Low Energy Particle Physics (Group of Klaus Kirch)
Insitute for Particle and Astrophysics

Laser System for the Hyperfine Splitting in Muonic Hydrogen

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Zürich PhD Student Seminar

Outline

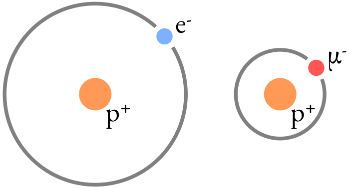
1. General overview: HyperMu
    - Motivation
    - Measurement principle

2. Requirements on the laser system

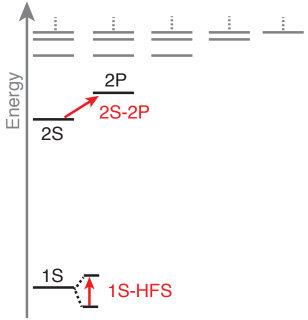
3. Schema of laser system
    - Thin-disk laser oscillator
    - Thin-disk laser amplifier

The HyperMu project

Motivation



$$E_n^{\mu p} = \frac{m_\mu}{m_e} \cdot E_n^{H} \qquad \langle r_n^{\mu p} \rangle = \frac{m_e}{m_\mu} \cdot \langle r_n^{H} \rangle$$

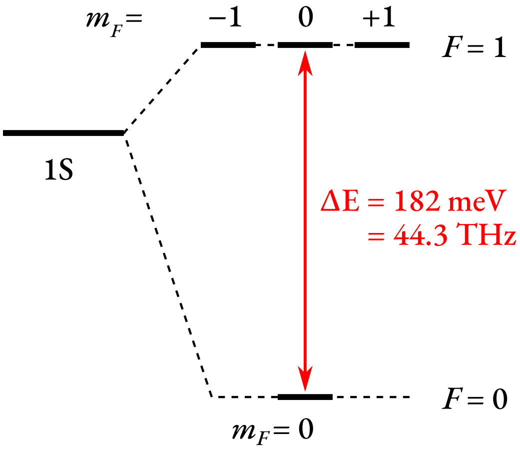


Muonic hydrogen: μp

- muon 200 times more massive than the electron
- sensitive to magnetic properties of the proton

The HyperMu project

Motivation

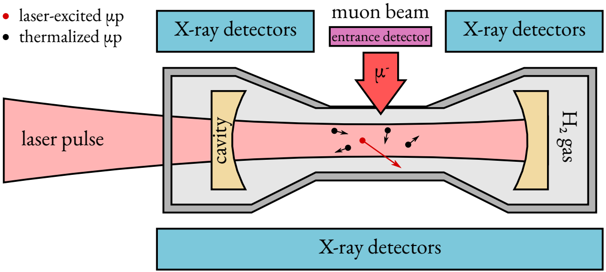


Measure the hyperfine splitting with a relative accuracy of 10^{-6}

$$\underbrace{\Delta E_{\mathrm{HFS}}}_{\text{measured}} = E_{\mathrm{F}} \left(1 + \Delta_{\mathrm{QED+weak}} + \Delta_{\mathrm{hVP}} + \underbrace{\Delta_{2\gamma}}_{\text{derived}} \right)$$

Measurement principle

- **Stop muon beam in** 1 mm **H_2 gas target at** 22 K **and** 0.5 bar
- Wait until μp atom de-excites and thermalises
- Laser excites HFS transition: $\mu p^{(F=0)} + \gamma \rightarrow \mu p^{(F=1)}$
- Collisional de-excitation: $\mu p^{(F=1)} + H_2 \rightarrow \mu p^{(F=0)} + H_2 + E_{kin}$
- μp atom diffuses to Gold-coated target walls
- Formed μAu* de-excites promptly and produces characteristic X-rays
- Detected X-rays are plotted against laser frequency



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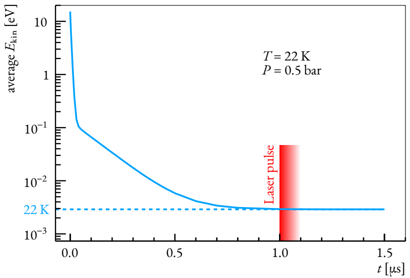

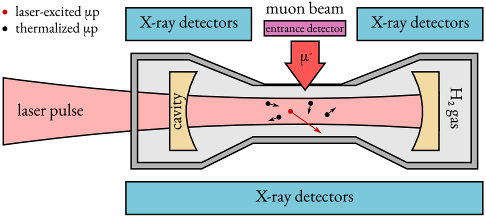

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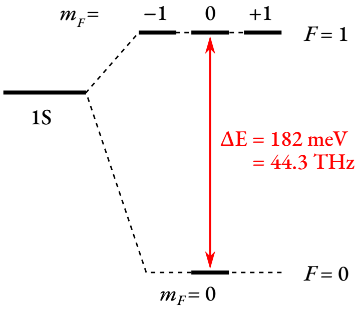

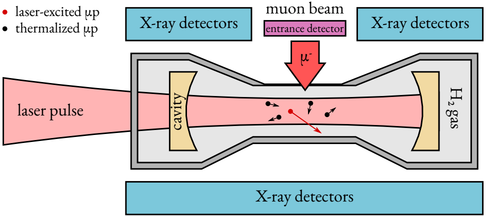

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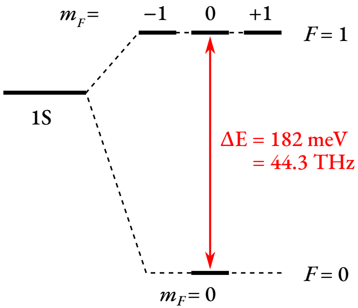

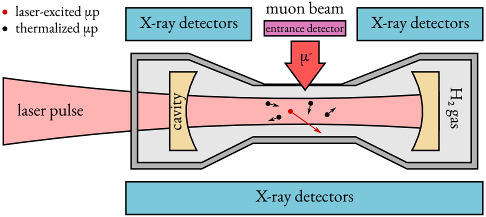

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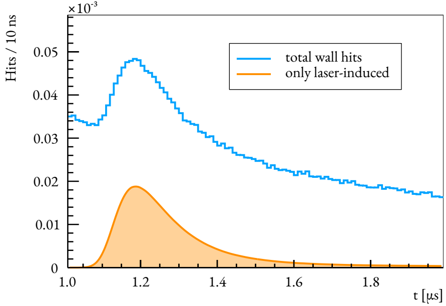

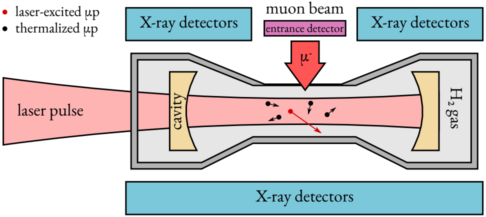

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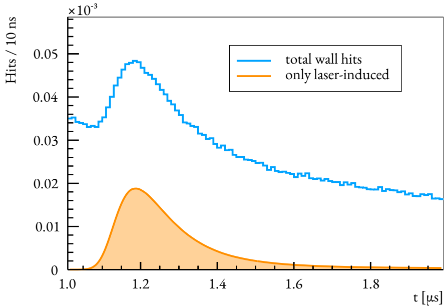

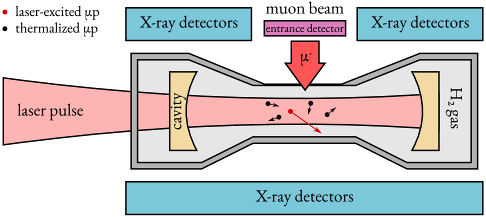

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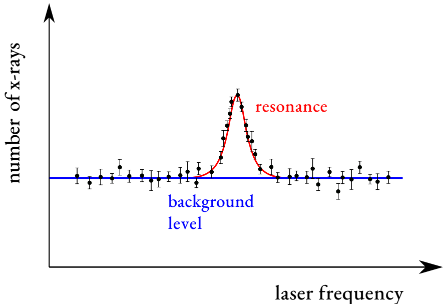
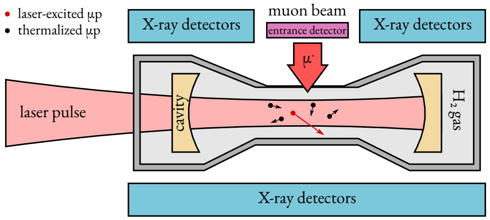
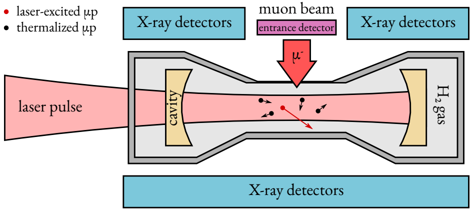
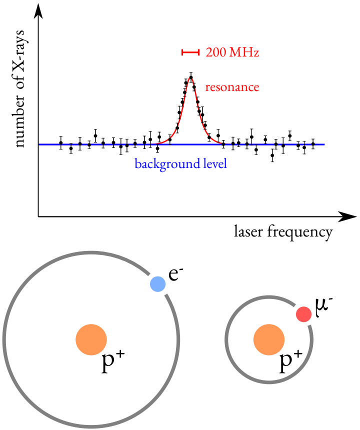




Requirements

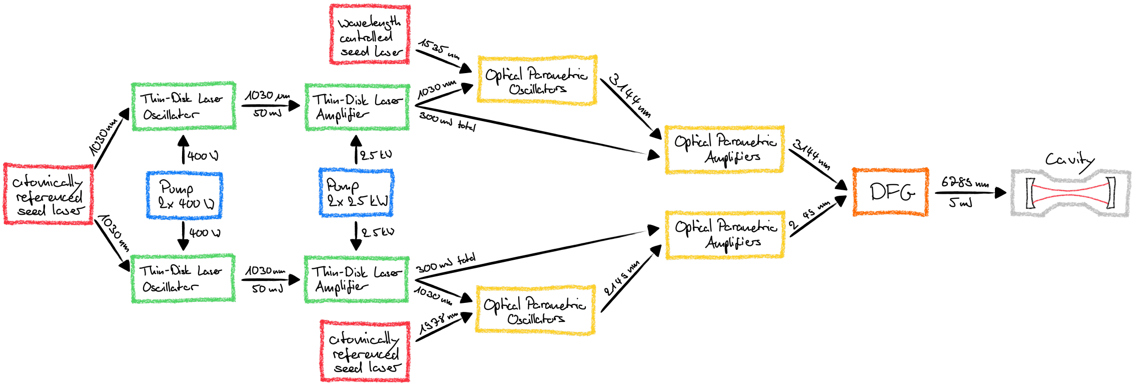
HFS transition energy of $\Delta E_{\mathrm{HFS}} = 182$ meV	$\Rightarrow$ wavelength $\lambda = 6.8$ µm
spectroscopy	$\Rightarrow$ tunable wavelength
rel. accuracy of 10^{-6}	$\Rightarrow$ <50 MHz line width
small matrix element	$\Rightarrow$ high fluence $F \approx 10\,\mathrm{J\,cm^{-2}}$ corresponds to $E_{\mathrm{pulse}} \approx 5$ mJ
continuous µ beam	$\Rightarrow$ stochastic trigger
muon lifetime	$\Rightarrow$ pulse delivery within 1 µs





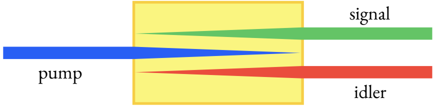
Simple schema

More detailed schema of the laser system

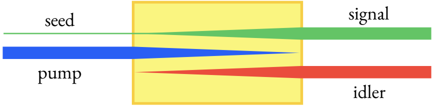


Optical parametric process

How it works



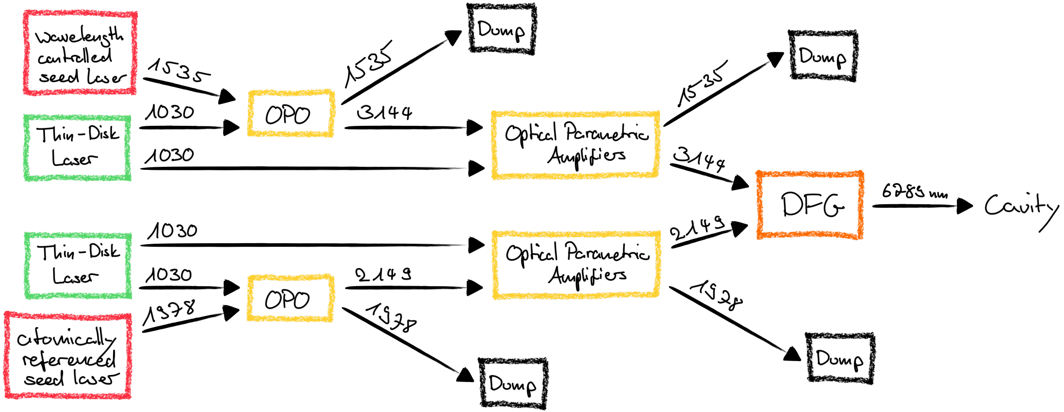
$$\nu_{\text{pump}} > \nu_{\text{signal}} > \nu_{\text{idler}}$$



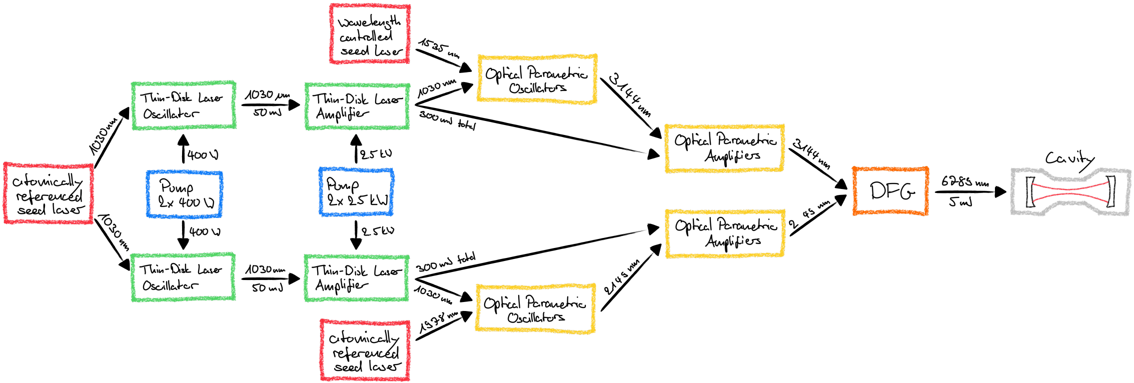
$$\nu_{\text{pump}} = \nu_{\text{signal}} + \nu_{\text{idler}}$$

$$\vec{k}_{\text{pump}} = \vec{k}_{\text{signal}} + \vec{k}_{\text{idler}}$$

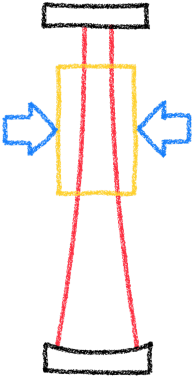
Schema of the non-linear downconversion

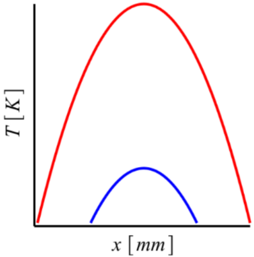


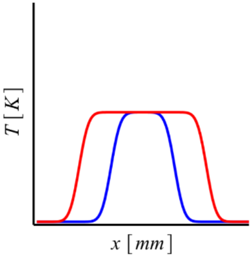
Detailed schematic



What is a thin-disk laser?







+ large gain
– energy not scalable

– small gain
+ energy is scalable

Thin-disk laser oscillator

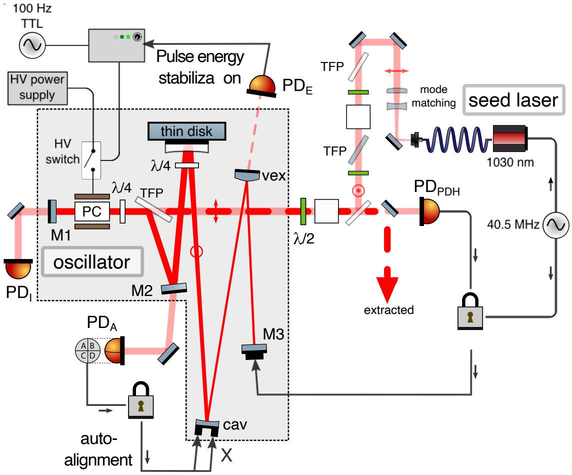
Schema

Before muon trigger

- cavity continuously injection seeded
- thin-disk continuously pumped

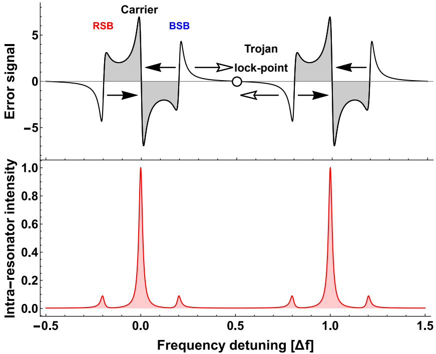
After muon trigger

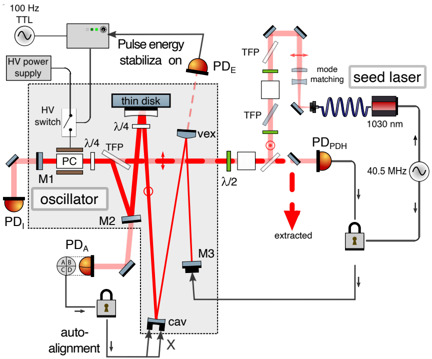
- cavity closed by rotating polarisation using Pockels cell
- pulse build-up during few 100 ns
- cavity is opened to extract the pulse



Thin-disk laser oscillator

PDH locking

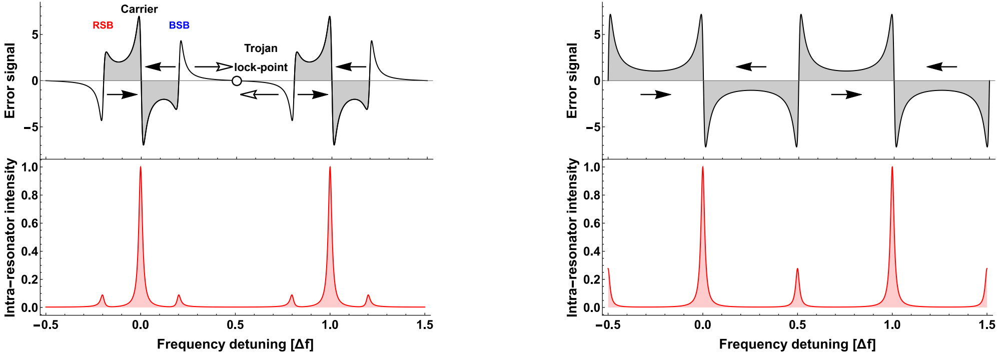




Zeyen, M. *et al.* Pound-Drever-Hall locking scheme free from Trojan operating points. *Review of Scientific Instruments* **94,** 013001. arXiv: 2210.05501 [physics.optics] (12th Jan. 2023)

Thin-disk laser oscillator

PDH locking



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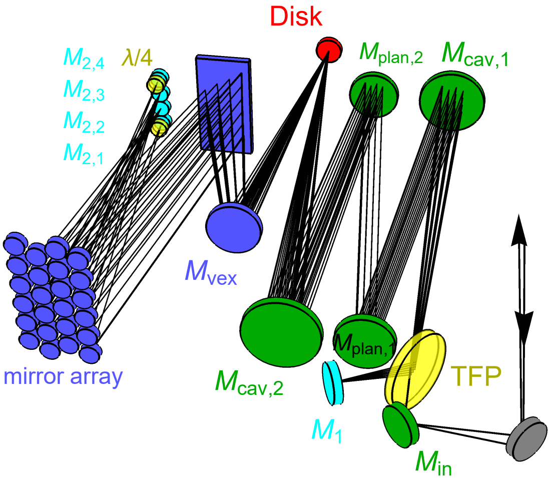
Multi-pass thin-disk laser amplifier

Setup

- Ytterbium:YAG disk amplifier
- 2.5 kW pump diode
- multi-pass design with 20 passes
- 4f-stage & Fourier transform



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Fourier transform
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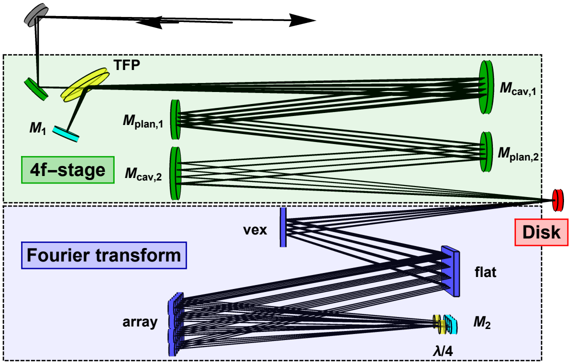
...

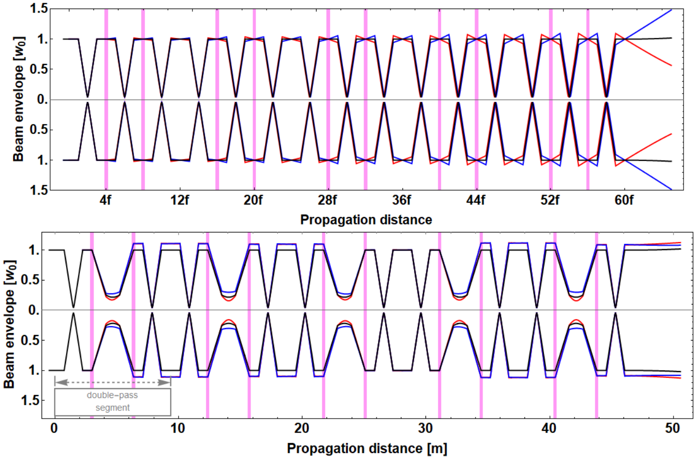


Advantages of this design

- compact layout due to 4f, including a small astigmatism
- Fourier transform helps stability against thermal effects

Multi-pass thin-disk laser amplifier

Propagation



Results

Oscillator

- injection seeding with PDH locking successful
- stability <1 %
- active auto-alignment of cavity

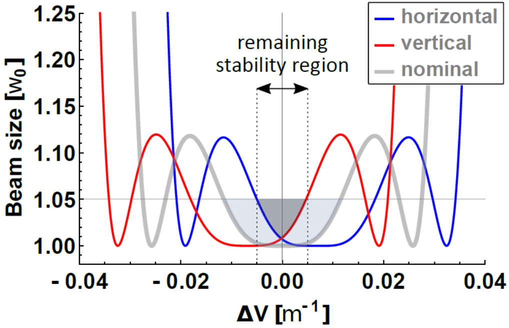
Amplifier

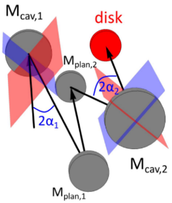
- propagation over 20 passes
- gain of 20 at small signal limit
- gain of 8 at 300 mJ

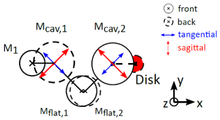
Thank you!

In the name of the full CREMA collaboration, I would like to thank you for your attention.

Astigmatism compensation in TDL Amplifier







Single pass through amplifier