# NaK STIRAP laser system
# (or, how to build your laser(s), if you have to)

Informal AMO round table

2023-07-30

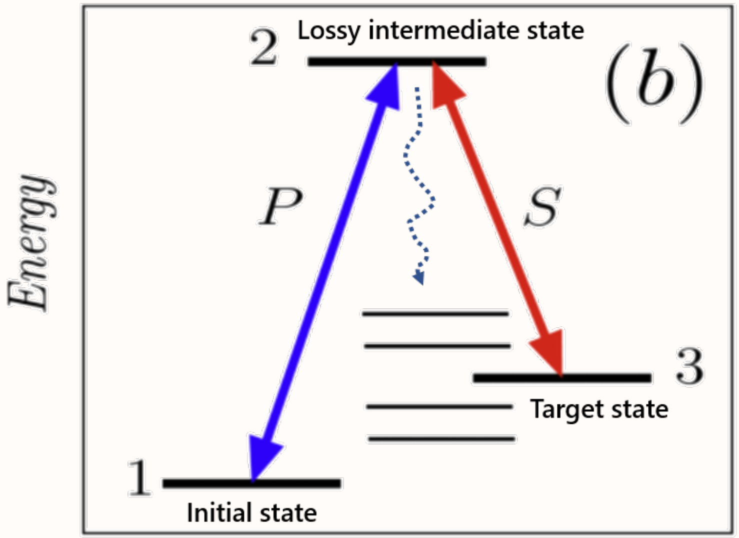
MIT Zwierlein Lab

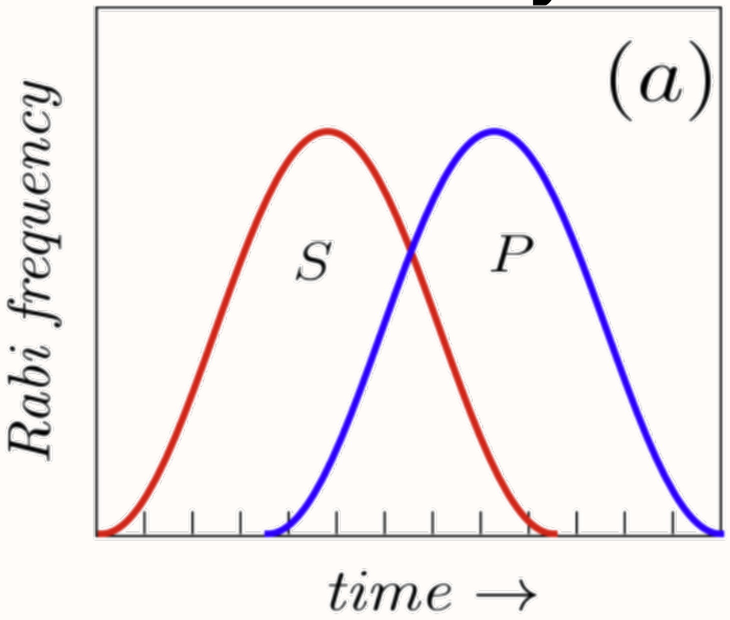
Yiming Zhang

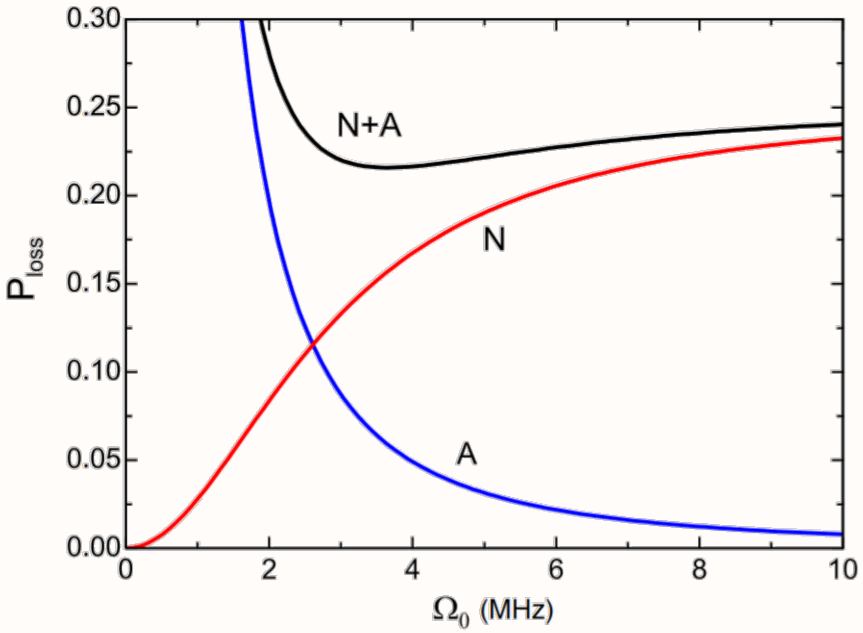
# NaK molecules

- Why?
  - Large dipole moment for quantum simulation
- Pathway
  - Prepare Na BEC and degenerate K40 mixture
  - RF associate into Feshbach molecule
  - STIRAP into ground state
  - Do science things to your molecule

# Phase noise kills STIRAP efficiency




Quick reminder:

- $|1\rangle \rightarrow |3\rangle$ not directly coupled by selection rules.
- Transfer is possible through a lossy intermediate $|2\rangle$.
- Luckily exists a dark state:

$$|D\rangle \propto \Omega_s\,|1\rangle - \Omega_p\,|3\rangle \;\rightarrow\; \langle 2|H_{int}|D\rangle \propto \Omega_p\Omega_s - \Omega_s\Omega_p = 0$$

- Adiabatically ramp $|\mathrm{D}\rangle_{initial} = |1\rangle$ to $|D\rangle_{final} = |3\rangle$

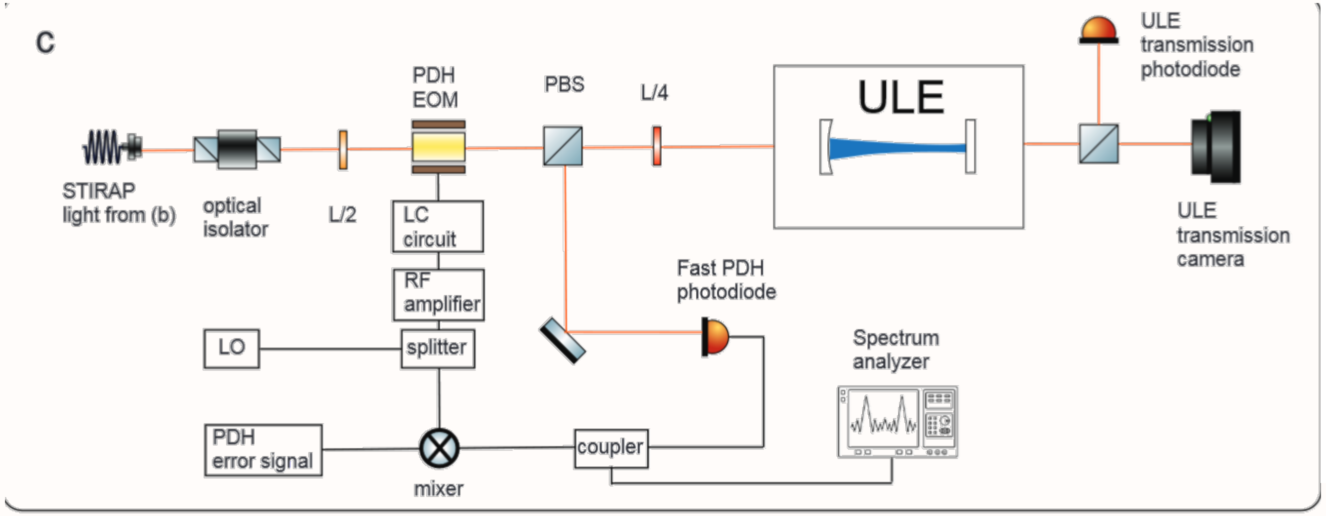
Broadband laser phase noise limits adiabaticity requirement (hence STIRAP efficiency)

-> need quiet laser

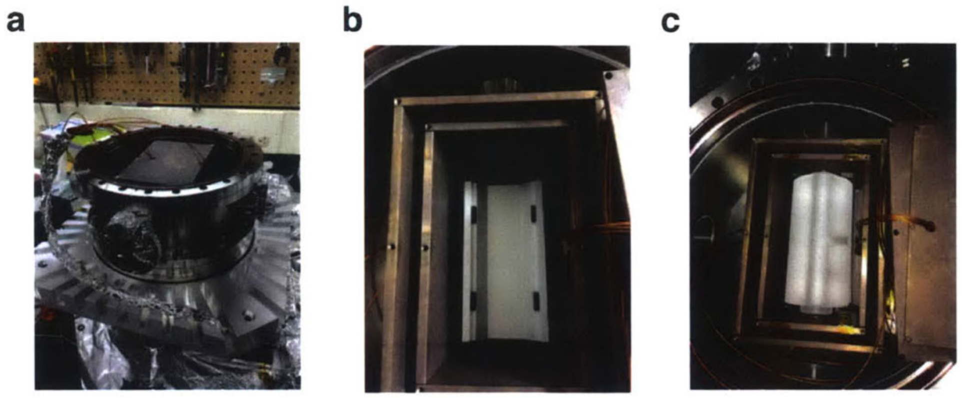
*Picture refs.*
*Rev. Mod. Phys., 70(3):1003, 1998.*
*Phys Rev A 89, 013831 (2014)*

# MIT NaK laser upgrade

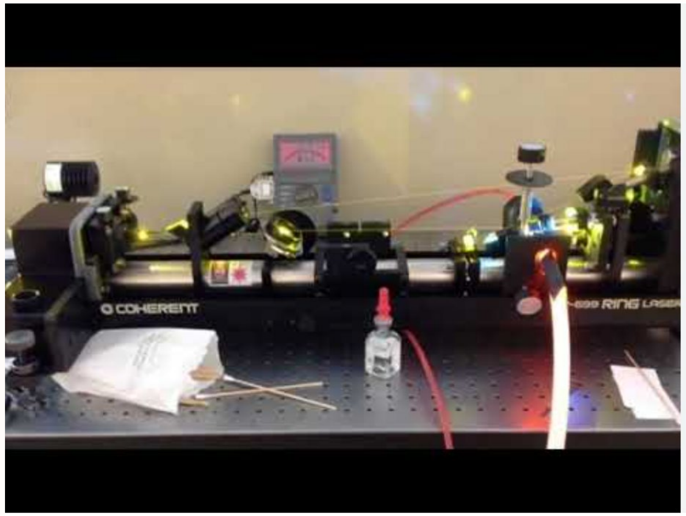
Current layout x 2 (for both pump and stokes beam)




Two lasers referenced to a single Ultra Low Expansion cavity




The ‘two lasers’:




Coherent 899 **dye** laser


Aging (10+ years in service) Ti:Sapphire laser

(company going bankrupt??)

*Picture refs.*
*Y. Ni & J.W Park Thesis*
*Youtube*
*Msquared webstite*

# Lasers: ingredients

Ingredients:

- Lasing medium that supports population inversion: ruby stick, $CO_2$ gas, semiconductor, flowing dye(!), …
- (Energy) pump: flash tube, electrical current, another laser, …
- Feedback for amplification and frequency selection: cavity, grating, etc…

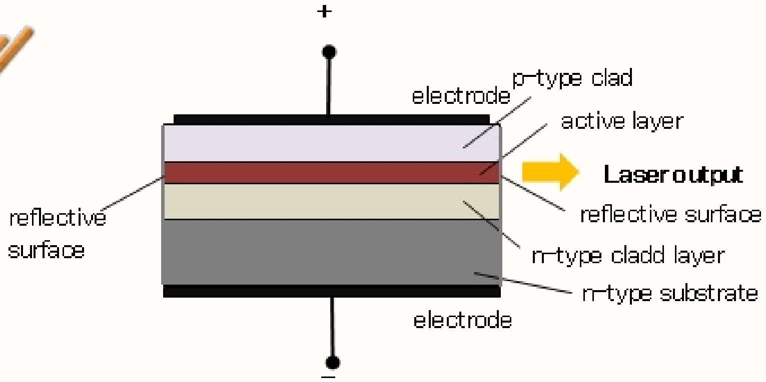
What do we want?

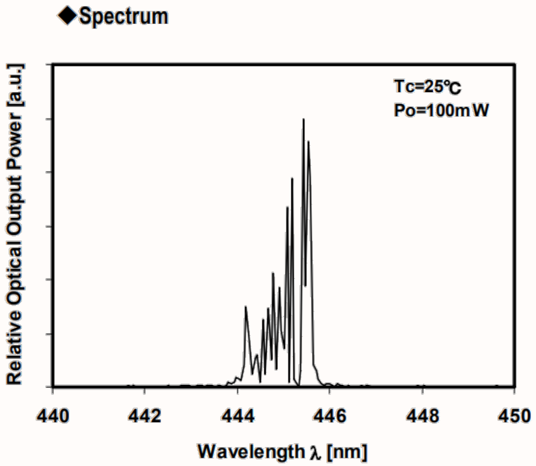
- Wavelength tunable
- Lockable for linewidth narrowing
- Reasonable cost and easy to construct

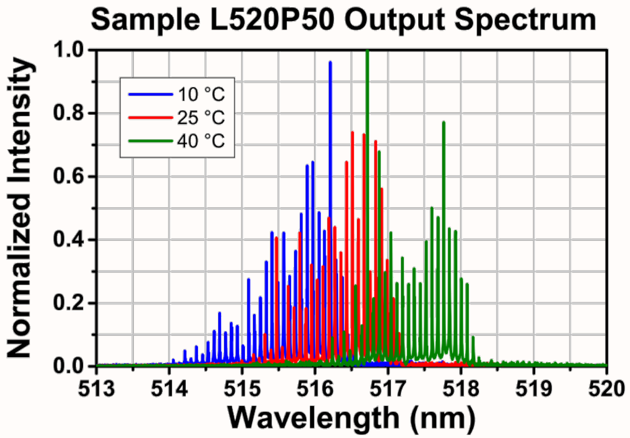
# Diode lasers

Fabry-Perot diodes: widely available across wavelength & powers

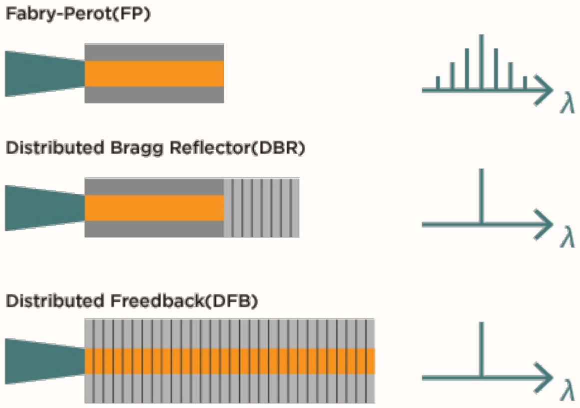
These are typically very broad on their own (several nm) and can be multi-mode

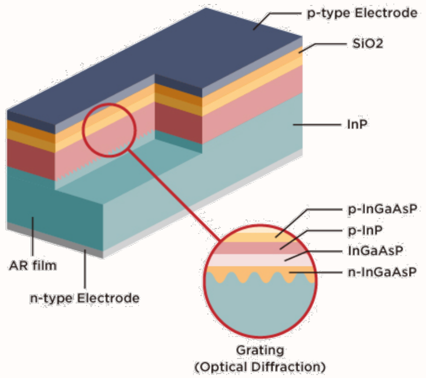


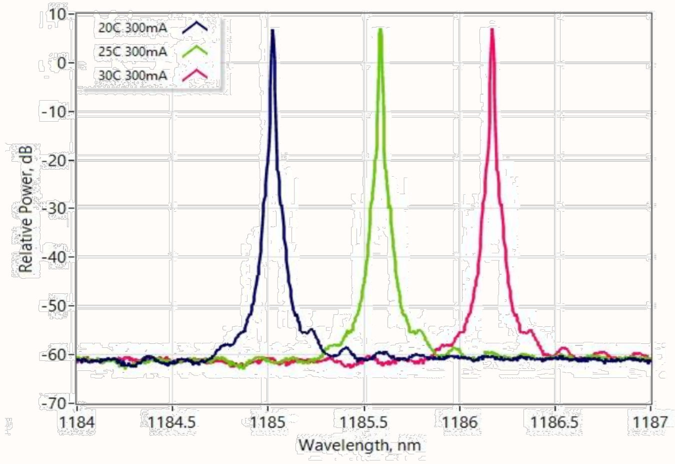




Can do better with nanofabricated grating -> interference condition imposes wavelength selection



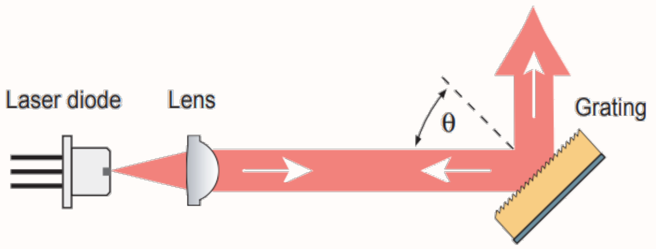

*Picture refs.*
*fiberlabs.com*
*scivax.com*
*Thorlabs*
*Innolume*
*Nichia*

# Better linewidth? Add long external cavity (ECDL)

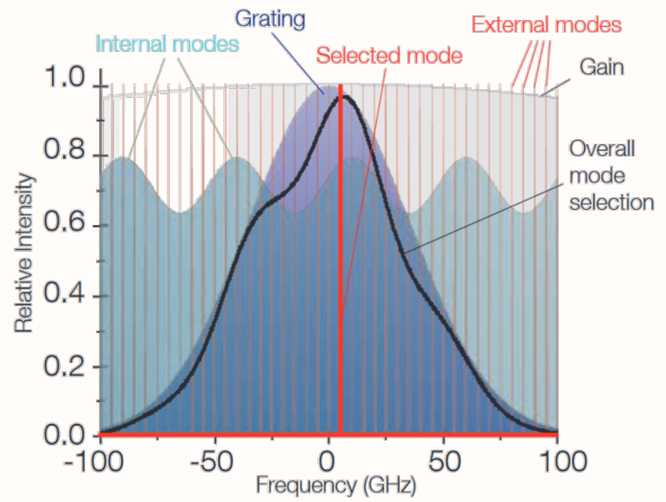
Fundamental linewidth limit of laser (Schawlow–Townes) set by cavity linewidth:

$\Delta\nu_{laser} \propto \left(\Delta\nu_{cavity}\right)^2 \propto L^{-2}$ -> get a long external cavity (~cm compared to ~mm of FP diodes)

Example: grating laser in Littrow configuration



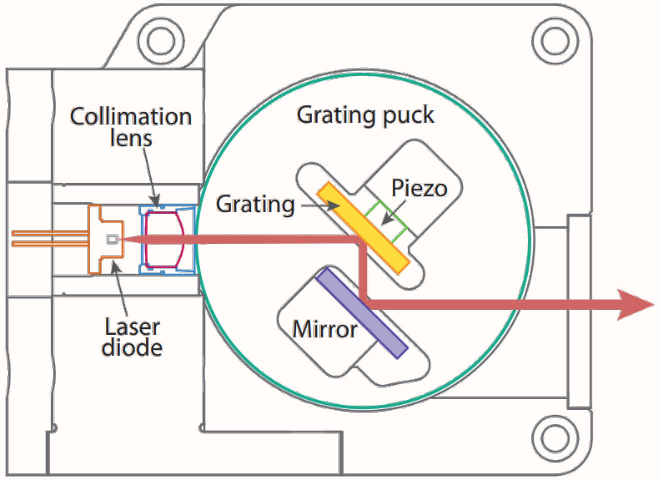

Transfer function multiplies and laser selects a single mode




*Picture refs.*
*Moglabs*
*Toptica*
*Nagourney, Quantum electronics for Atomic Physics*

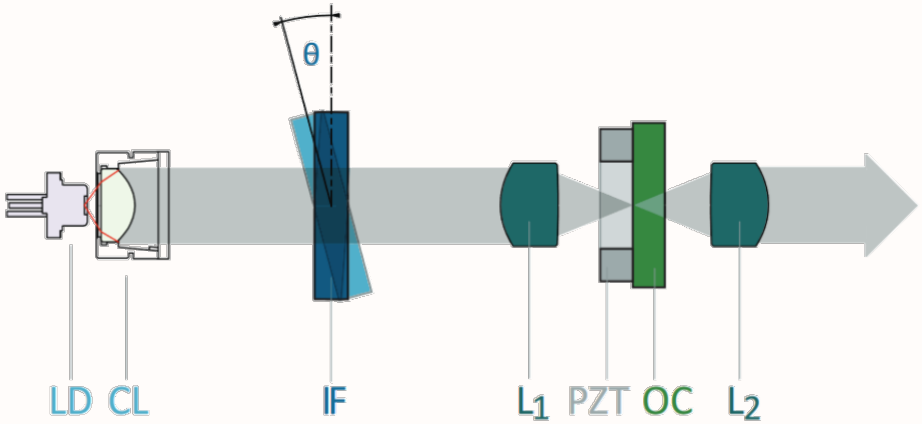
# Decoupling things to make practical ECDL

Decouple beam pointing and coarse wavelength selection




Rotate entire grating package
Also see Littman configuration, etc..

Decoupling feedback and coarse wavelength selection
+ improved robustness against misalignment



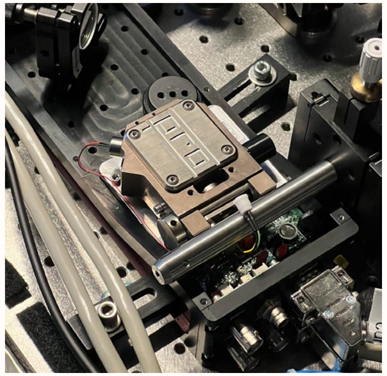

Cat-eye + filter

*Picture refs.*
*Moglabs*
*D.J Thompson & R.E. Scholten, Rev. Sci. Instrum. 83, 023107 (2012)*

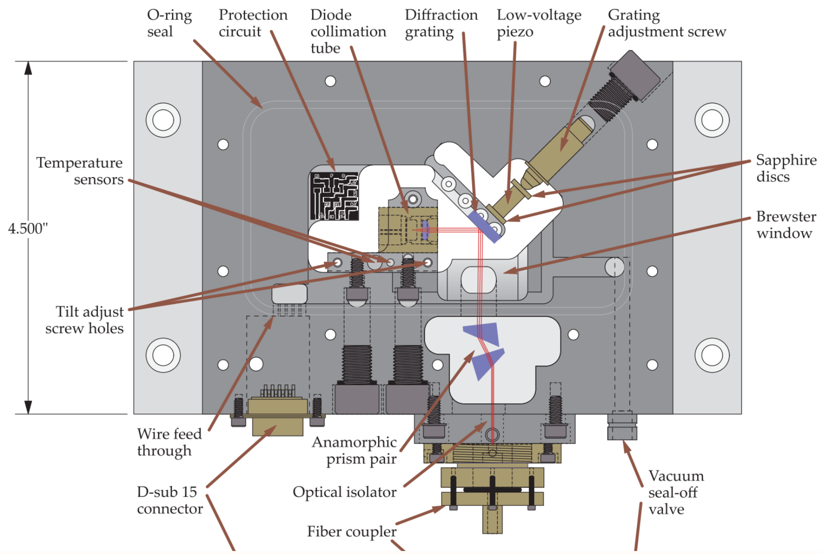
# How to actually build one?

# Passive stability: mechanical

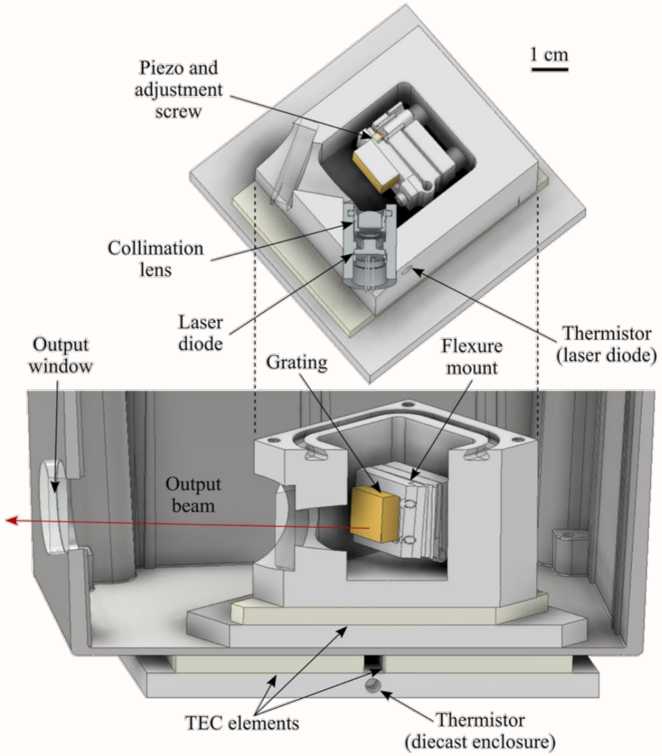
Toptica



Daniel Steck group, Rev Sci Instrum 83, 043101 (2012)



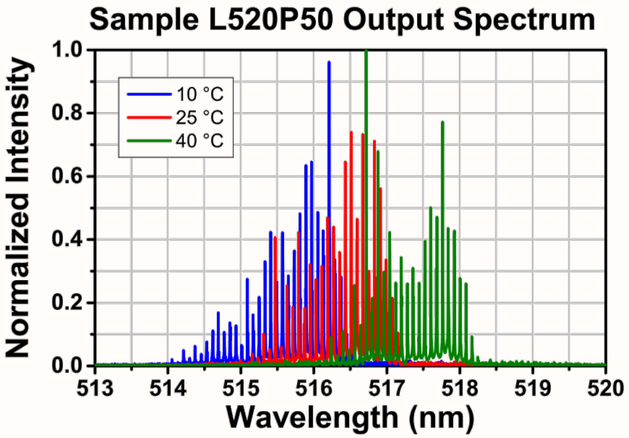

Eric Hudson group, Rev. Sci. Instrum. 94, 043001 (2023)



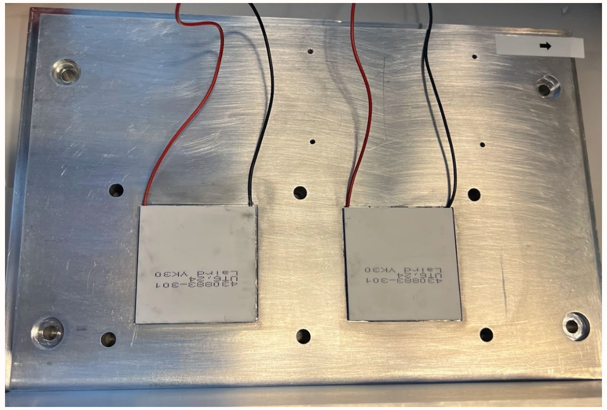

- Monolithic cavity
- Pump to rough vacuum if necessary
- Outer enclosure to shield cavity from perturbations

# Active stability: thermal

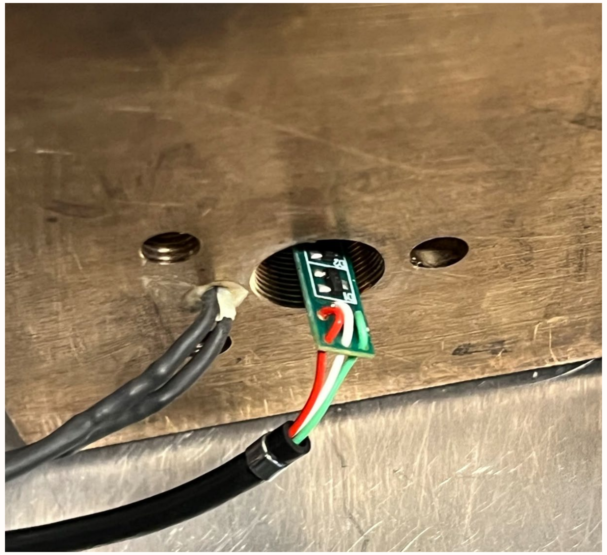
Laser emission changes with temperature
-> need active stabilization

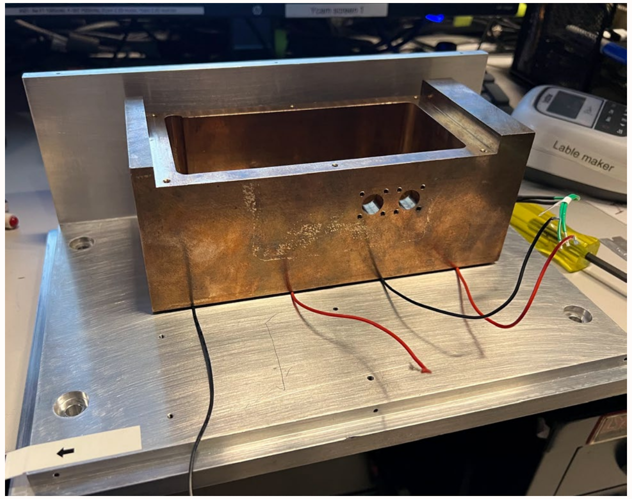



TEC on the cavity + secondary enclosure for passive stability



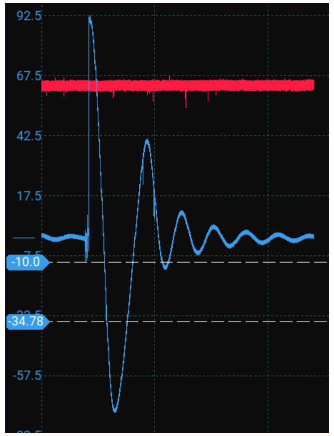
Thermistor as close to diode as possible

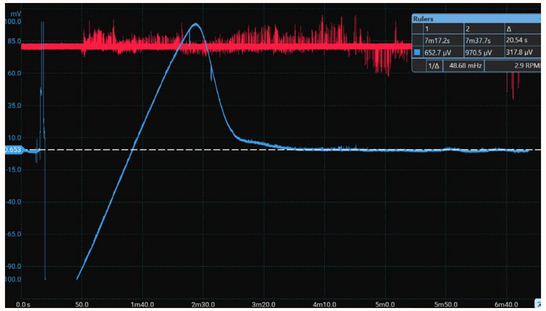





*Design credit C Robens*

Temperature PID tuning with standard Ziegler–Nichols heuristic



Painful lesson: setpoint not away from room temperature (Vescent photonics)


# Choosing a diode for ECDL

AR coated vs Fabry Perot diodes:
Better tuning range by eliminating diode cavity

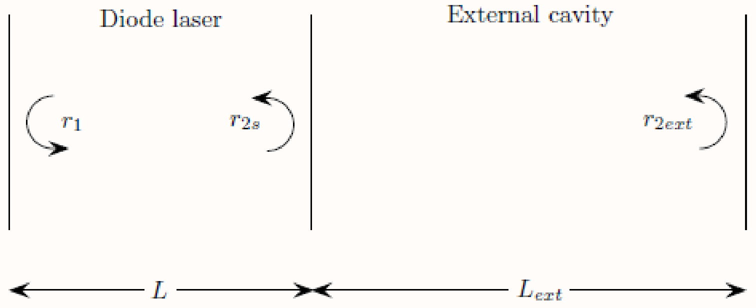
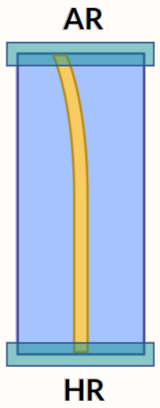
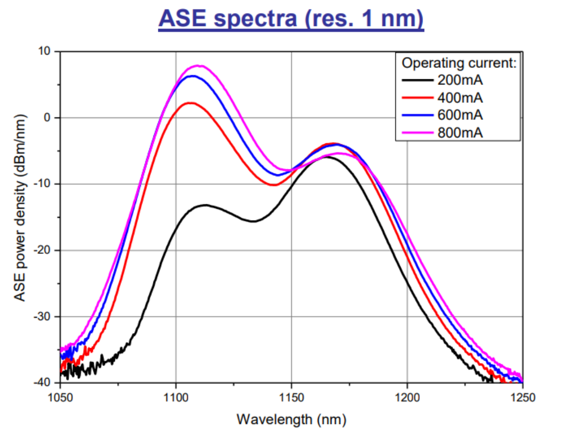
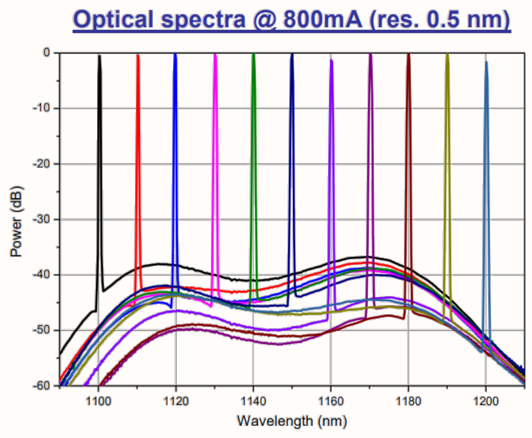


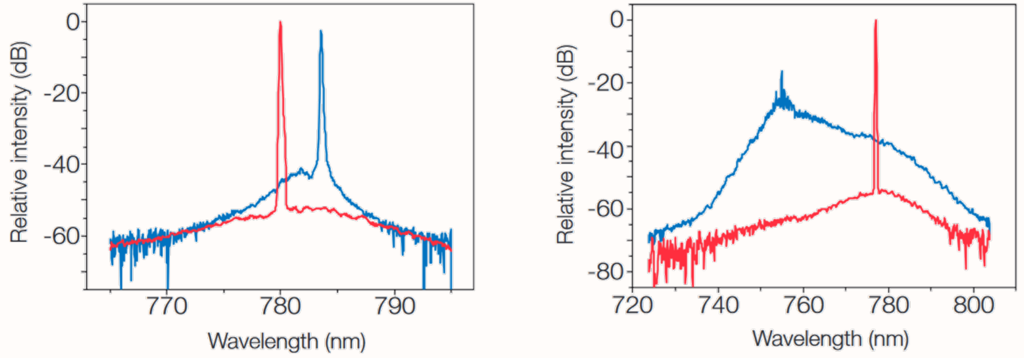

**Fig. 9.17** Schematic of laser cavity reflectors together with external reflector.




Look at diode spectra without/with external cavity

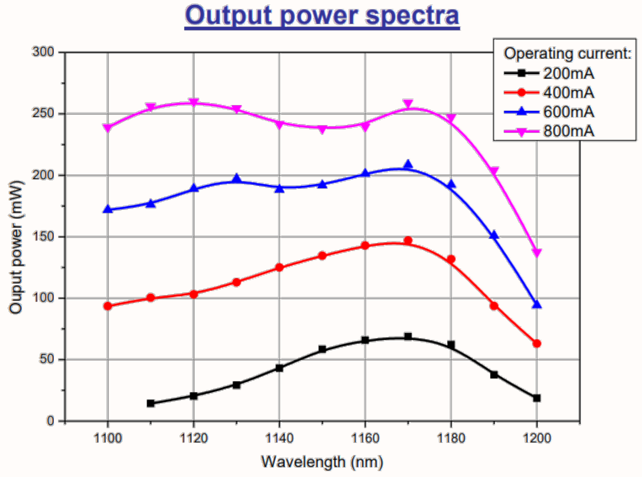


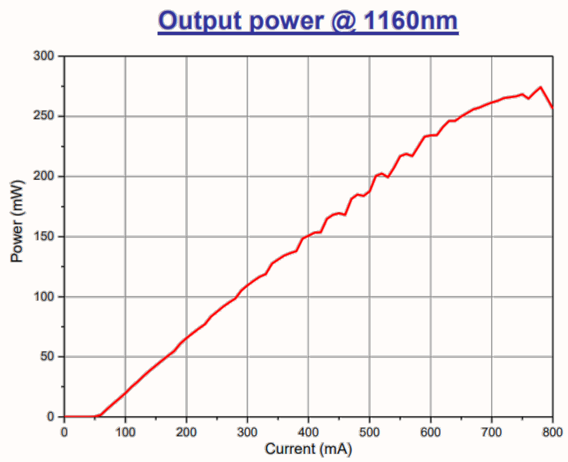




Laser diode with (red) and without (blue) external grating feedback.
The left graph shows an FP diode, the right graph an AR diode.

Power budget?

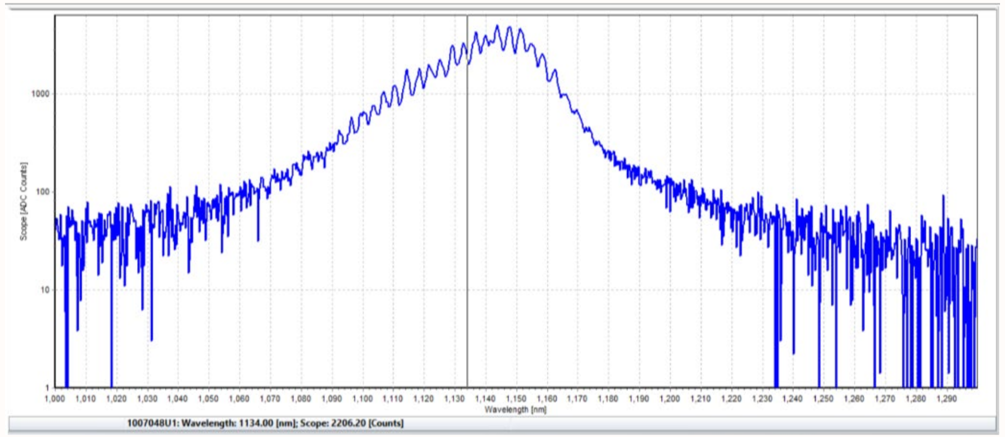


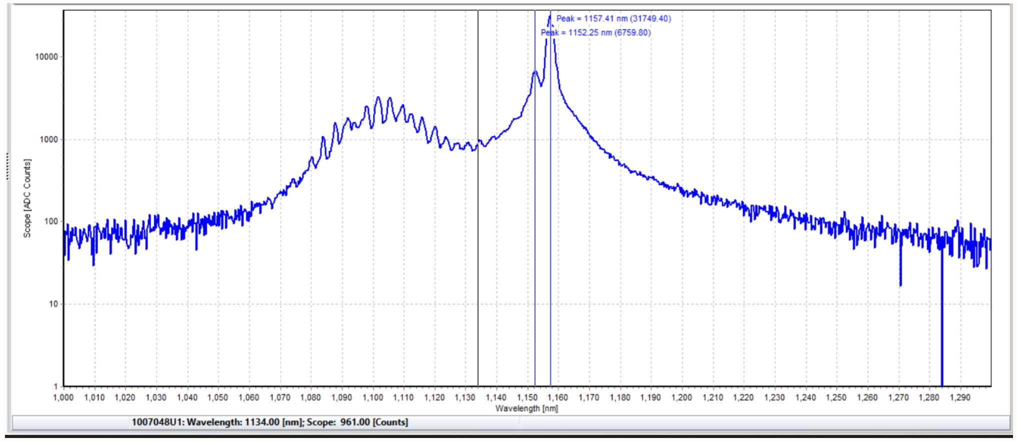

*Picture refs. topganlasers.com, Toptica, Innolume Nagourney, Quantum electronics for Atomic Physics*

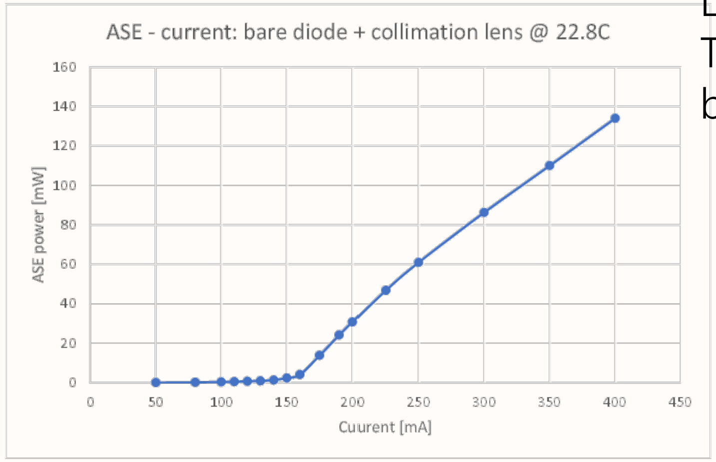
# What you do not want

100mA

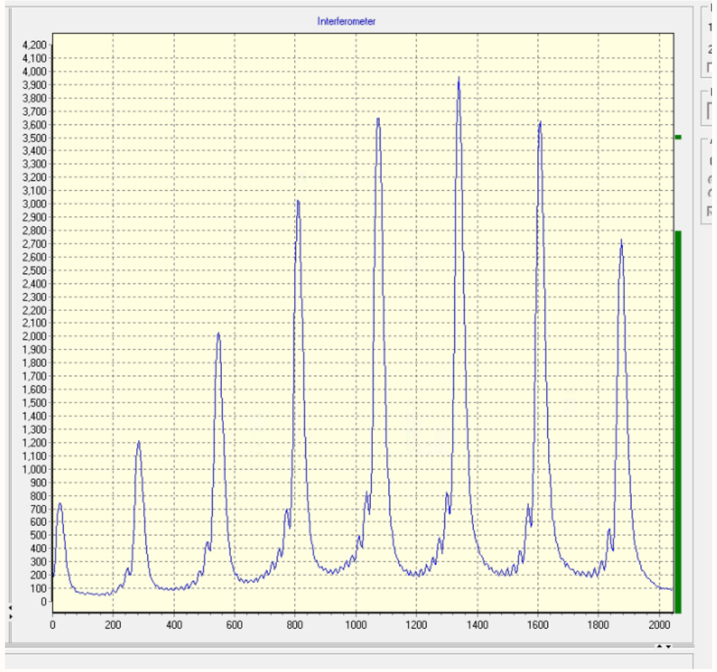



400mA



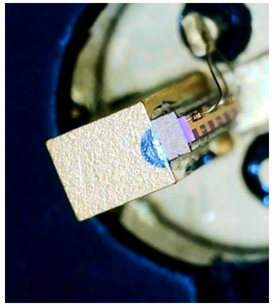



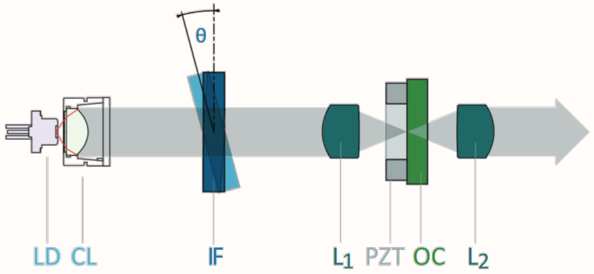

Laser self-lases at moderately high current
Tuning to right frequency & single-mode becomes a nightmare

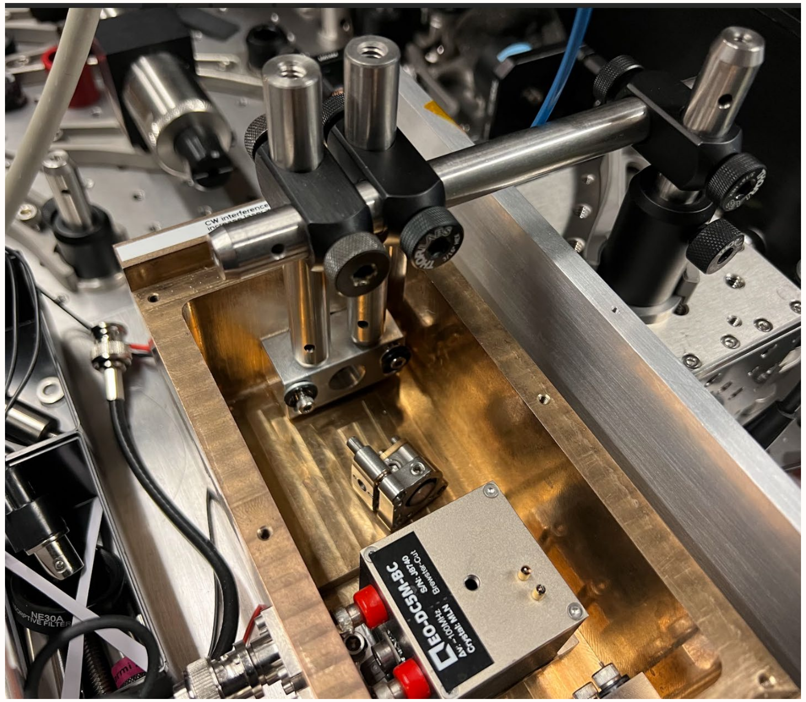



# Alignment and lase!

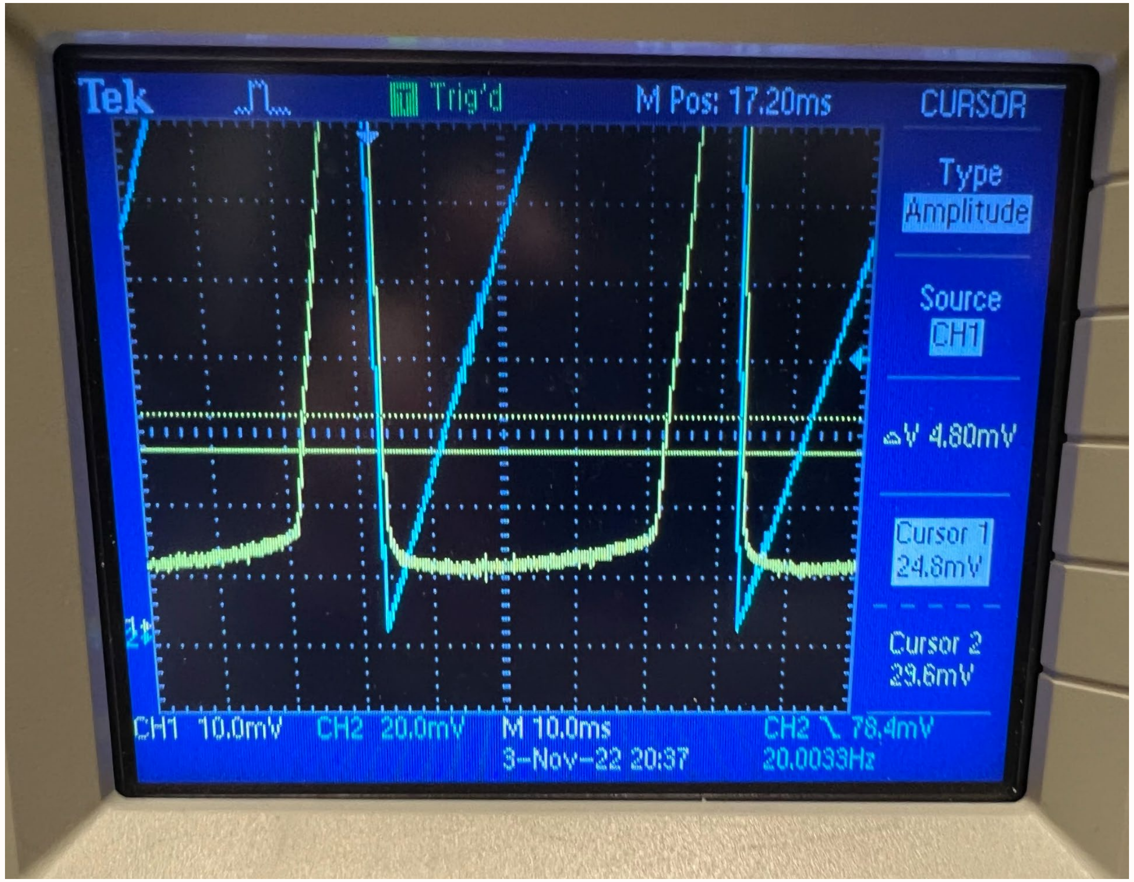
Coarse: get reflected light into diode and look for sudden increase in intensity





Fine: monitor output power while sweeping current.
Try to lower the lasing threshold



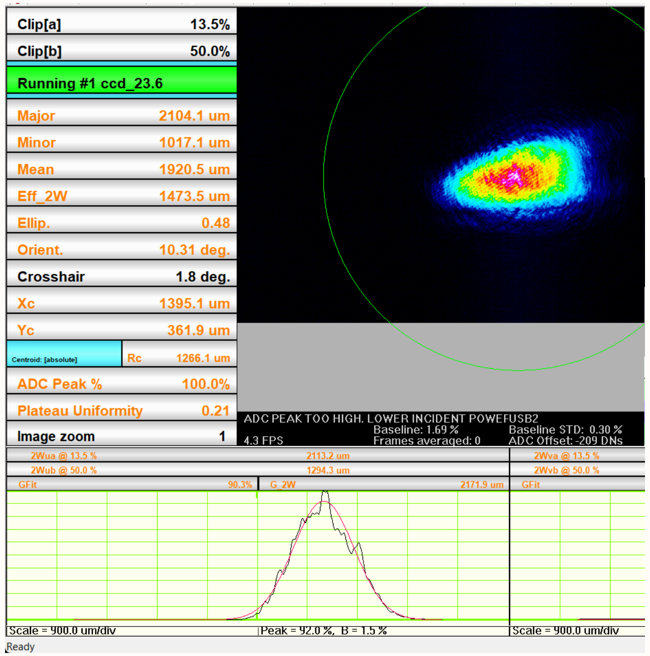

*Picture refs.*
*Moglabs*

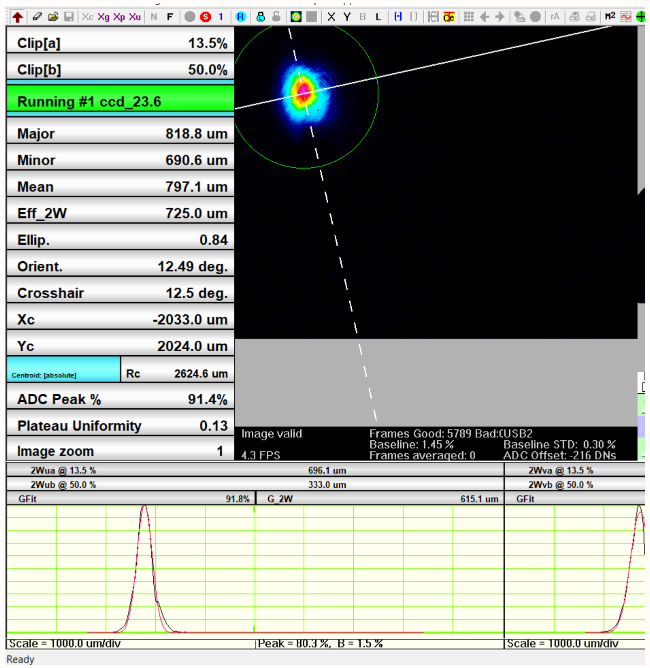
# Finishing touches

- Back reflections are detrimental. Use isolators (30dB at least, 60dB if amplification stage exists downstream)

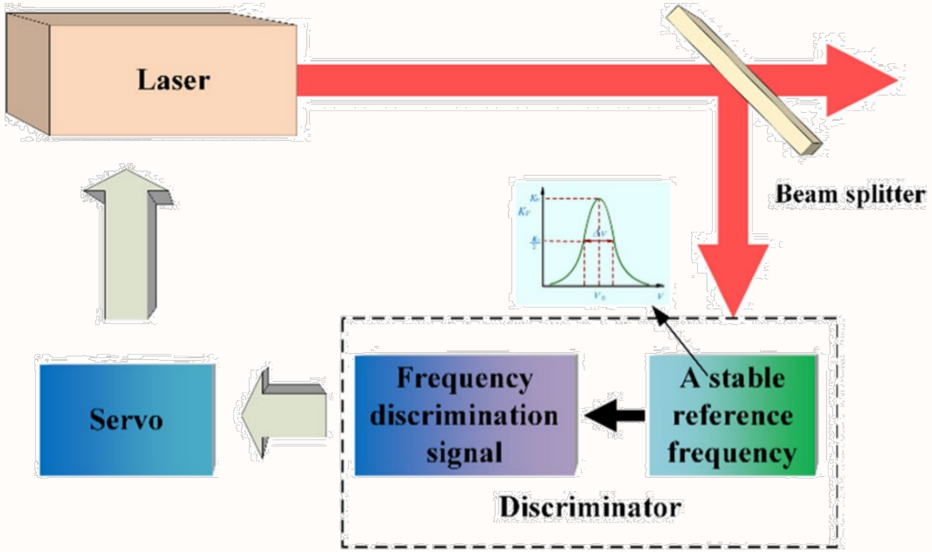
- Filters will age, mostly due to humidity (interference filter we use typically die after two years) -> try to seal and pump down, add desiccators, fill with argon, etc…

- Diode typically have funky spatial mode. Use cylindrical lenses / anamorphic lens pair to improve your fiber coupling efficiency



# Frequency stabilization



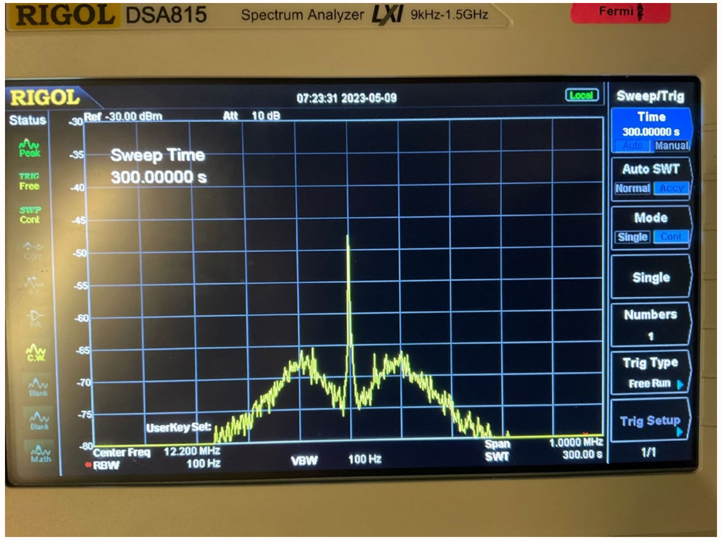

Ingredients (examples not exhaustive):

- Frequency reference
    - Interferogram (wavemeter)
    - Atomic transition (vapor cell)
    - Cavity resonance
    - Another laser
- A way to generate error signal
    - Just take the difference
    - Frequency modulation spectroscopy
    - Pound-Drever-Hall
    - Beatnote and phase lock loop
- Actuator to change frequency
    - Temperature (very slow)
    - Piezo (~1 – 10s kHz)
    - Current (~100s kHz to >1 MHz)
    - Intracavity EOM (>1MHz)

*Picture refs.*
*J. Korean Phys. Soc. 79, 795–809 (2021)*

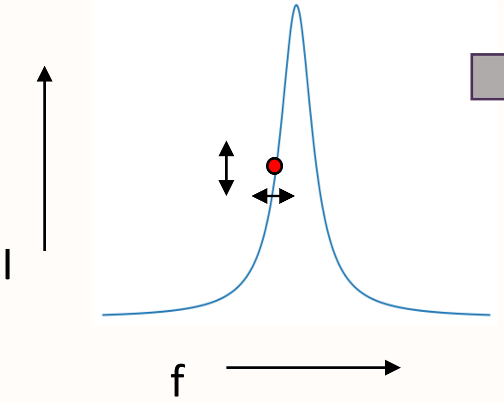
# Phase noise characterization -> phase to amplitude conversion

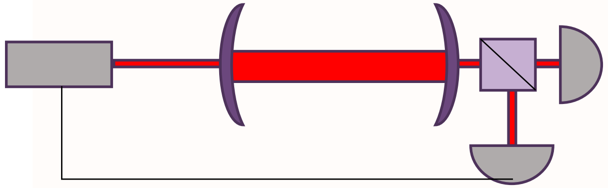
Directly looking at error signal on a spectrum analyzer



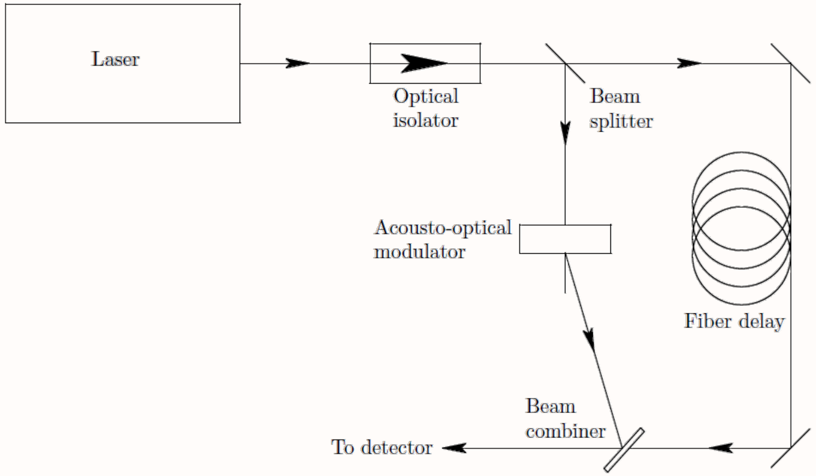

- Plus: get this measurement for free
- Minus: In-loop signal (can trick you), also convolved with electronic noises

Transmission from a cavity



Self heterodyne with a delay line



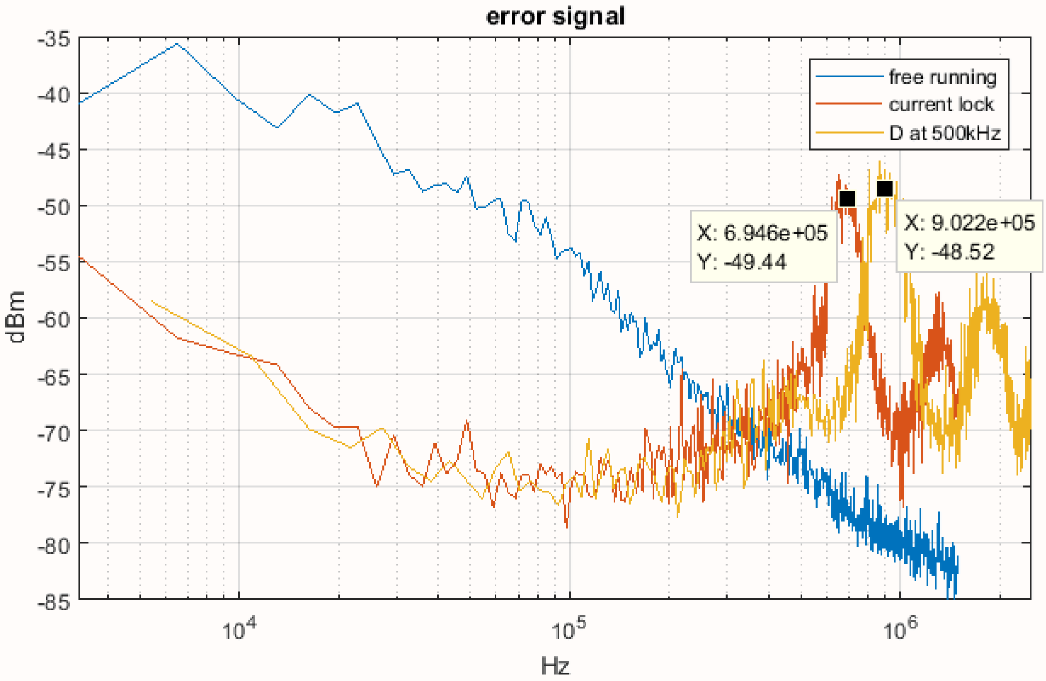

- Might need very long delay line (delay > coherence time)

Heterodyne with another good laser

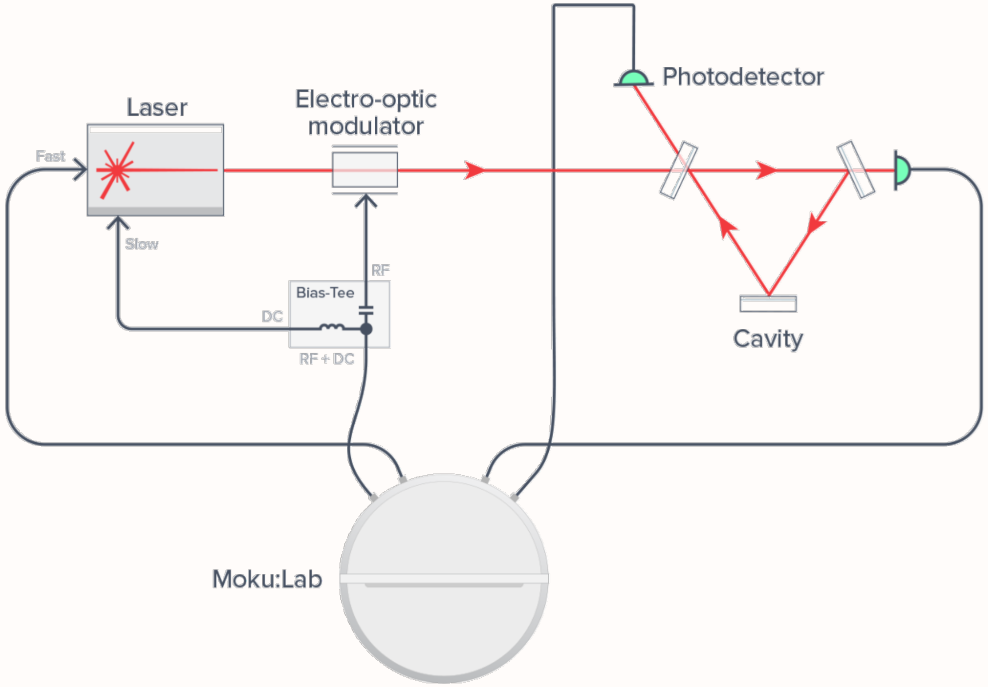

*Picture refs.*
*Nagourney, Quantum electronics for Atomic Physics*
*A Chuang & E Wolf, Internal Group Seminar*
*T Fortier, APL Photonics 7, 026105 (2022)*

# Servo bump

Phase lag at resonance of frequency actuators *add* noise instead!




Usually add filters to condition noise trade bandwidth for stability



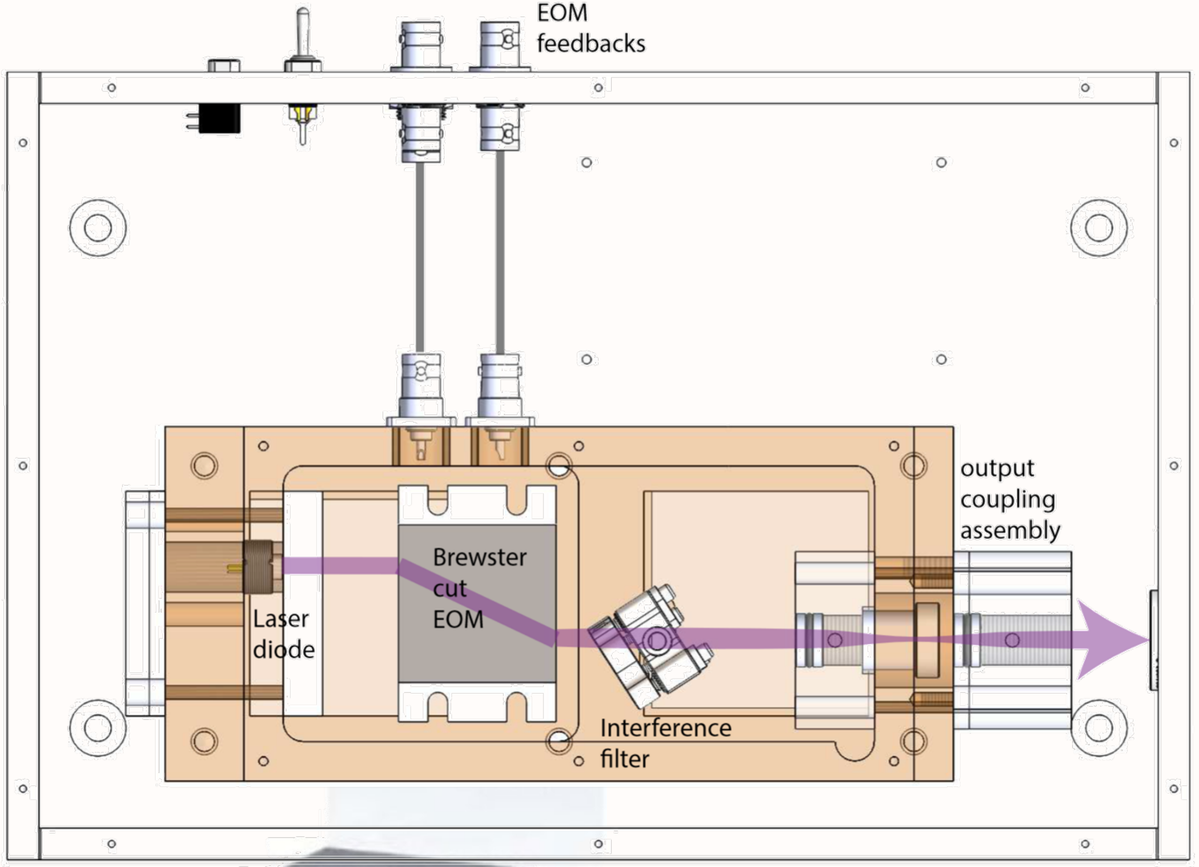

Normally pizeo takes care of ~1-10s kHz and current takes care of up to 1MHz

Unfortunately certain diodes at our wavelength (1134nm) has very low current modulation bandwidth (known problem amongst some people doing Yb clock transition as well)

*Picture refs.*
*Y. Ni, internal lab notebook*
*Liquid instrument*

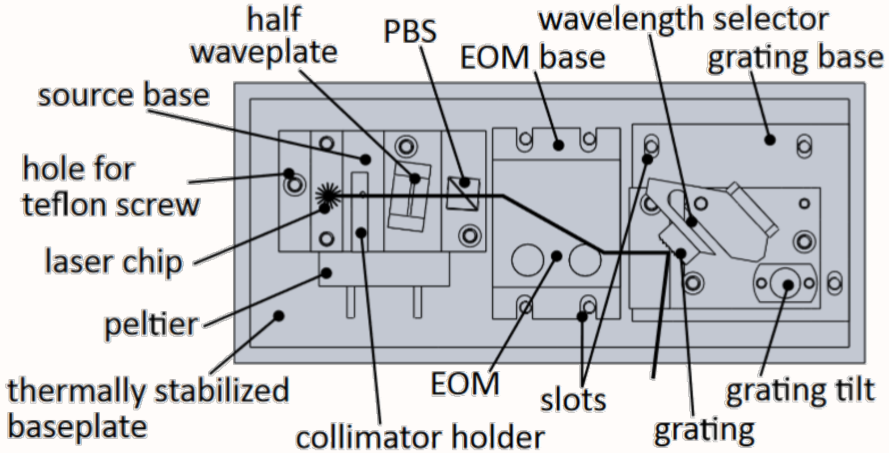
# Intracavity EOM laser

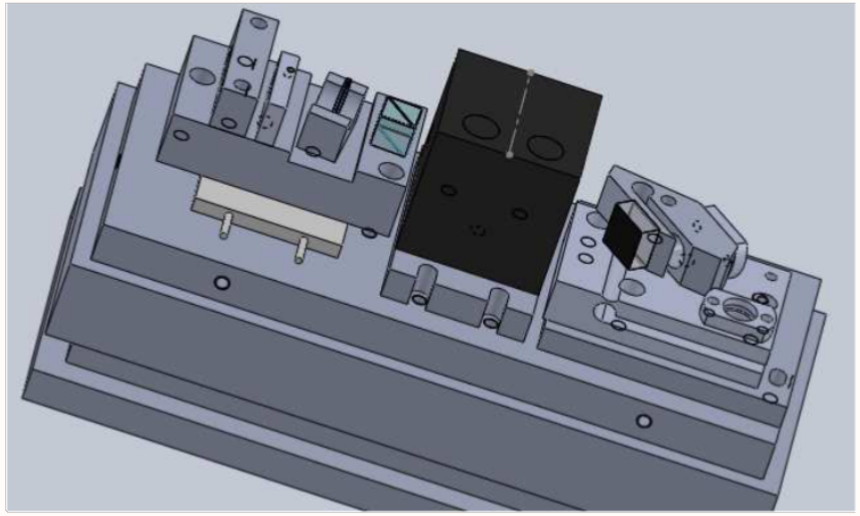
EOM modulates index of refraction -> effective cavity length with bandwidth easily in the MHz range





Similar (grating instead of filter) design from J. Catani group and Moglabs

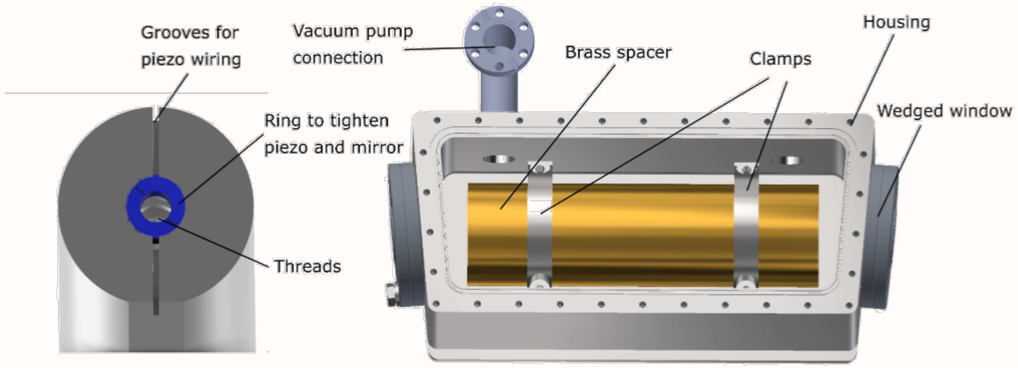


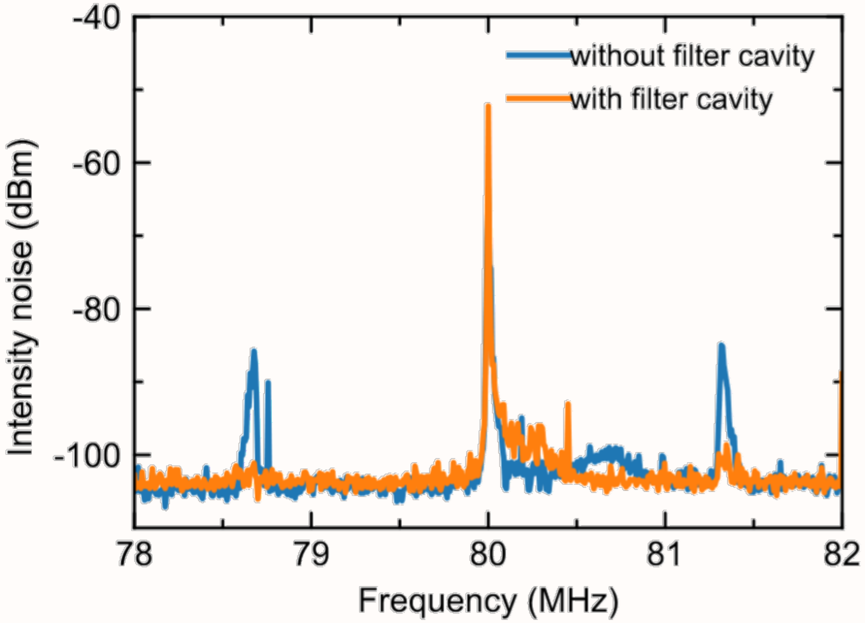
*Picture refs.*
*Y. Ni, PhD thesis (2023)*
*Qubig*

# Filter cavity

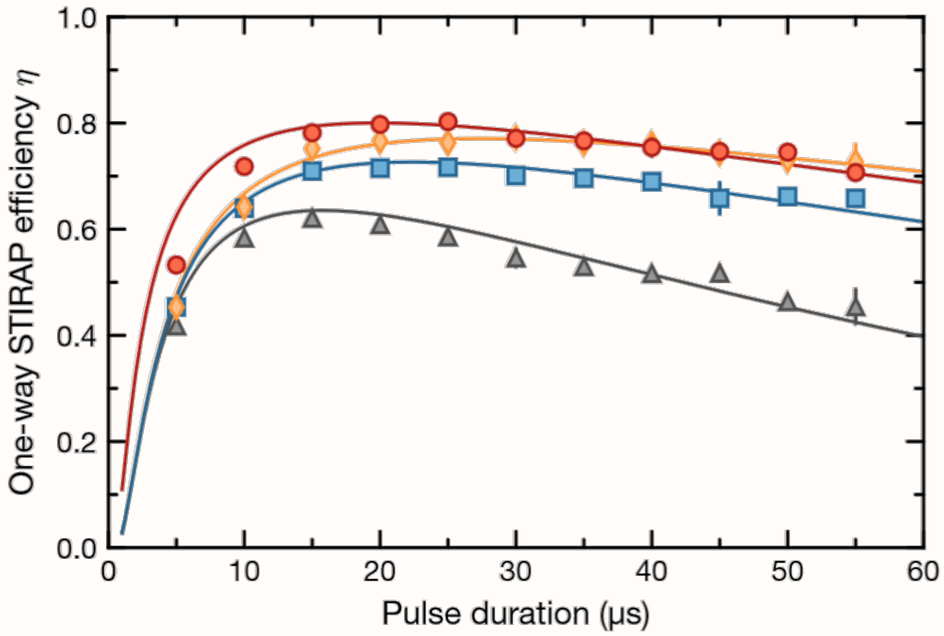
Use a moderately high finesse cavity as low pass filter




Test with intentionally destabilized laser




Other group demonstrated 60% (black) -> 80% (yellow) improvement on SITRAP efficiency!




Downside: lower power available -> need to add amplifiers

*Picture refs.*
*Joop Age Harm Adema, Masters Thesis (2019)*
*A Kamijo, masters thesis*
*Phys. Rev. A 104, 043321*

# Next steps?

- High NA objective
- Microwave shielding
- Near resonant (to K40) trap for better spatial mode matching between Na and K40

# Thank you!