Thin-Disk Laser for the Measurement of the Hyperfine-Splitting in Muonic Hydrogen

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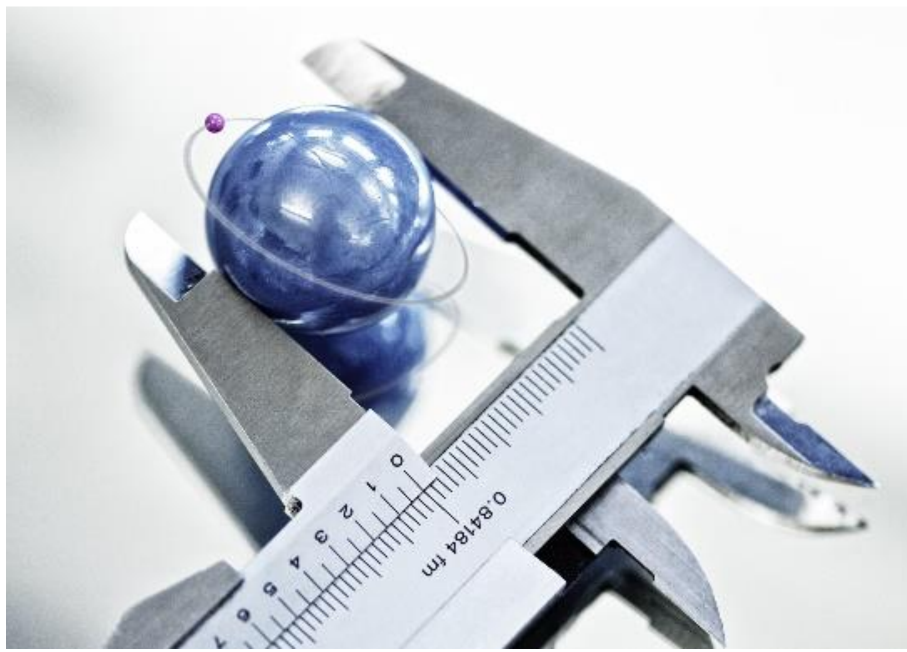
Introduction

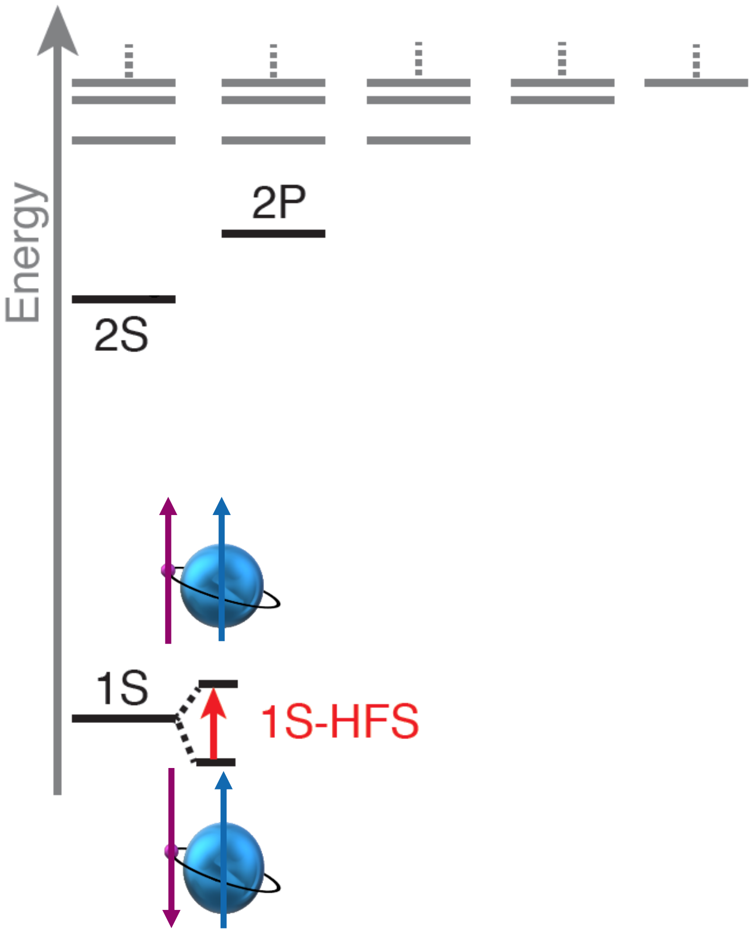
We do spectroscopy of muonic hydrogen to probe the proton



Introduction

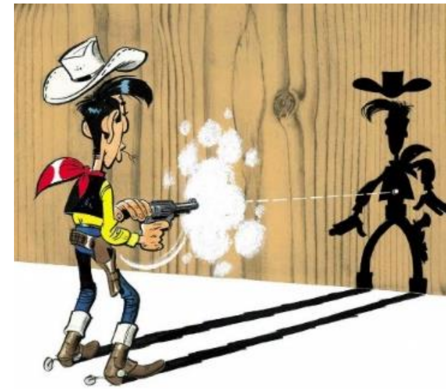
- We aim to measure the ground-state hyperfine transition in muonic hydrogen to extract the Zemach Radius (≈ magnetic radius) of the proton

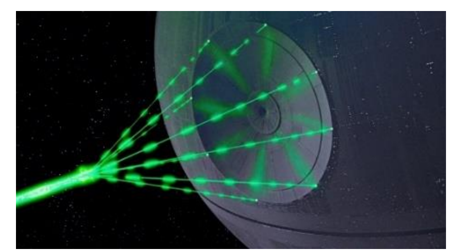
- We have to develop a challenging laser system in the near infrared



Requirements for the laser in our experiment

Requirement	Reason
Fast response to trigger → 1 µs from trigger to pulse delivery	Muons decay in 2.2 µs
Frequency tuneable & single mode → ± 100 nm	We have to find the resonance
High power → 5 mJ pulse energy @ 6.8 µm & 50 MHz bandwidth	To efficently drive the transition (dipole forbidden transition)

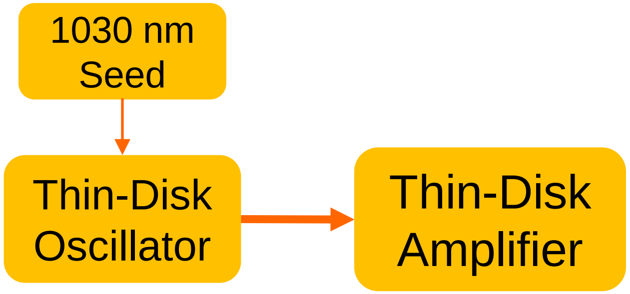


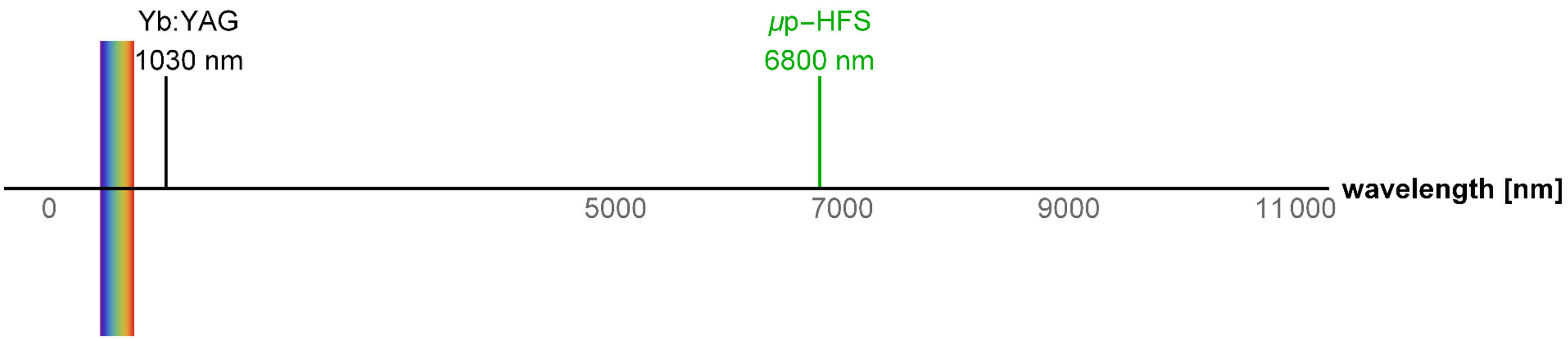


No commercial laser source meets this combination of requirements!

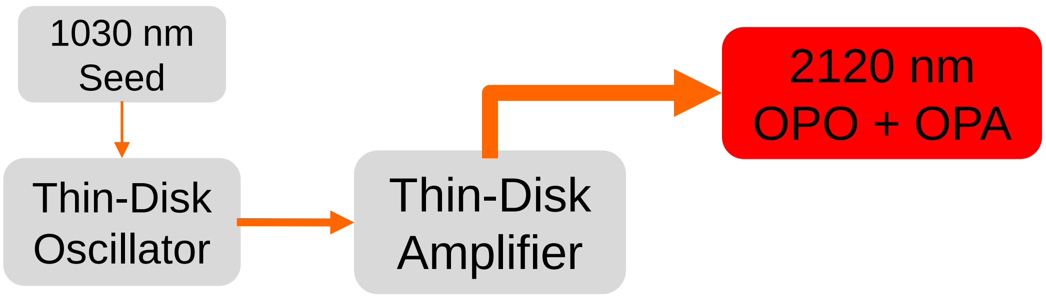
→ This experiment is interesting from a laser physics point of view

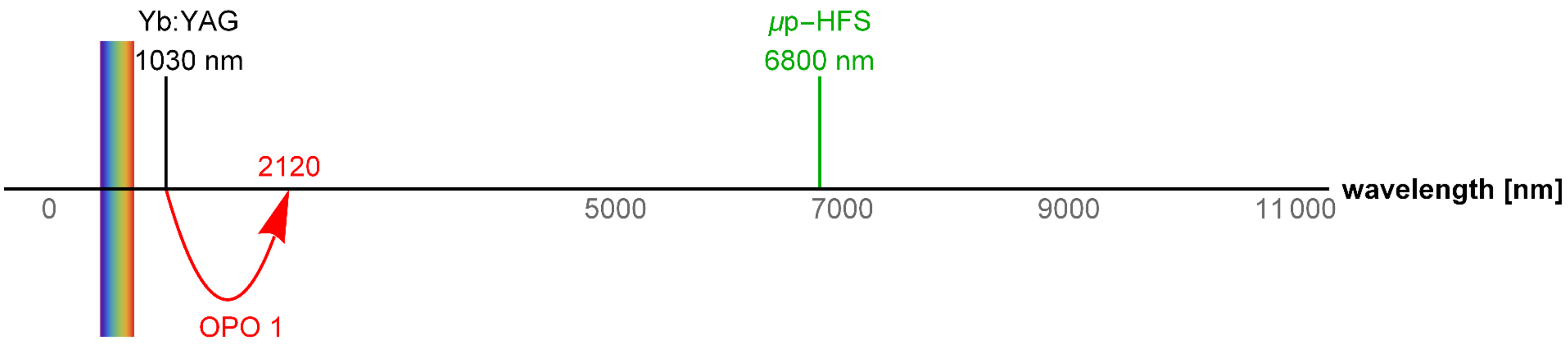
The planned laser system – thin-disk laser



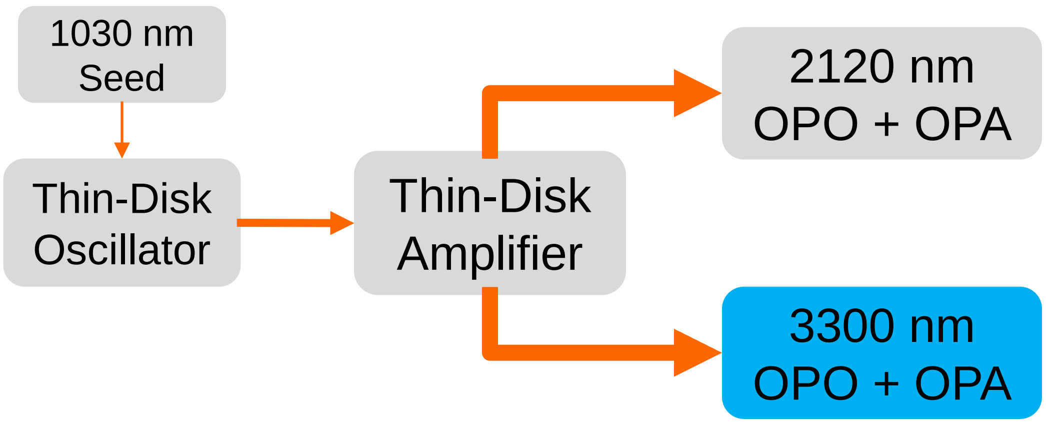


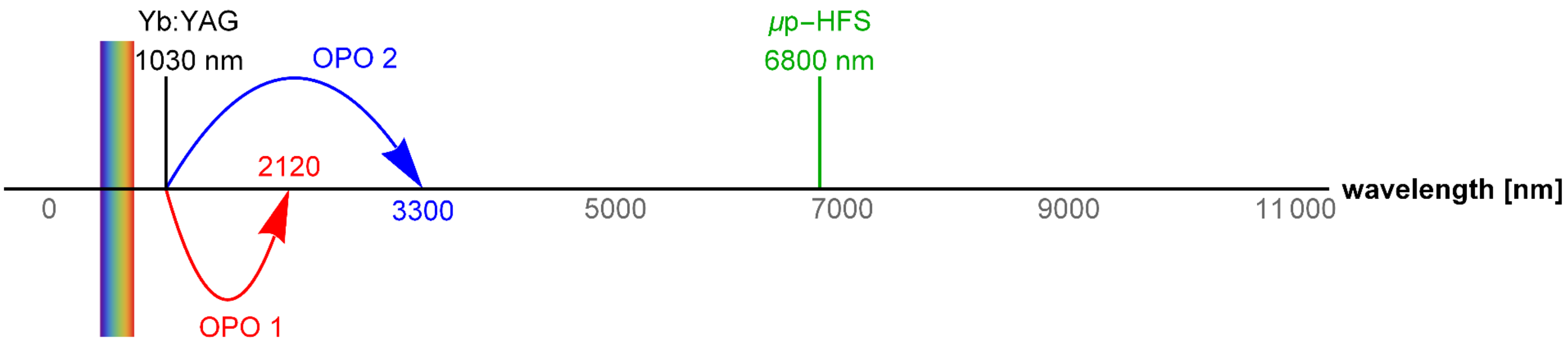
The planned laser system – OPO/OPA 1



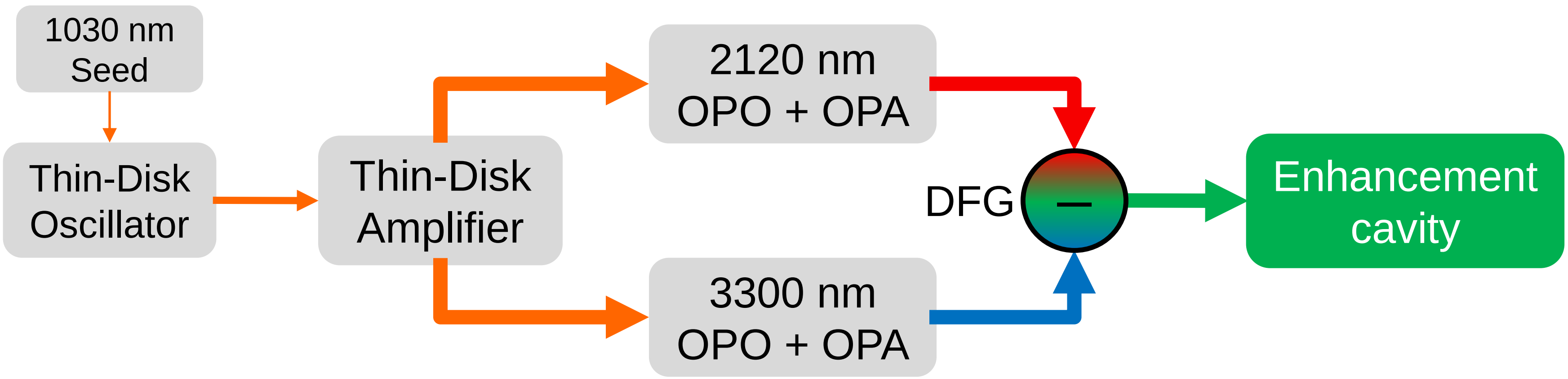


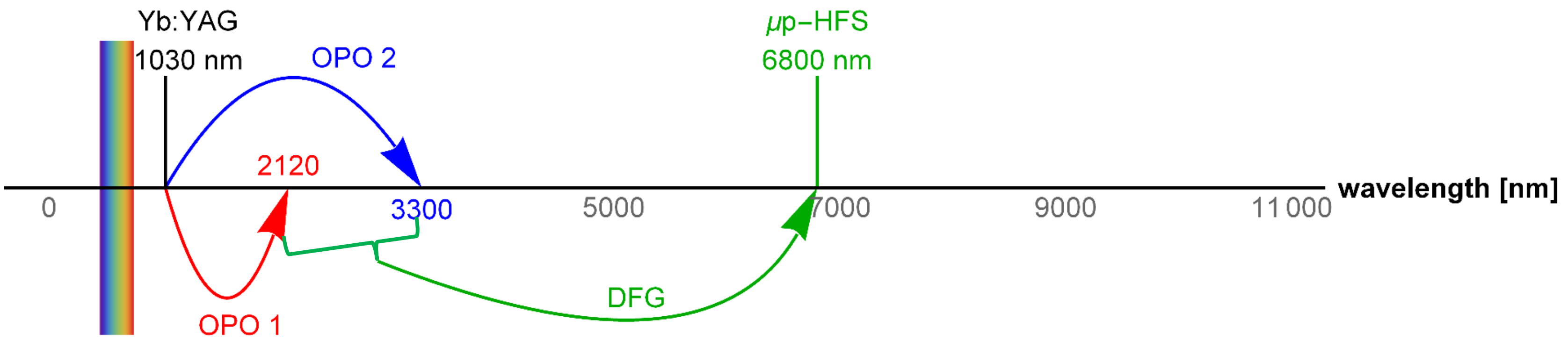
The planned laser system – OPO/OPA 2



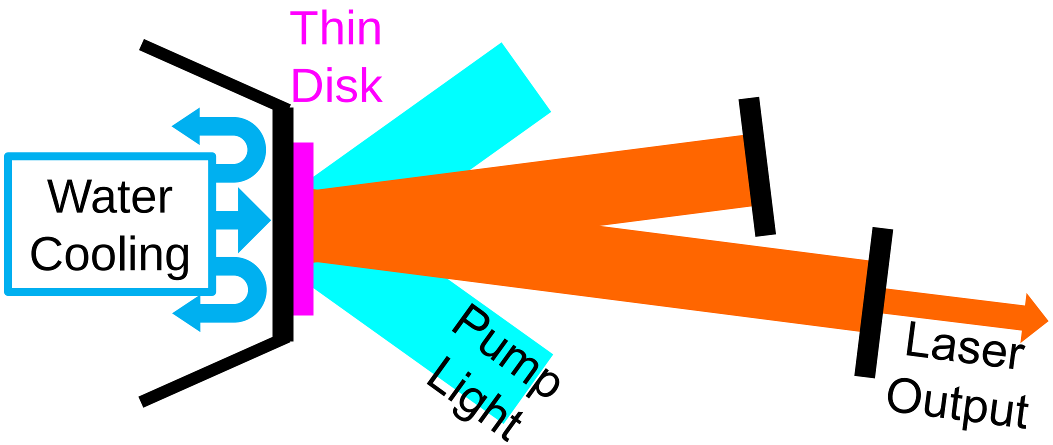


The planned laser system – DFG





Concept of the thin-disk laser



Efficient and clever cooling

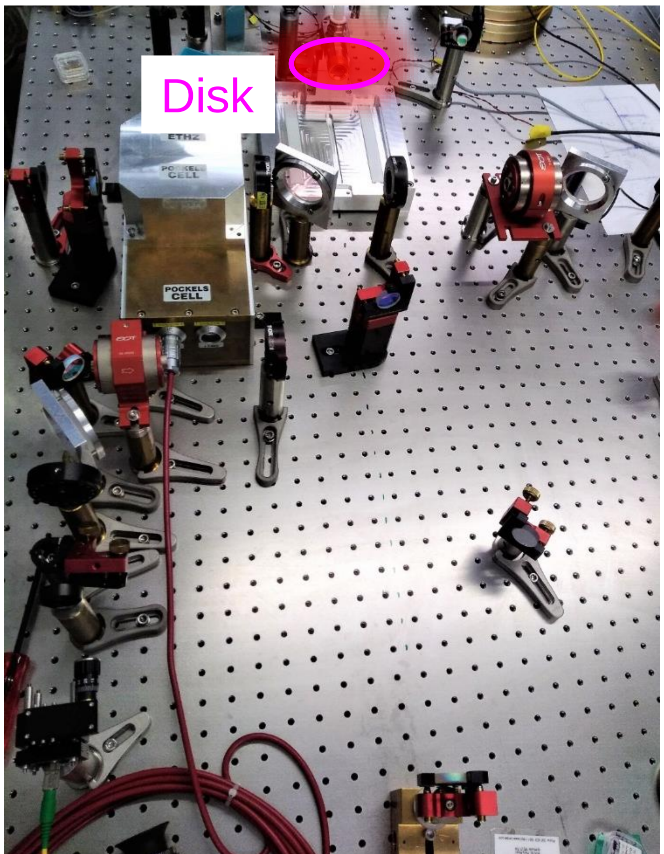
→ Power scalable

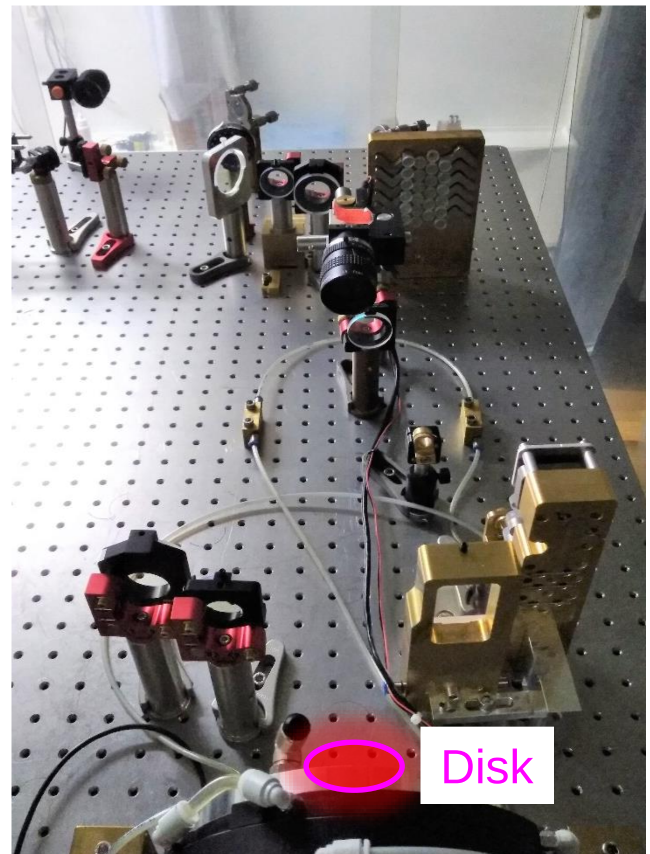
We don't know when the μ^- comes
→ Have a lot of energy ready

→ Thin-Disk Laser!

The thin-disk laser system

Thin-Disk **Oscillator** → Thin-Disk **Amplifier**

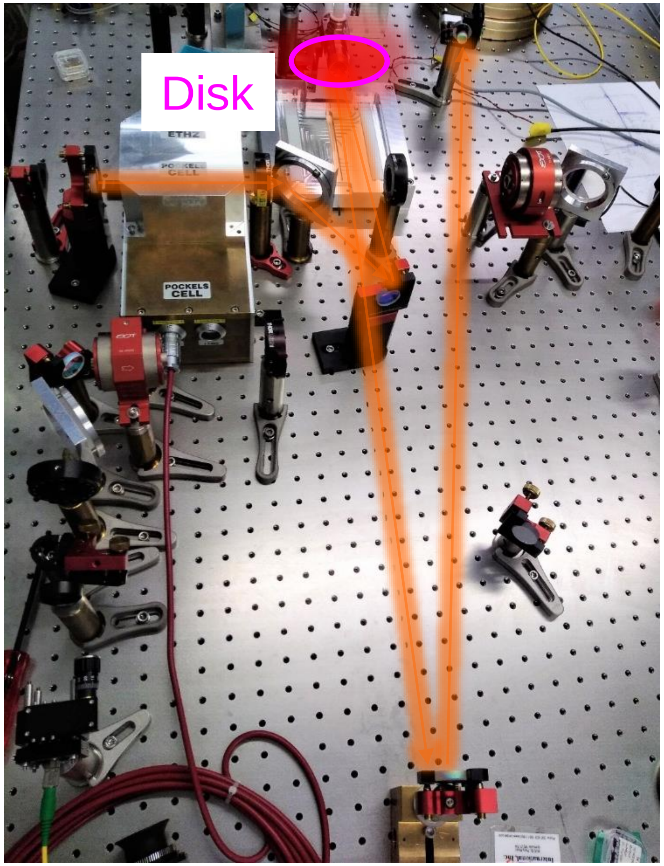


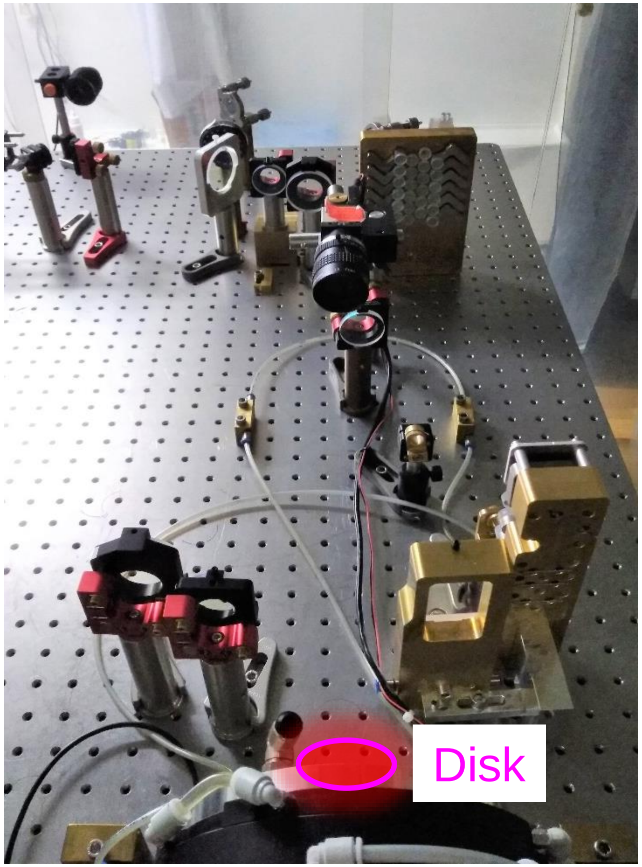


A. Antognini et al., «Thin-disk Yb: YAG oscillator-amplifier laser, ASE, and effective Yb: YAG lifetime,» *IEEE Journal of Quantum Electronics*, ***45***(8), 993-1005.

The thin-disk laser system

Thin-Disk **Oscillator** → Thin-Disk **Amplifier**

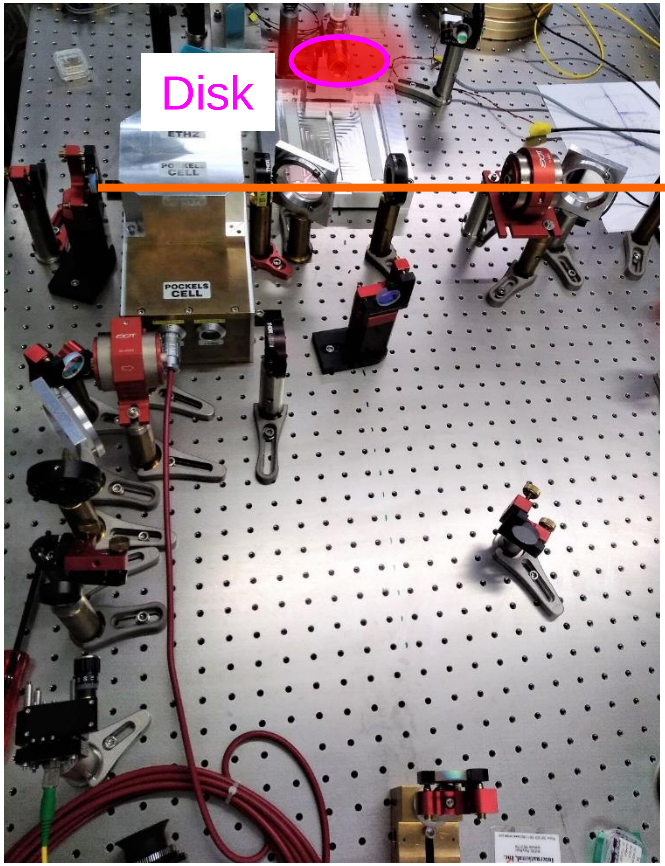


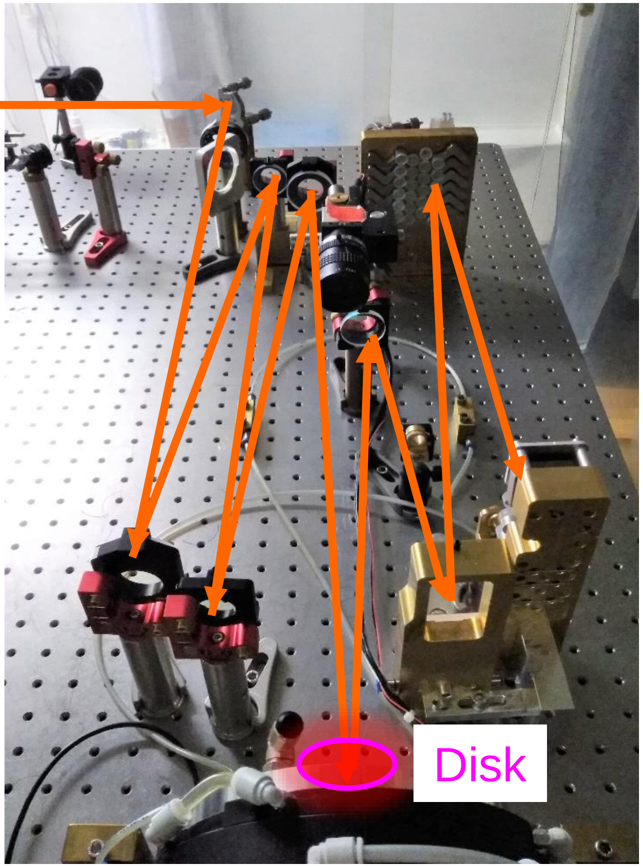


The thin-disk laser system

Thin-Disk
Oscillator

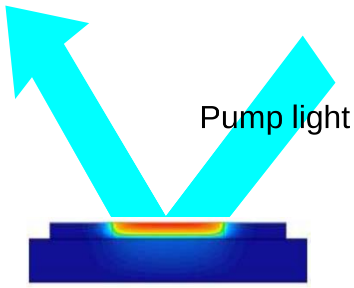
Thin-Disk
Amplifier





How to achieve a stable laser beam?

The problem of thermal lensing

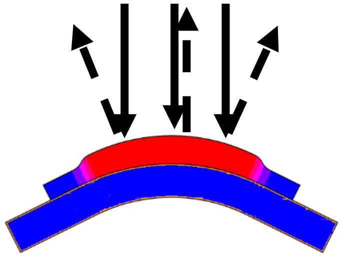


Problem:

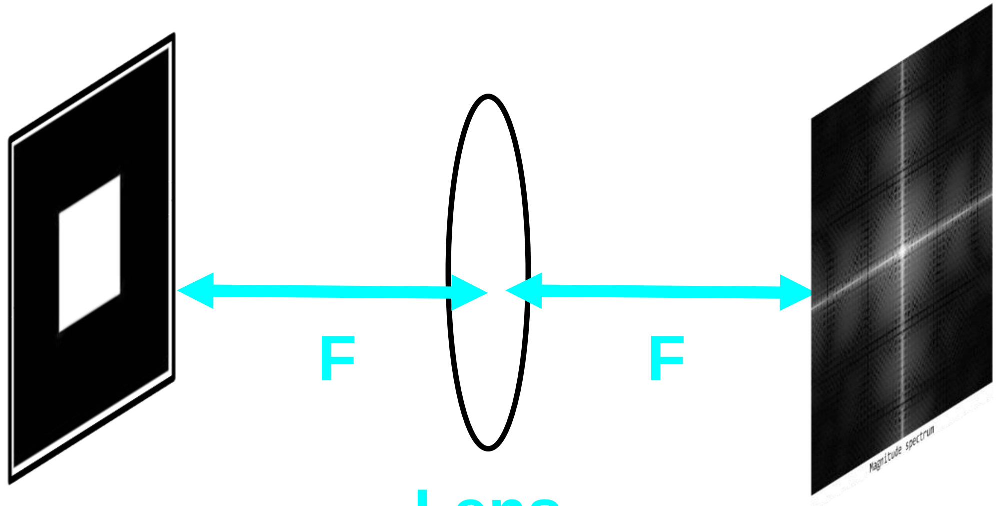
Thermal lensing
(deformation of the disk)

Solution:

Optical Fourier Transform Propagation



The optical Fourier transformation

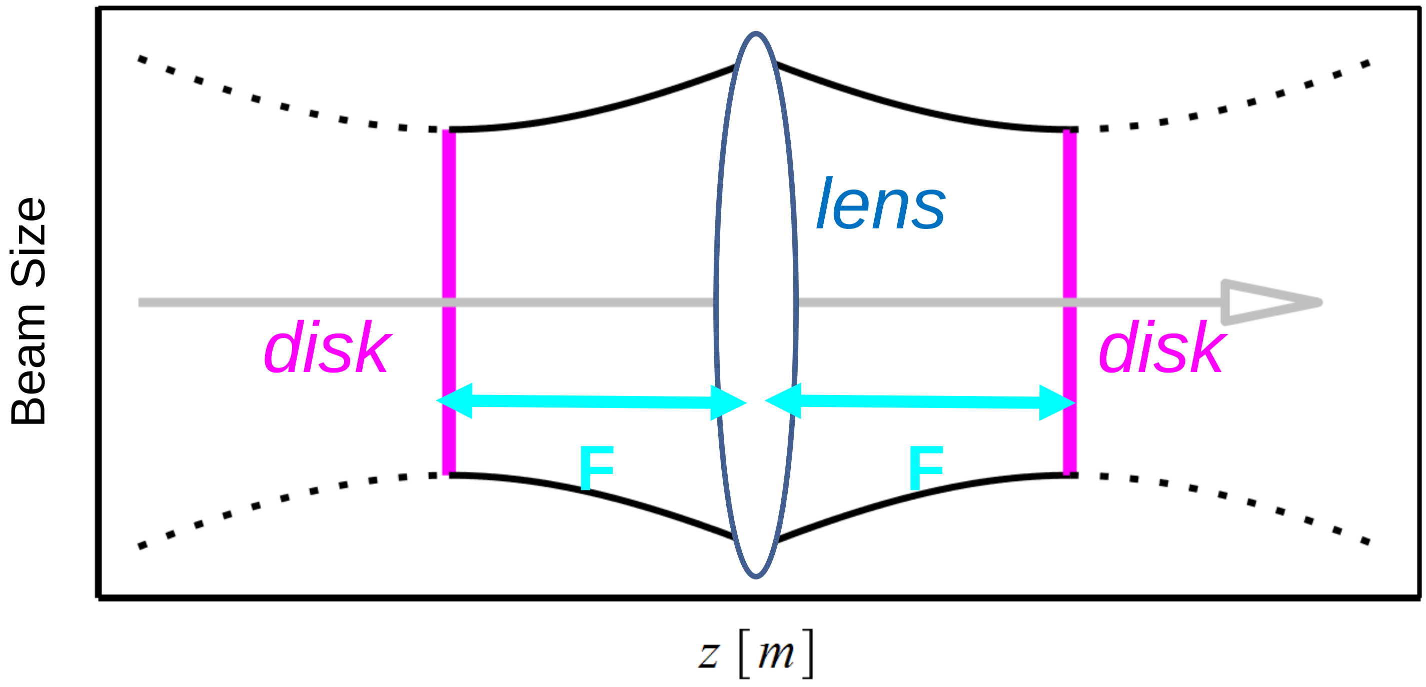


Lens with focal length F

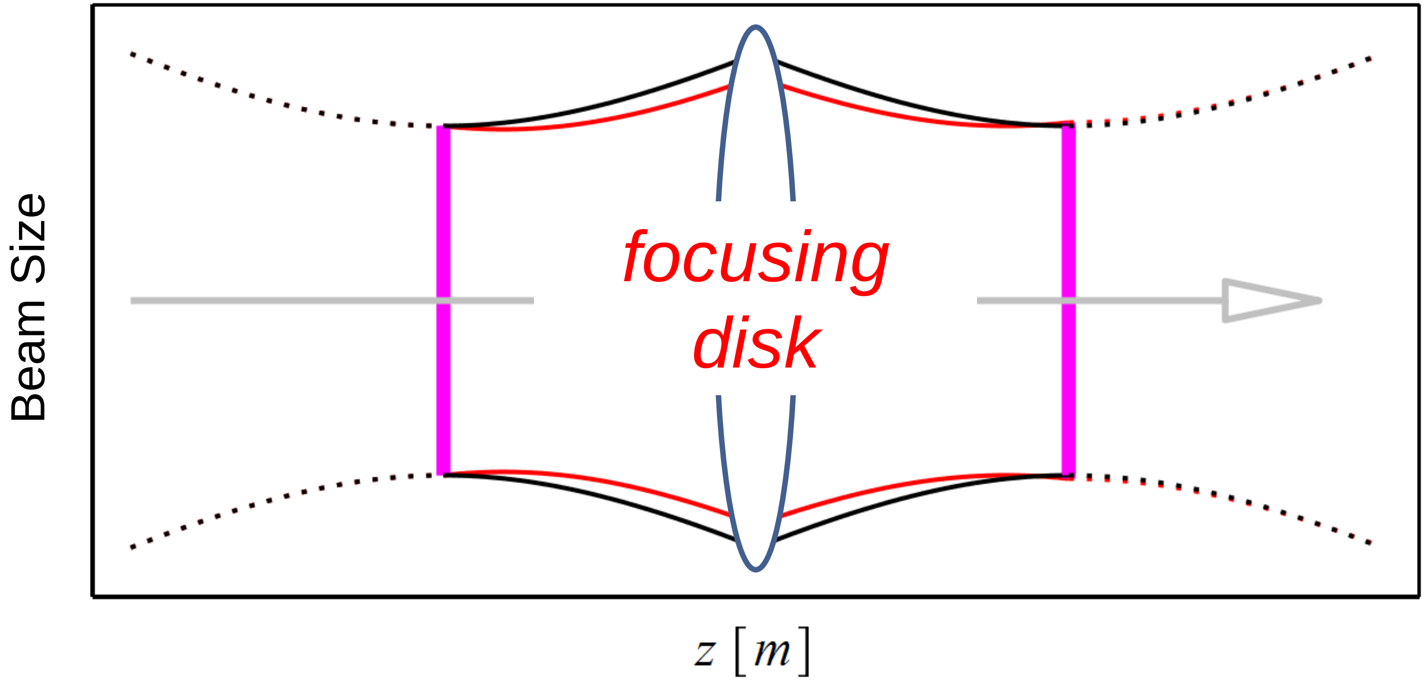
Object

Fourier transformed Object

The “magic” of the Fourier transform propagation



The “magic” of the Fourier transform propagation



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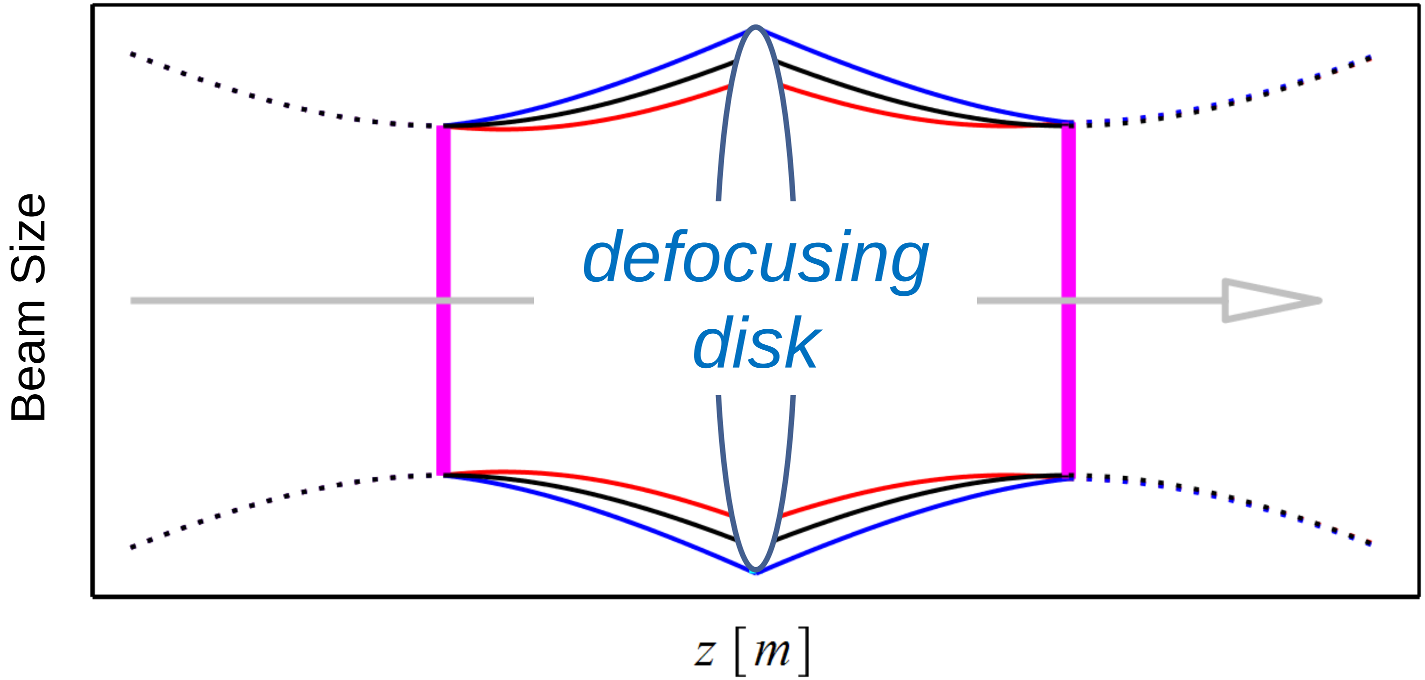
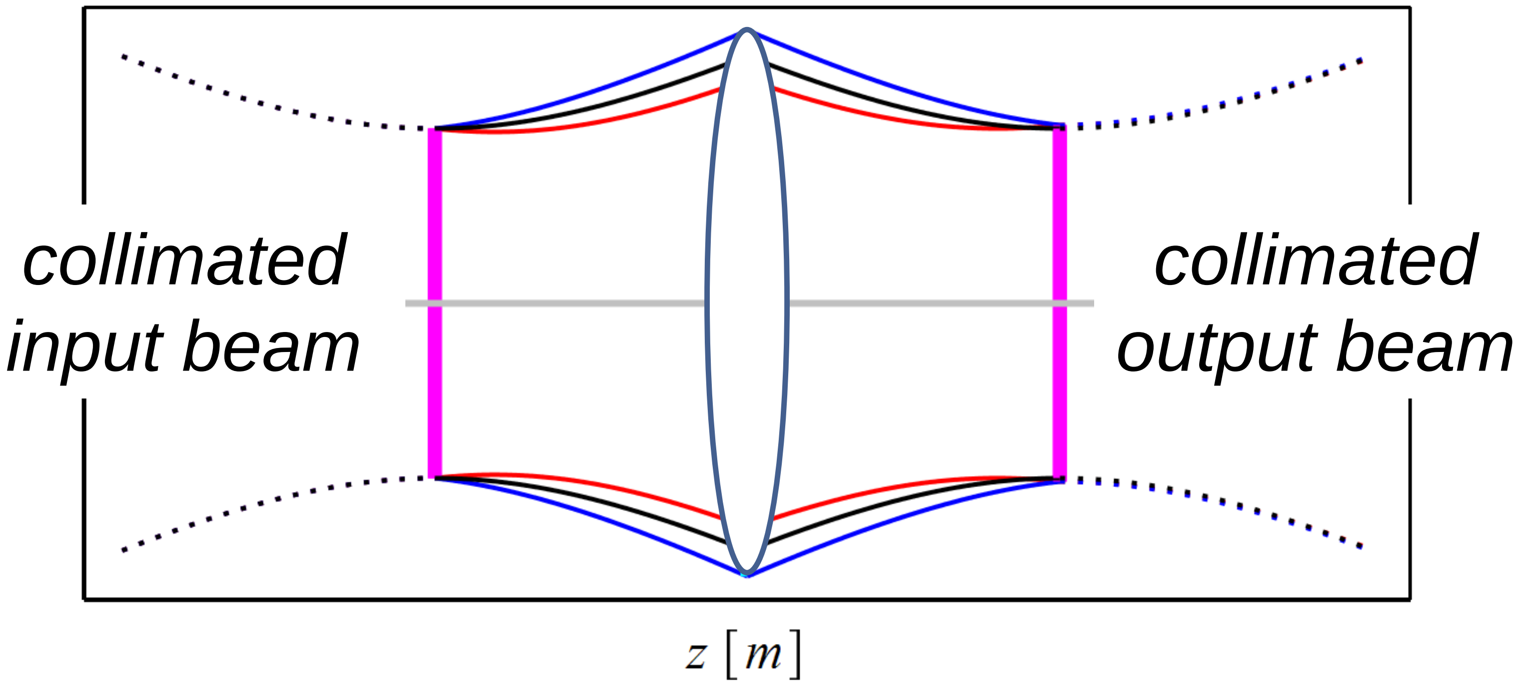
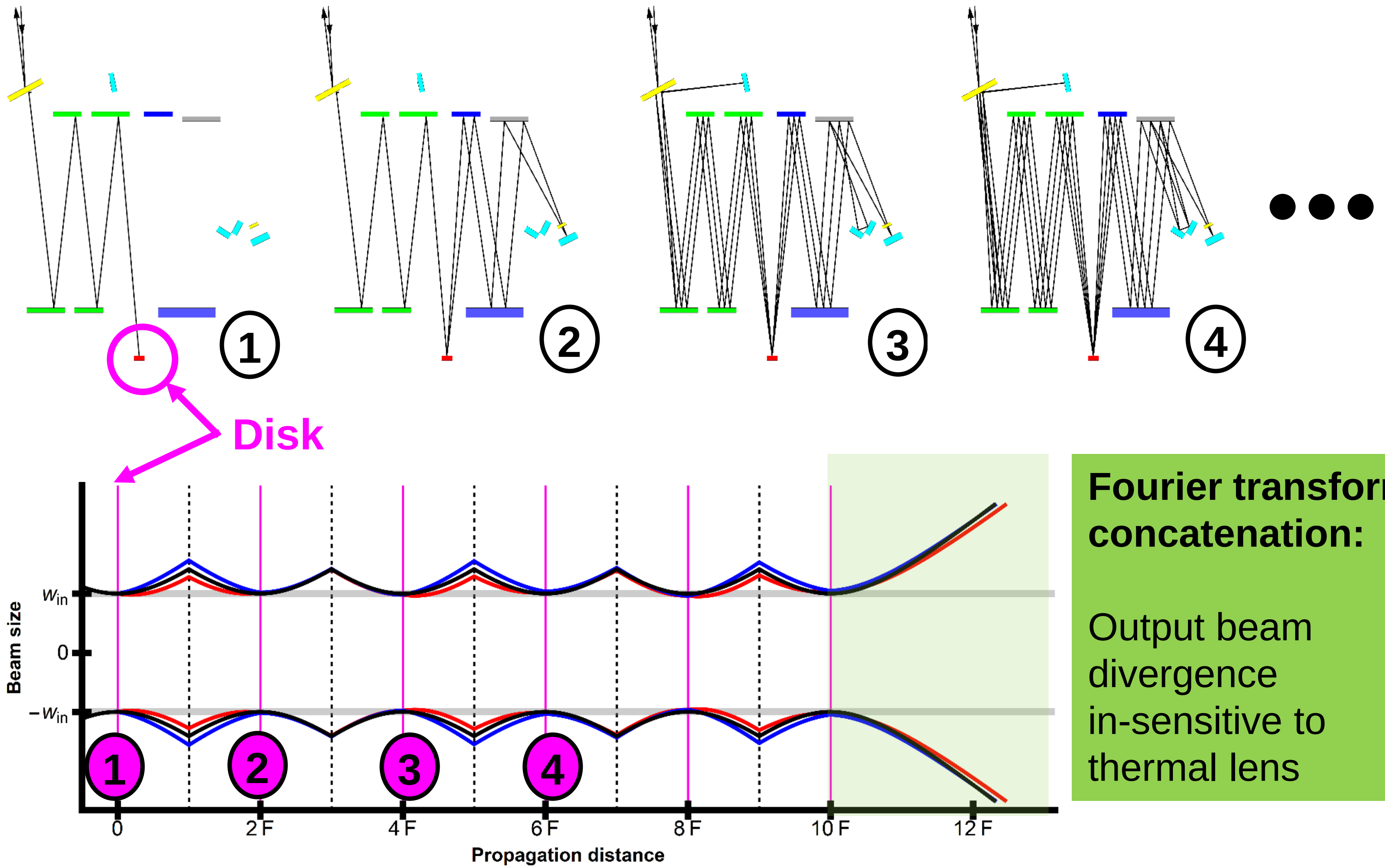


The “magic” of the Fourier transform propagation



Concatenation of stable Fourier segments

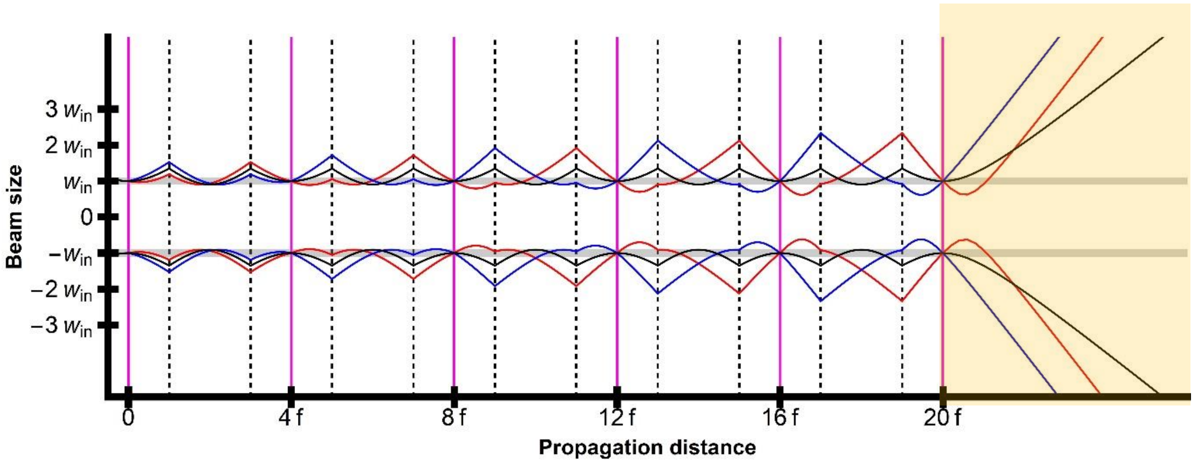


Fourier transform concatenation:

Output beam divergence in-sensitive to thermal lens

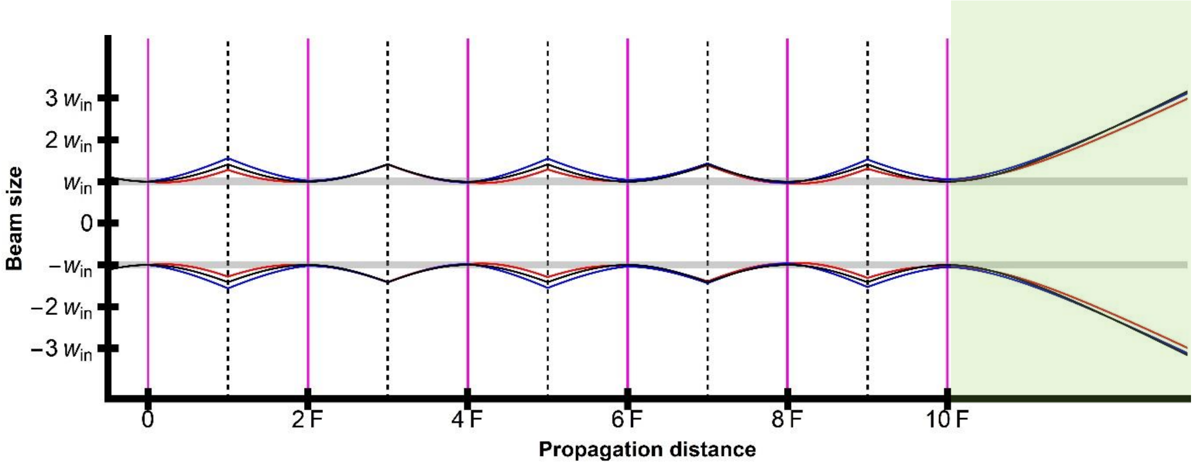
K. Schuhmann et al., "Multipass amplifiers with self-compensation of the thermal lens," Appl. Opt. ***57****, 10323-10333 (2018)*

Fourier propagation vs. 4f-propagation



4f-concatenation:

Output beam divergence sensitive to thermal lens



Fourier transform concatenation:

Output beam divergence in-sensitive to thermal lens

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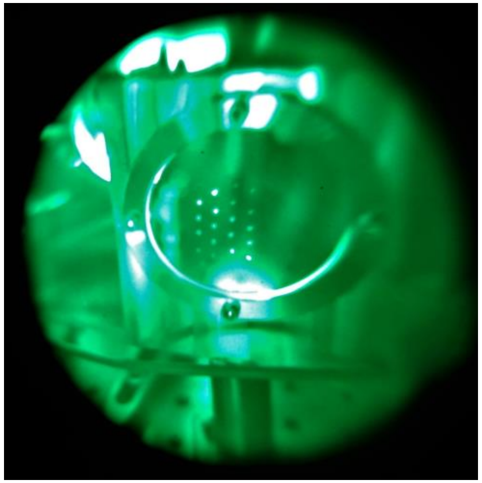
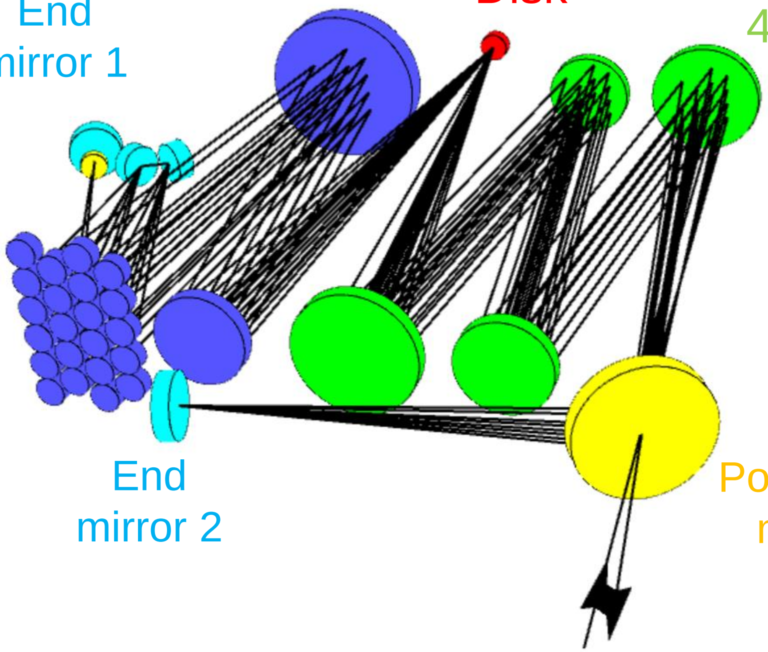
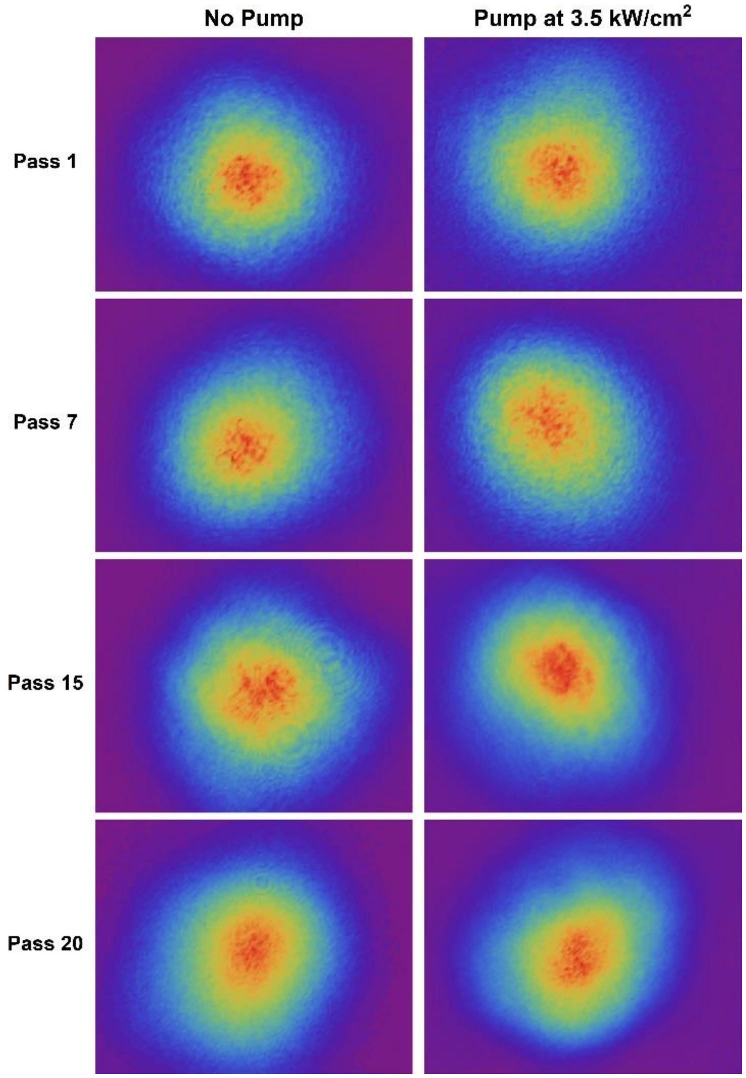
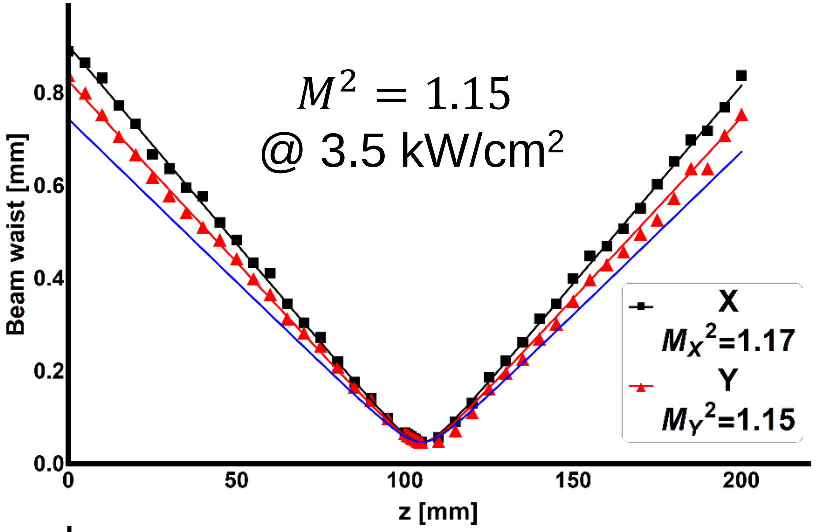
Our 20-pass Fourier transform amplifier

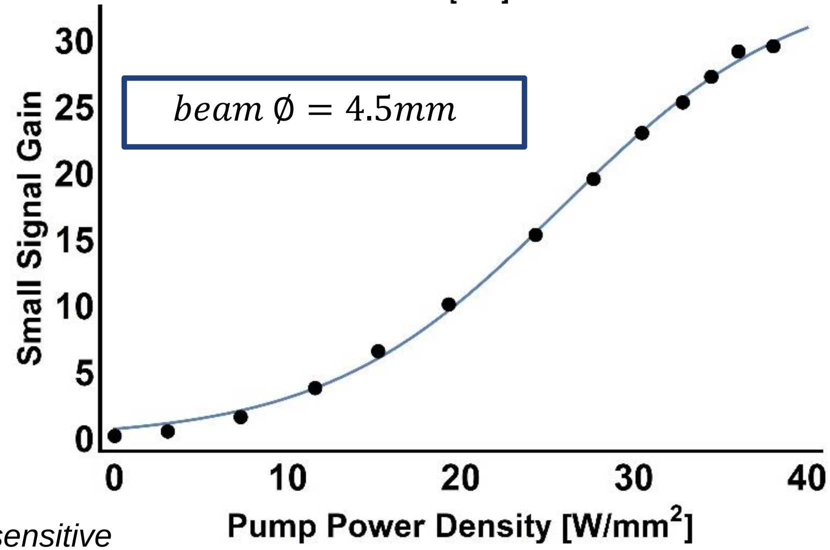




Preliminary results







M. Zeyen et al. "Compact 20-pass thin-disk amplifier insensitive to thermal lensing." LASE (2019).

How to achieve a stable laser frequency?

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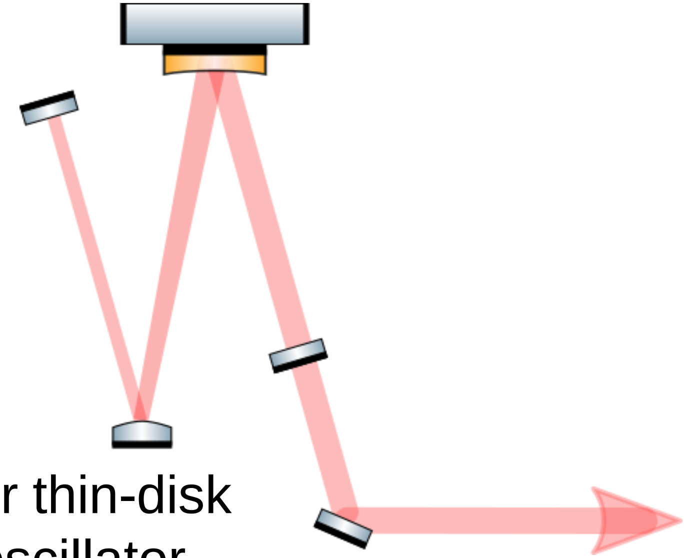
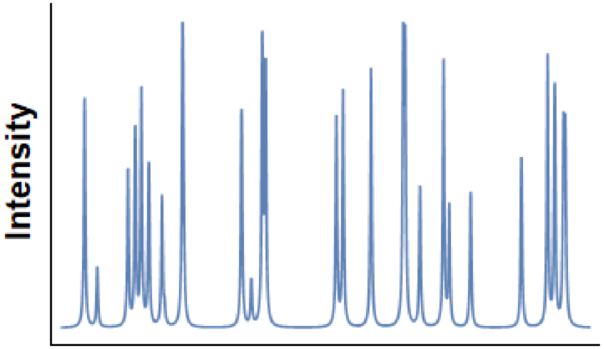
Injection seeding the oscillator: the concept

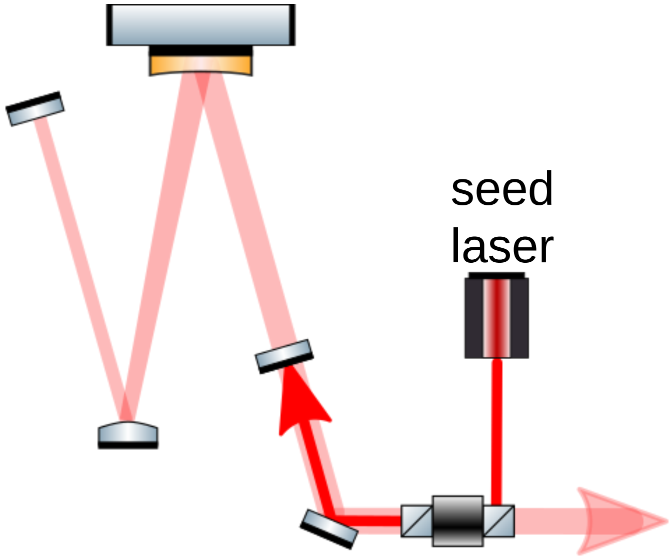


Our thin-disk oscillator

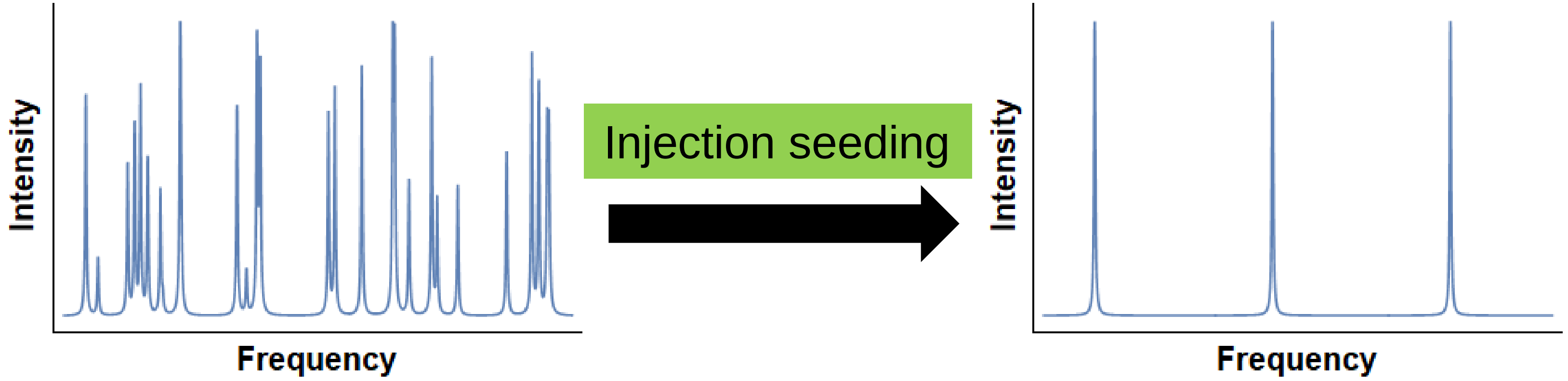


Output usually multimode

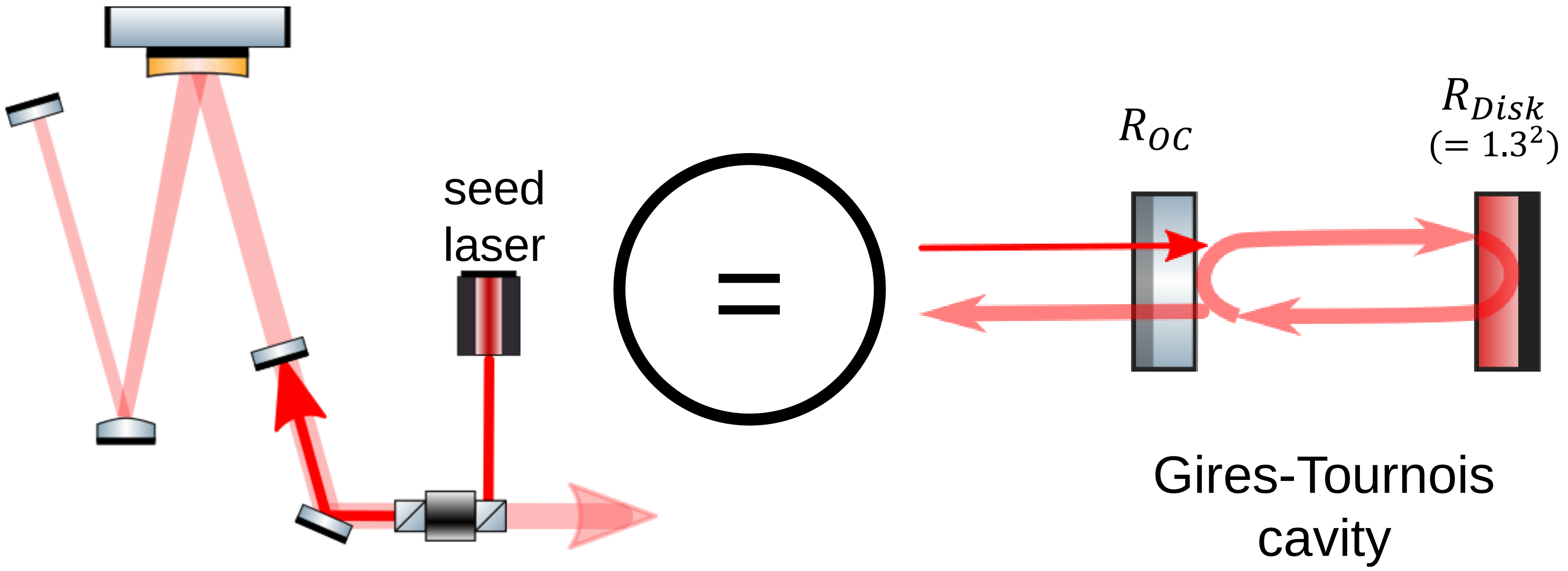
Injection seeding the oscillator: the concept

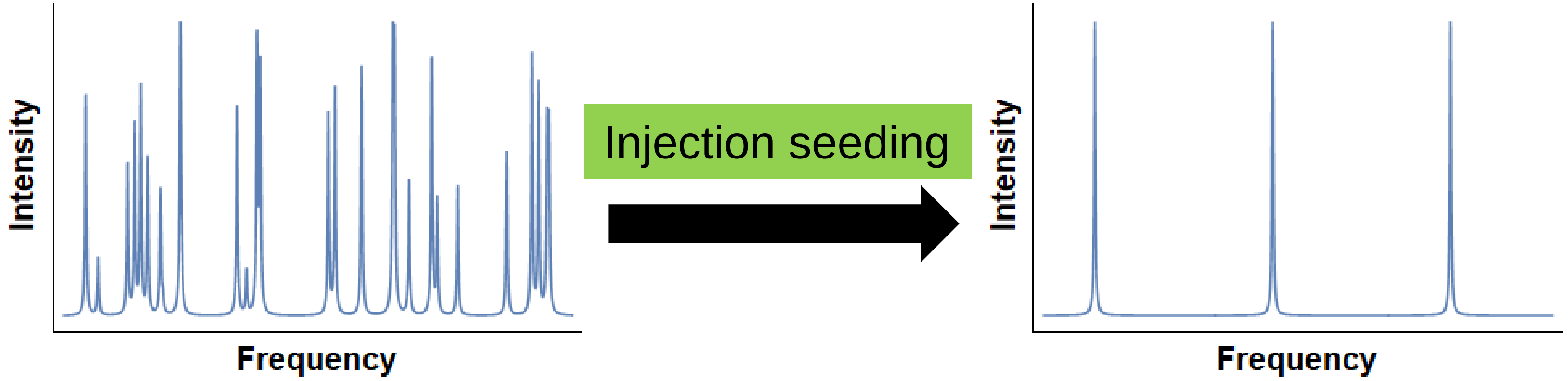


Injection seeding:
Populating the oscillator cavity with light from a single frequency laser before the pulse

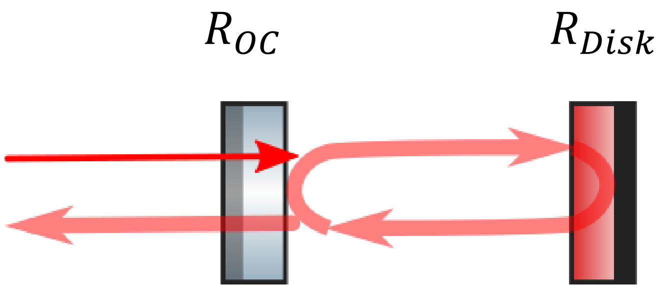


Injection seeding the oscillator: the concept

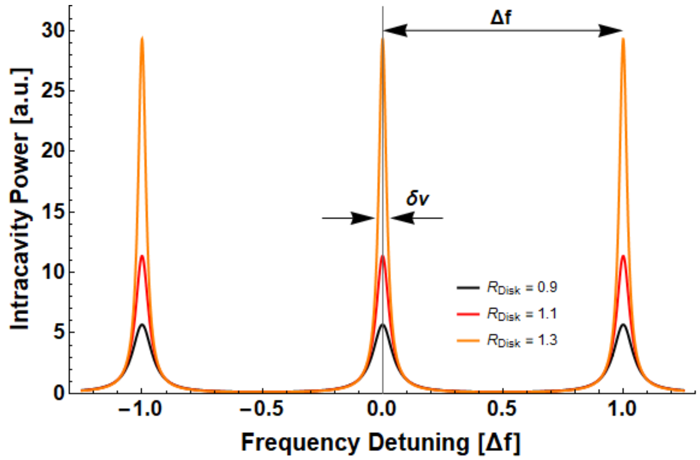




Injection seeding the oscillator: the problem

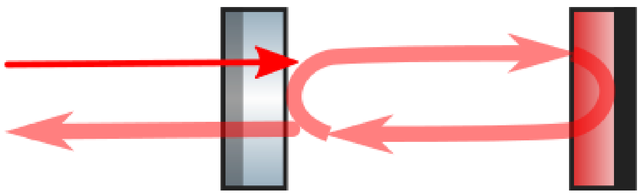


$$\mathcal{F} = \frac{\Delta f}{\delta \nu}$$

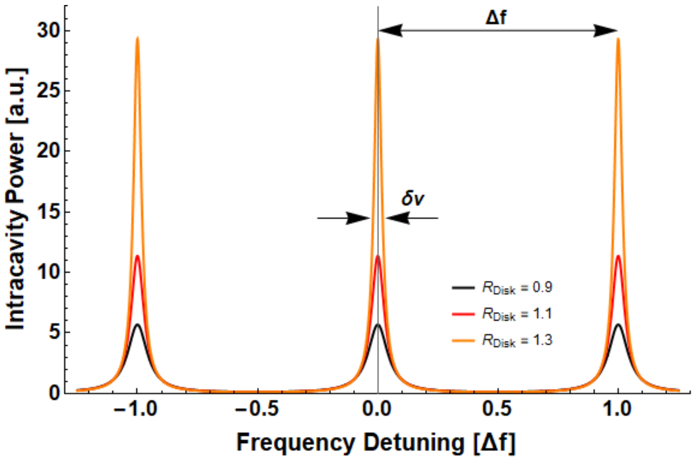


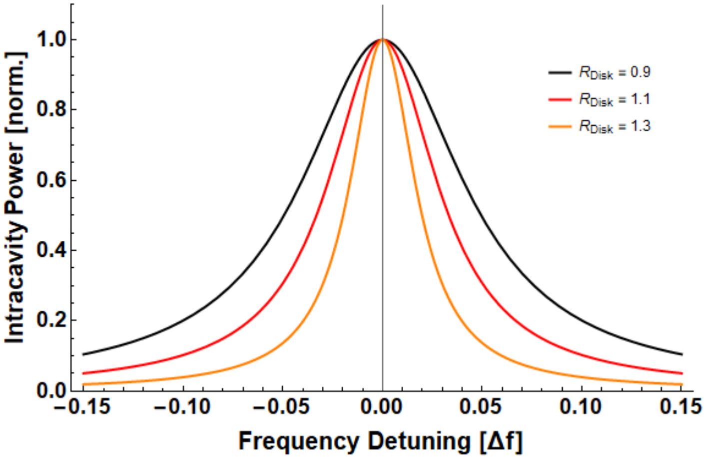
After successfully seeding lock the cavity length to fix the oscillator frequency

Injection seeding the oscillator: the problem



$$\mathcal{F} = \frac{\Delta f}{\delta\nu} = \frac{2\pi}{-\ln R_{OC} R_{Disk}}$$





The cavity mode we want to lock on gets sharper with laser gain (i.e. laser power)!

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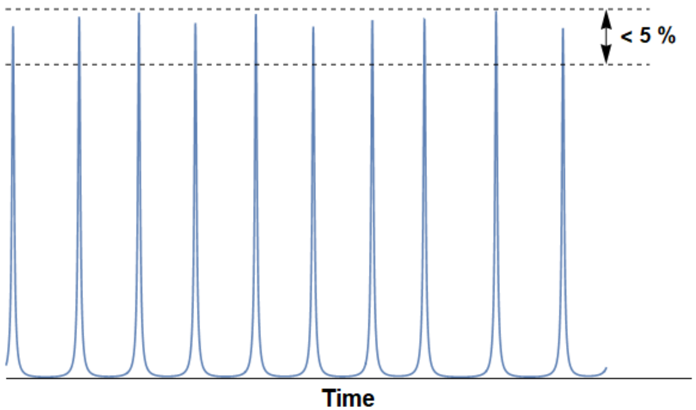
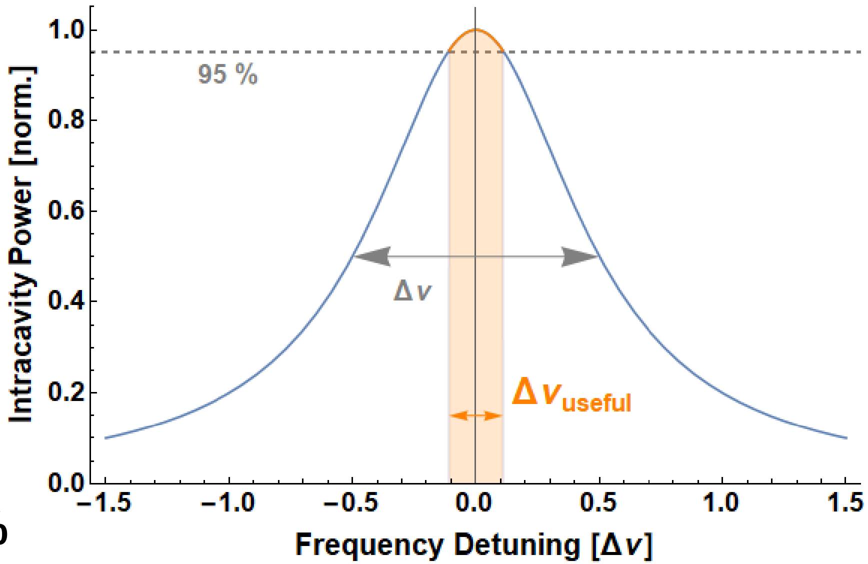
Injection seeding the oscillator: the problem gets worse



Pulse to pulse energy variation < 5 %



→ «Useful linewidth» reduces further! (< 1 MHz)
→ Relative length control $\approx 10^{-8}$
→ Lock needs to be really tight...

For comparison:
Measure Zürich ↔ Paris to less than 1 mm

Conclusion

European Research Council
Established by the European Commission

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

- We demonstrated a thin-disk multi-pass amplifier compensating thermal lens effects
  - 20 passes
  - Small signal gain 30
  - Footprint 400 mm x 1000 mm

- Future work
  - Pulsed operation of amplifier
  - Injection seeding of the oscillator
  - Integration into the laser system for spectroscopy of muonic hydrogen at PSI, Switzerland

R. Pohl, et al. "The size of the proton." *Nature* 466.7303 (2010): 213.