Studies of the electro-optic noise in crystalline coatings and cryogenic coating mechanical losses

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GRASS
Jun. 6, 2022

Contents

- Electro-optic noise in crystalline AlGaAs coating
- Cryogenic Gentle Nodal Suspension (GeNS)
- Summary

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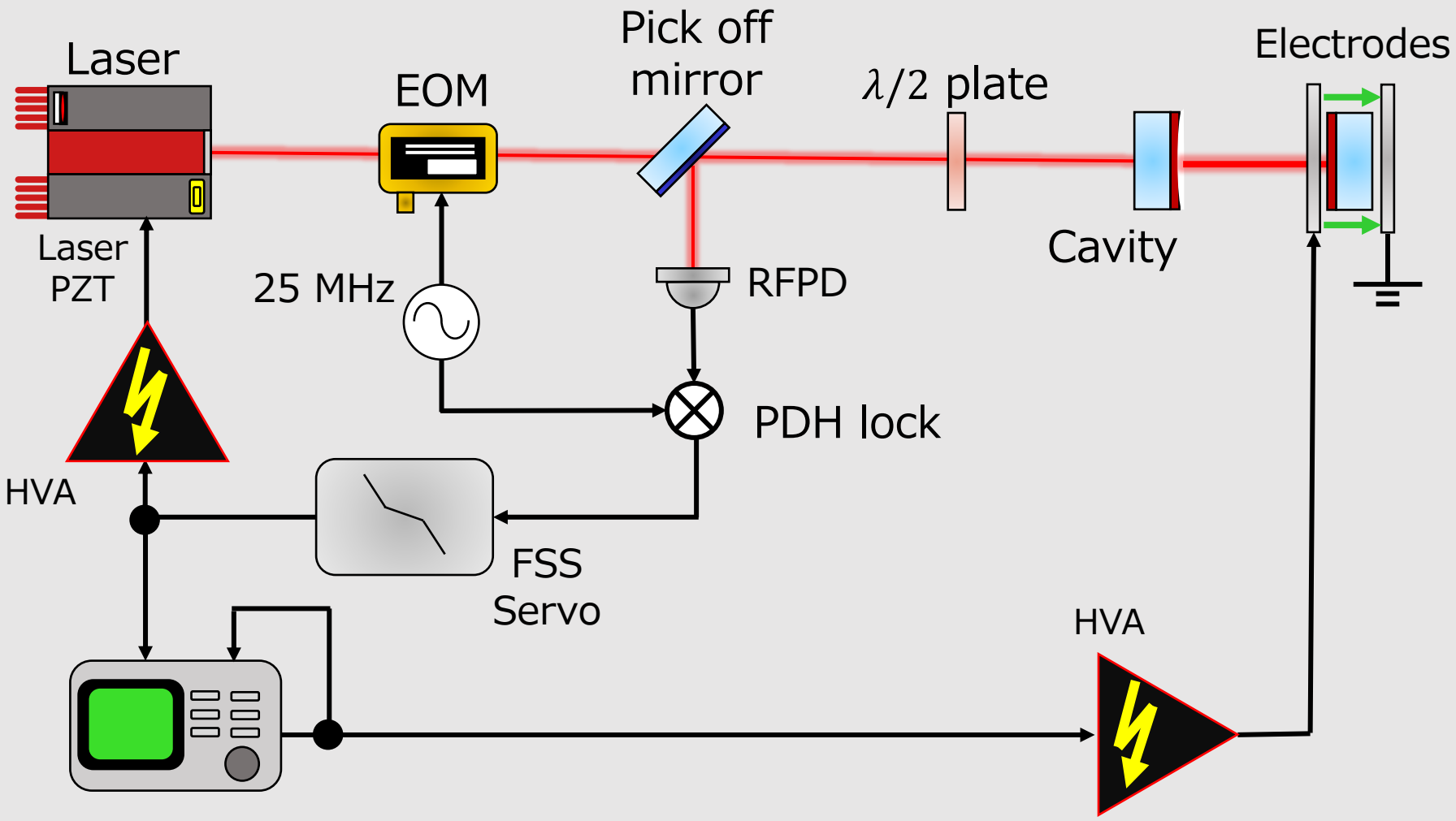
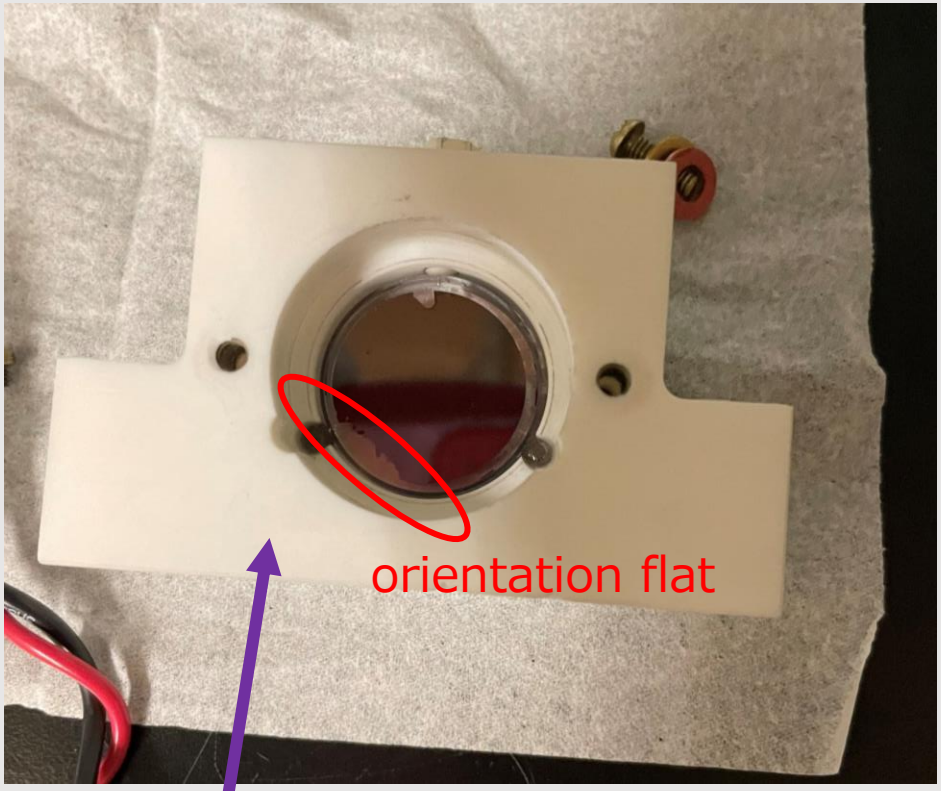
Purpose of this experiment

- Feasibility study to realize crystalline AlGaAs coated mirrors in gravitational wave (GW) detectors.
- Investigate the noise in crystalline AlGaAs coating mirror induced by fluctuations in the electric field.
  - ✓ Electro-Optic noise
  - ✓ Electric field couples to “cavity length”

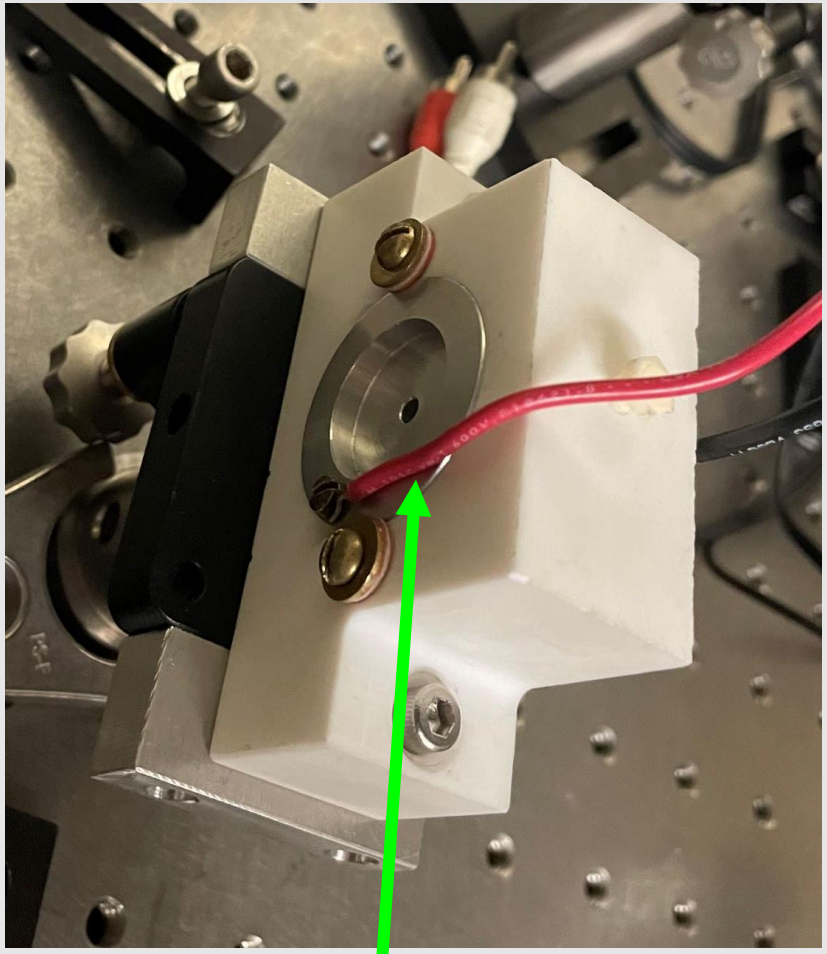
Schematic


Laser
EOM
Pick off mirror
$\lambda/2$ plate
Electrodes
Laser PZT
25 MHz
RFPD
Cavity
PDH lock
HVA
FSS Servo
HVA

Mirror mount



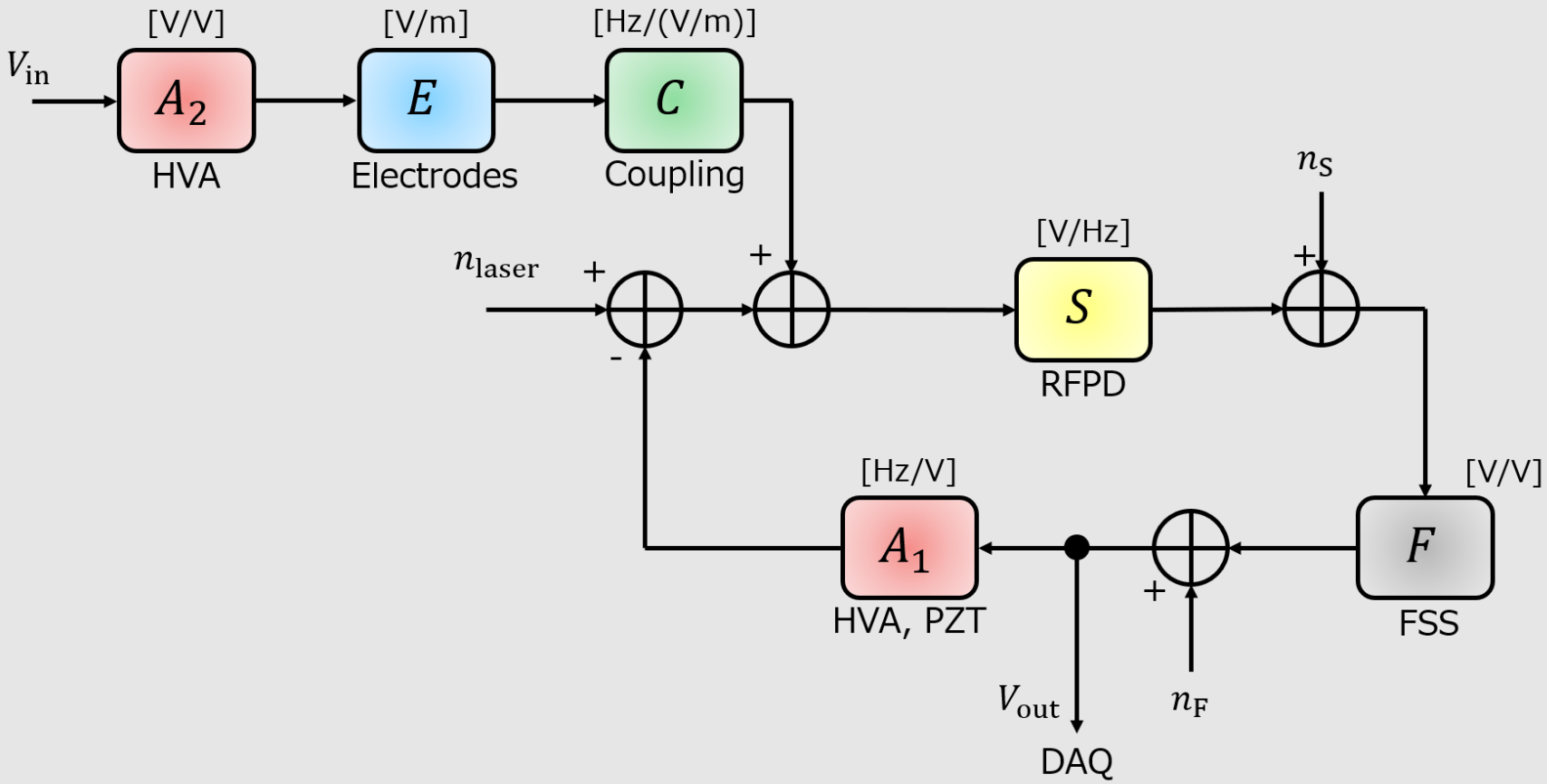
Made of machinable glass
- MACOR [1]



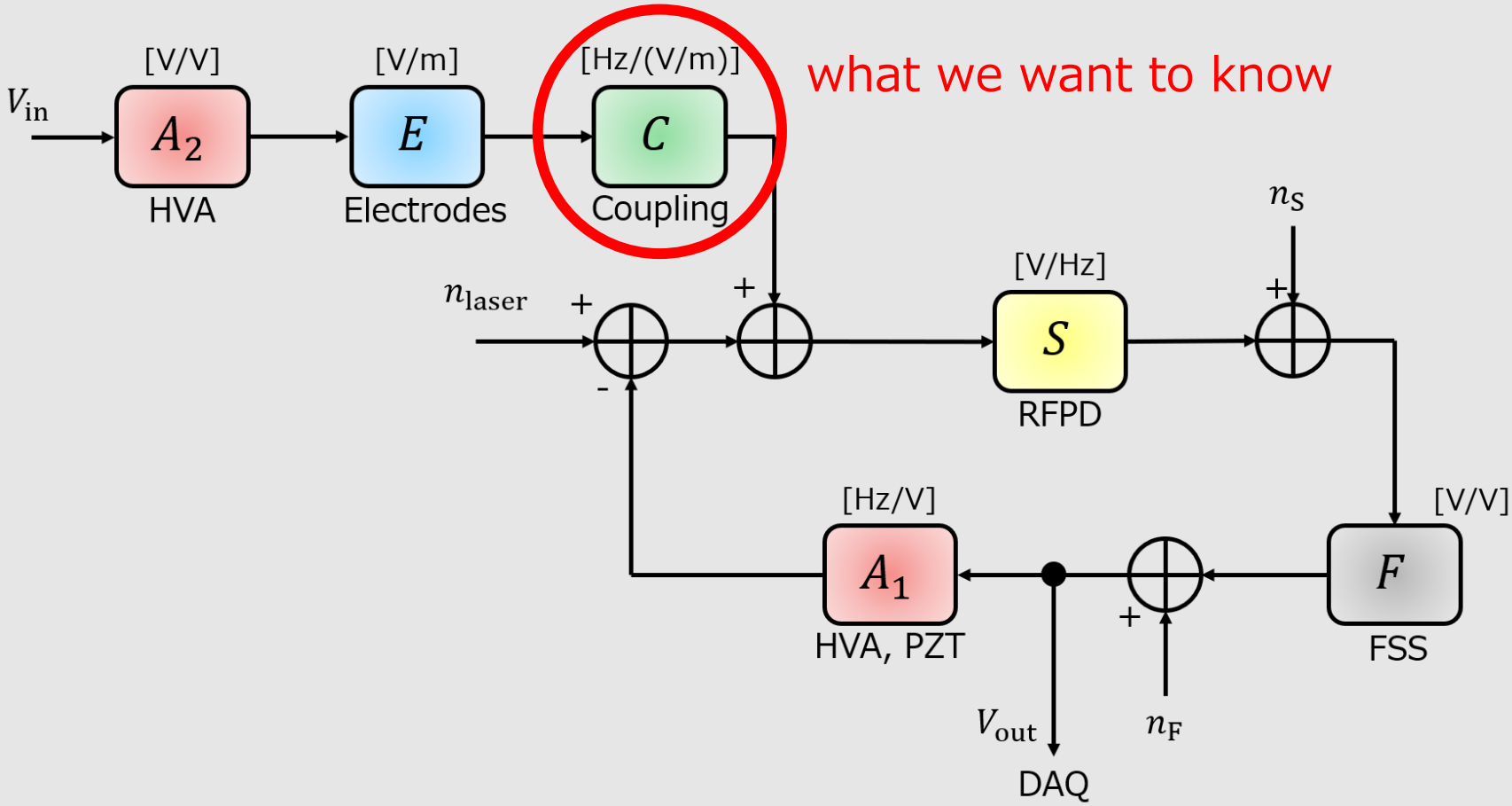
front electrodes

[1] https://www.corning.com/au/en/products/advanced-optics/product-materials/specialty-glass-and-glass-ceramics/glass-ceramics/macor.html

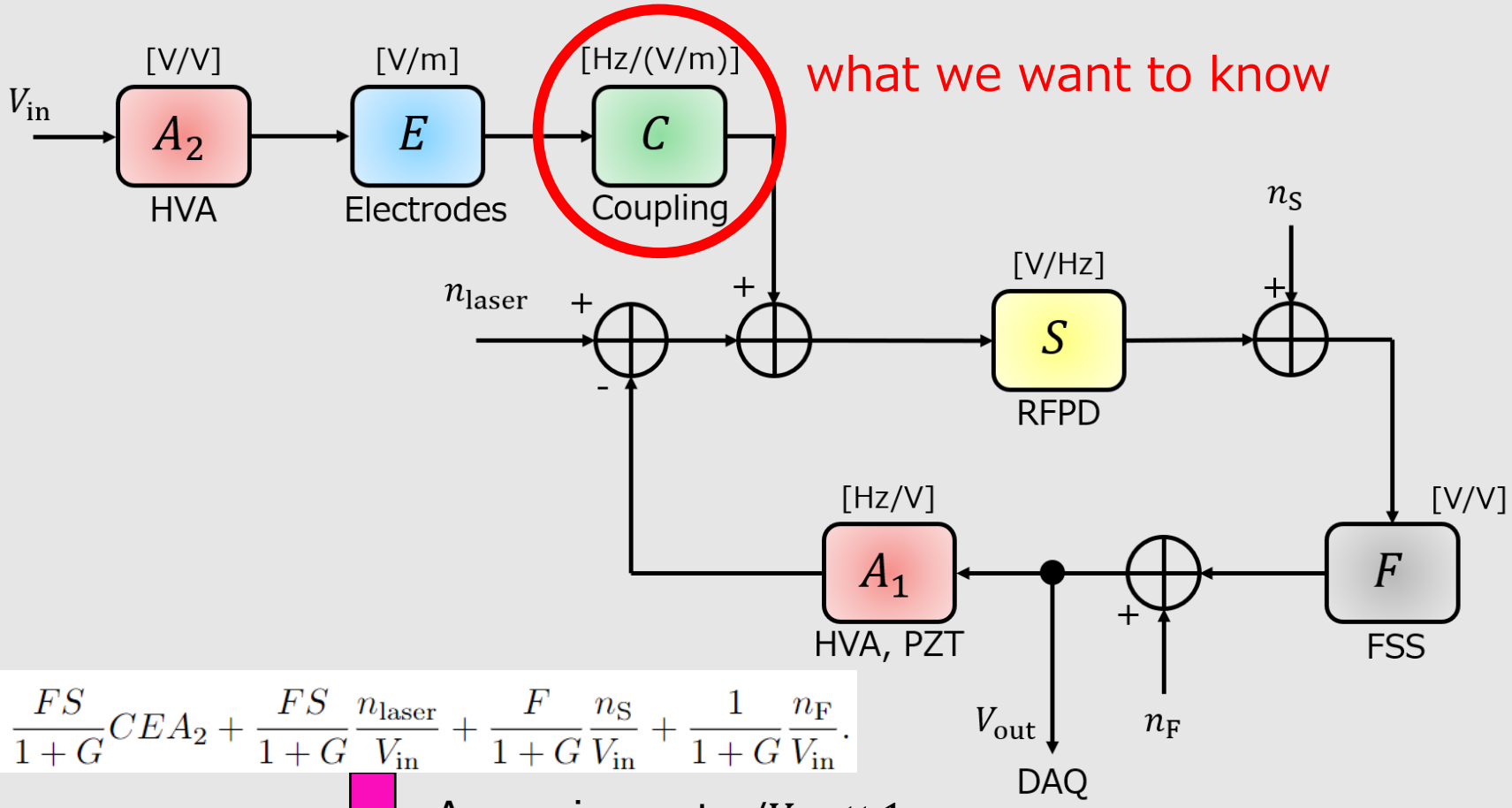
Block diagram



Block diagram



Block diagram



$$\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}} = \frac{FS}{1+G}CEA_2 + \frac{FS}{1+G}\frac{n_{\mathrm{laser}}}{V_{\mathrm{in}}} + \frac{F}{1+G}\frac{n_{\mathrm{S}}}{V_{\mathrm{in}}} + \frac{1}{1+G}\frac{n_{\mathrm{F}}}{V_{\mathrm{in}}}.$$

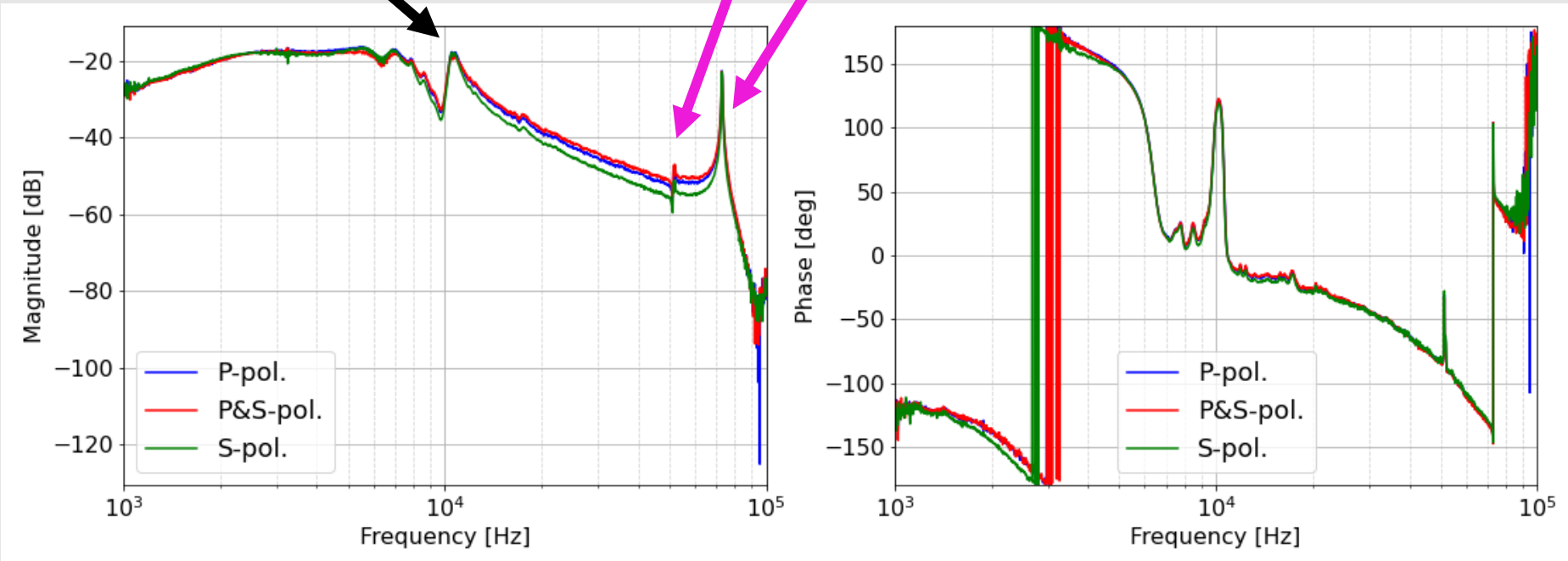
Assuming noise/$V_{\mathrm{in}} \ll 1$

$$\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}} \approx \frac{FS}{1+G}CEA_2 = \frac{G}{1+G}CE\frac{A_2}{A_1}.$$

Obtained TF

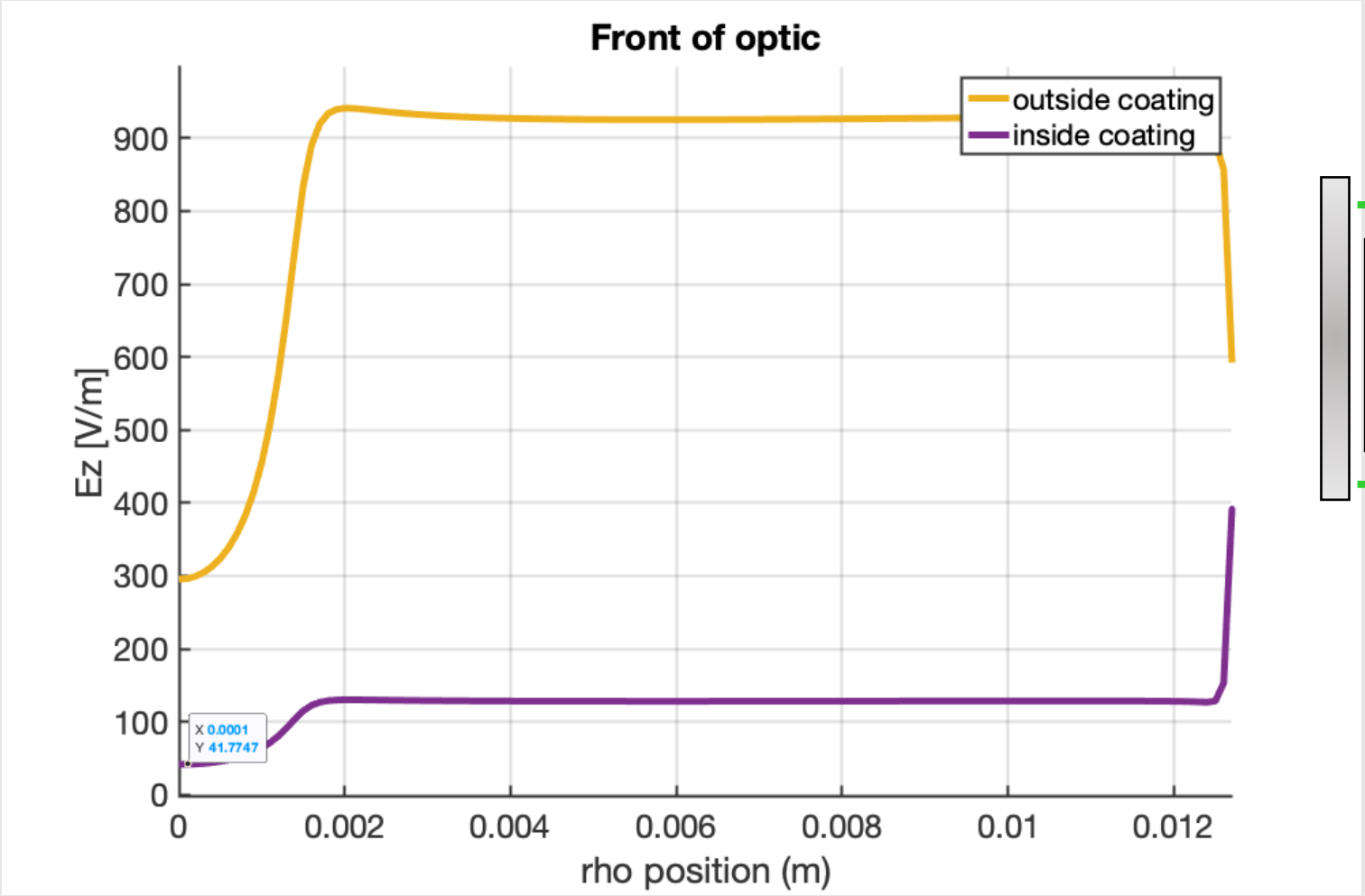
Mechanical resonance of mount

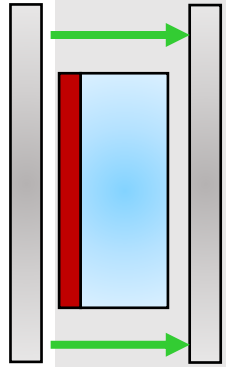
Resonances of sample mirror



Electric field also couples through mechanical motion.

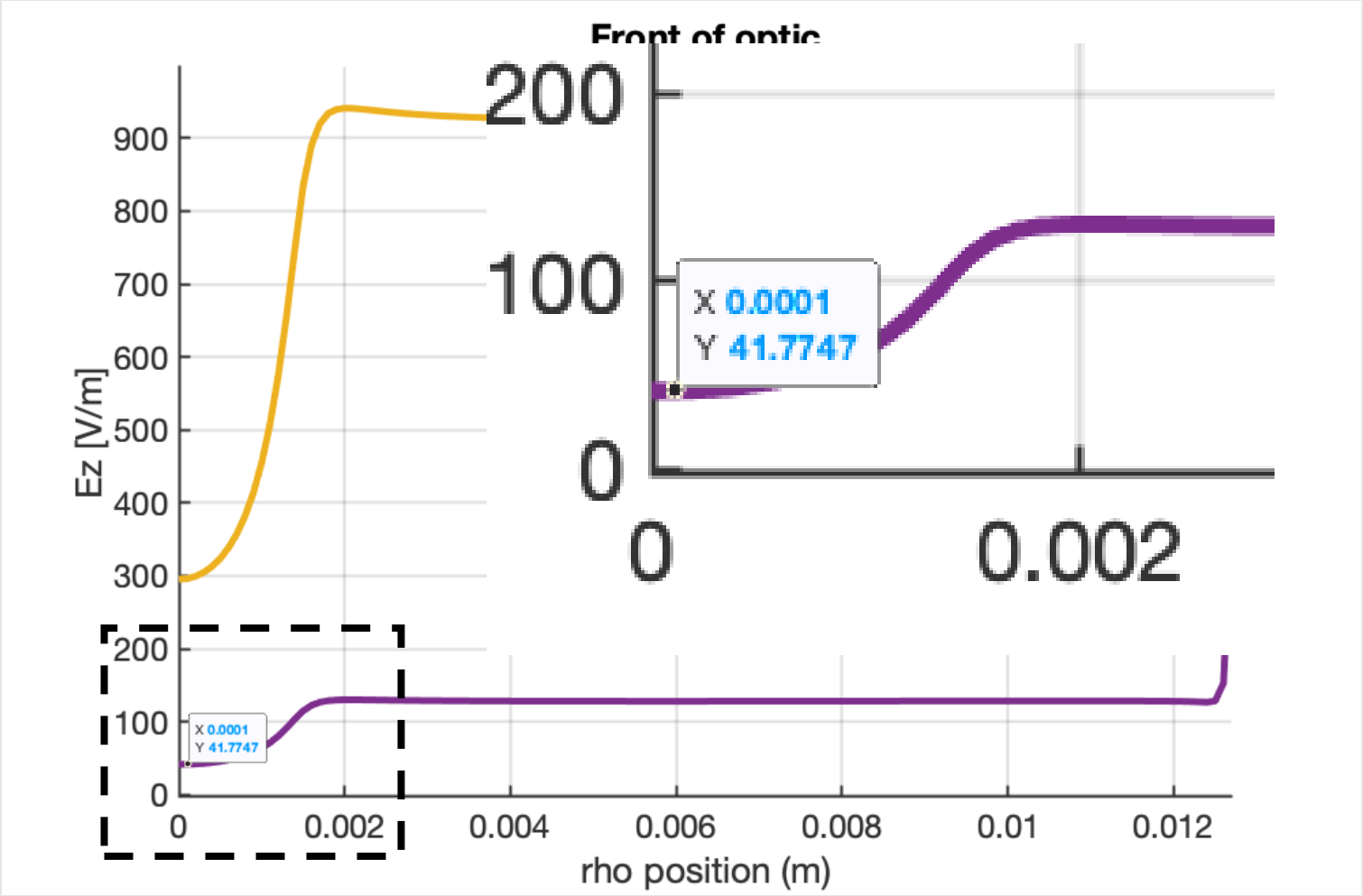
Electric field





- ✓ Perpendicular to the sample mirror surface
- ✓ An effective 3D electro static solution

Electric field



$41.7[(\mathrm{V/m})/\mathrm{V}]$

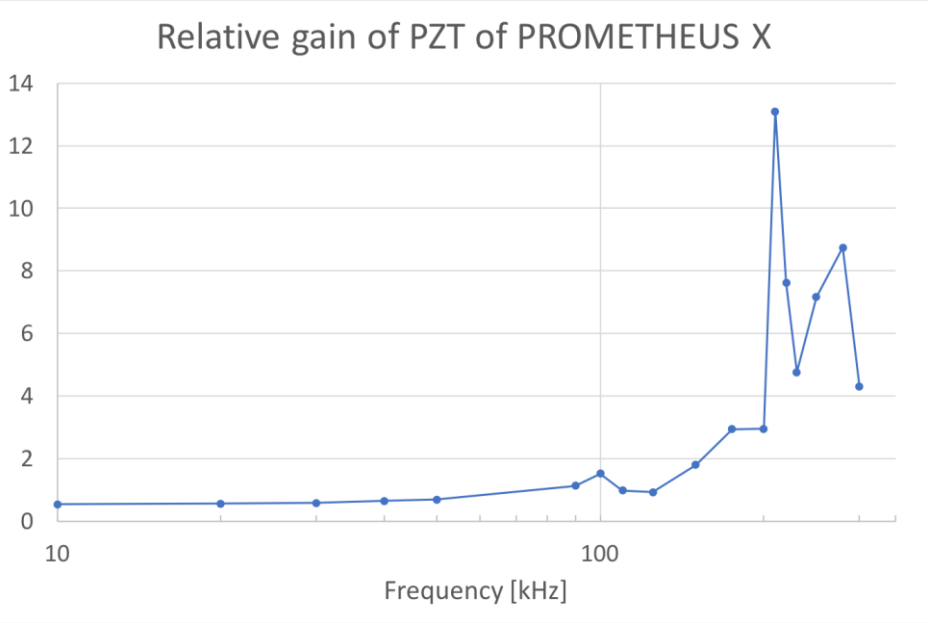
Flat in measured frequency region

PZT efficiency

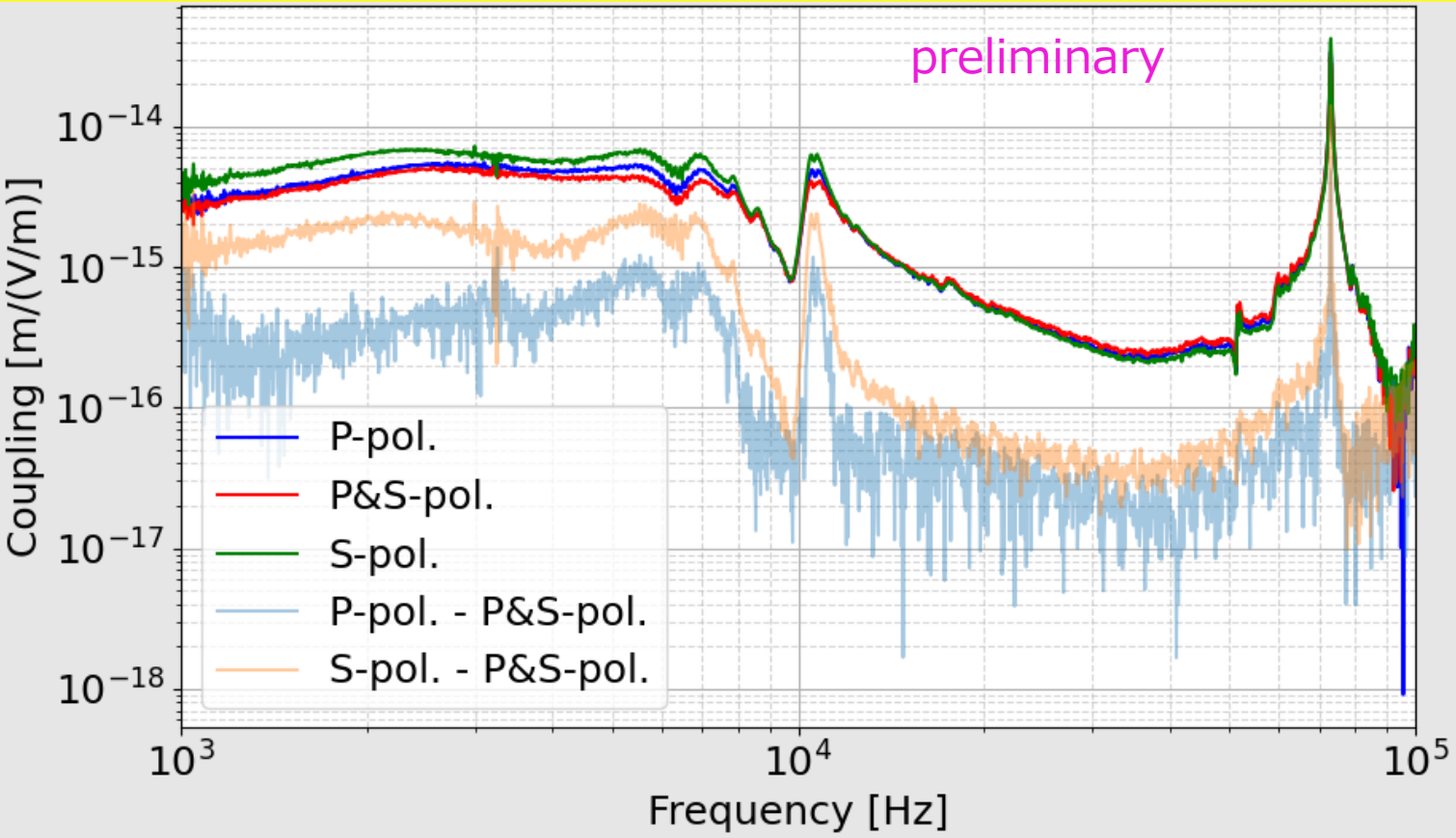
- Assume flat response of laser PZT
- 1.6 MHz/V
  - ✓ obtained by cavity scan

https://klog.icrr.u-tokyo.ac.jp/osl/?r=8378

Assume flat up to ~100 kHz

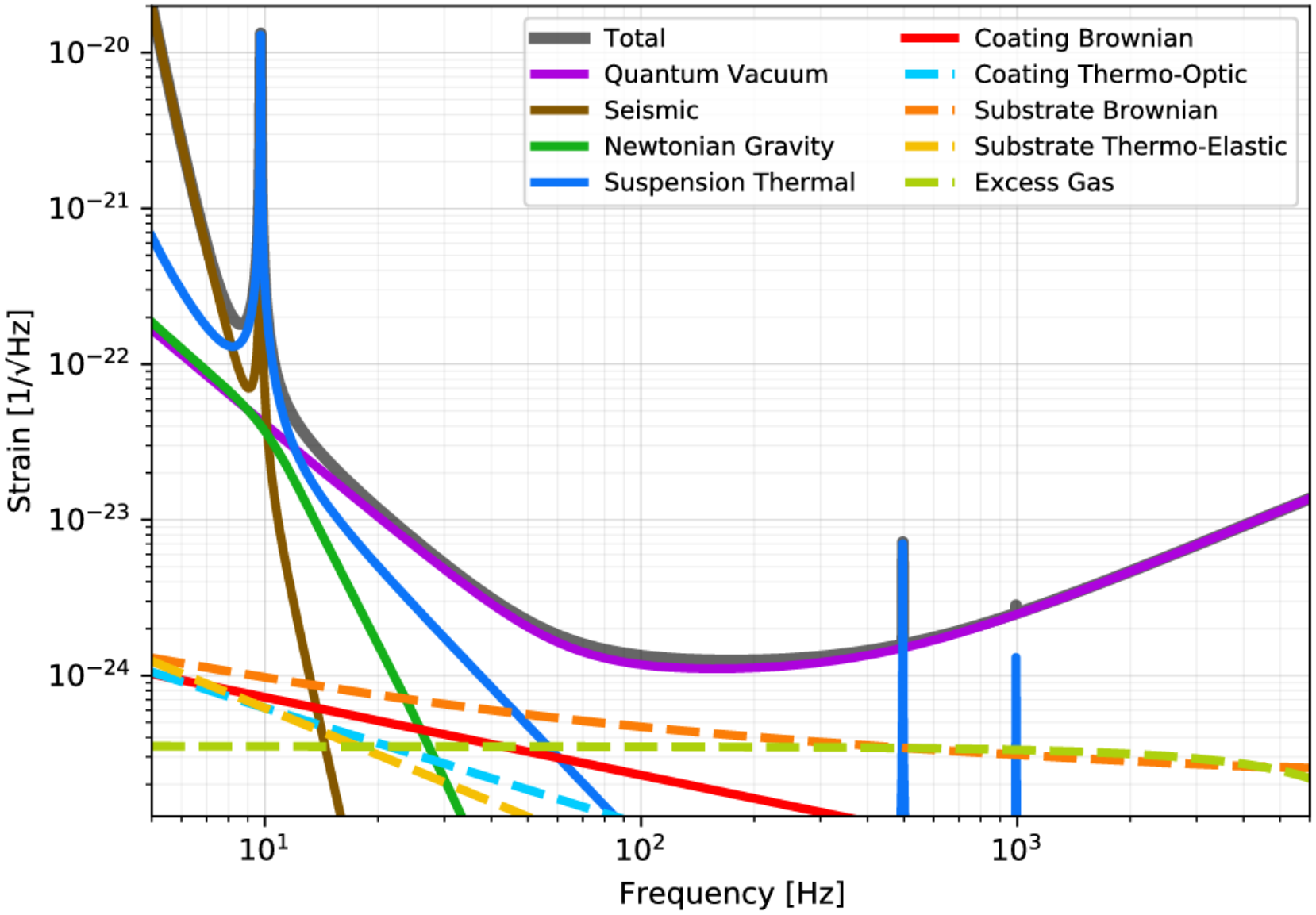


Result



- EO effect is induced in P- or S-polarization
- Focusing on the frequency range 20 – 50 kHz
- Difference is smaller than 10^{-16} [m/(V/m)]
  - roughly $\sim 5 \times 10^{-17}$ [m/(V/m)]
- Further characterization is ongoing

A+ Design Sensitivity + Crystal Coating (Mean Value)



G2101071-v2 by S. Penn (2021 Sep.)

Implications

- Strain sensitivity is $\sim 10^{-24}$ [1/rtHz] @100 Hz
- Fluctuations in the electric field is 3×10^{-6} [(V/m)/rtHz]
  - ✓ Buikema *et al*. 2020
- Upper limit (strain sensitivity):

$$\frac{2 \times 3 \times 10^{-6}[(\mathrm{V/m})/\mathrm{rtHz}] \times 5 \times 10^{-17}[\mathrm{m/(V/m)}]}{4 \times 10^{3}[\mathrm{m}]} = 7.5 \times 10^{-26}[1/\mathrm{rtHz}]$$

- 10 times below the strain sensitivity
  -> The EO effect in crystalline AlGaAs coatings will not limit the sensitivity

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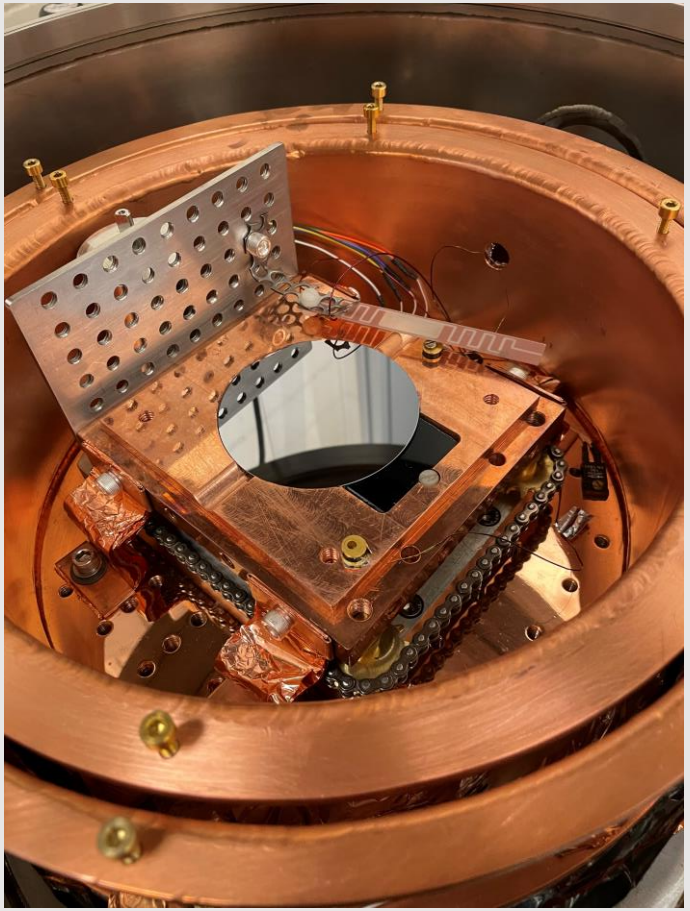
Cryogenic GeNS

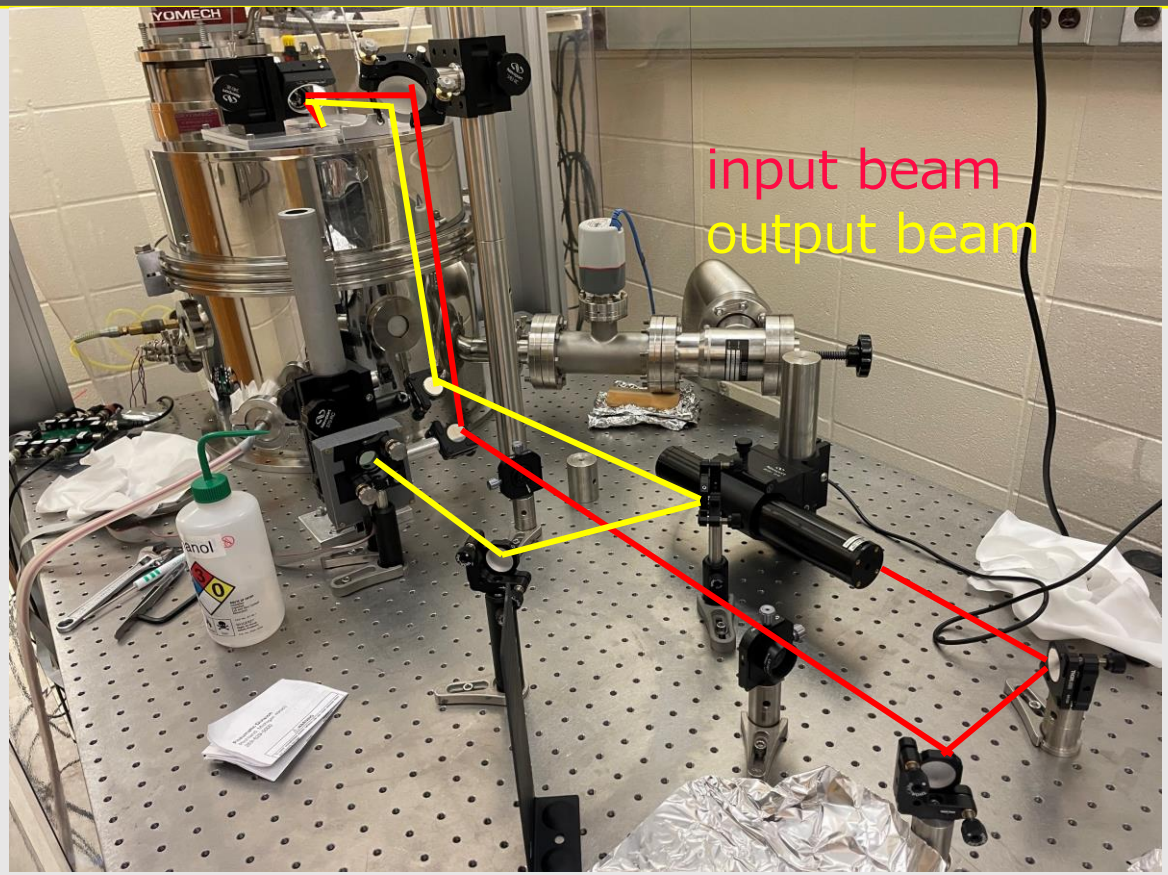
- To develop low thermal noise coatings at cryogenic temperature.
- To understand the origin of mechanical loss of coatings.

Cryostat

- GeNS is housed inside the cryostat.
- Main components are made of copper.
  - ✓ high thermal conductivity
- Both 3 inch and 4 inch samples can be measured by switching the holders.
- Sample is suspended by a sapphire lens.



Optical layout

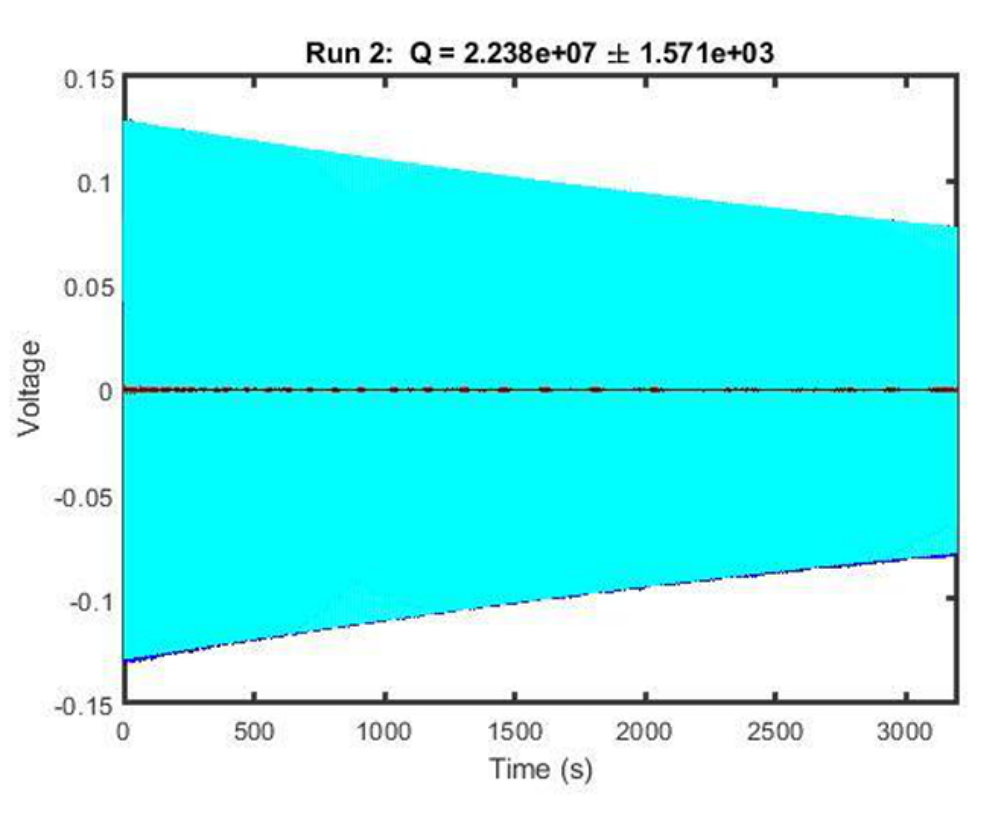


- ~2 m arm length.
- ~100 μW beam power at QPD
- ~200 μm beam size at QPD

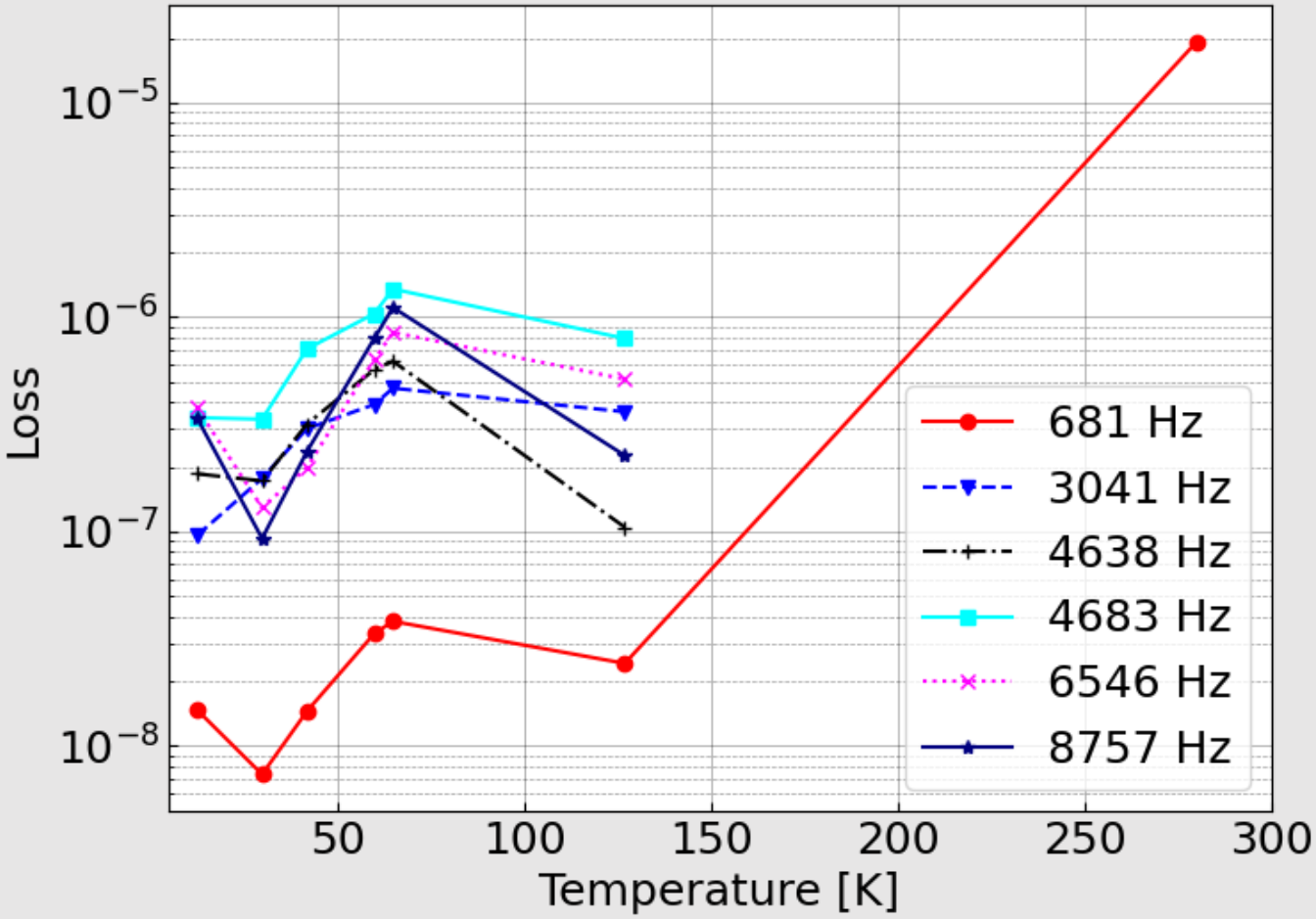
➢ Almost the same sensitivity to disk motions compared to Caltech's GeNS

Test with Fused silica disk

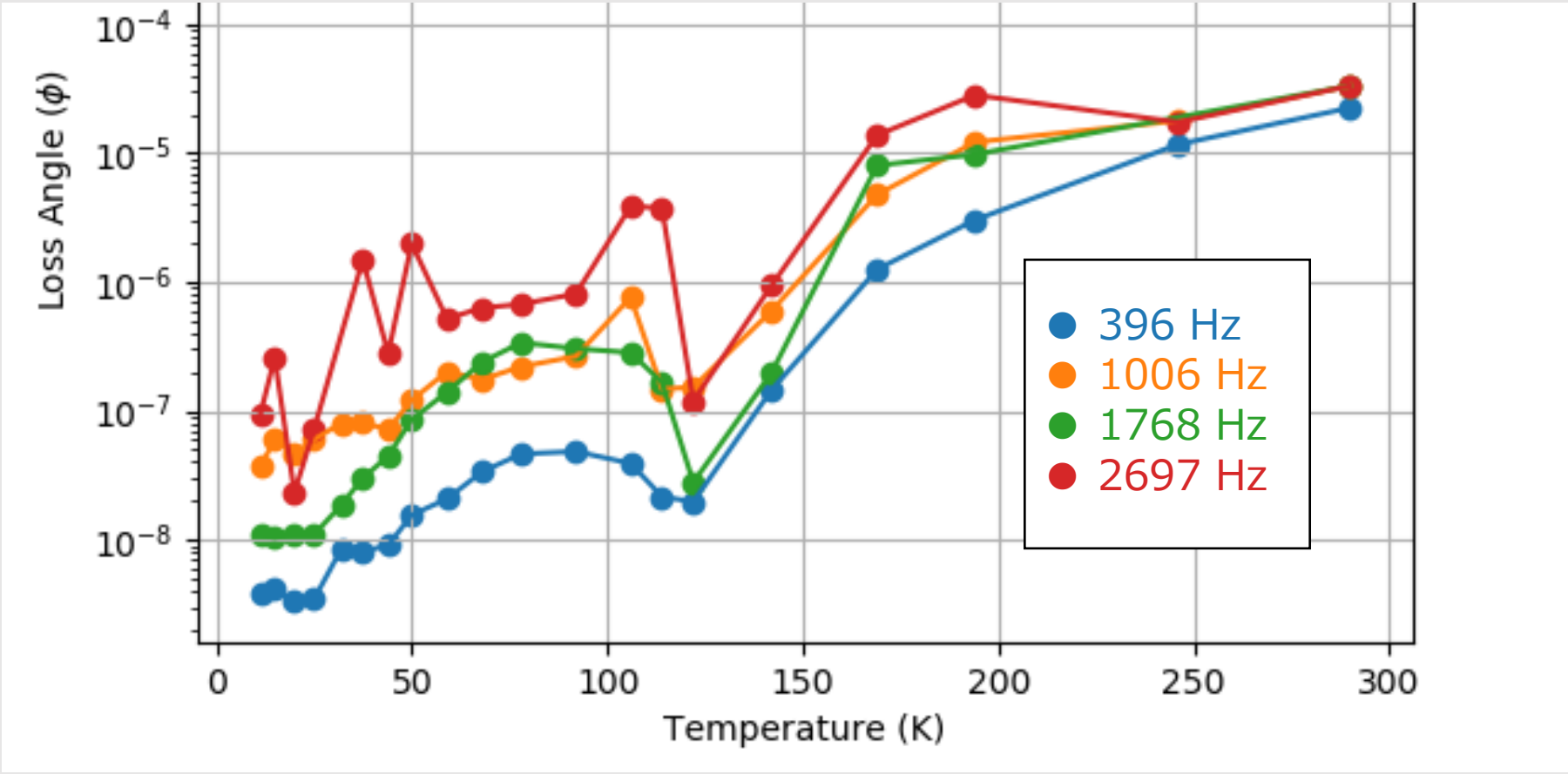
- Check the performance at room temperature.
- Extrinsic loss is below 5×10^{-8}.



3 inch Silicon disk



4 inch Silicon disk



CryoGeNS

- Cryogenic GeNS has been developed.
- The performance of the cryo GeNS is good to measure the high Q-values.
  - ✓ both at room temperature and cryogenic temperature
- Coatings to be measured
  - ✓ amorphous coatings (deposited at CSU)
    - ❑ SiO_2
    - ❑ a-Si
  - ✓ 4 inch AlGaAs coating

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- The electro-optic effect in crystalline AlGaAs coatings has been investigated.
  - ✓ the upper limit is well below the design sensitivity.
    -> not be a limiting noise source
- Cryogenic GeNS has been developed.
  - ✓ capable to both 3 inch and 4 inch diameter disks
  - ✓ works between 15 – 300 K
  - ✓ performance was verified at both room temperature and cryogenic temperature
  - ✓ ready to measure Qs at cryogenic temperature

Appendix

HVA

Trek 10/10B-HS

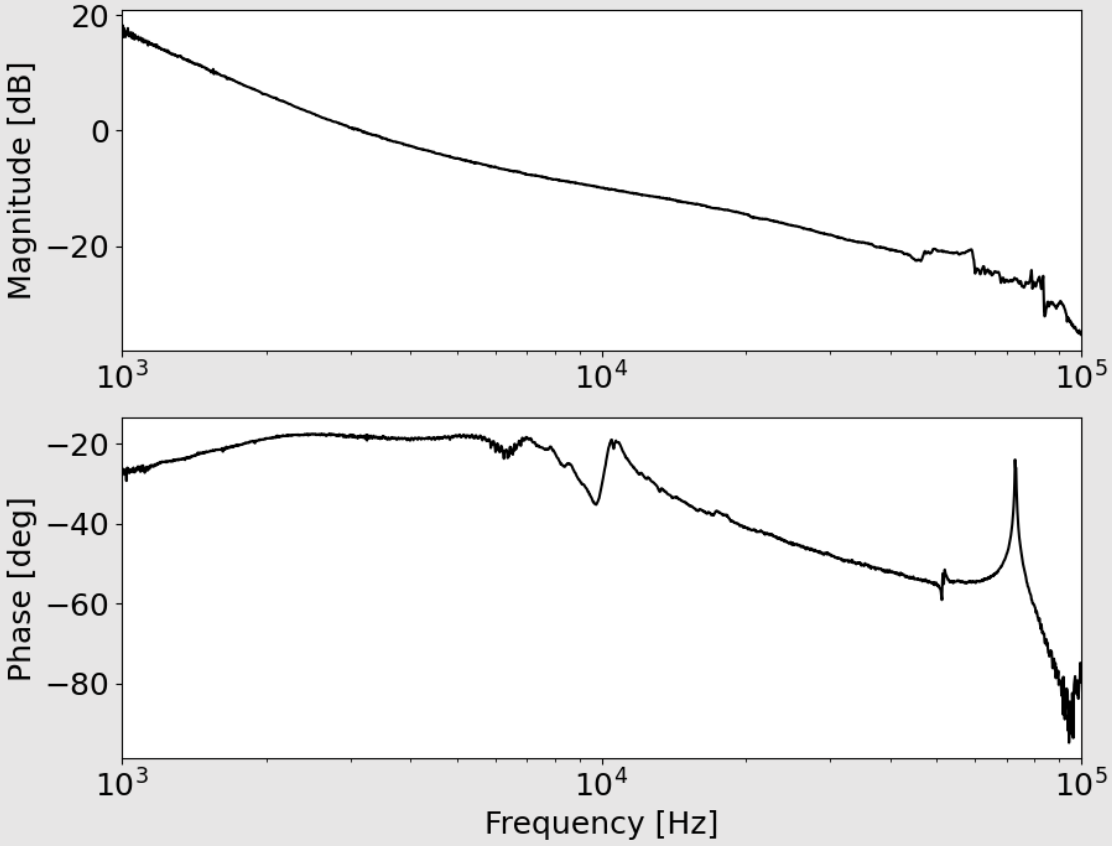
High Speed, High Voltage Amplifier, Output Voltage 0 to ±10 kV DC or Peak AC

The Advanced Energy Trek 10/10B-HS is a DC-stable, high-speed, high-voltage power amplifier that showcases precise control of output voltages. It features an all-solid-state design, high slew rate, wide bandwidth, and low-noise operation.

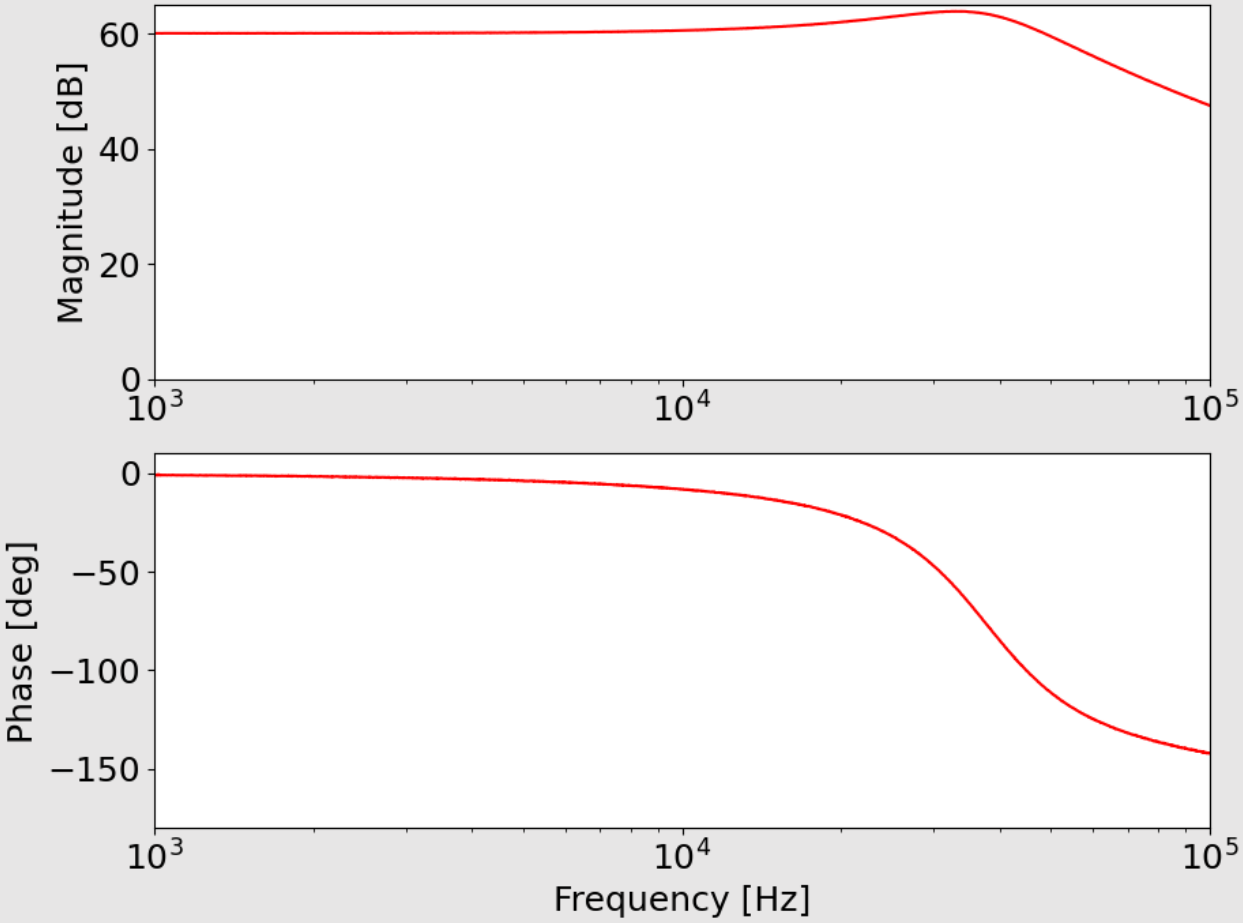
- **Output Voltage:** 0 to ±10 kV DC or Peak AC
- **Output Current:** 0 to ±10 mA DC or 40 mA peak AC for 1 ms
- **Slew Rate:** Greater than 700 V/µs
- **Large Signal Bandwidth:** DC to greater than 19.5 kHz (-3dB)
- **Gain:** 1000 V/V fixed

https://www.advancedenergy.com/products/high-voltage-products/high-voltage-amplifiers/standard-high-speed-amplifiers/trek-1010b-hs/

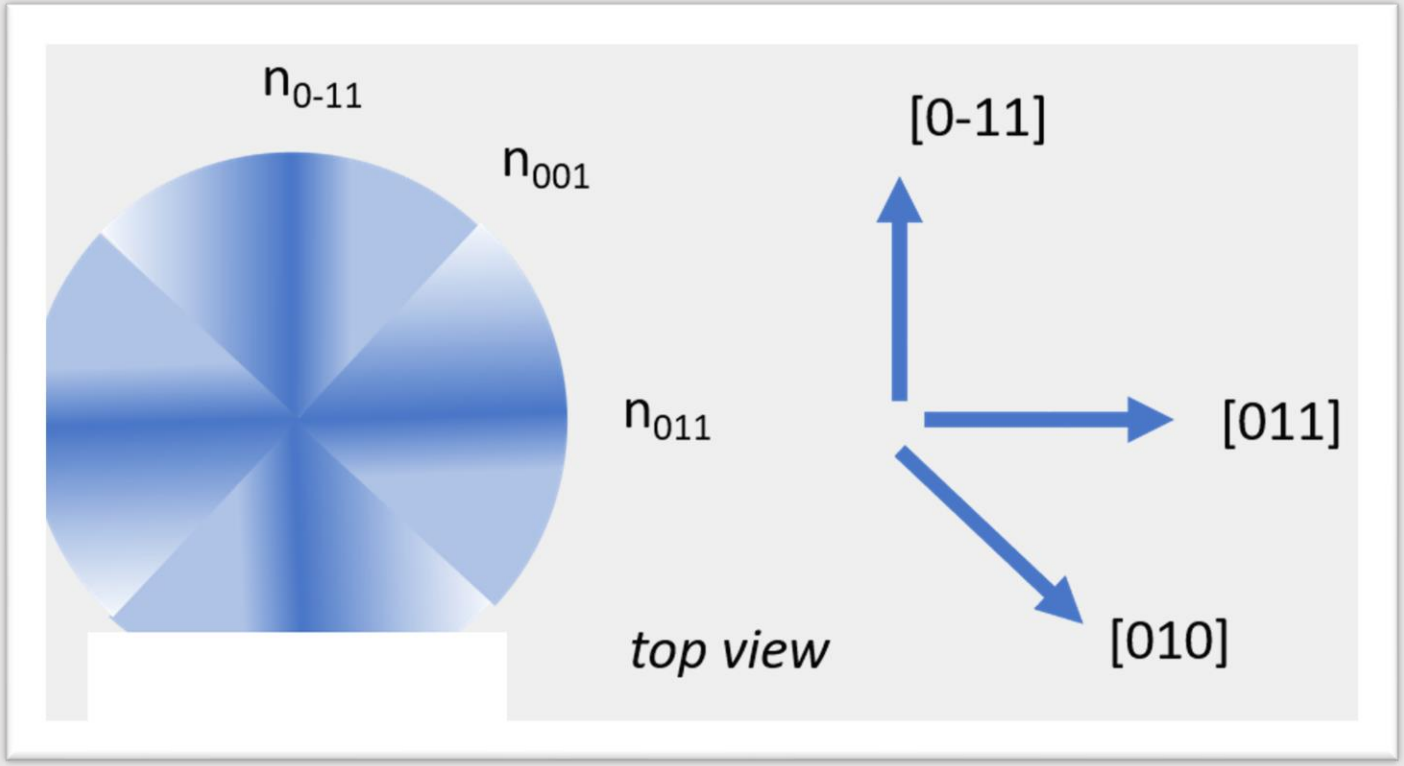
OLG


Magnitude [dB]
20
0
−20
10^3
10^4
10^5
Phase [deg]
−20
−40
−60
−80
10^3
10^4
10^5
Frequency [Hz]

HVA


Magnitude [dB]
60
40
20
0
10^3
10^4
10^5
Phase [deg]
0
−50
−100
−150
10^3
10^4
10^5
Frequency [Hz]

Orientation



a-SI