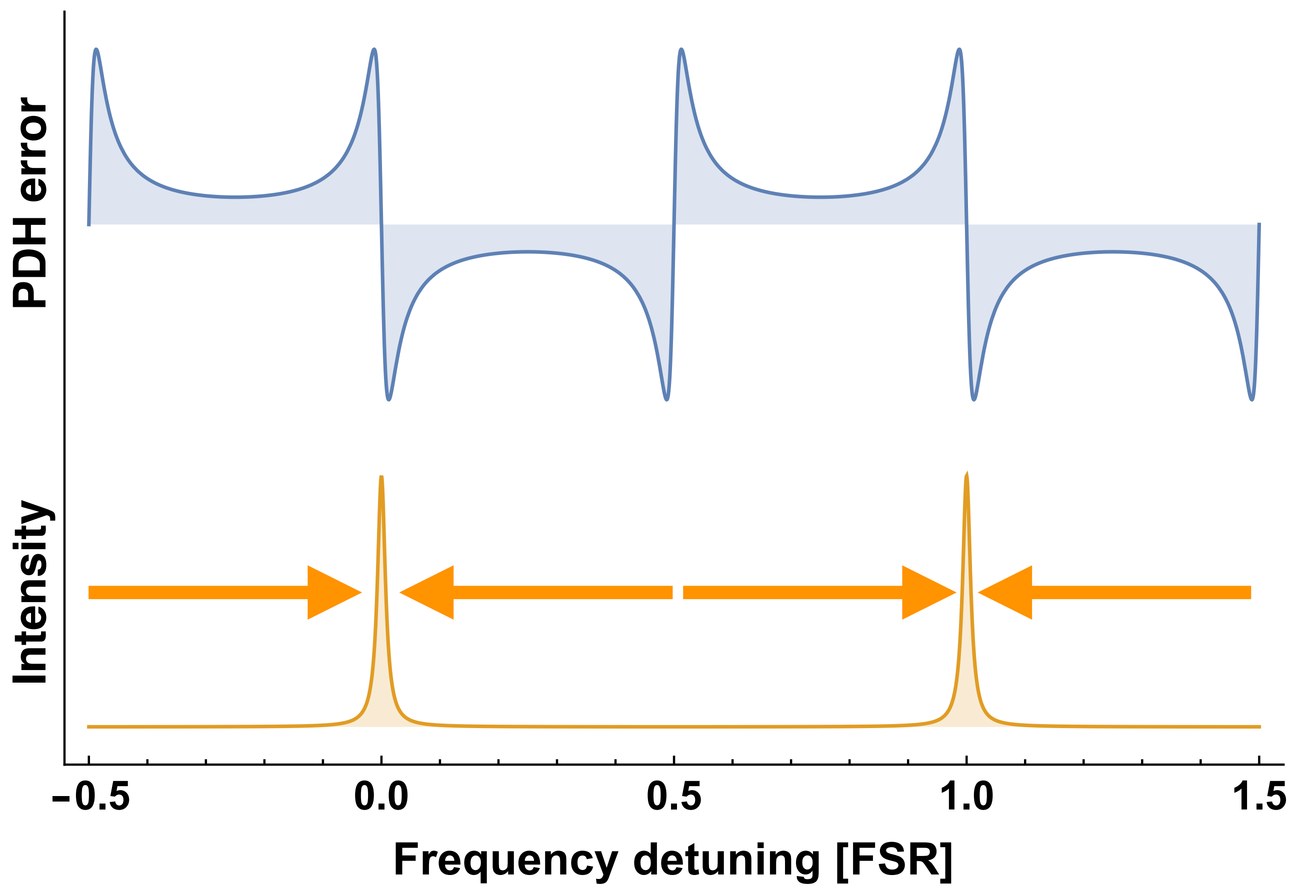
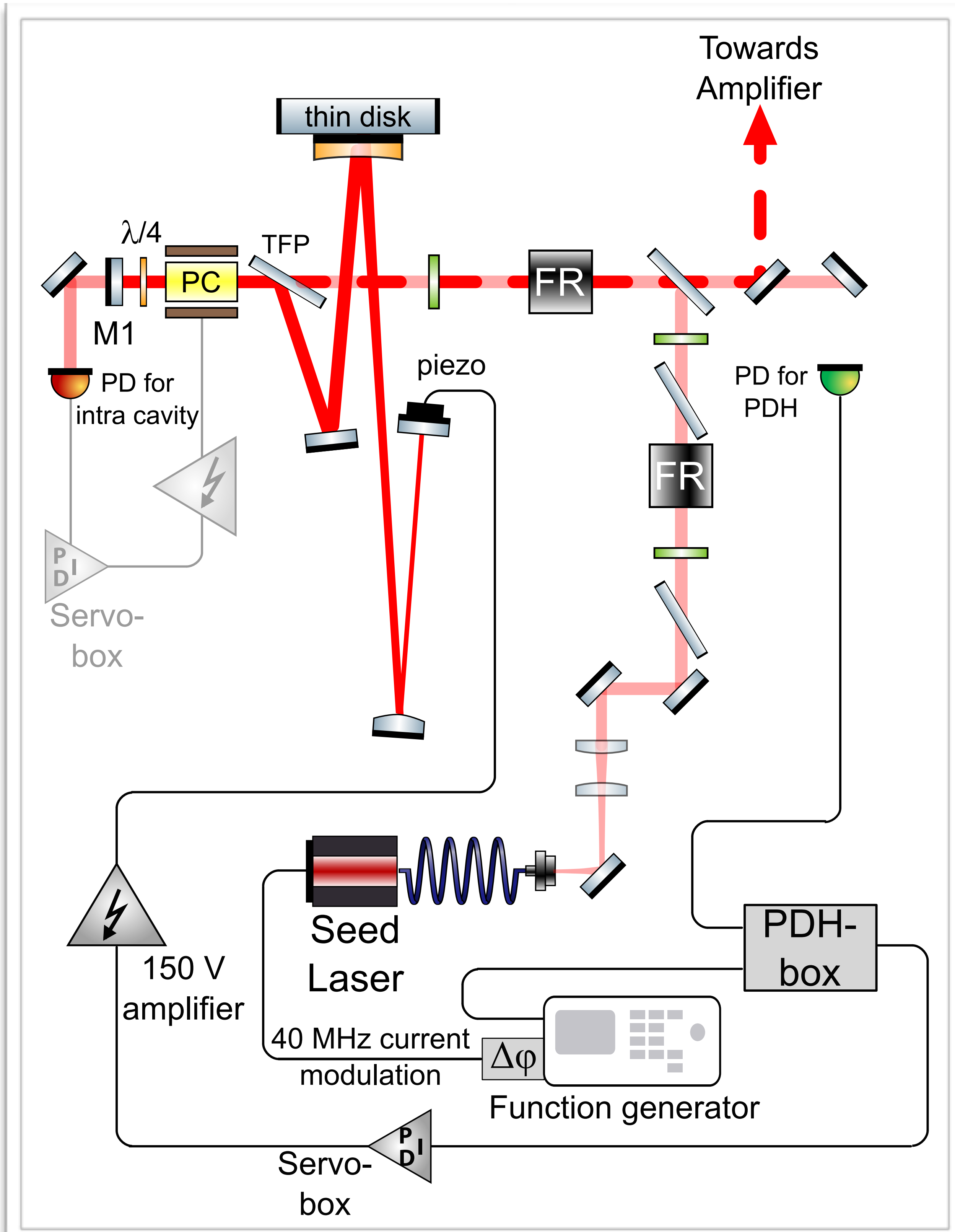


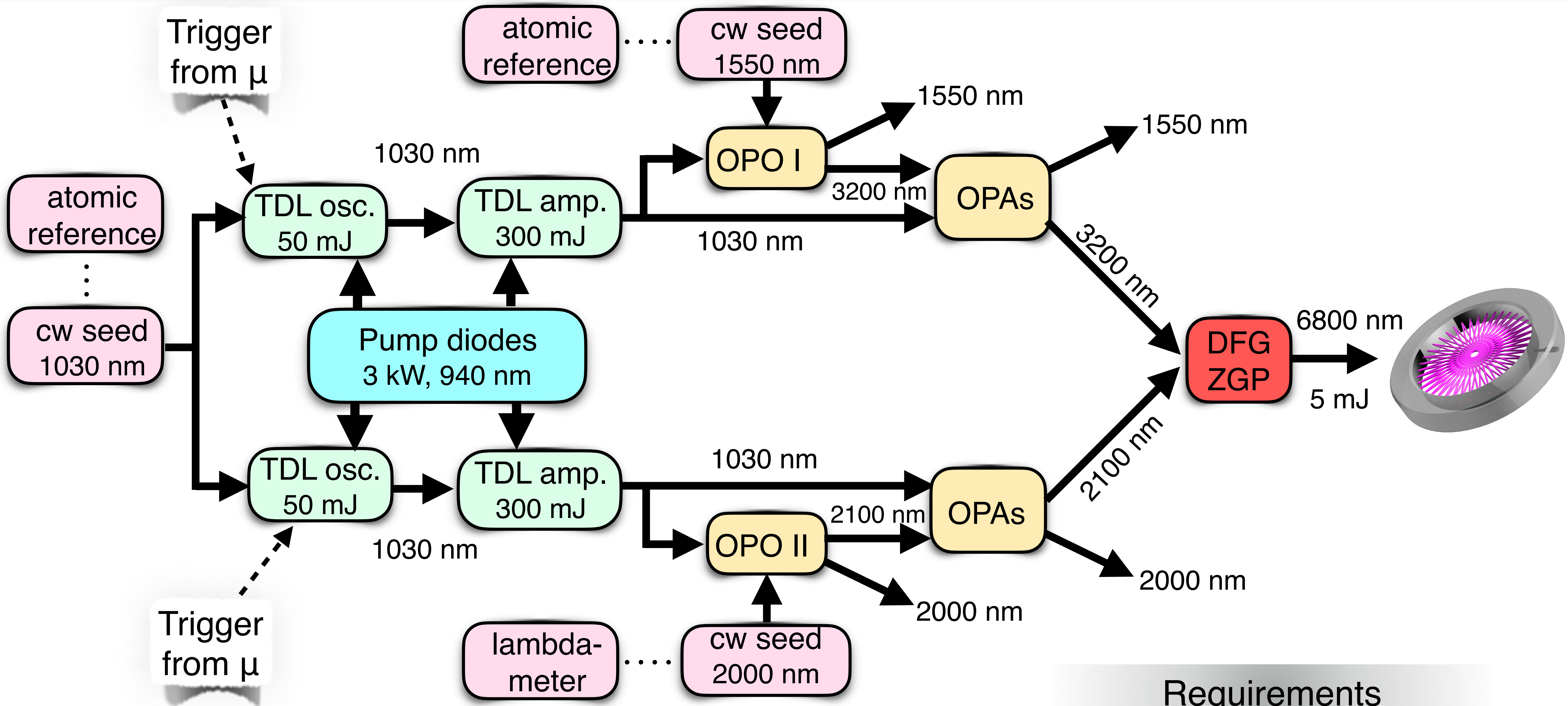
The thin-disk oscillator: results



Proof of principle of single-frequency Q-switched TDL oscillator

- ☐ Energy: 29 mJ — Goal: 50 mJ
- ☑ Delay: 900 ns
- ☑ Pulse-to-pulse stability: 1% (rms)
- ☑ Single-frequency operation
- ☑ Laser chirp < 2 MHz
- ☐ Bandwidth: to be measured

The laser system



Requirements

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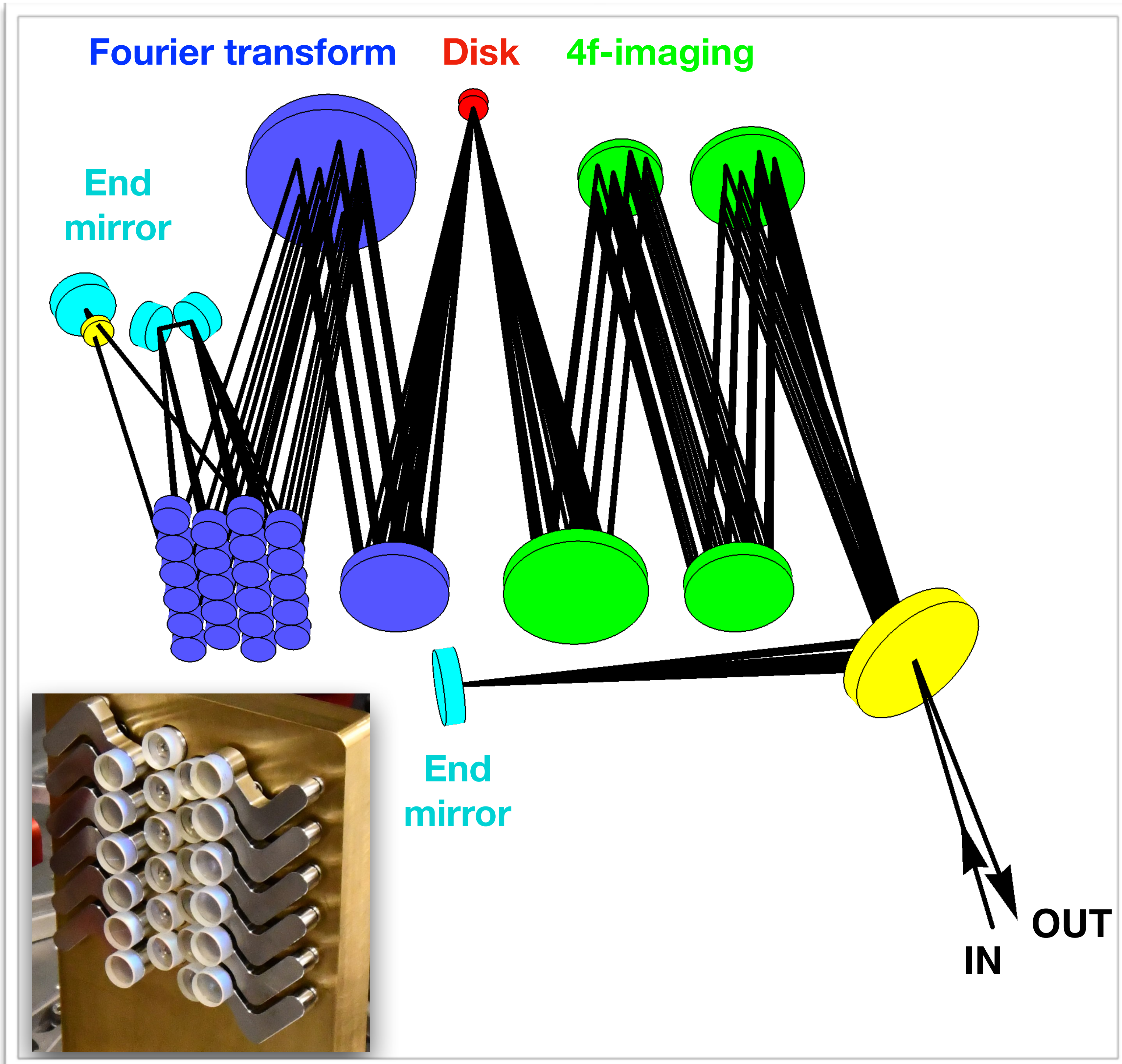
The thin-disk multi-pass amplifier

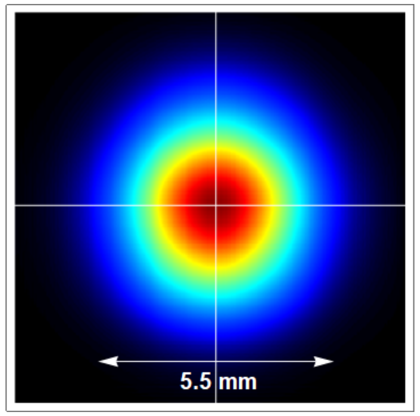
⋮

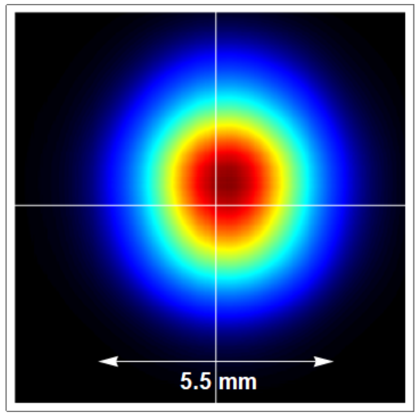
4f
amplification
Fourier Transform
amplification
4f
4f
amplification
Fourier Transform
amplification
4f
4f
amplification
Fourier Transform
amplification
4f
4f

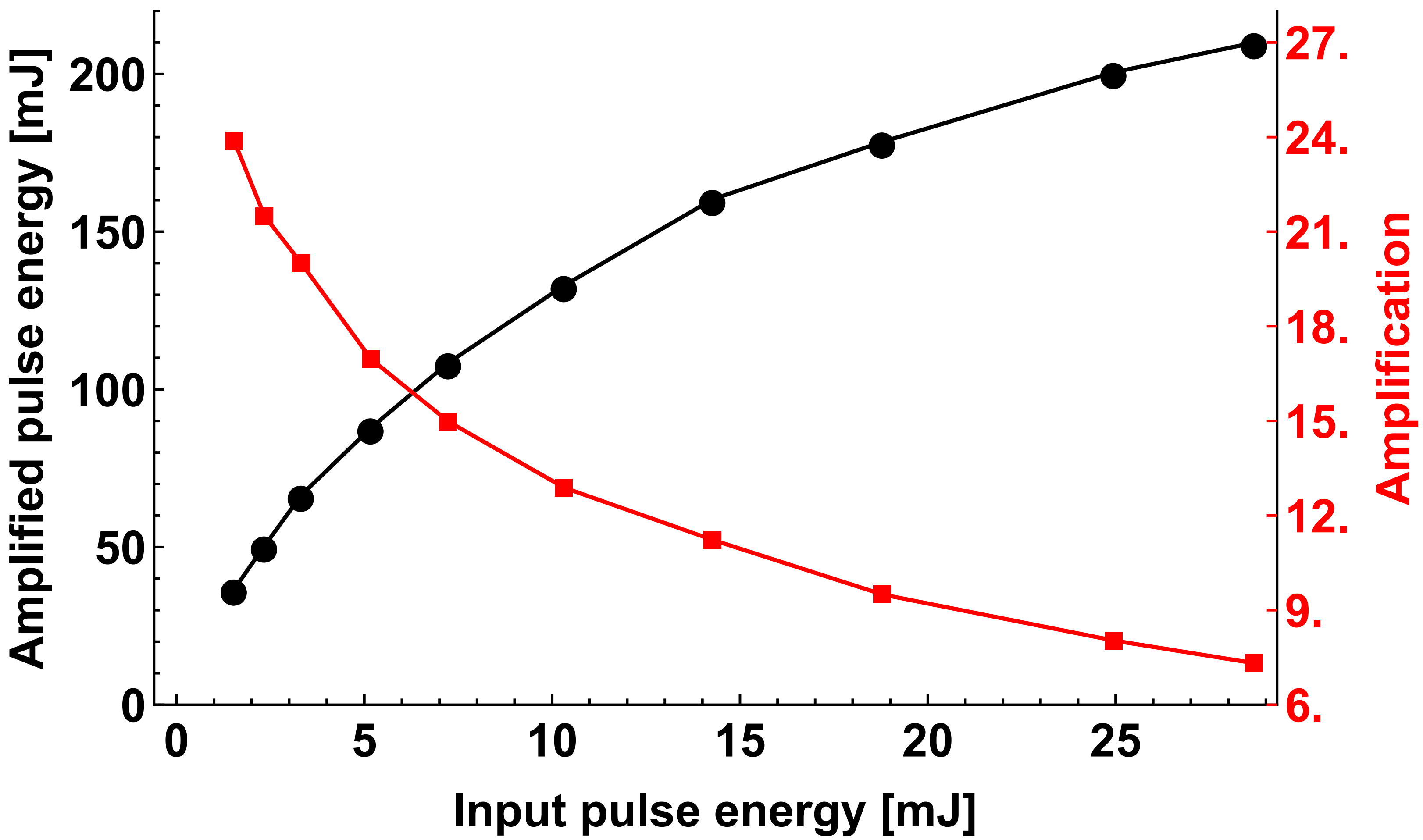
⋮



Thin-disk amplifier results in perspective

IN


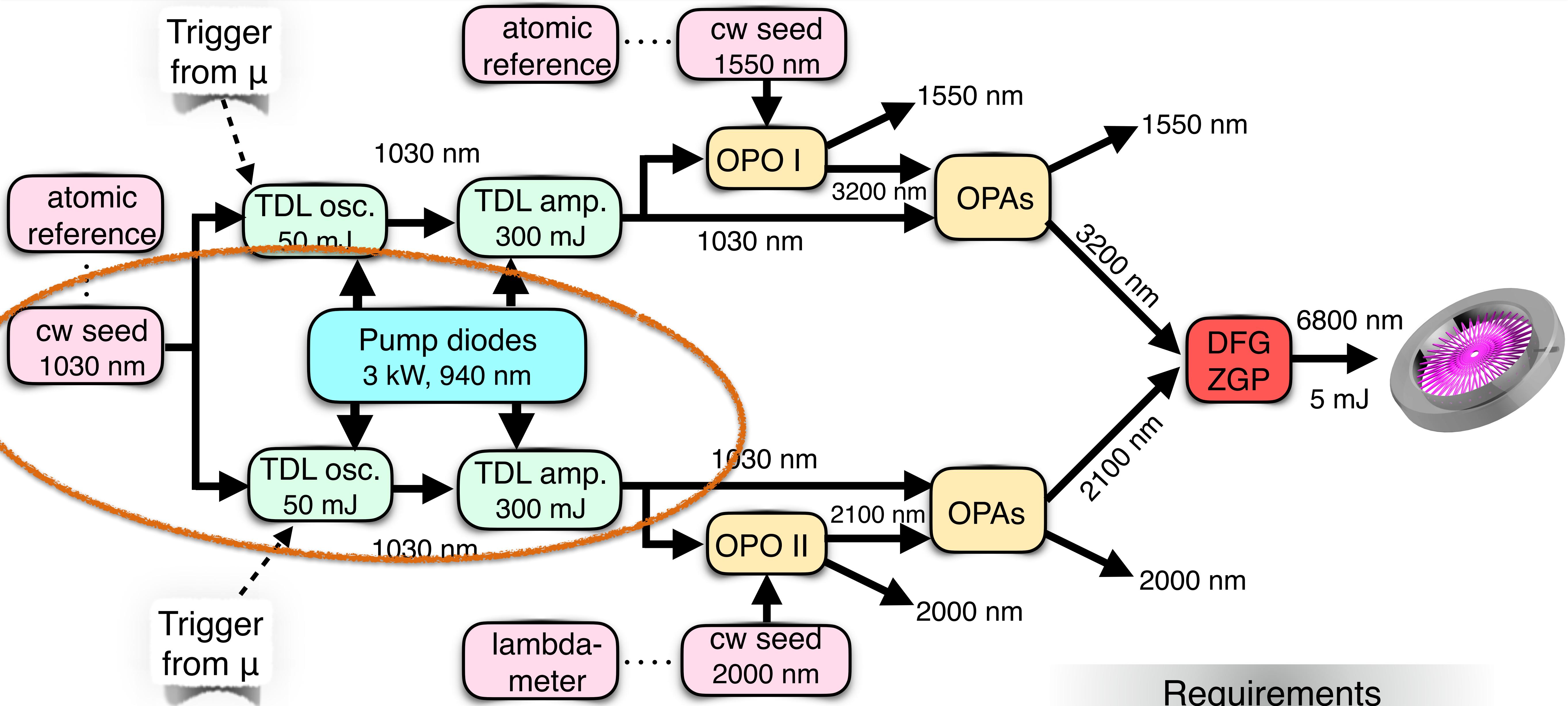
OUT




- ☐ Energy: 210 mJ — Goal: 300 mJ
- ☑ Beam quality: $M^2=1.05$
- ☑ Pulse-to-pulse stability: < 2% (rms)
- ☑ Pointing stability

μHe(2S-2P) Gain=3 @ 85 mJ
μH(HFS) Gain=7.5 @ 220 mJ

The laser system



Requirements

- delay time: 1 µs
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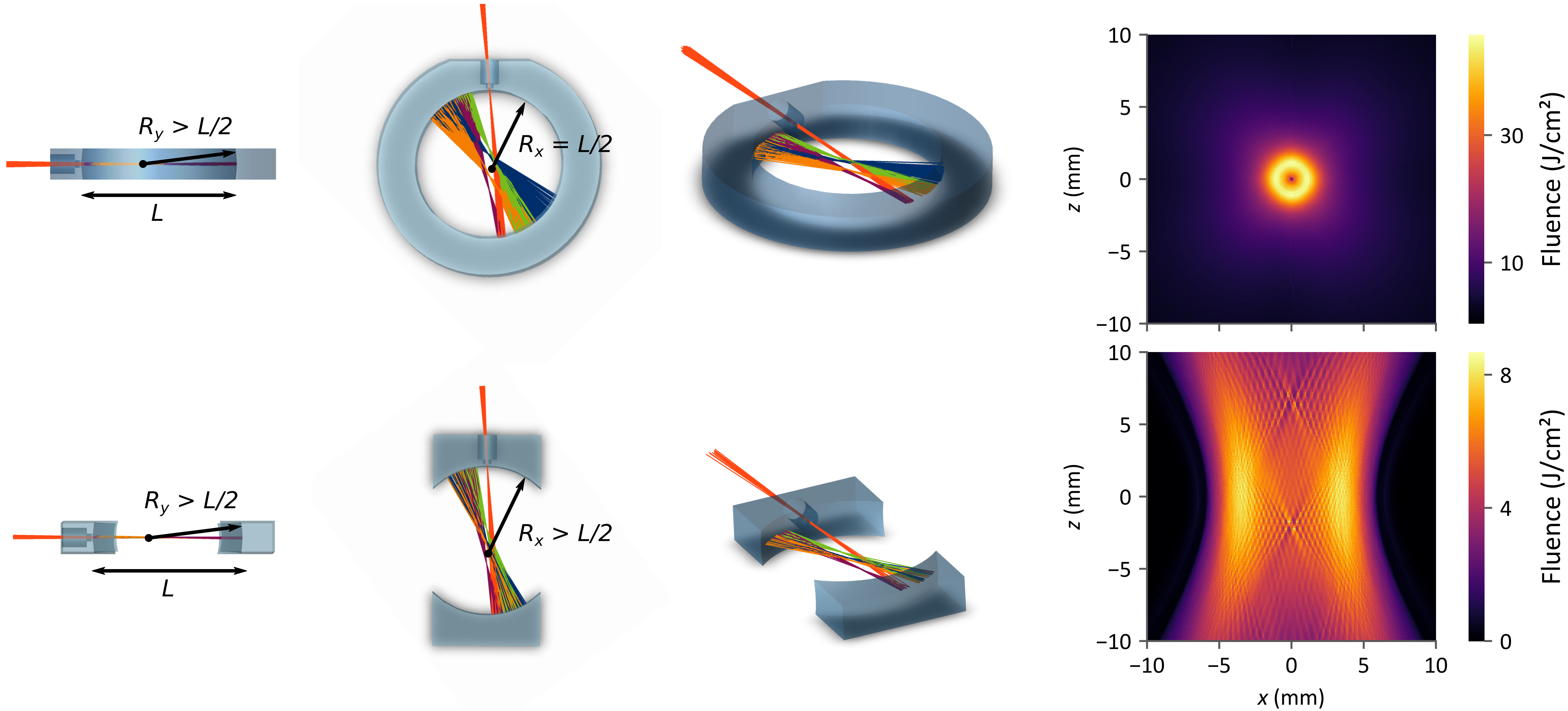
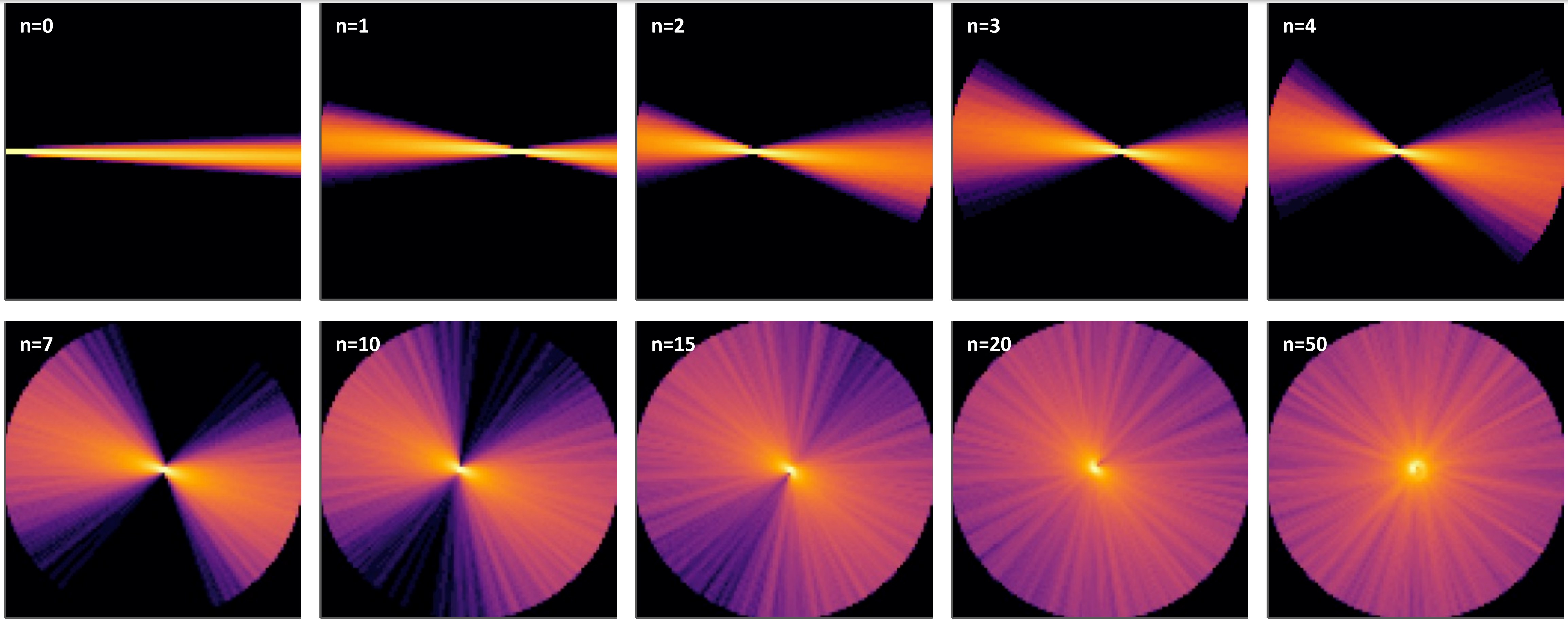
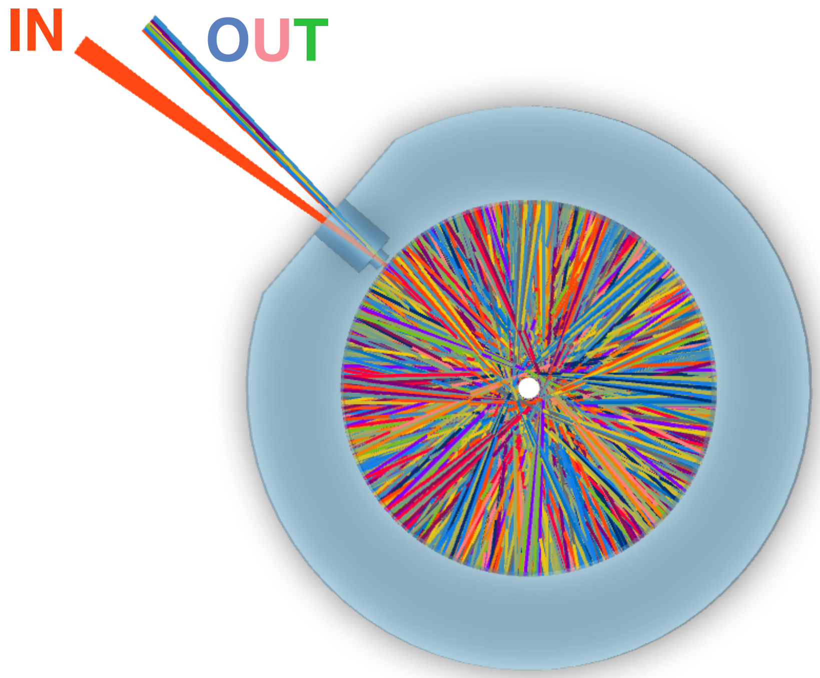
The multi-pass cavity: design and simulations

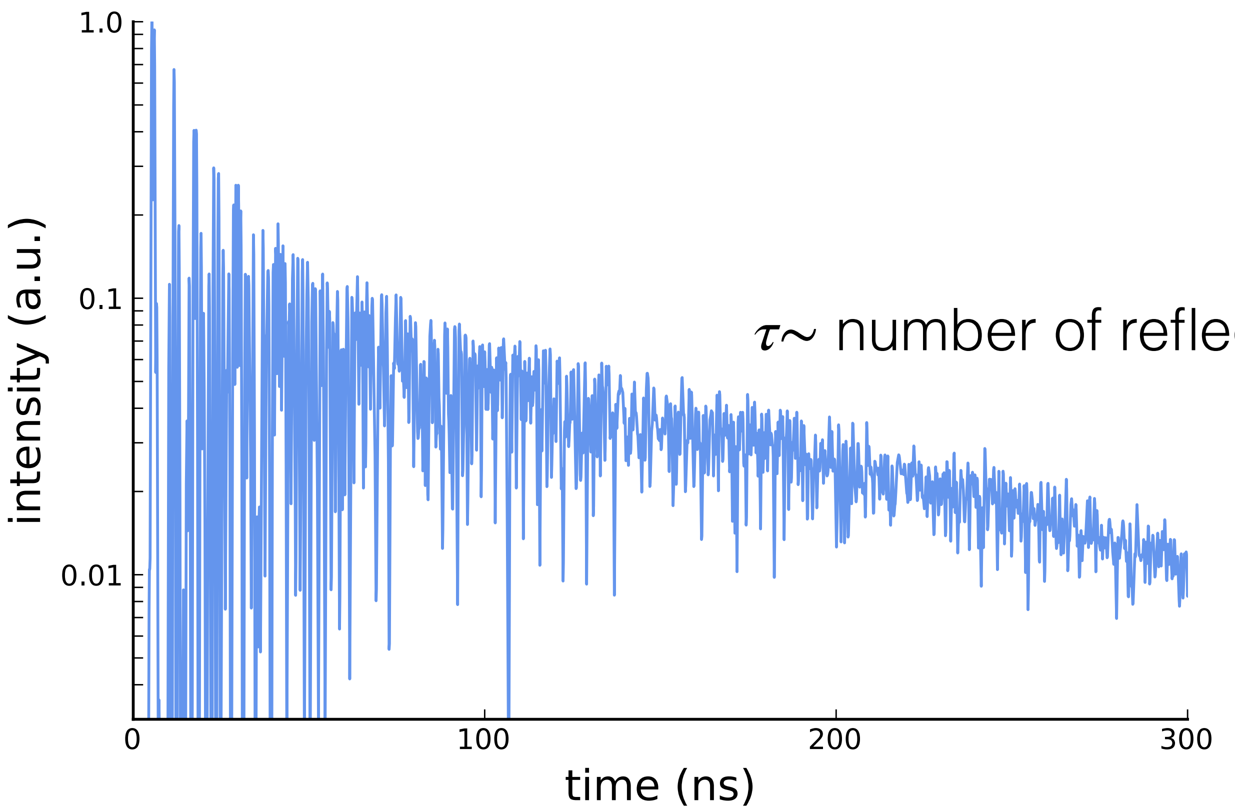


Type A:	Ring cavity,	Cu-substrate,	Cu-reflector
Type B:	Ring cavity,	Cu-substrate,	Dielectric-reflector
Type C:	Ring cavity,	Glass-substrate,	Dielectric-reflector
Type D:	Two-mirror cavity,	Glass-substrate,	Dielectric-reflector

The multi-pass cavity: design and simulations

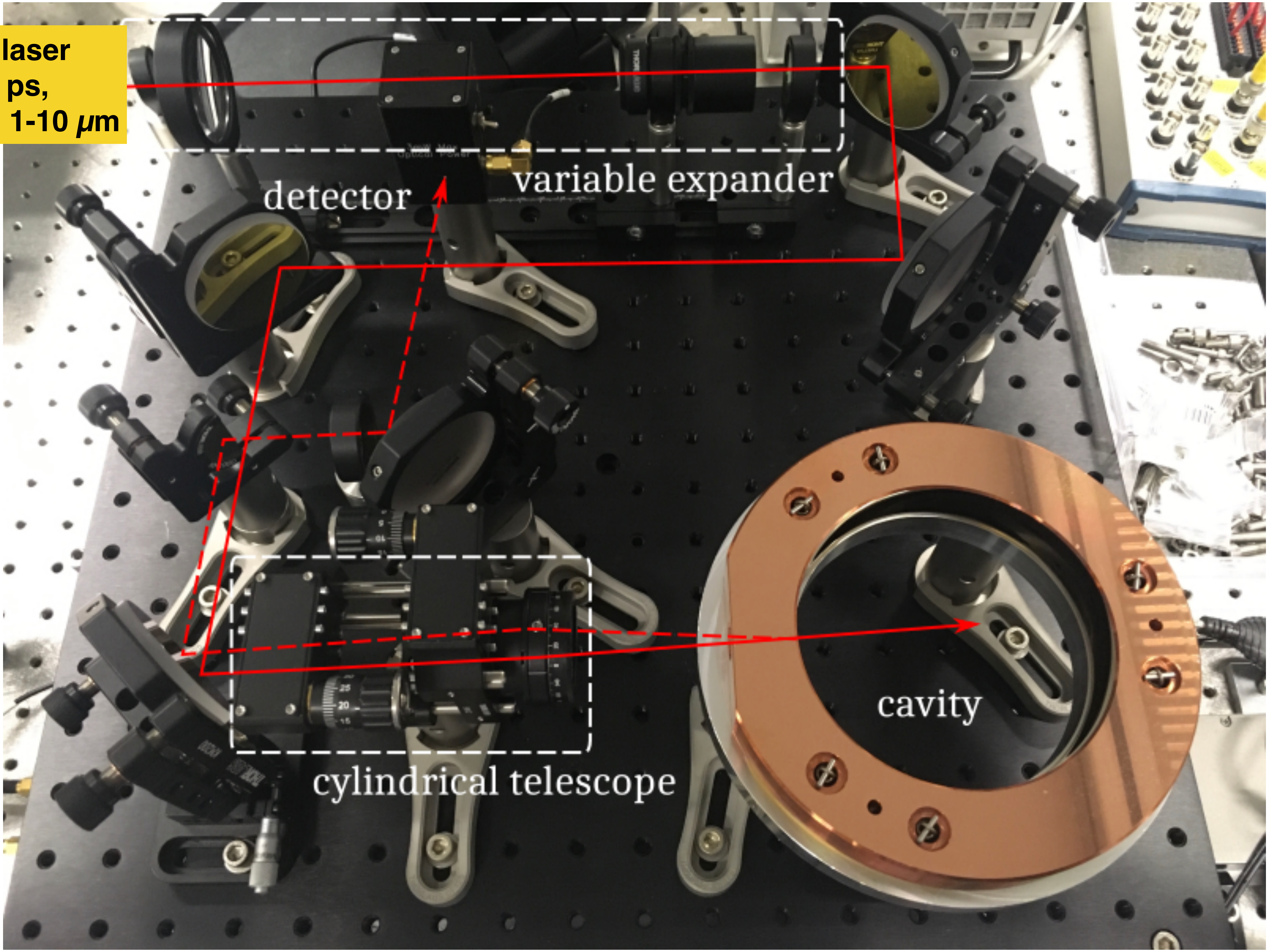




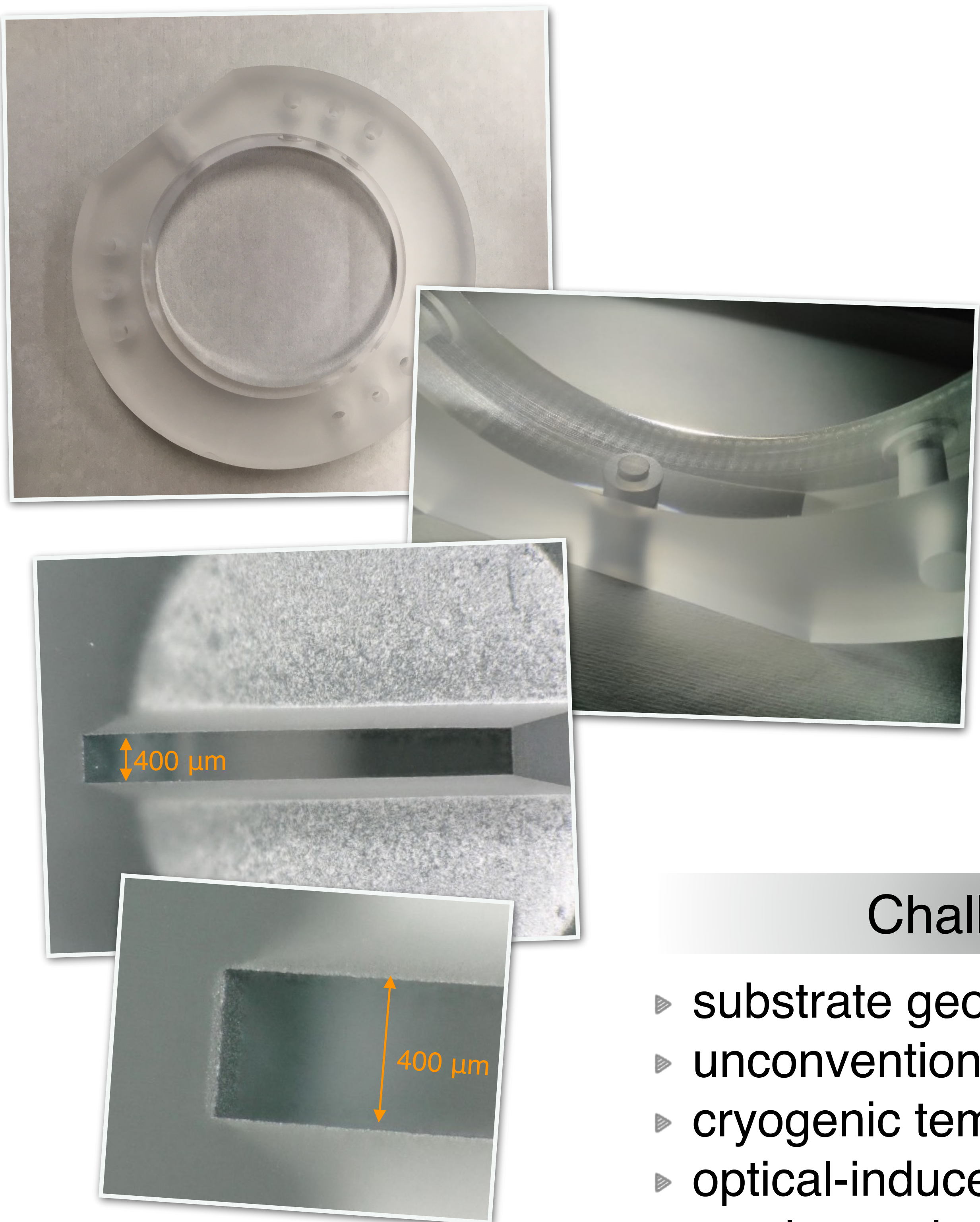


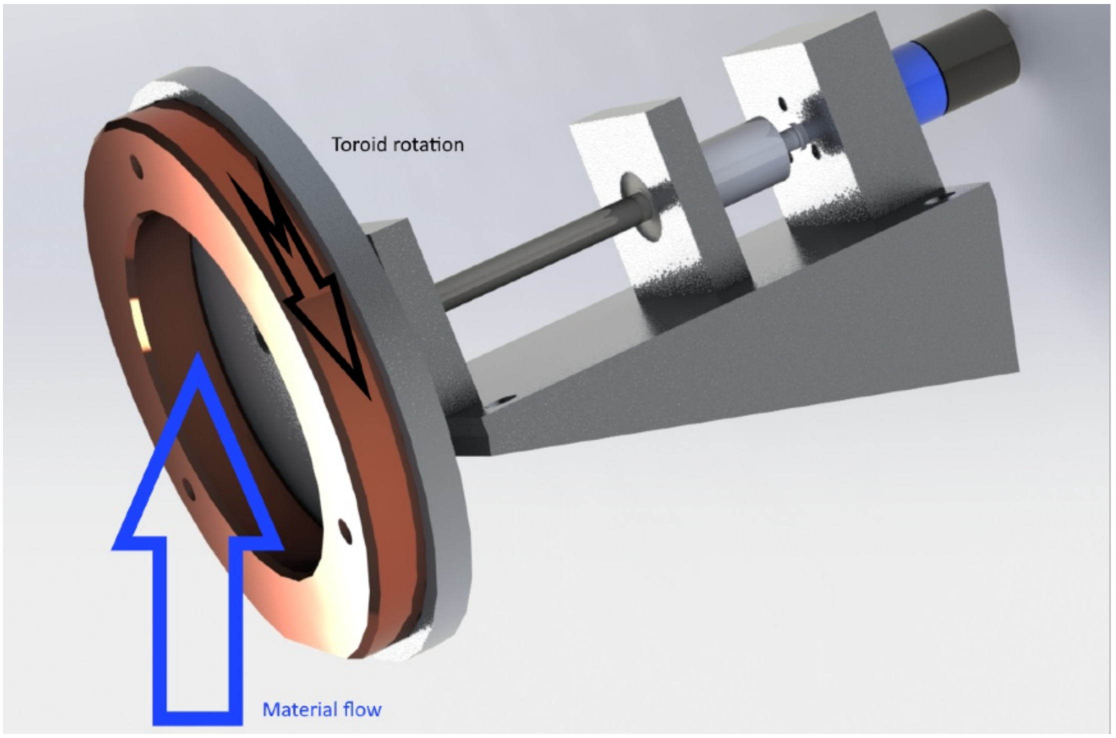
The multi-pass cavity: test setup at SLS

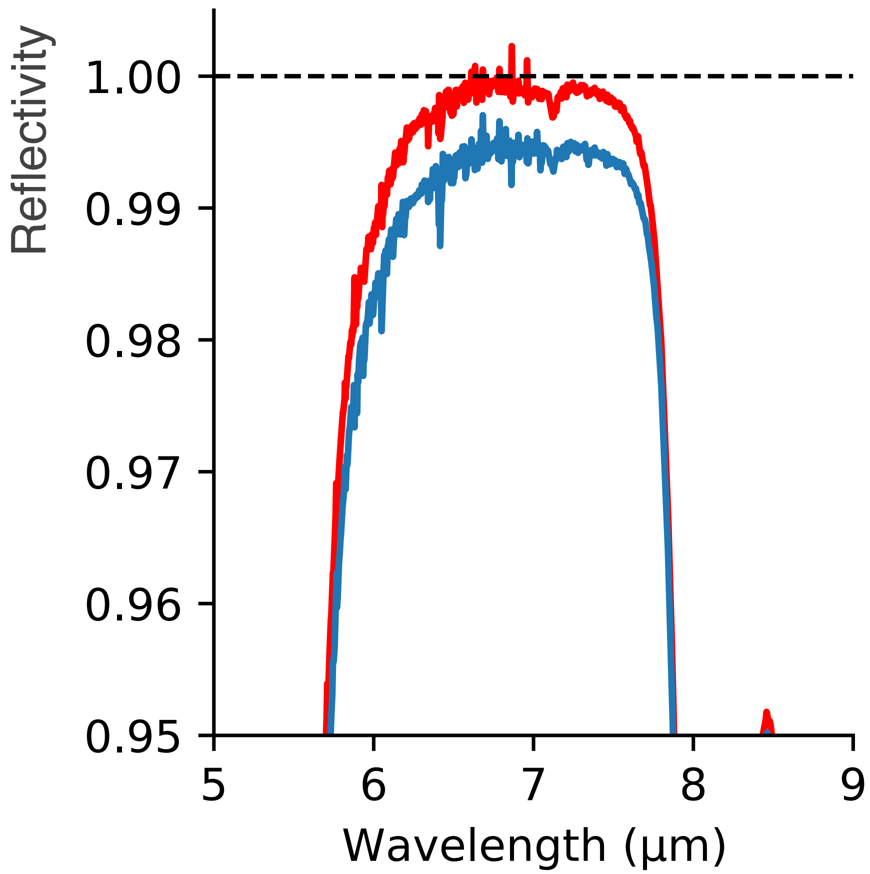
OPO laser
100 ps,
tunable: 1-10 μm



The multi-pass cavity: production



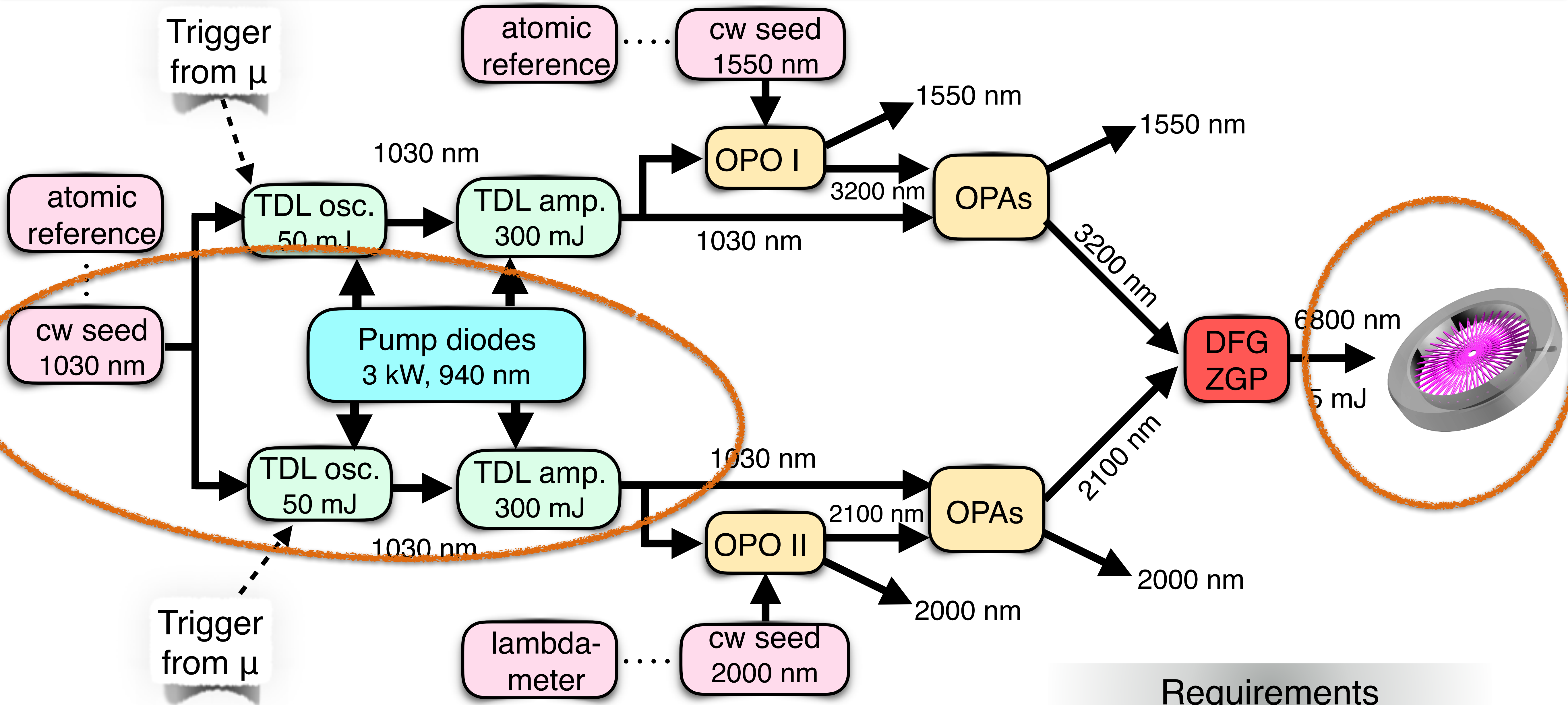




Challenges

- substrate geometry
- unconventional wavelength
- cryogenic temperature
- optical-induced damage
- coating on internal surface

The laser system



Requirements

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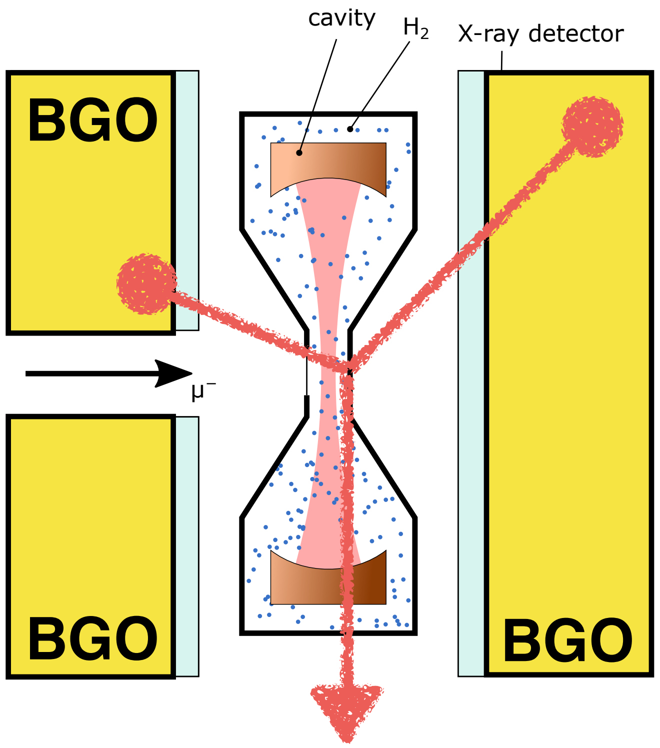
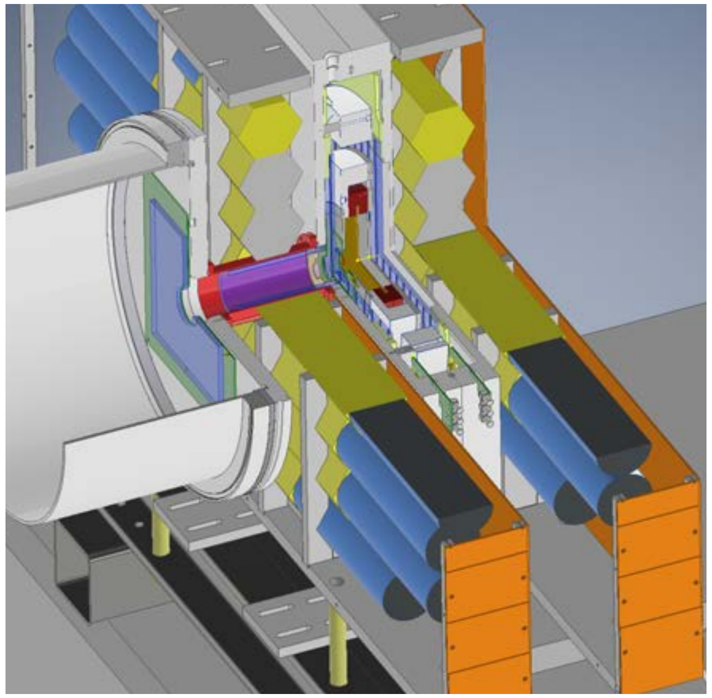
Detection system prototype





Event signal

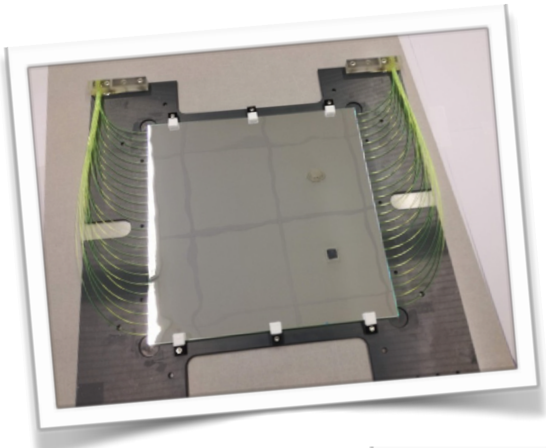
$$\mu\mathrm{Au}^* \rightarrow \mu\mathrm{Au} \quad + \quad \text{X-rays}$$
$$\ldots \quad + \quad \mathrm{n} + \gamma + \cdots$$

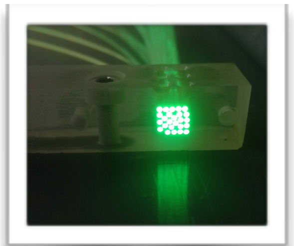
efficiency: 60 %

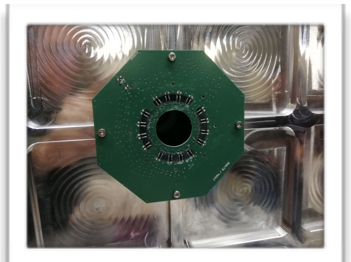
Background signal

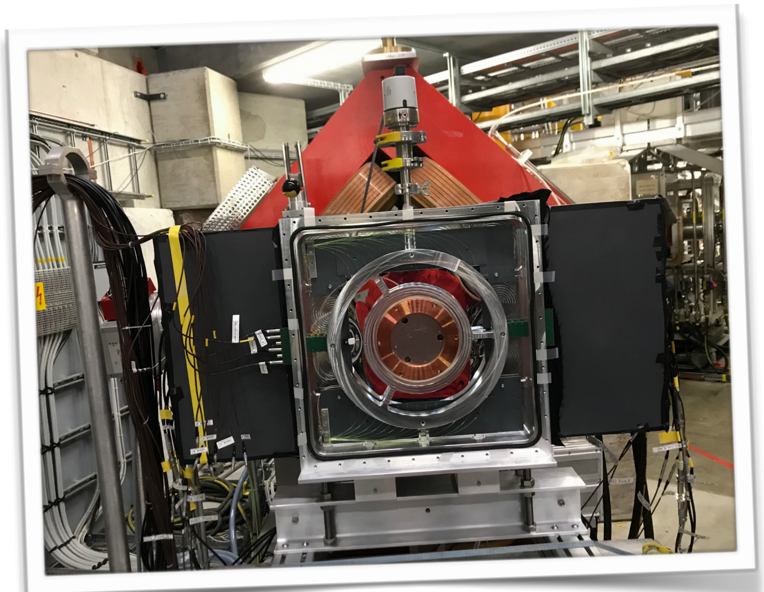
$$\mu \rightarrow \quad e + \nu + \bar{\nu}$$
$$\downarrow$$
$$\text{Bremstrahlung} + ...$$

false identification: 6%



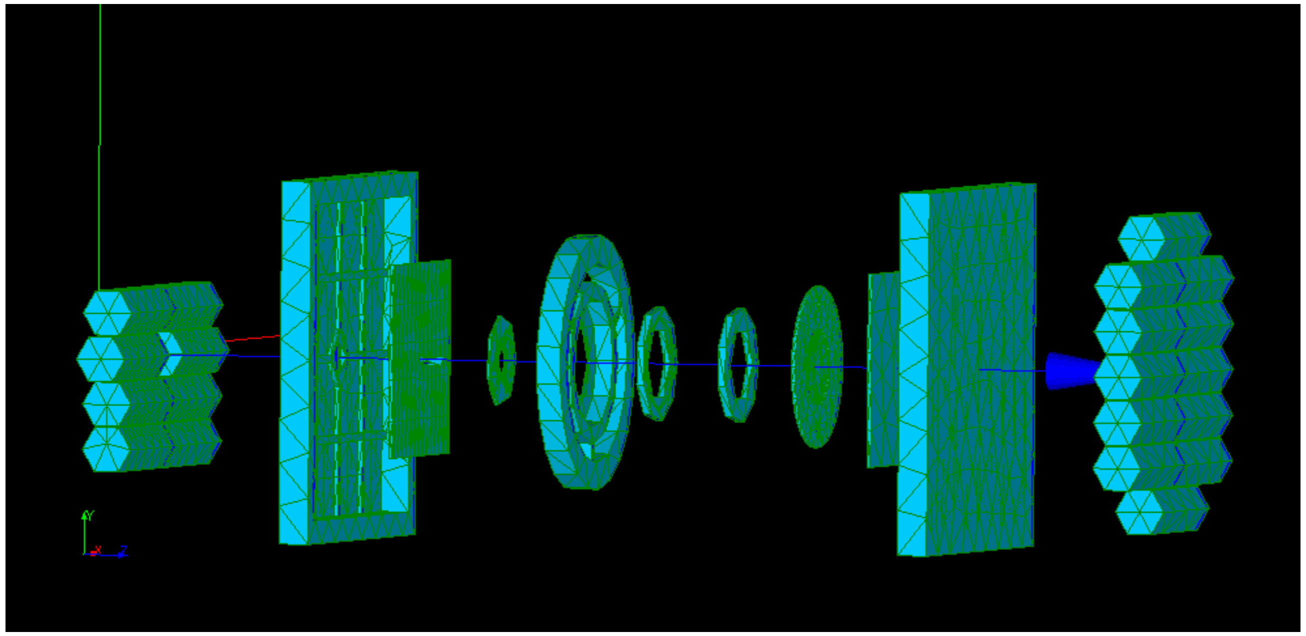




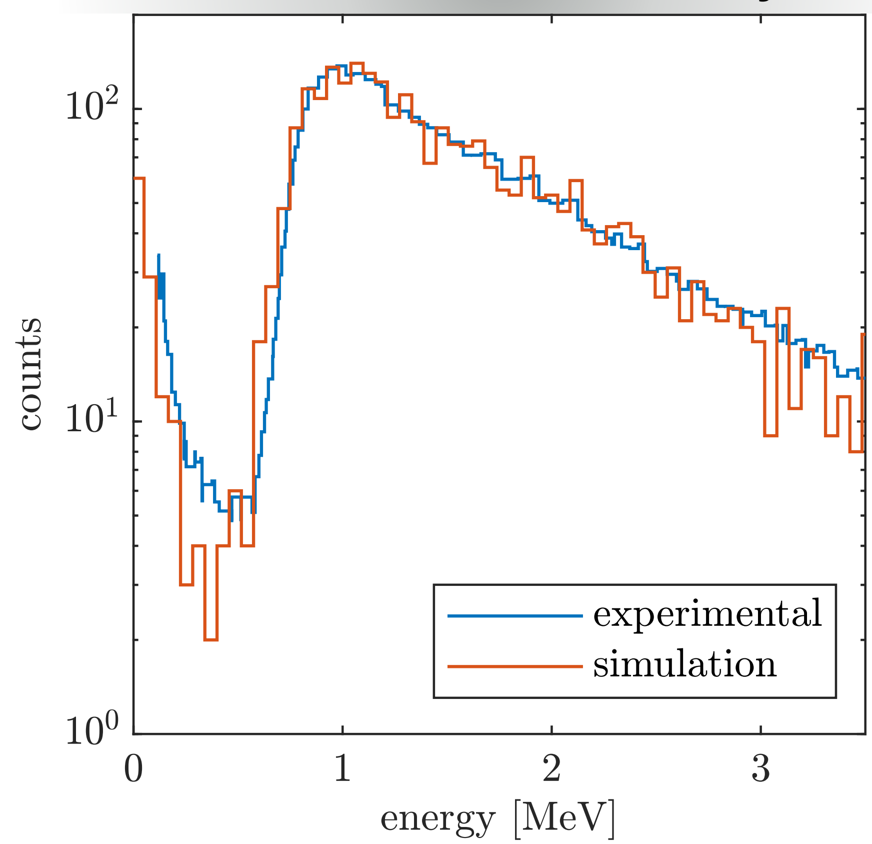


Getting ready for final design

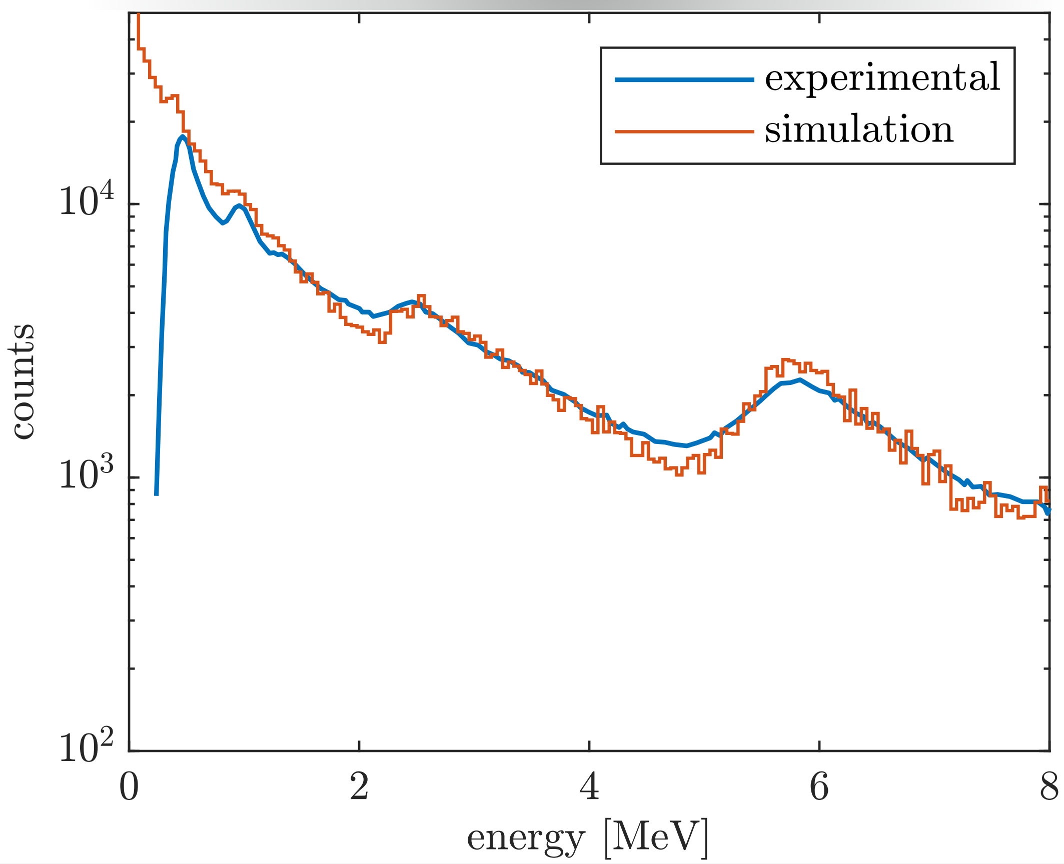
- prototype realised
- detection efficiency and BG measured
- Geant4 simulations (cascade, capture)
- studied light collections in the detectors
  implemented resolutions
- optimisation to improve resonance
  search ongoing



Veto for muon decays



BGO cluster for µAu events



Other advances

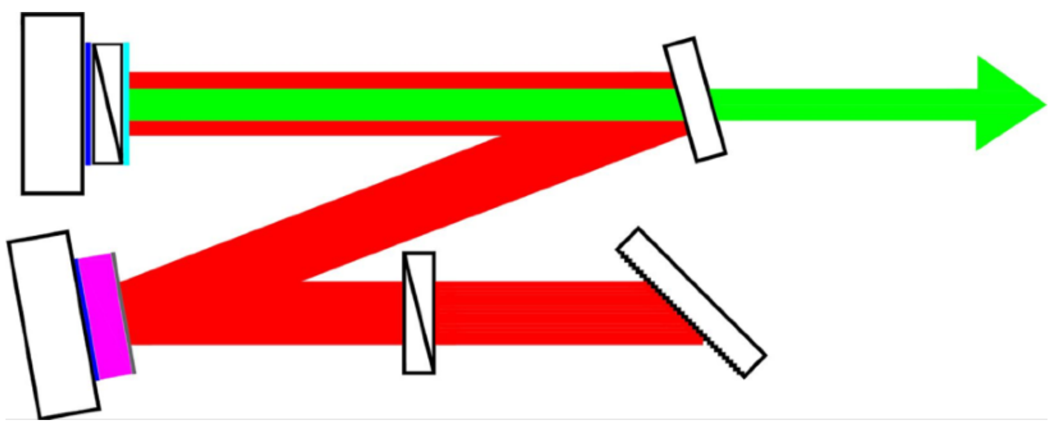
2S-2P measurement in μ^4He

$$r_\alpha = 1.67824\,(13)_{\rm exp}\,(82)_{\rm theo}\ \text{fm}$$

CREMA coll., Nature (2021)

Patent submitted: Power-scalable optical system for nonlinear frequency conversion

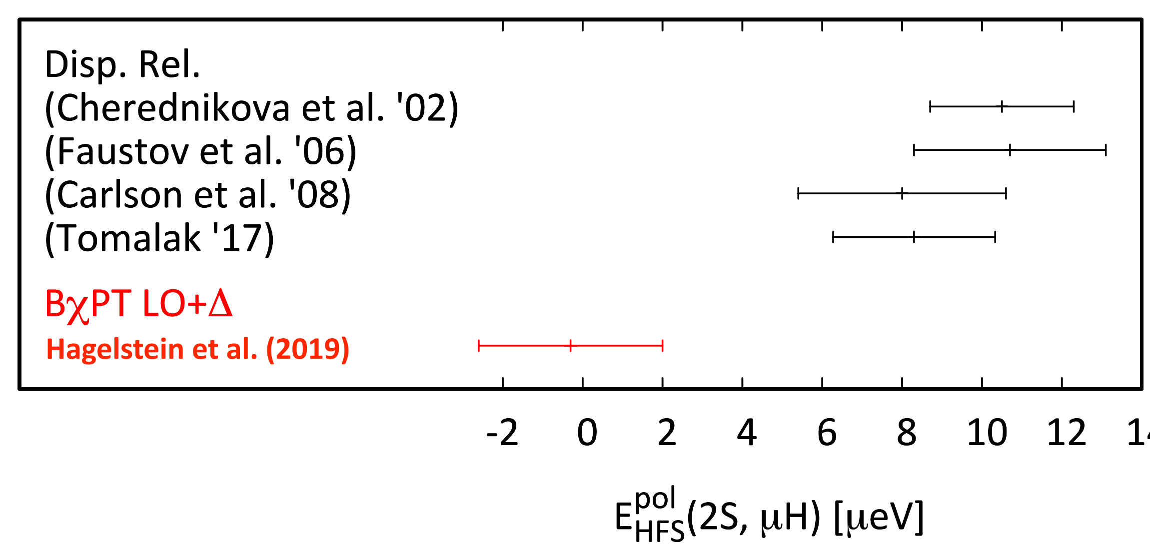
K. Schuhmann & AA, ETHZ+PSI



High power beams at 515 nm, 207 nm and from 1.1 µm to 6 µm when starting with a thin-disk laser at 1030 nm.

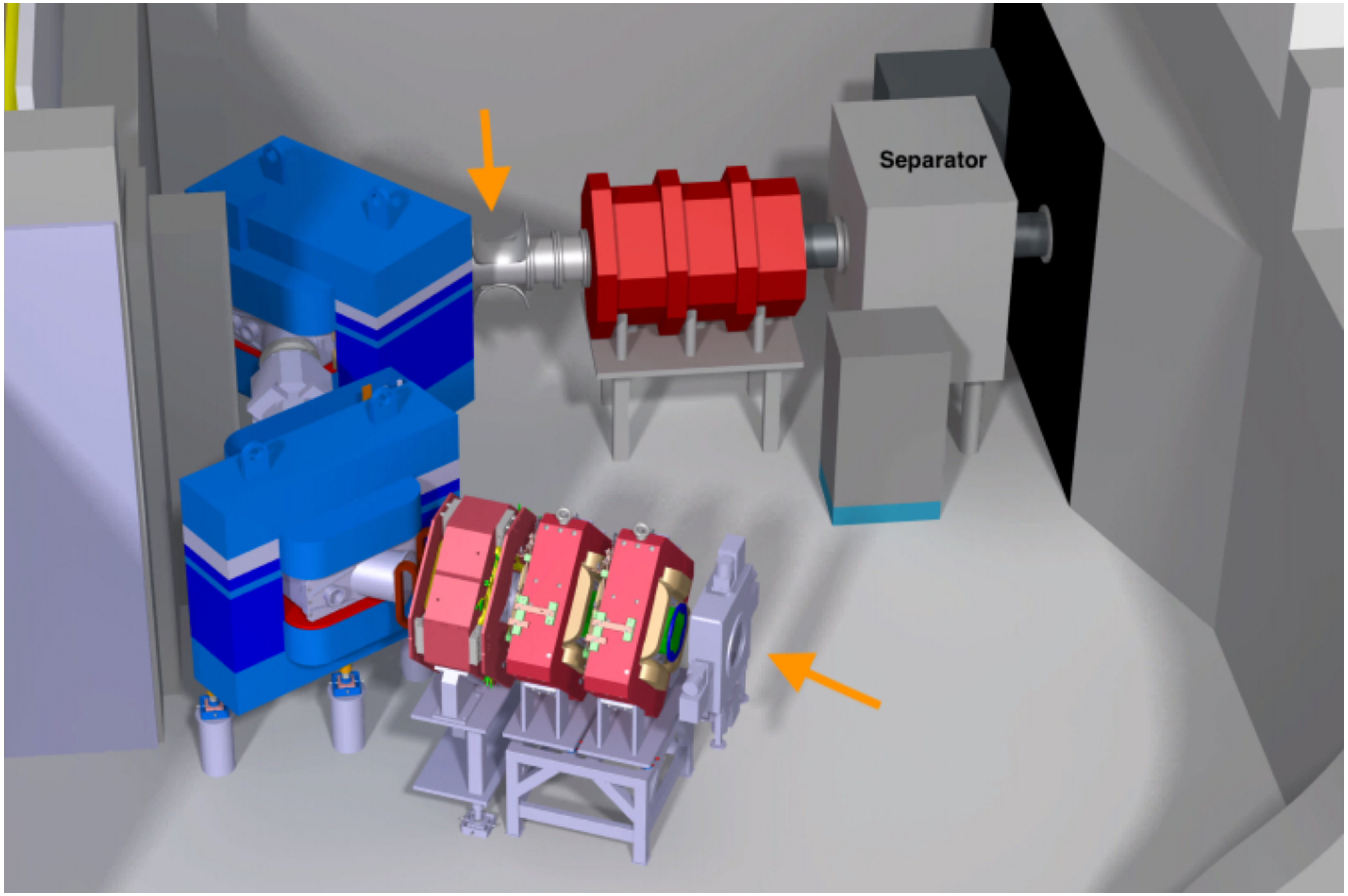
F. Hagelstein joined LTP theory group

- advance chPT prediction of the TPE
- fit structure function data with theory guidance
- compute TPE with dispersive approach



Beam time request

12 days in πE5



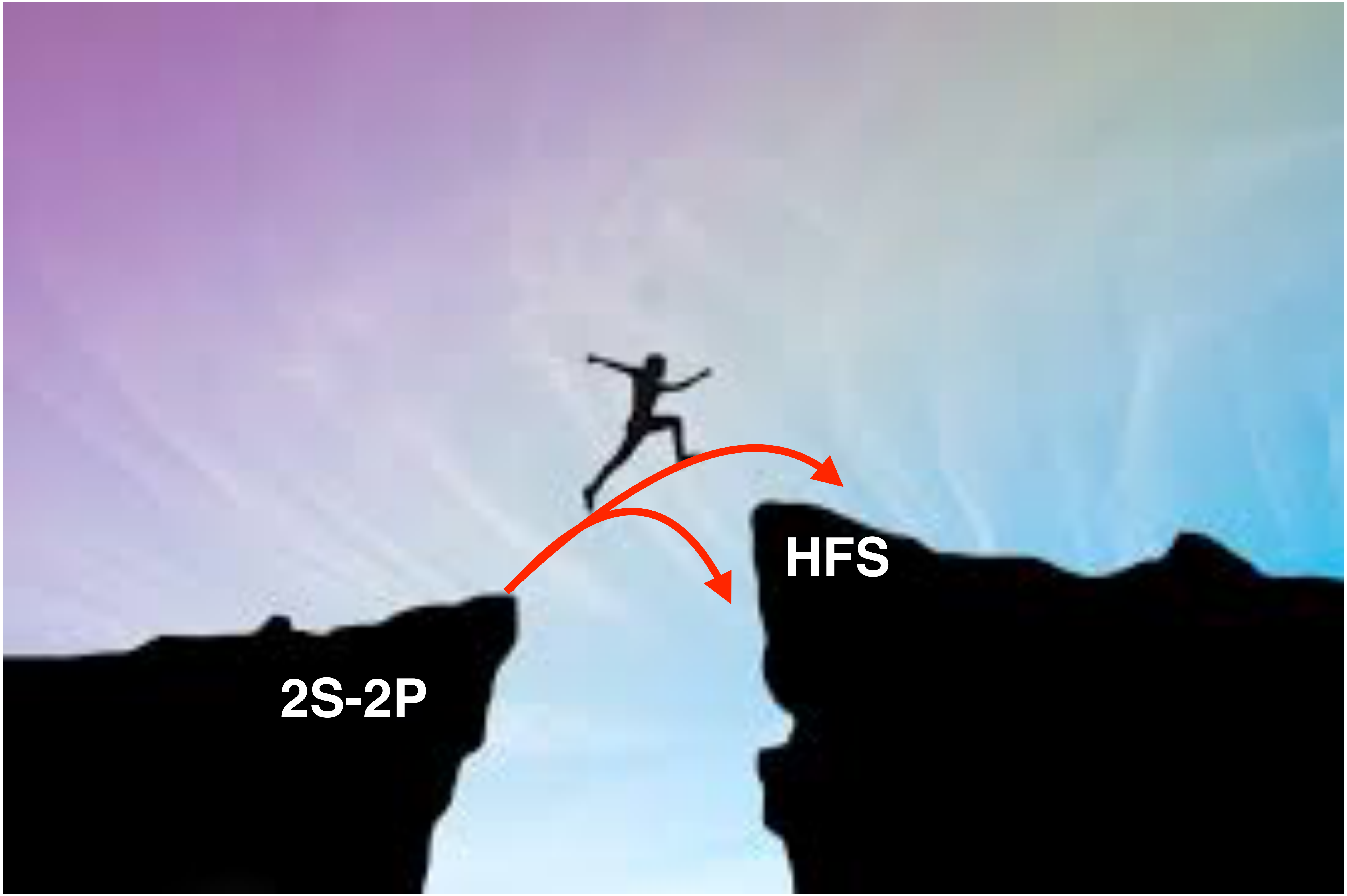
Planned measurements

- μ^- rates at two positions at low momenta 10-13 MeV/c
- e^- contamination

- Vary collimation if needed
- Vary target position (focal length)
- commission a movable 1D-array for online monitoring purposes

- CMBL extended with a doublet
- use upgraded separator

Status: pursuing the needed technology leap



Conclusions

Laser system

- Good progress in 2020 but still a long way
- Development of down-conversion stages is now possible

Cavity

- Simulations “completed”
- Test setup ready
- Coating development ongoing

Detection system

- Proof of principle demonstrated
- Detection efficiency and background quantified

Strategic developments for 2021

- Down-conversion stages
- Multi-pass cavity

Laser fluence ?

The CREMA collaboration

Laboratoire Kastler Brossel
Physique quantique et applications

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F. Nez, N. Paul, P. Yzombard

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MPQ

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