Development of two crossed actively stabilized Fabry-Perot cavities for dual color X-ray generation through Compton scattering for the MariX project

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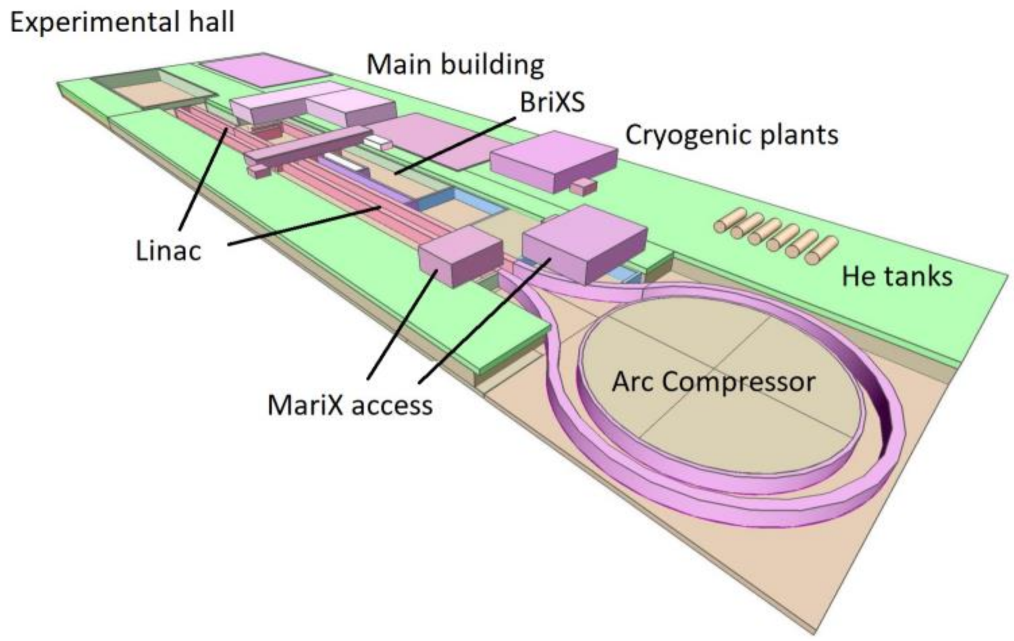
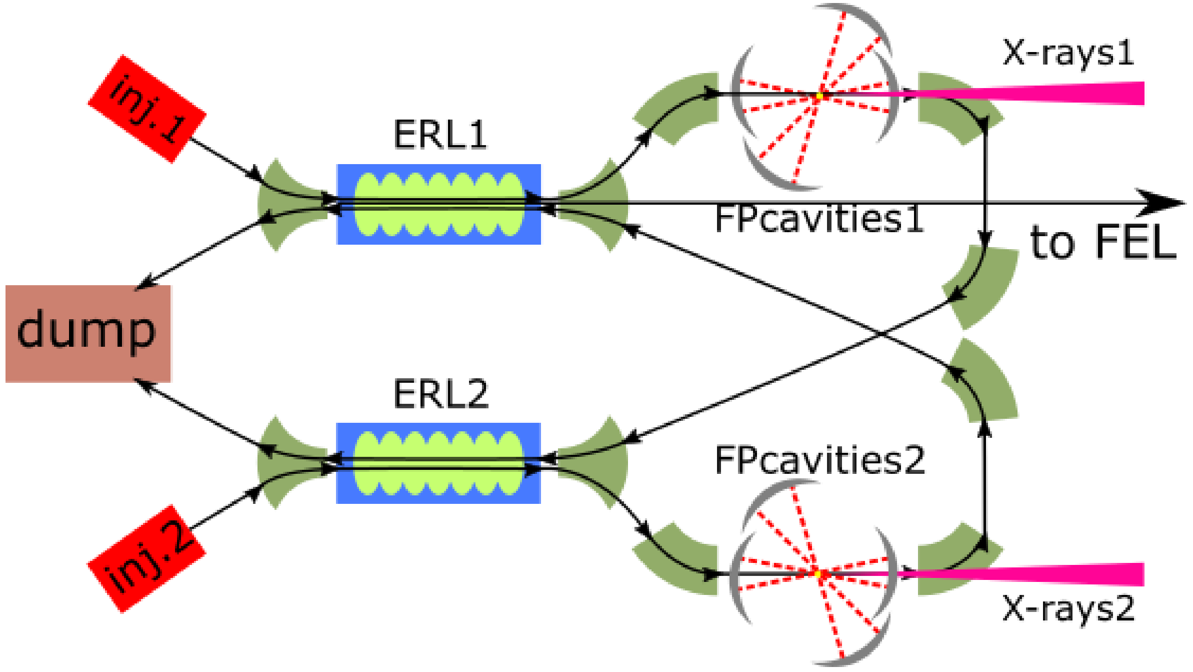
The MariX project: two X-ray sources





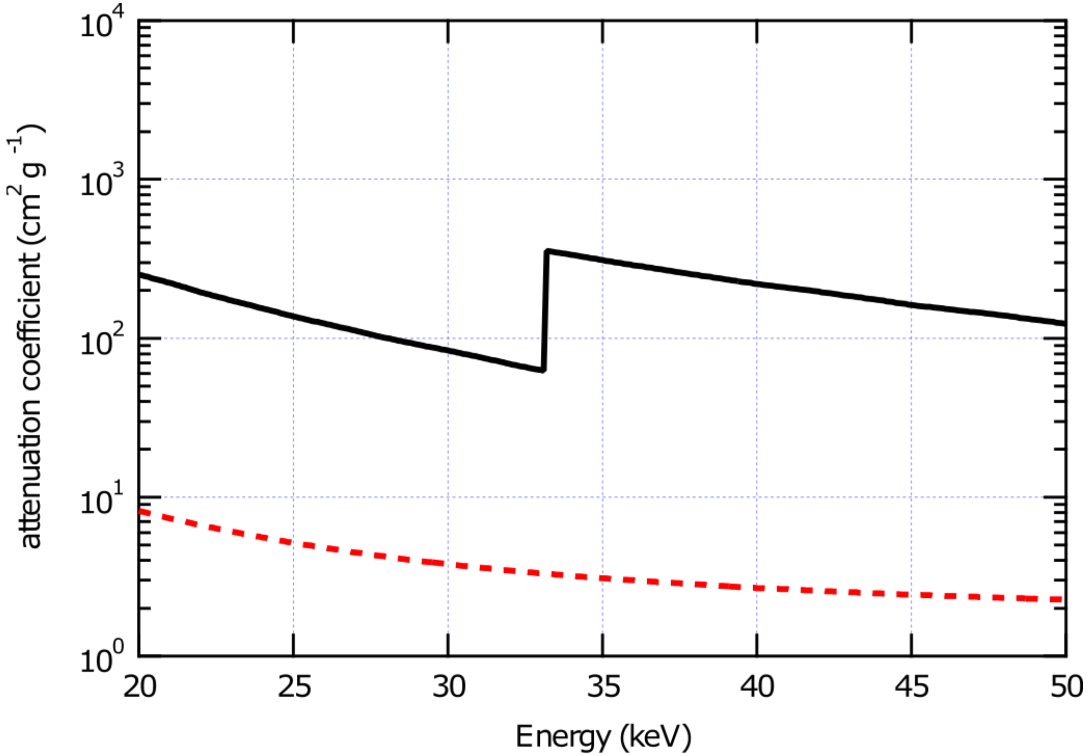
Free Electron Laser:

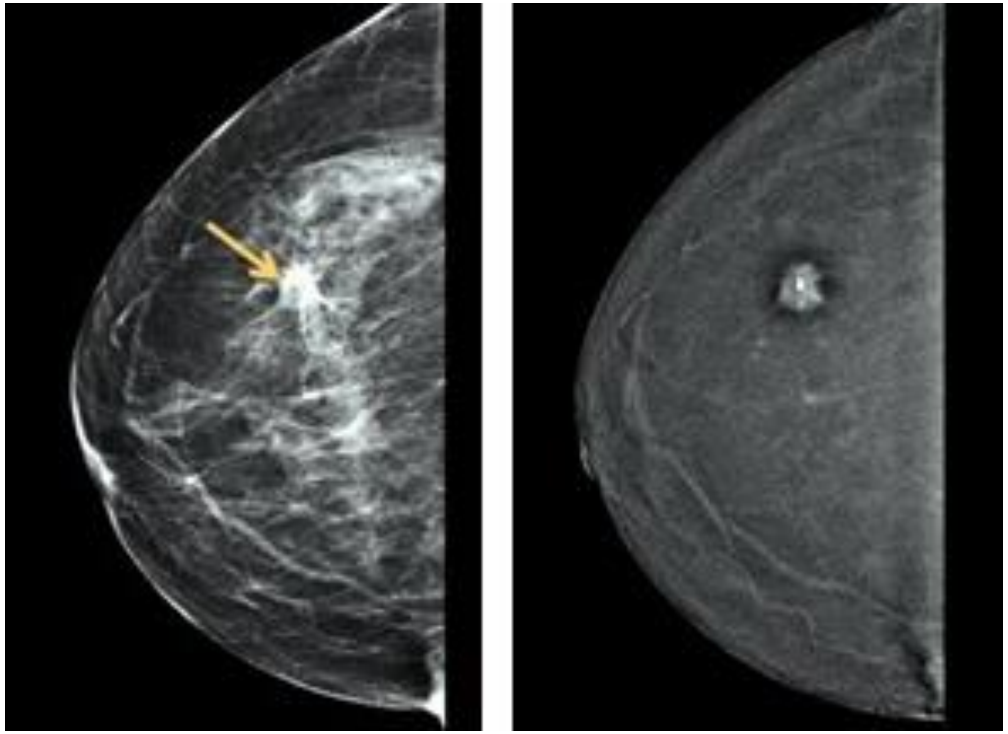
- 10^{-18} s pulses at 1 MHz
- 10^{17} photons/s
- 200 eV – 8 keV
- Femto-second linear spectroscopy

Inverse Compton Scattering:

- 10^{-12} s pulses at 100 MHz
- 10^{13} photons/s
- 20 keV – 180 keV
- Medical diagnostic and radiotherapy

Application: K-edge subtraction imaging (KES)

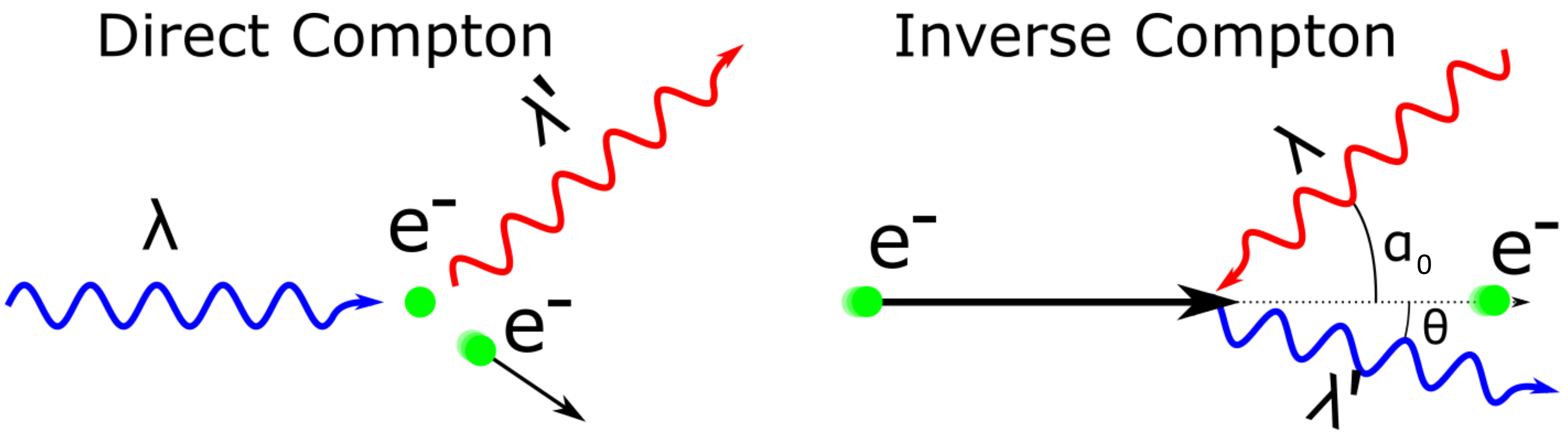




- Use of a contrast agent (iodine)
- Radiographies with two different X-rays energies (under and above the K-edge energy, 33 keV)

- Logarithmic subtraction of two images
- Example: coronary angiography for cancer detection

Inverse Compton Scattering (ICS)



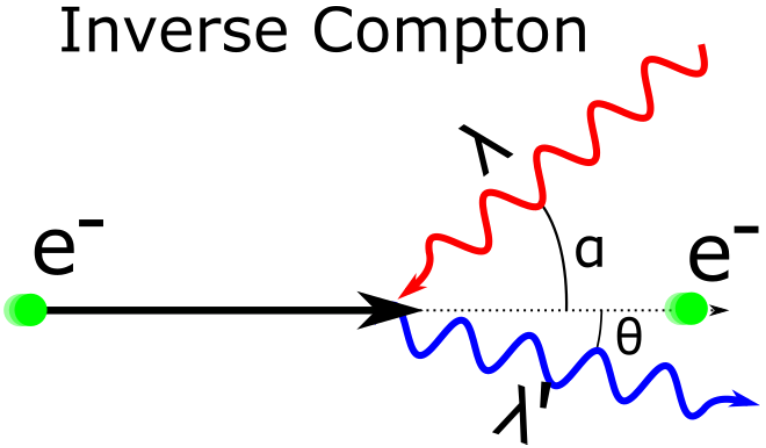
Upshifted energy:

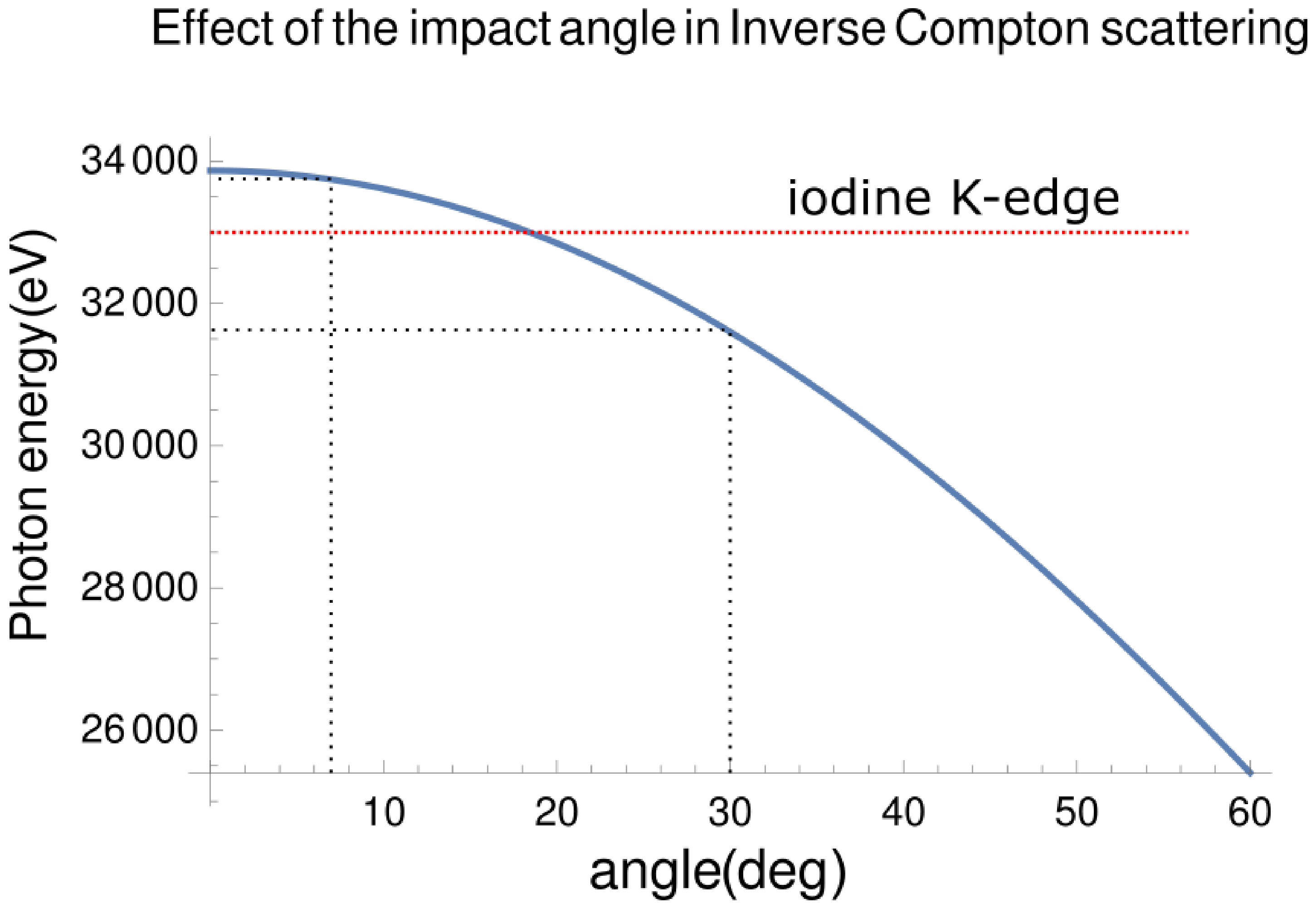
$$E_{ph} = \frac{2E_L\gamma^2\left(1+\cos\alpha_0\right)}{1+\gamma^2\theta^2}$$

E_L	= laser photons energy	1.2 eV
E_{ph}	= scattered photons energy	20-180 keV
γ	= Lorentz factor	60-200

- By changing the incidence angle α_0 we can obtain the two X-ray energies for KES
- Radiation confined in a small angle $\theta_M \sim 1/\gamma$
- High monochromaticity ($\Delta E/E = 0.01$) by controlling the acceptance angle θ

Inverse Compton Scattering (ICS)

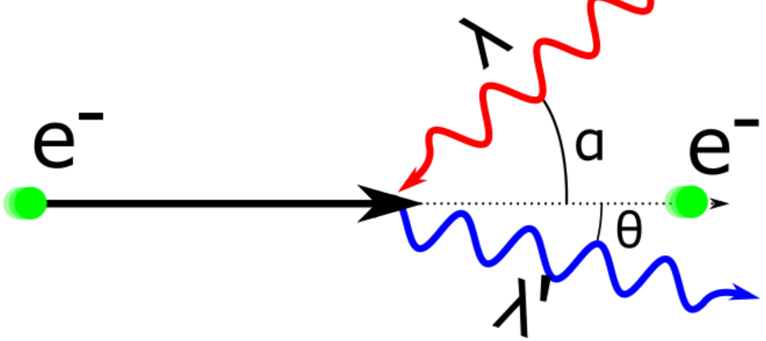




for iodine KES:

- Energies 34 and 32 keV
- Angles 7° and 30°
- $\gamma = 86$

Inverse Compton Scattering (ICS)



Photon flux:

$$N = \frac{\sigma_T f_{\mathrm{rep}} N_{ph} N_e}{2\pi\sqrt{\sigma_{Ly}^2+\sigma_y^2}\sqrt{\sigma_{Lx}^2+\sigma_x^2+(\sigma_{Lz}^2+\sigma_z^2)\tan^2(\frac{\alpha}{2})}}$$

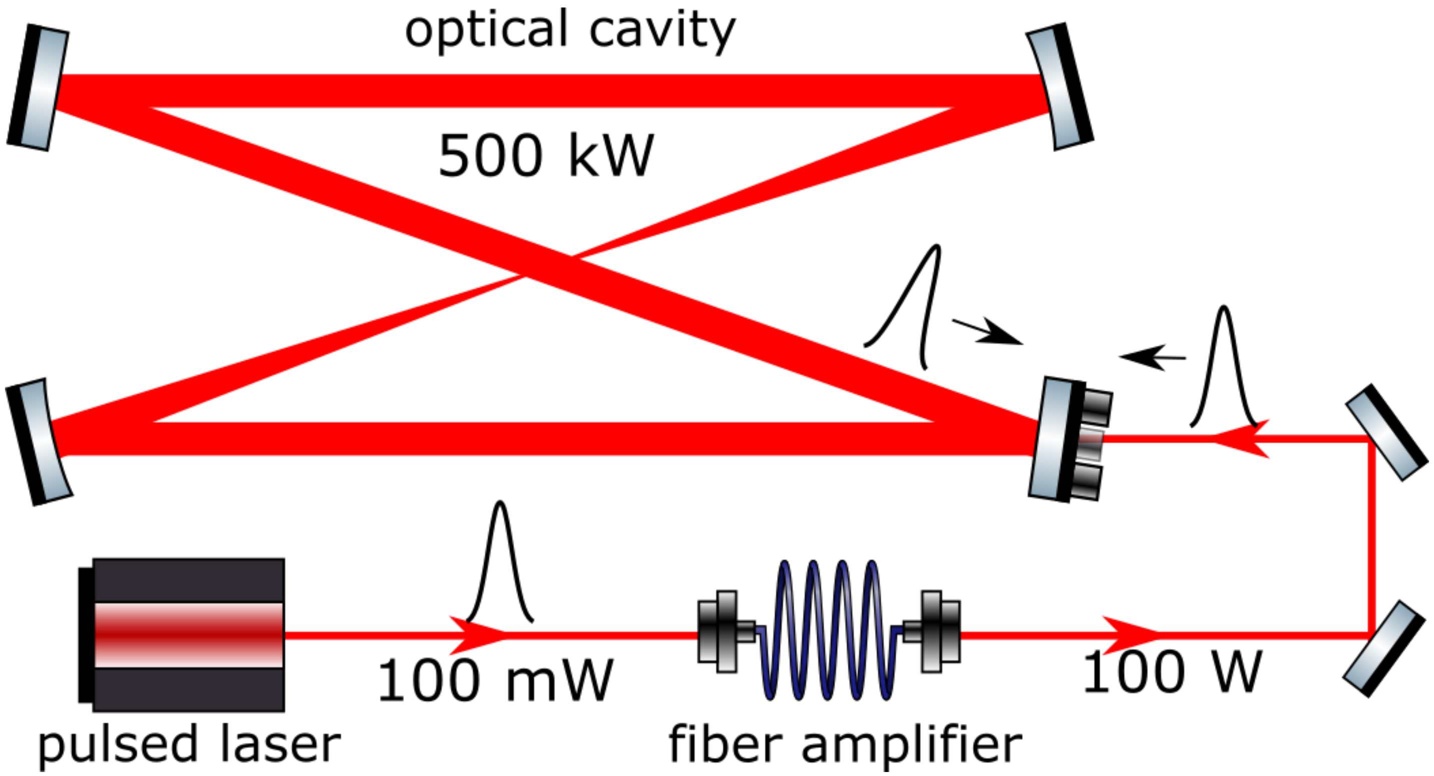
$$\sigma_{\mathrm{T}} \approx 6.652 \times 10^{-29}\mathrm{m}^2$$
$$N = 10^{13}\mathrm{ph/s}$$

$\longrightarrow$

$$I_e = 20\,\mathrm{mA}$$
$$P = 500\,\mathrm{kW}$$

Power out of reach of doped fiber amplifiers,
an enhancement optical cavity is needed

Fabry-Perot cavity: temporal domain

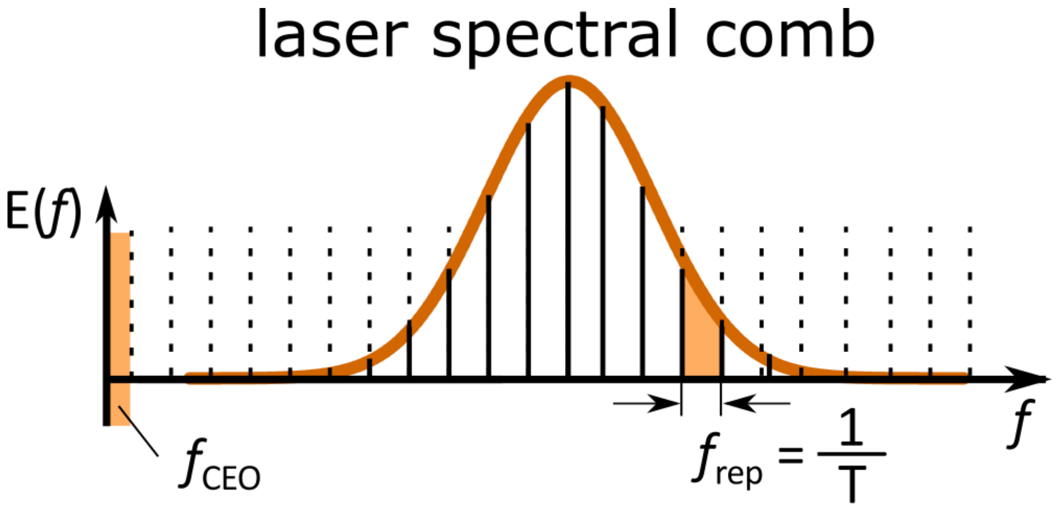


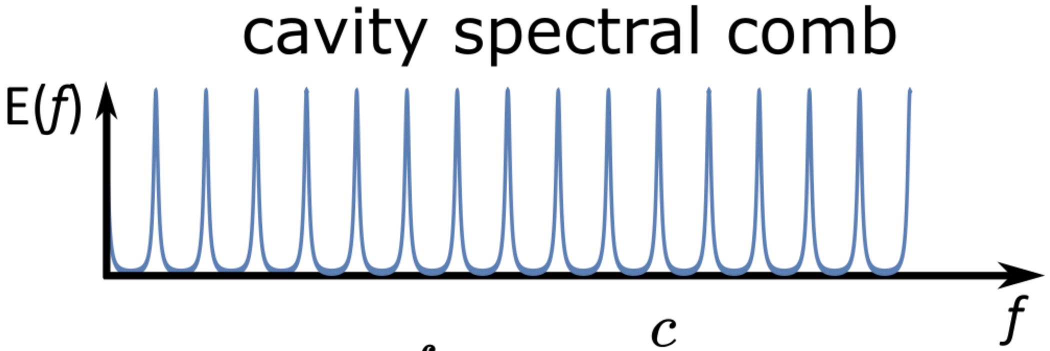
- In the cavity the laser pulses overlap, resulting in an increase of the optical power
- The power gain is given by the cavity Finesse, which depends on the mirror reflectivities
- Gain 5000, Finesse 8000
- Mirror reflectivities 99.999%
- Input coupler reflectivity 99.9%

Laser pulses must overlap in phase: cavity length is fixed by the laser repetition rate

$$f_{\mathrm{rep}} = 100\,\mathrm{MHz} \rightarrow T_{\mathrm{rt}} = 10\,\mathrm{ns} \rightarrow L = 3\,\mathrm{m}$$

Fabry-Perot cavity: frequency domain

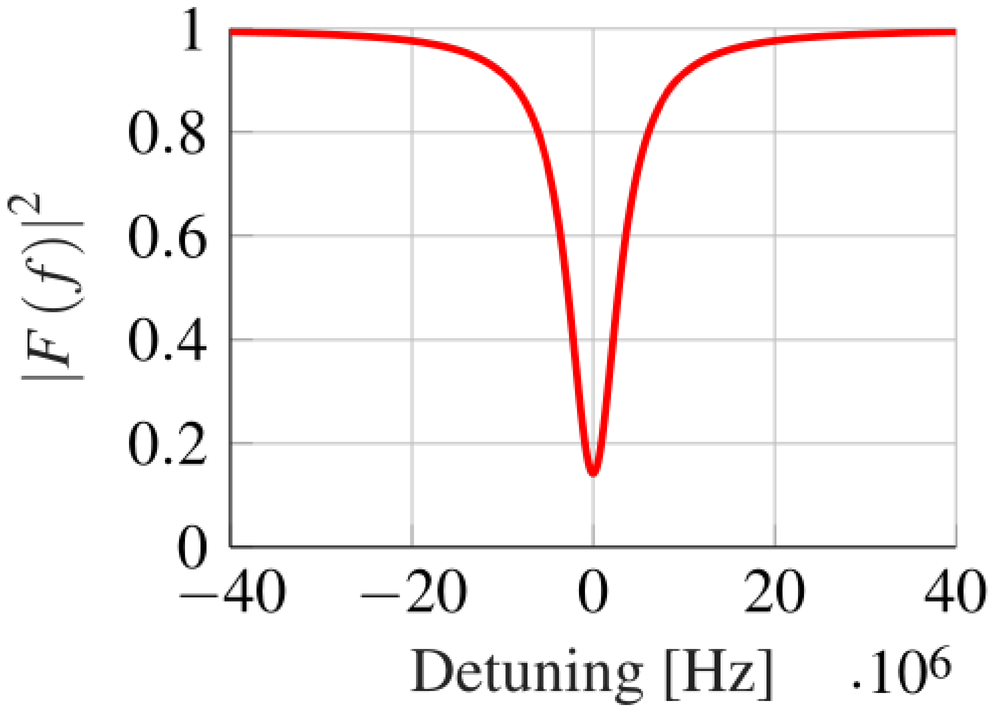




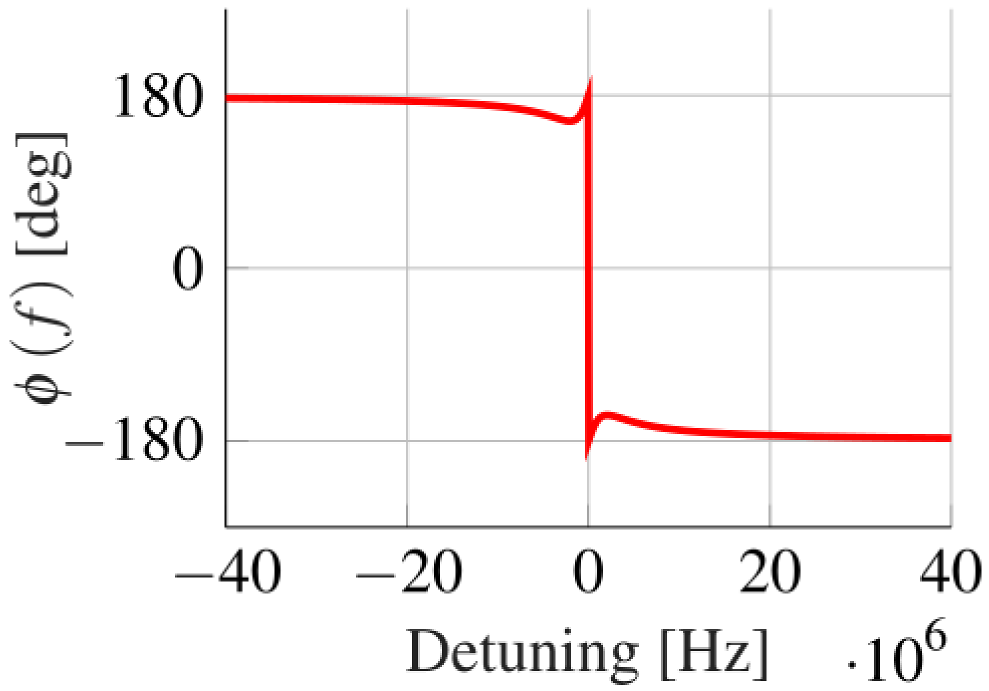
$$f_{cm} = m\frac{c}{L}$$

- Only precise frequencies can resonate inside the cavity
- Cavity linewidth is given by the Finesse (mirror reflectivities)
- Cavity and laser spectral comb must overlap
- Both are subjected to noise
- Need for a stabilization system for the cavity length (<<150 pm)

Fabry-Perot cavity: stabilization system

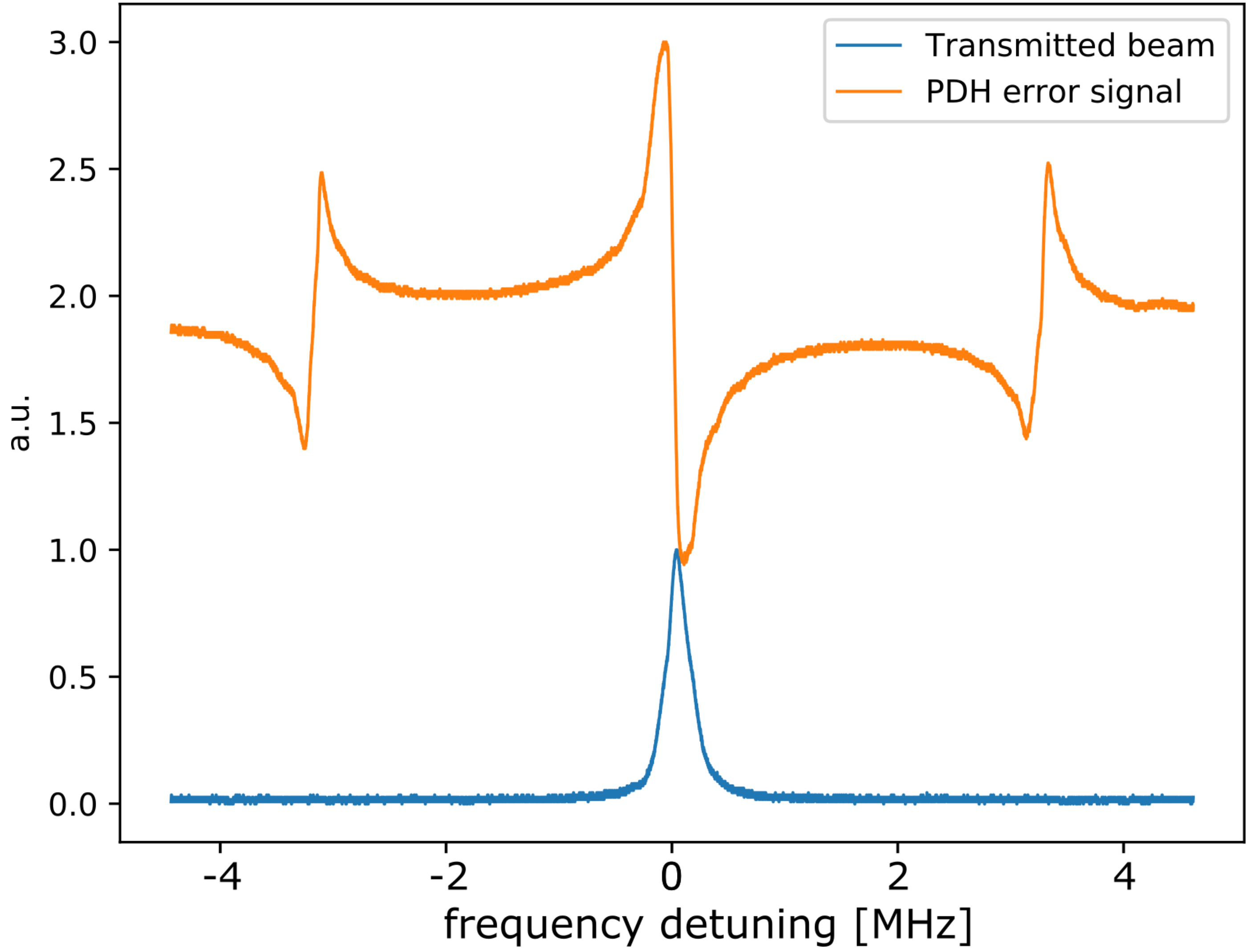


Reflected field power:
symmetric signal



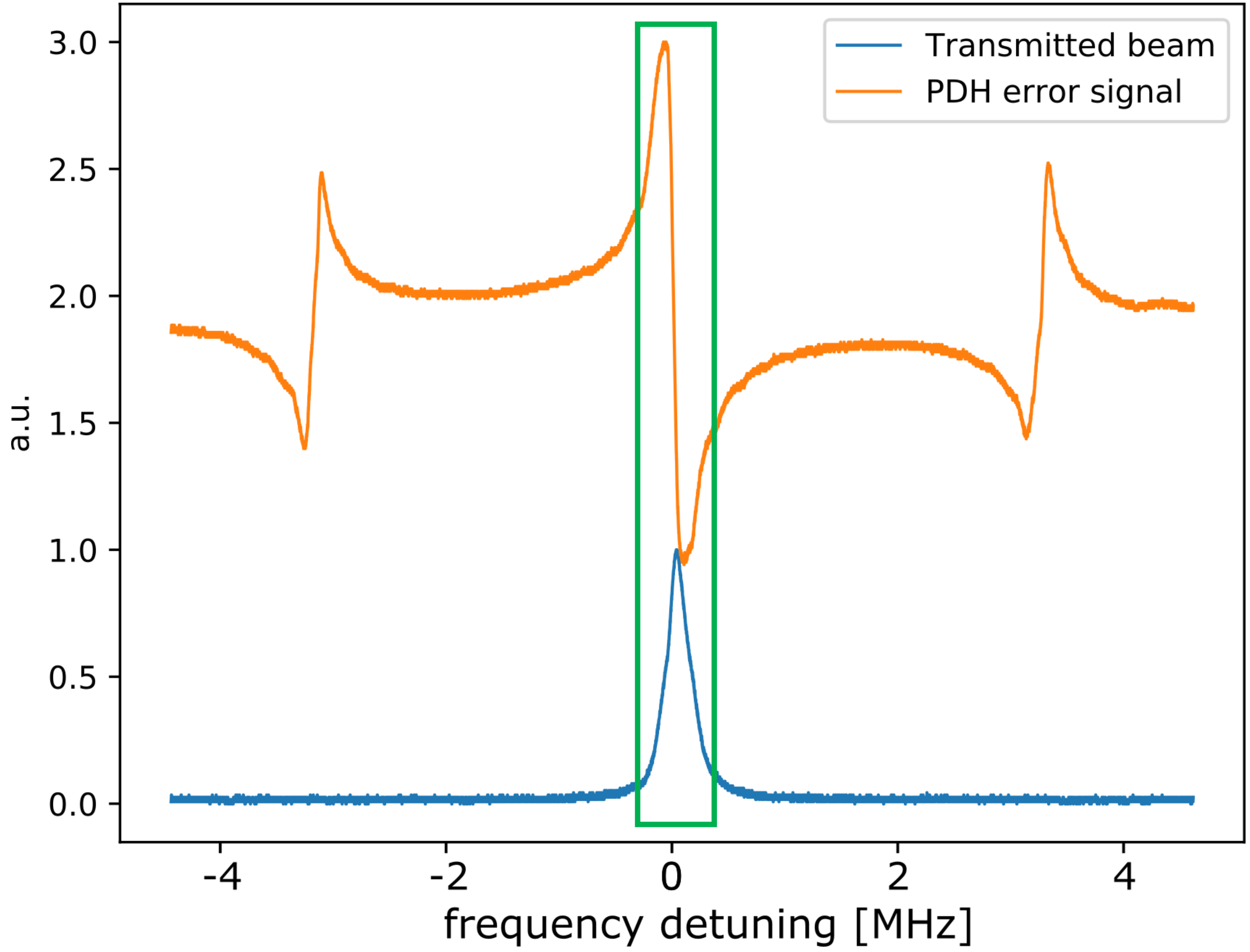
Reflected field phase:
asymmetric signal

Fabry-Perot cavity: stabilization system



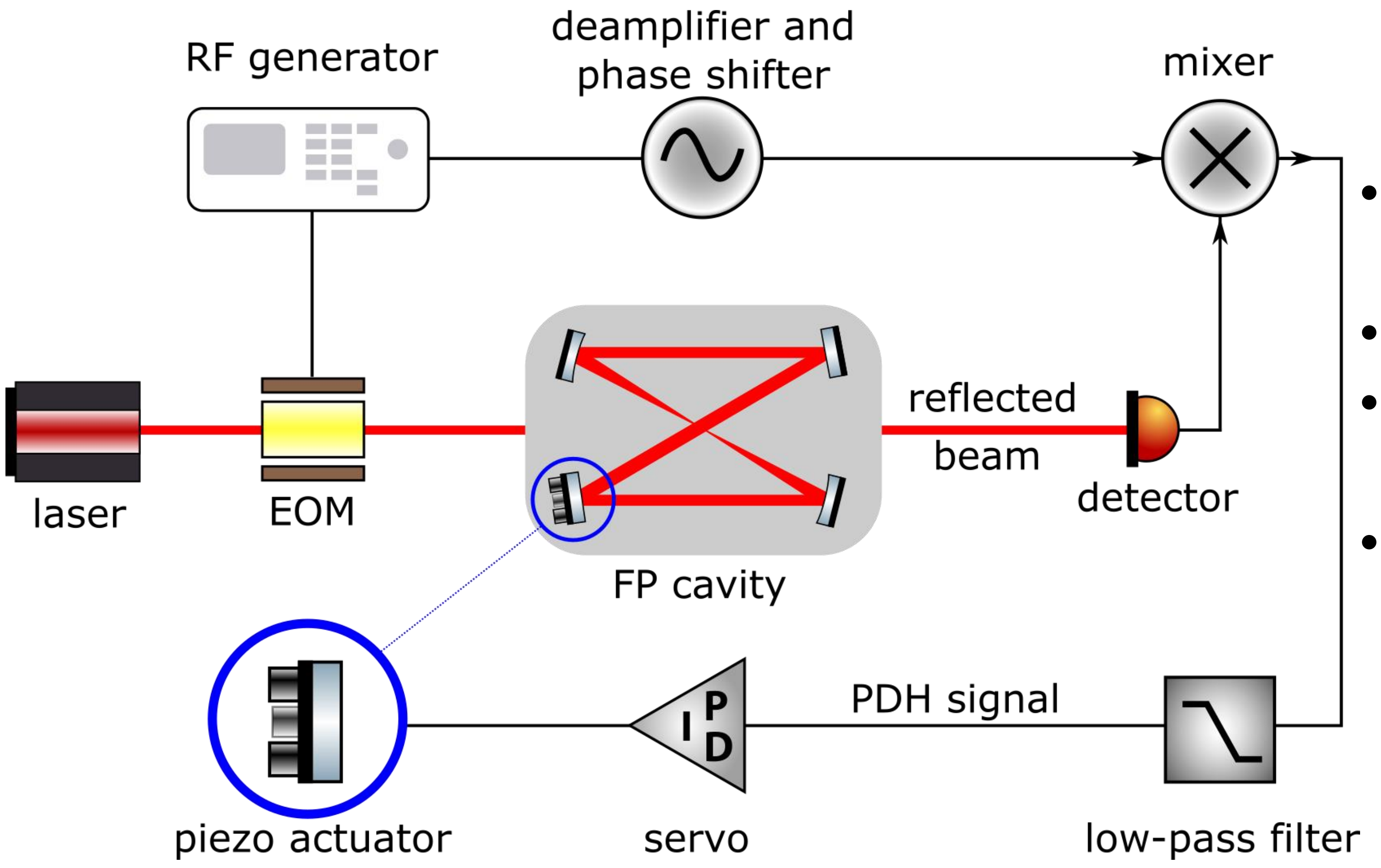
- Pound-Drever-Hall technique to generate the error signal
- Length is corrected using a piezo

Fabry-Perot cavity: stabilization system



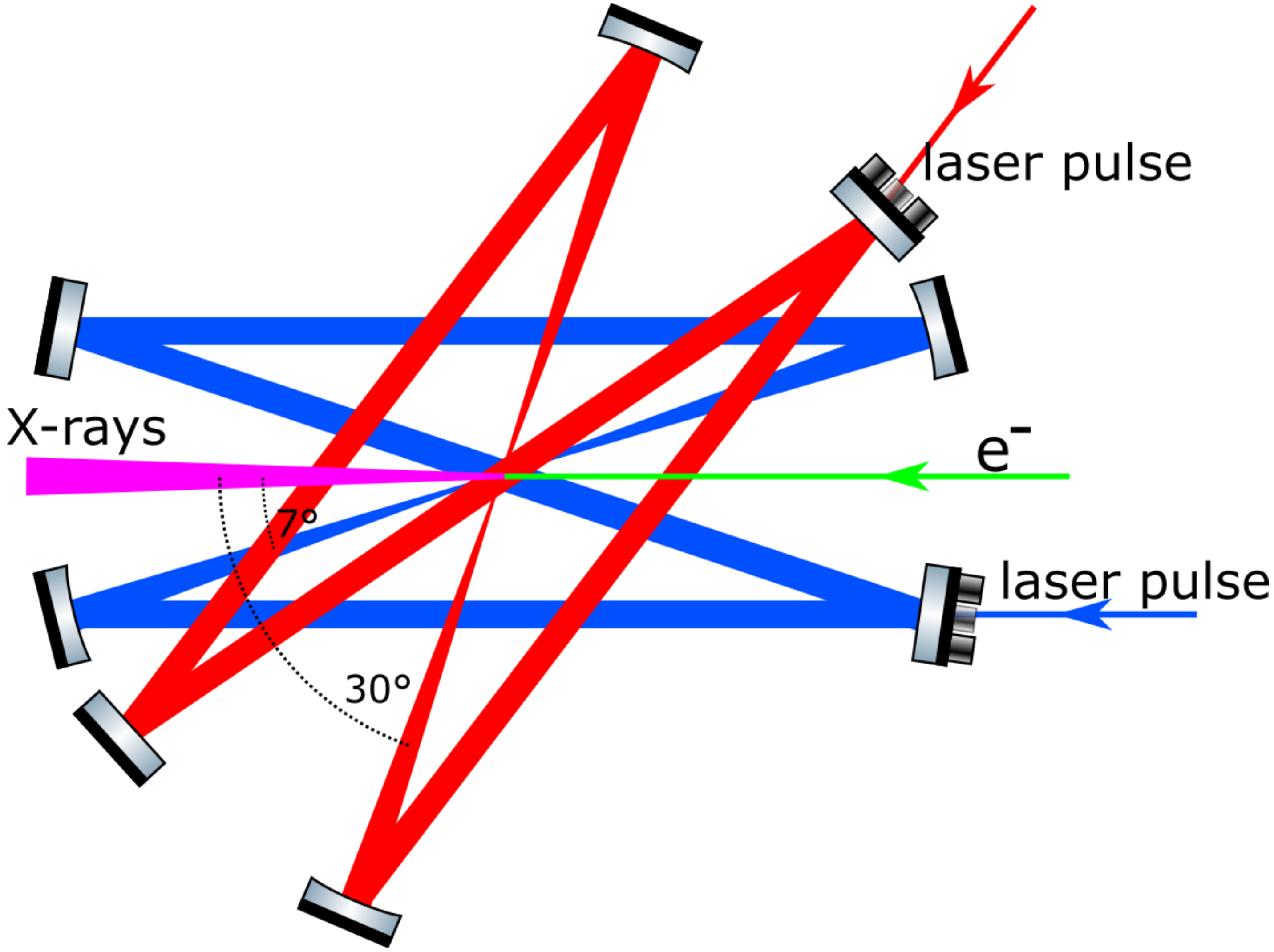
- Pound-Drever-Hall technique to generate the error signal
- Length is corrected using a piezo
- Signal is linear and asymmetric around resonance

Fabry-Perot cavity: stabilization system



- Pound-Drever-Hall technique to generate the error signal
- Length is corrected using a piezo
- Signal is linear and asymmetric around resonance
- Feedback system

Implementation: crossed Fabry-Perot cavities



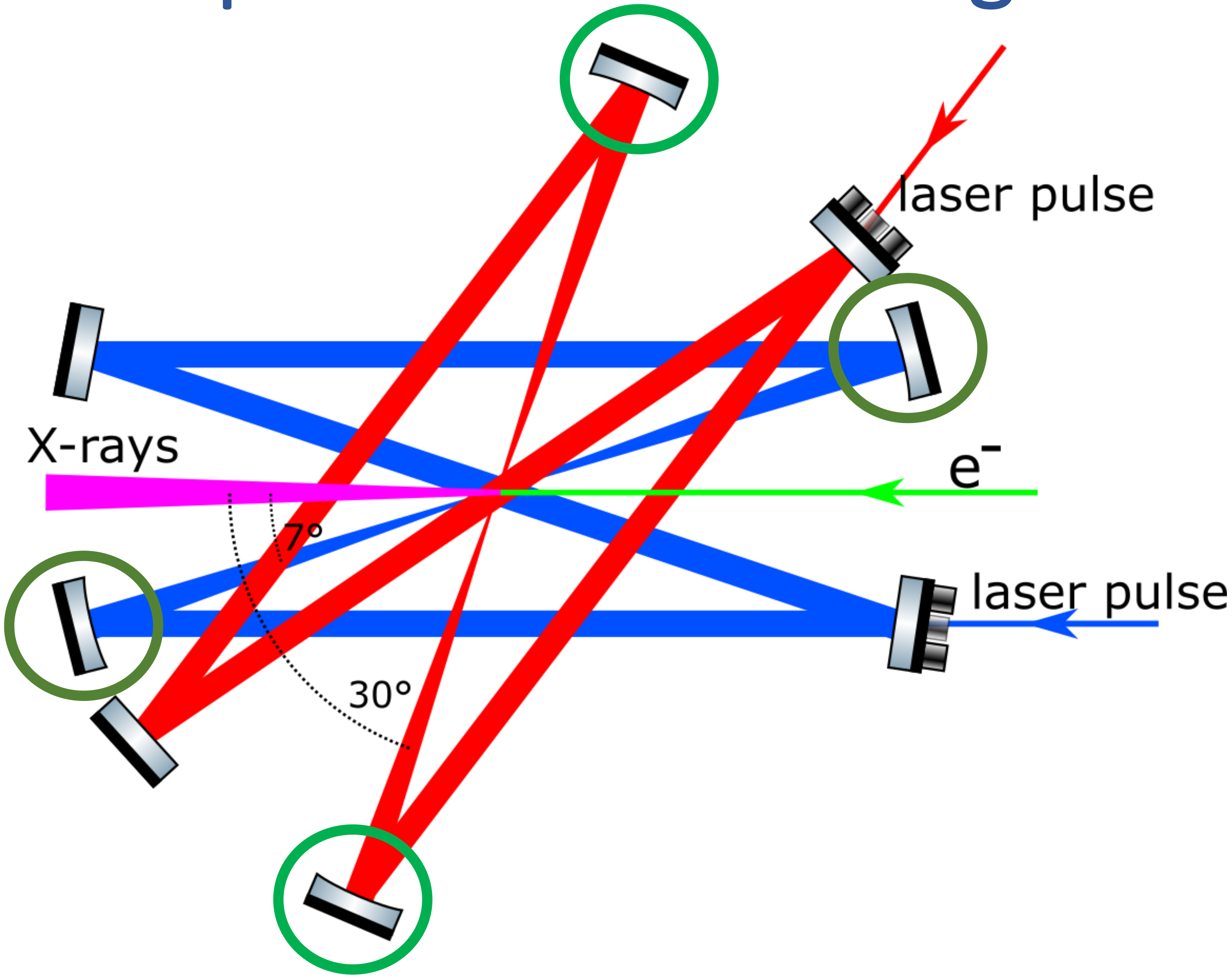
Features:

- Dual color X-ray generation
- Same electrons energy
- Same electrons trajectory

For Iodine KES:

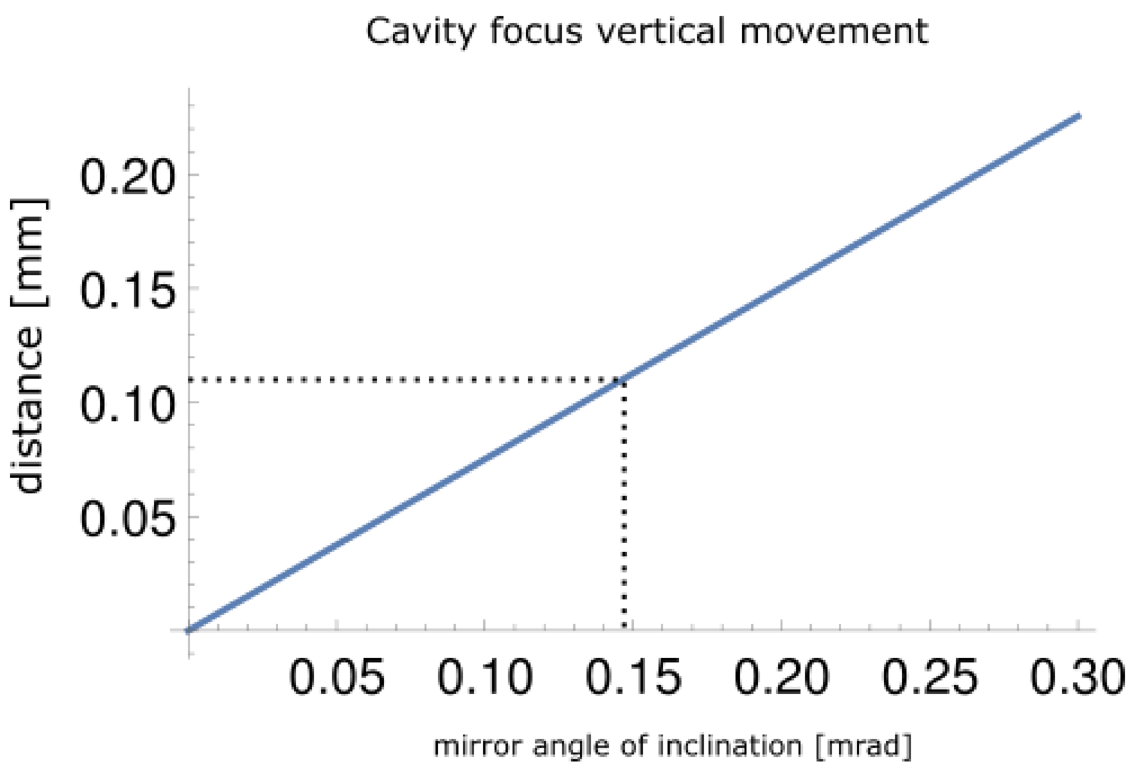
- electron energy ~43 MeV
- incidence angles at 7° and 30°

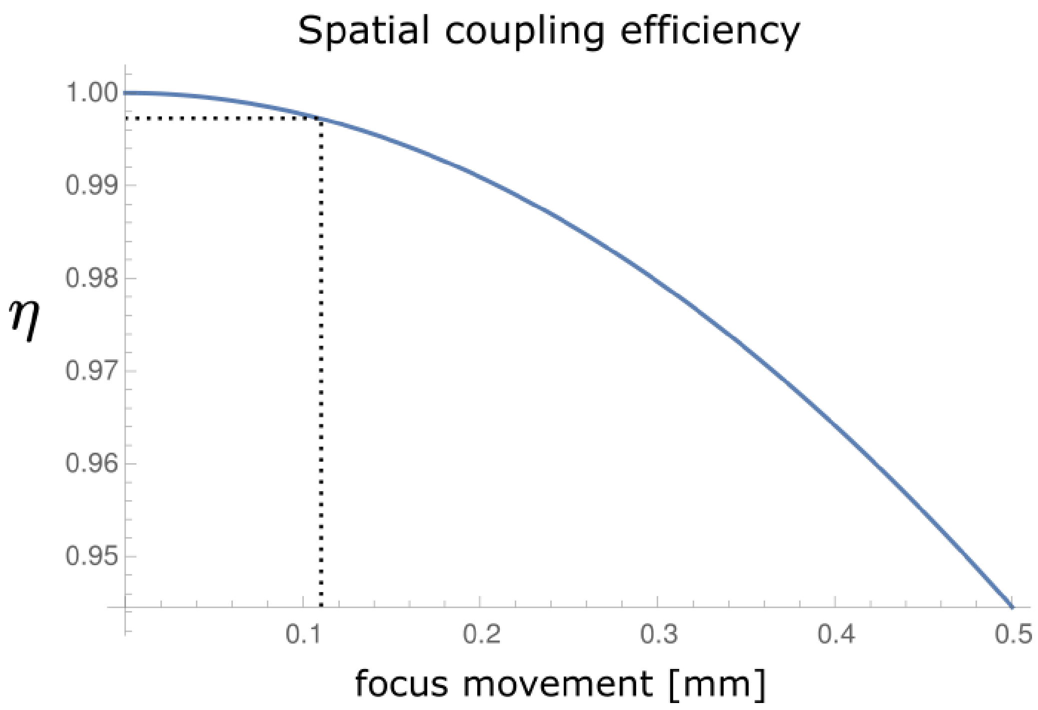
Implementation: tilting mirrors



- 2 Piezo-driven moving mirrors can move the laser beam in and out of the interaction point
- Movement needed is about 100 µm
- Fast switch-time (~100 ms, compatible with patient/sample movement)
- Cavity must remain stabilized during movement
- Coupling with external laser must not change

Implementation: tilting mirrors

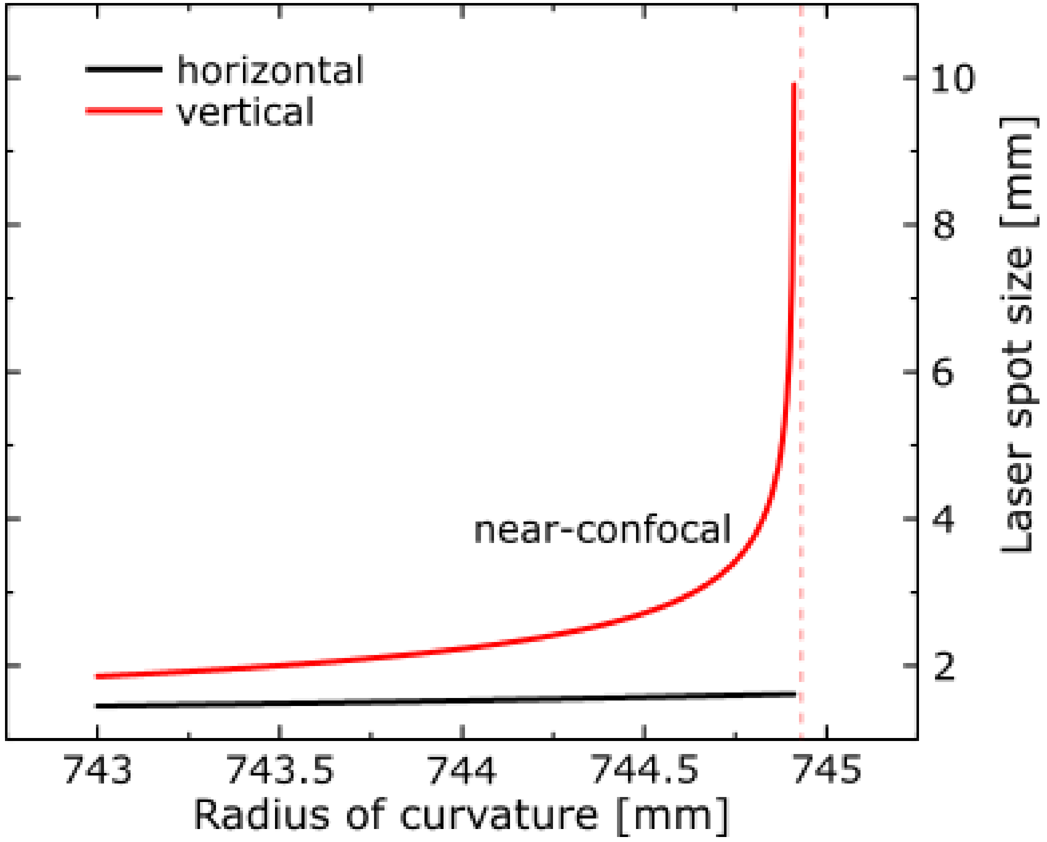




Theoretical prediction:

- Distance of 110 µm is reached for an inclination of 150 µrad
- Spatial coupling with the laser source changes less than 1%

Challenges



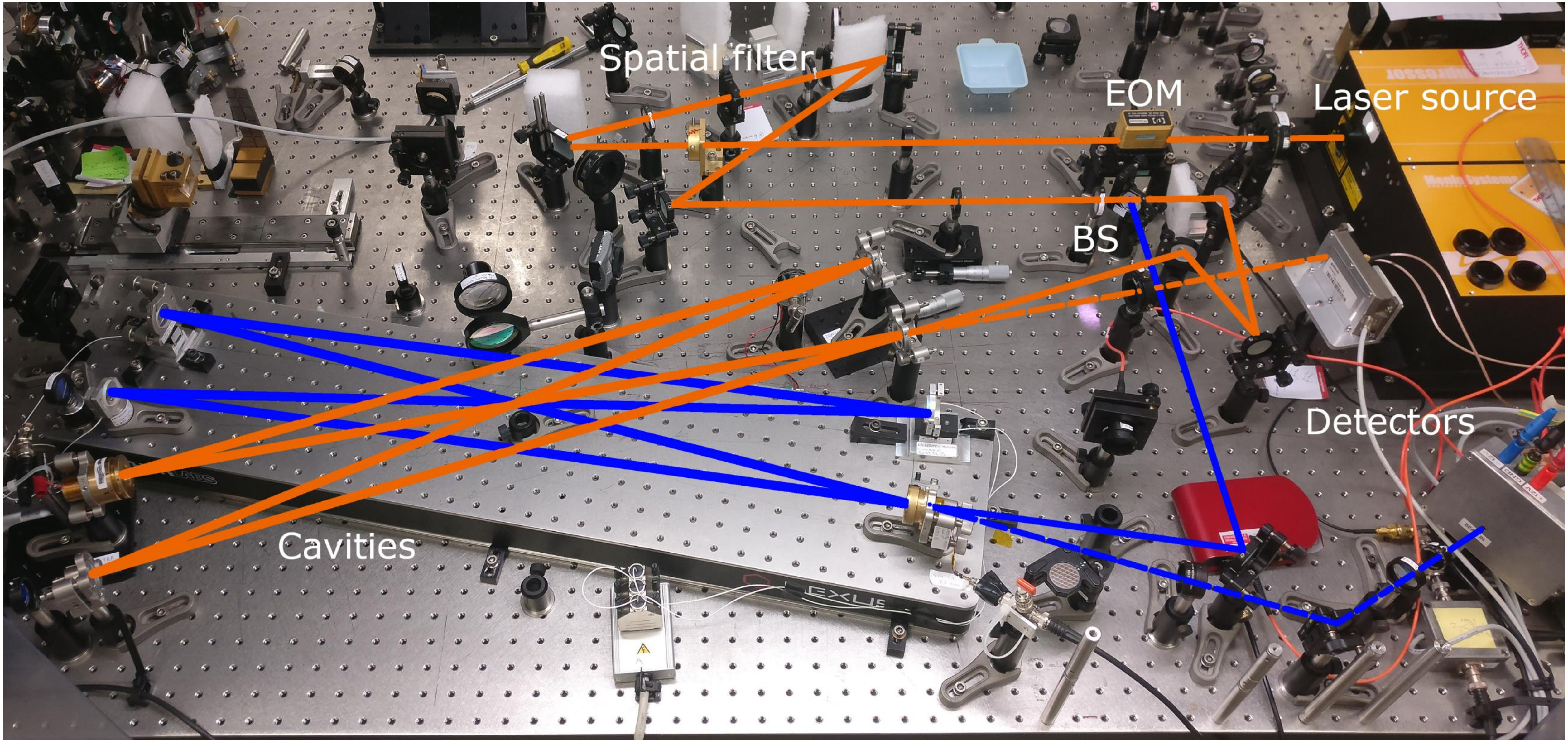
High power effects due to mirrors deformation:

- Change in beam size due to change in mirror curvature
- Degenerate mode coupling can lead to additional losses (as in LIGO)

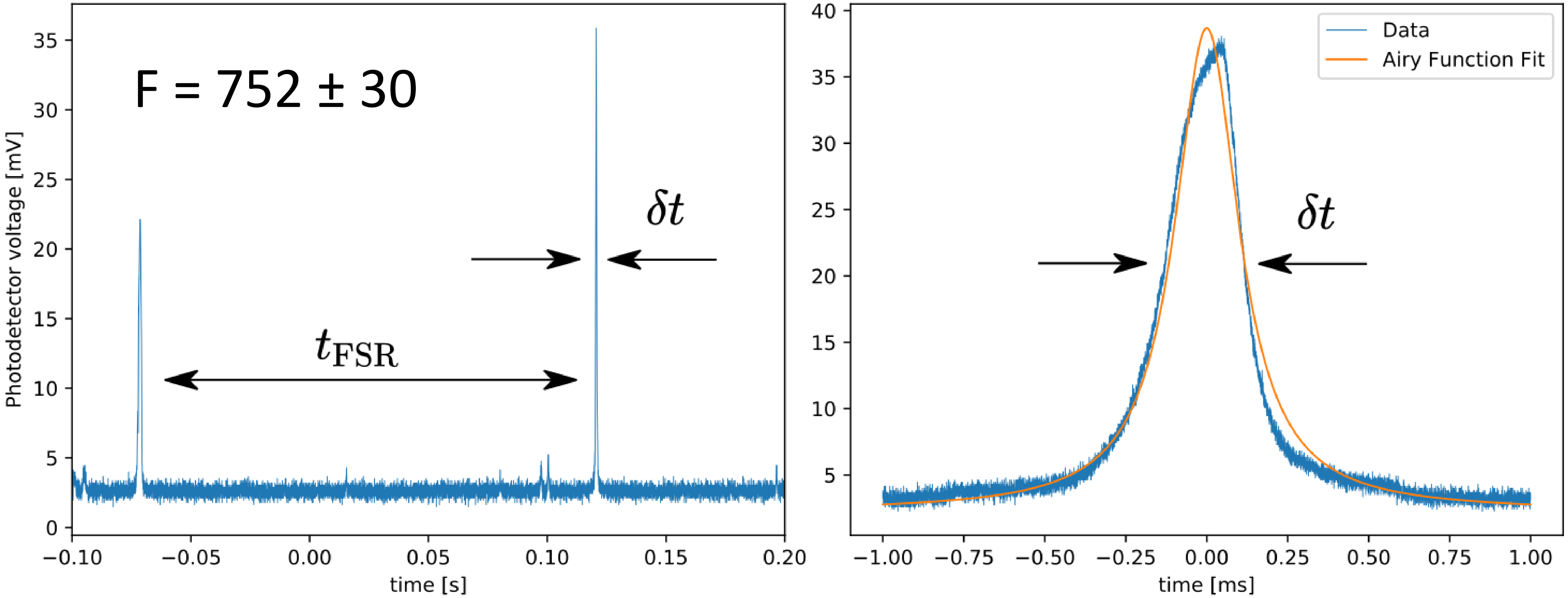
Proposed solution:

- Change the distance between curved mirrors to compensate for mirror deformation
- Restore cavity length by moving flat mirrors
- ~0.5 mm at 500 kW

Experimental setup: two stabilized cavities

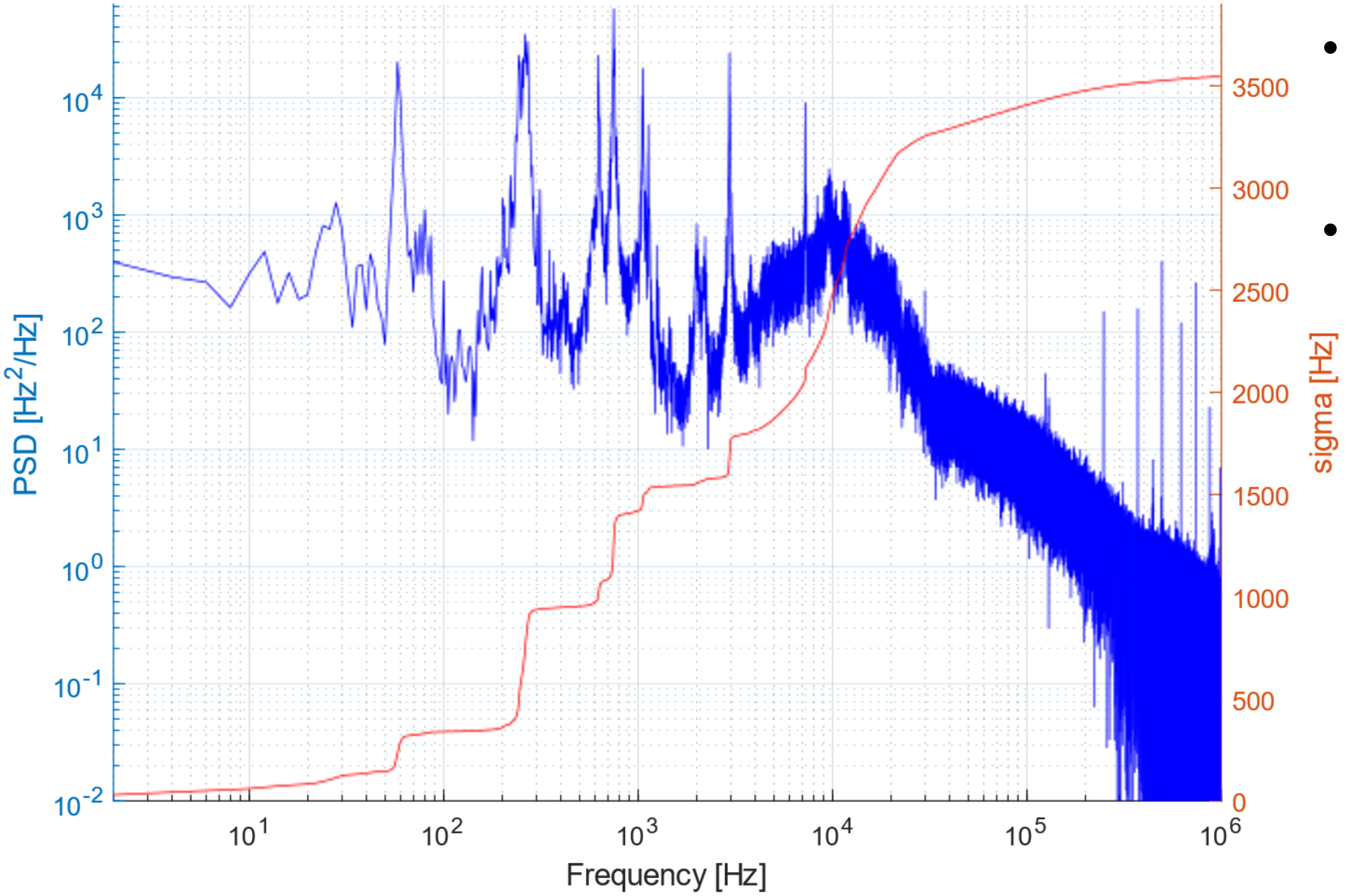


Experimental result: cavity Finesse



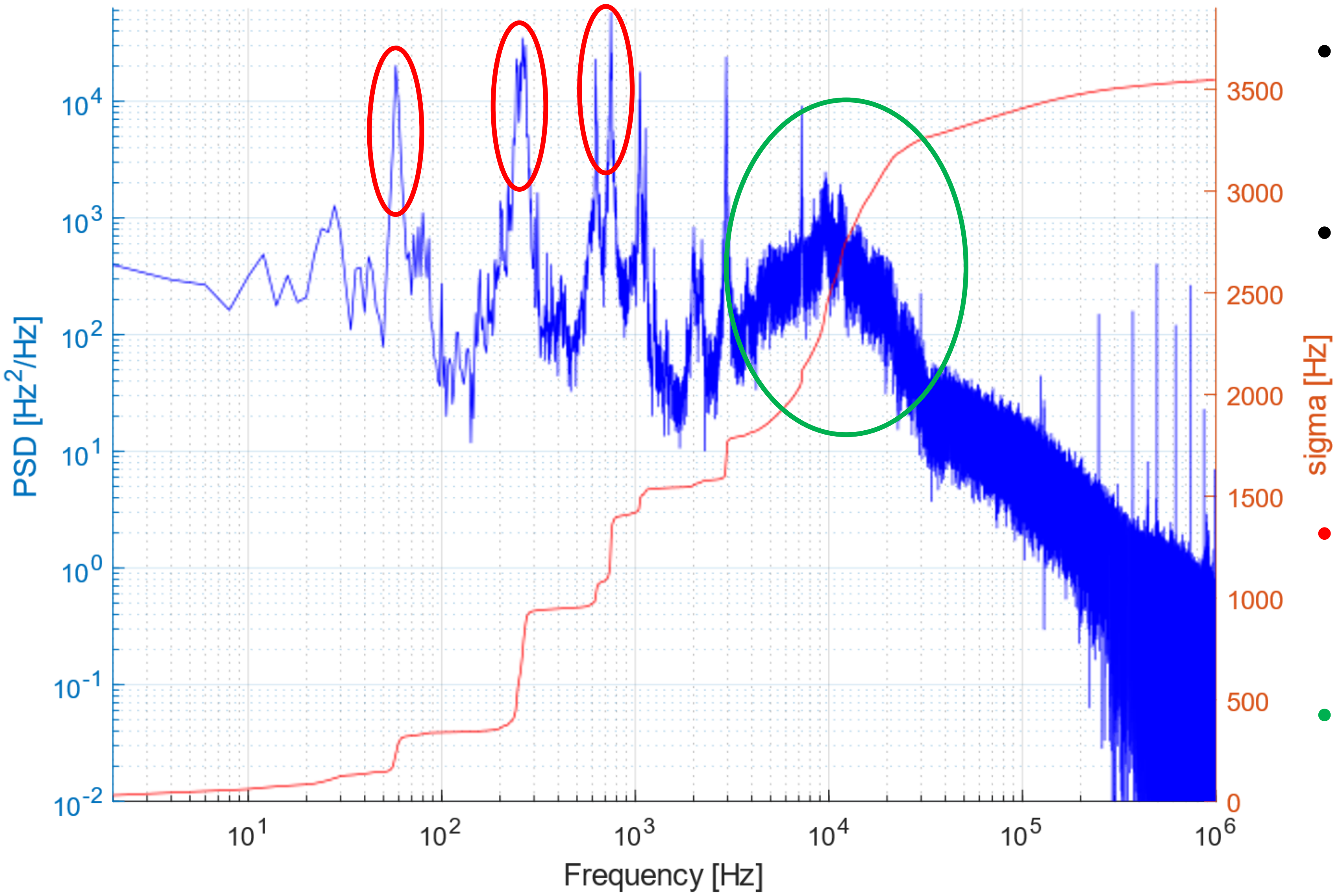
- The Finesse is the ratio between the FSR (100 MHz) and the cavity linewidth
- We are developing a new method to measure F for higher Finesse cavities (3000)

Experimental result: laser-cavity frequency noise



- RMS frequency noise is about **3500 Hz**, giving a relative noise of 10^{-11}.
- RMS length variation is **35 pm**.

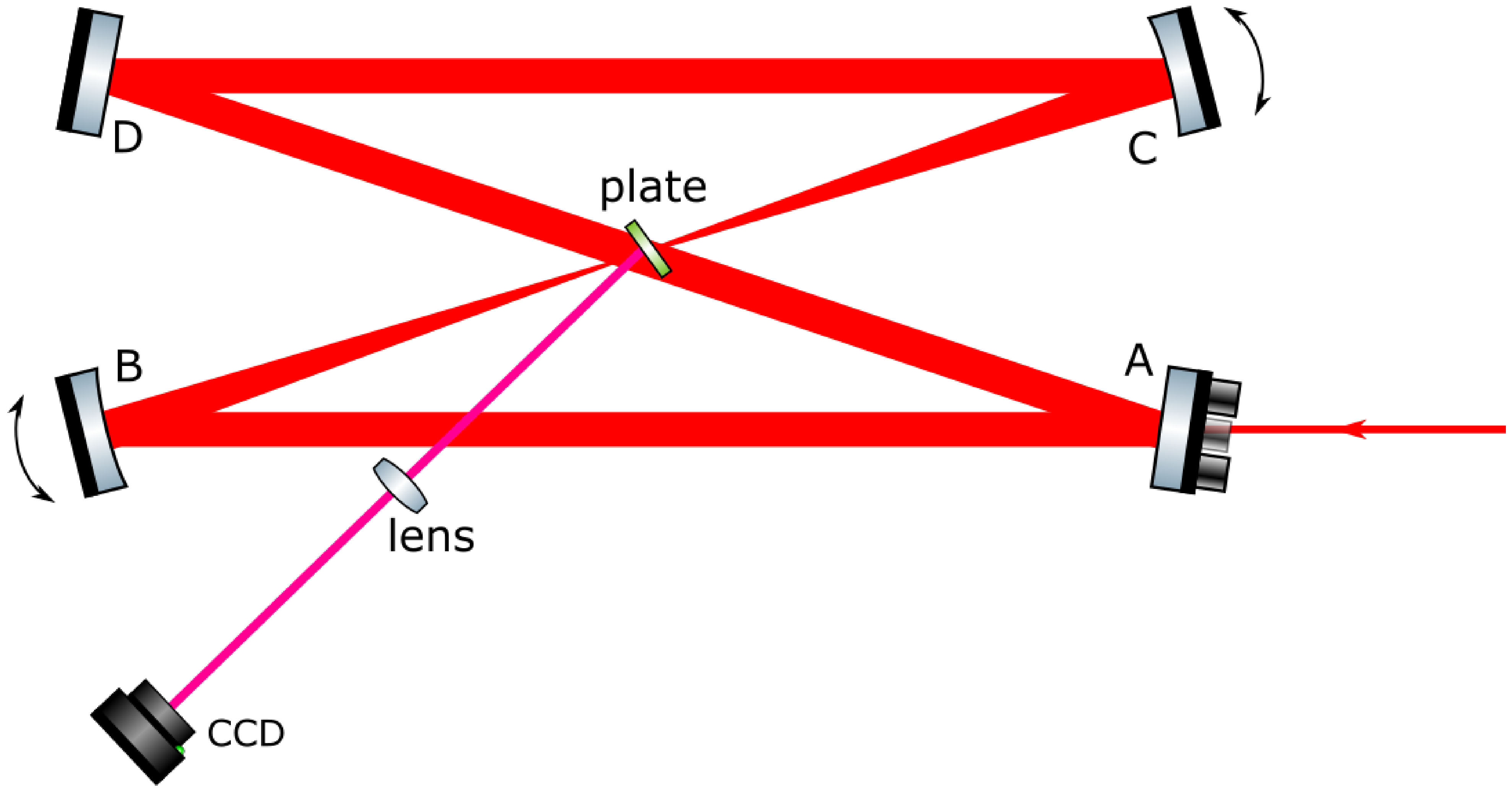
Experimental result: laser-cavity frequency noise



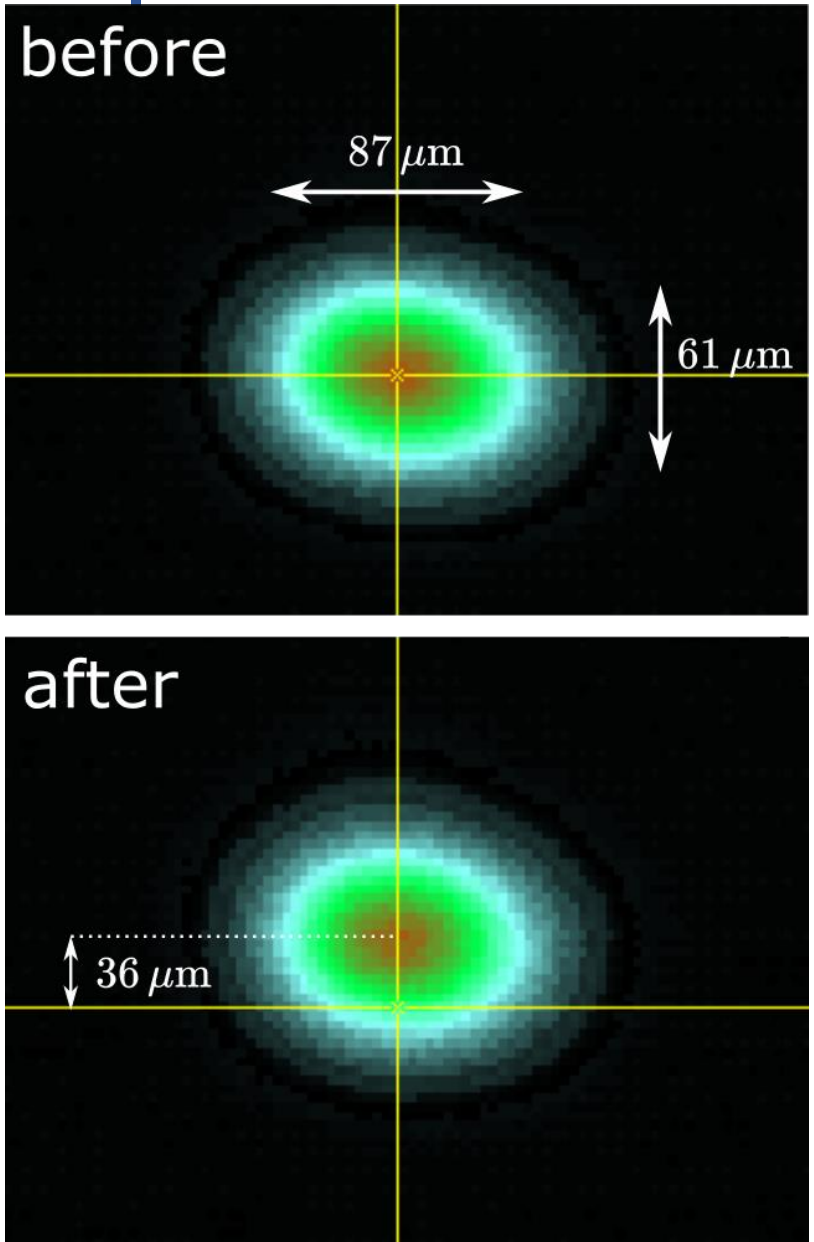
- RMS frequency noise is about **3500 Hz**, giving a relative noise of 10^{-11}.
- RMS length variation is **35 pm**.

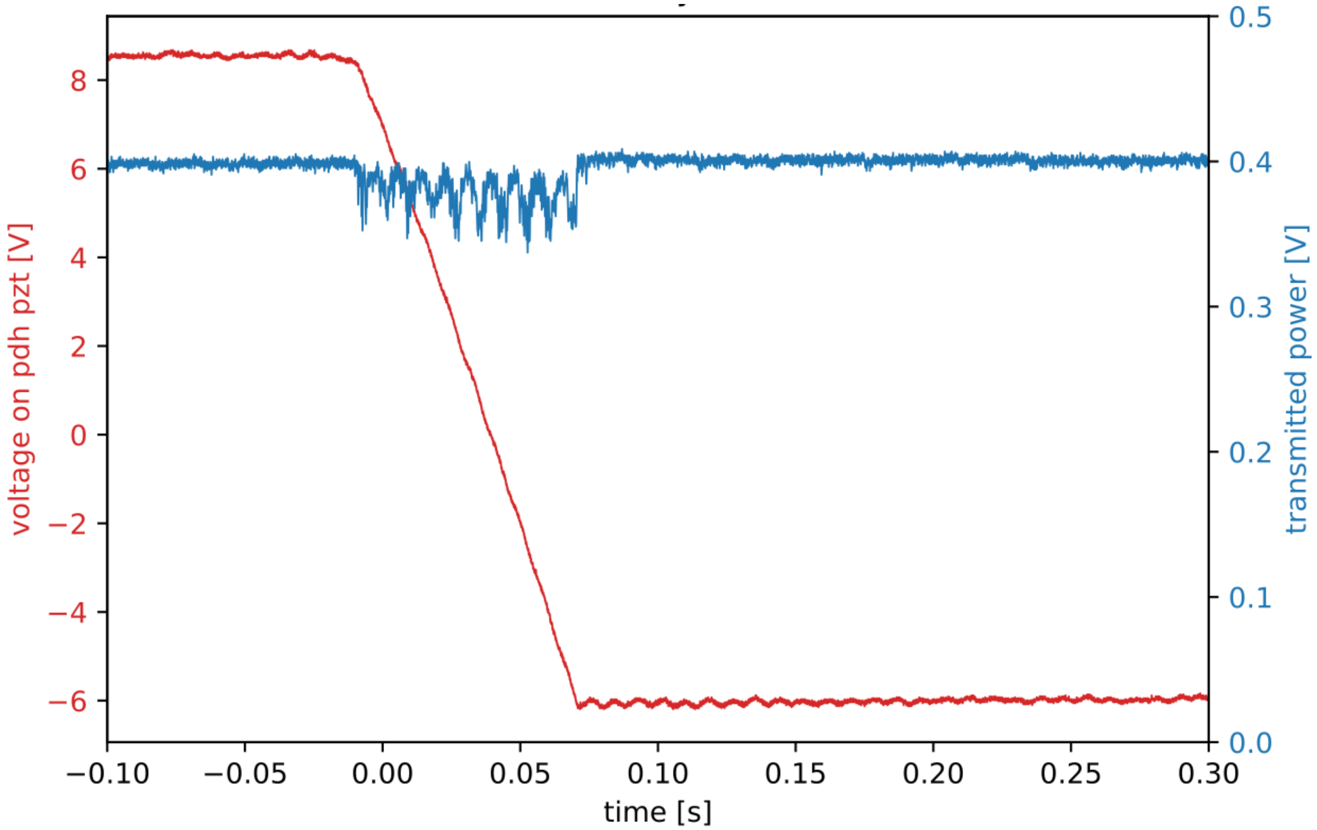
- Low frequency peaks: mechanical oscillators, air turbolence
- High frequency peaks: Feedback auto-oscillations

Experimental result: cavity focus movement



Experimental result: cavity focus movement





- Measured movement of 36 µm
- Accordance with theoretical predictions
- Cavity remains stabilized during movement

Conclusions

- We built two crossed Fabry-Perot cavities and frequency stabilized them against a laser source
- We characterized their noise and spectral properties
- We developed and tested the method to switch between two X-ray energies
- We developed a method to compensate high power effects

Next steps

- Further reduce cavity-laser frequency noise
  - goal: under 2000 Hz for the final cavity at Finesse 8000
- Amplification system
  - goal: 100 W incident on the cavity
- Quantification of high power effects
  - Mode coupling losses
  - Test of compensation method
- New moving mountings with bigger stroke
  - goal: over 100 µm movement