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The investigation of thermal and non-thermal noises in fused silica fibers for Advanced LIGO suspension

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Advanced LIGO limitation factors: mechanical noises in the mirror suspension system

- Equilibrium thermal noise – can be obtained by Fluctuation-Dissipation theorem:

$$S_x^2(\omega) = \frac{4kTH(\omega)}{m^{*2}\left(\left(\omega^2 - \omega_0^2\right)^2 + \frac{\omega^2\omega_0^2}{Q^2}\right)}$$

- Results achieved on the fused silica fibers suspension is promising:

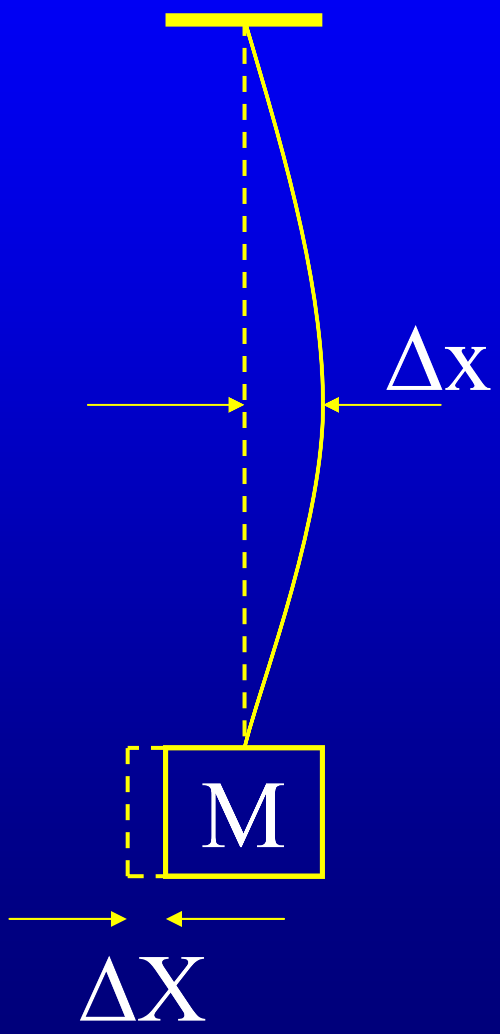
$$H \sim \frac{1}{Q_0} \qquad Q_0^{silica,best} > 10^8 \ \left(P.Willems\ V.Mitrofanov,\ et.all\ 2002\right)$$

Excess mechanical noise is possible!

Stationary and non-stationary fluctuations can exists.

- Has been observed on the bar gravitational wave antennae
- Has been measured in stressed inhomogeneous solids
  (*Dykhne et. all Physica A241 94 1997*)
- Investigated experimentally in LIGO team *(P.Saulson A.M.Gretarsson, in press}*.
- Observed by MSU group in the LIGO suspension models (tungsten and steel wires)

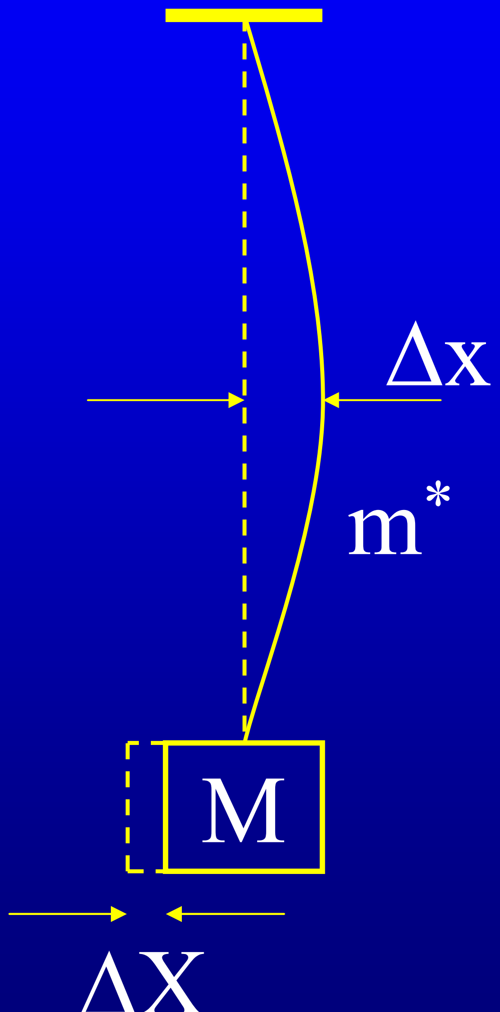
Noise in the suspension wire (fiber)



$$E_{kT}^{violin} \approx 10^{-21} E_{elastic}^{fiber}$$

- if there is some mechanism of the “energy diffusion” from the elastic (static) form to the oscillatory (kinetic), then the noise of non-thermal origin may appear.

Noise in the suspension wire (fiber) – method of measurement



$$m^* << M$$

$$\Rightarrow \Delta x >> \Delta X$$

- Let us to monitor oscillation the wire (fiber) instead of the test mass motion
(Braginsky 1994)

- It is interesting to observe amplitude variations during

$$\Delta t << \tau^*$$

Excess noise in the steel wires

Has been detected in the samples from the material used in Initial LIGO under high stress:

Fundamental violin mode amplitude variation over the time $t = 0.2\ s$

$$\overline{A_i} \cong \sqrt{\frac{2kT}{m^* \omega^2}} \sqrt{\frac{2t}{\tau^*}}$$

$\Delta A_i > 5\overline{A_i}$: 1 – 20 events/10 hours observed on some samples under stress >50% of breaking value

Relaxation time: $\tau^* \approx 10\ s \quad \left(Q_0^{steel} \approx 3 \times 10^4\right)$

Sensor: He-Ne laser based Micelson interferometer

Best sensitivity achieved: $\Delta x_{\min} \cong 2 \times 10^{-11} cm / \sqrt{Hz}$

corresponds: $\Delta E_{\min} \approx 0.1 kT$

(Ageev, Bilenko, Braginsky 1998)

Excess noise in the fused silica fibers

Goals:

- Keep high quality factor of the fiber: $Q_0^{silica} >> Q_0^{steel}$

  - reduce recoil losses

  - minimize fiber contamination

- Measure the amplitude variations over the time short as compared to ringdown time. Desired sensitivity:

$$S_x^{\min} \approx 10^{-13} cm / \sqrt{Hz}$$

- Check for non-Gaussian distribution of the amplitude variations

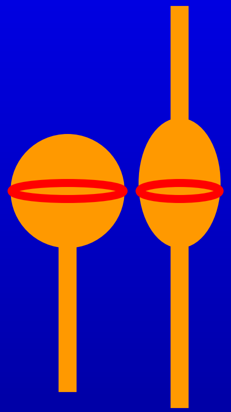
Measurement of the noise in the fused silica fibers – approaches tested and denied:

- Single pass He-Ne based optic :

$$S_x^{HeNe-1\,pass} \approx \frac{\lambda}{2}\sqrt{\frac{h\omega}{W}} = 5\times 10^{-13}\, cm/\sqrt{Hz} > 10^{-13}\, cm/\sqrt{Hz}$$

- Optical microcavities ("twin balls") based sensor -

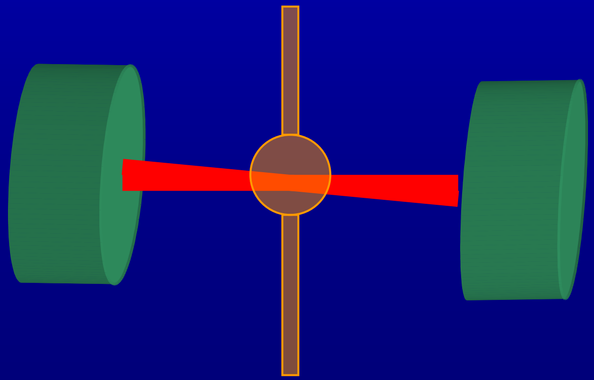
electrostatic sealing is inevitable



$$\delta\omega \sim \delta x$$

- Fabry-Perot with intermediate sphere (semi-transparent mirror) -

mode matching is hard-hitting



Fabry-Perot with a mirror welded into the sample

- Finesse: $F = 50 \ldots 100$

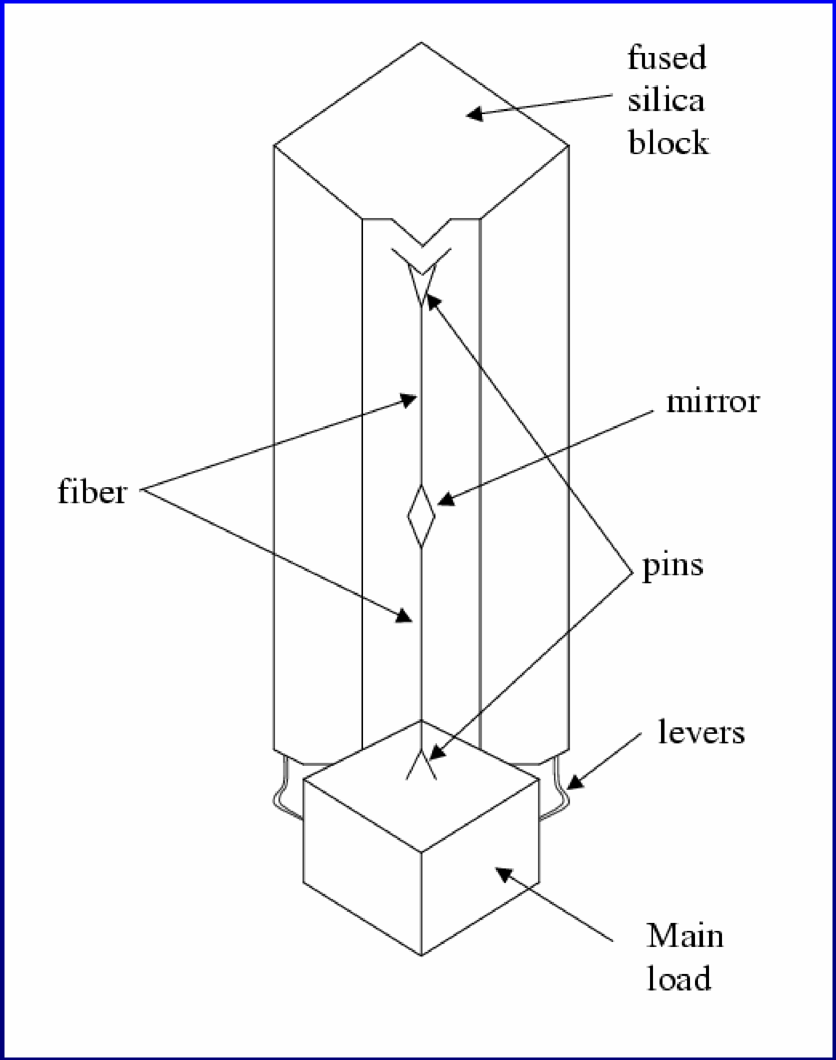
- Maximum sensitivity:

$$S_x^{\min} \approx \frac{\lambda}{2F}\sqrt{\frac{h\omega}{W}} =$$

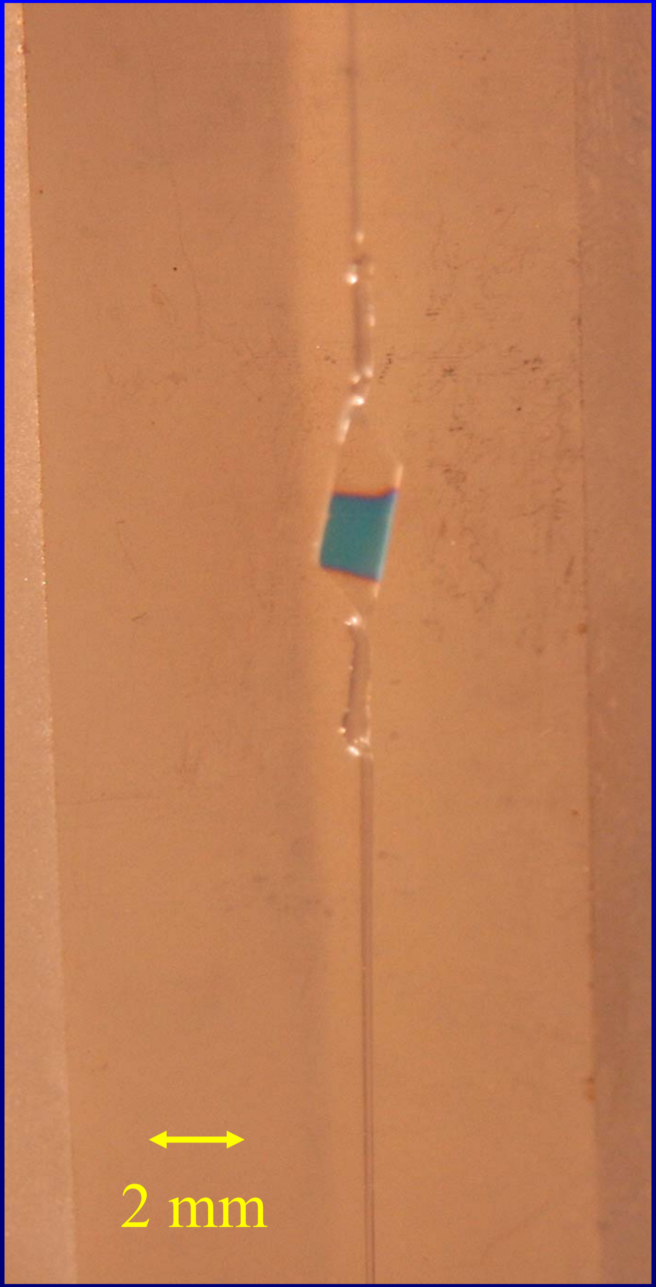
$$3 \times 10^{-15}\, cm/\sqrt{Hz}$$

- Quality factor achieved:

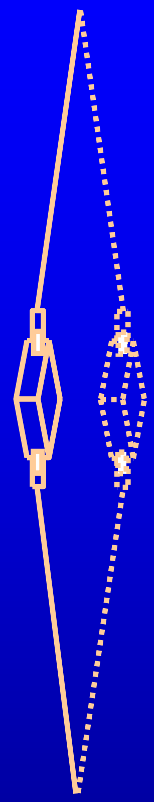
$$Q = 10^5 \ldots 10^7$$

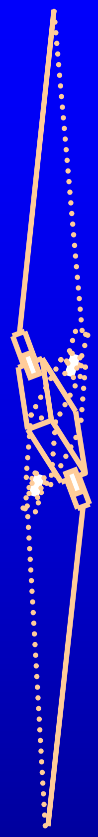


Silica fiber with support and mirror



Oscillation modes tested





Violin-like mode:

$$f = 400 \div 760\, Hz$$

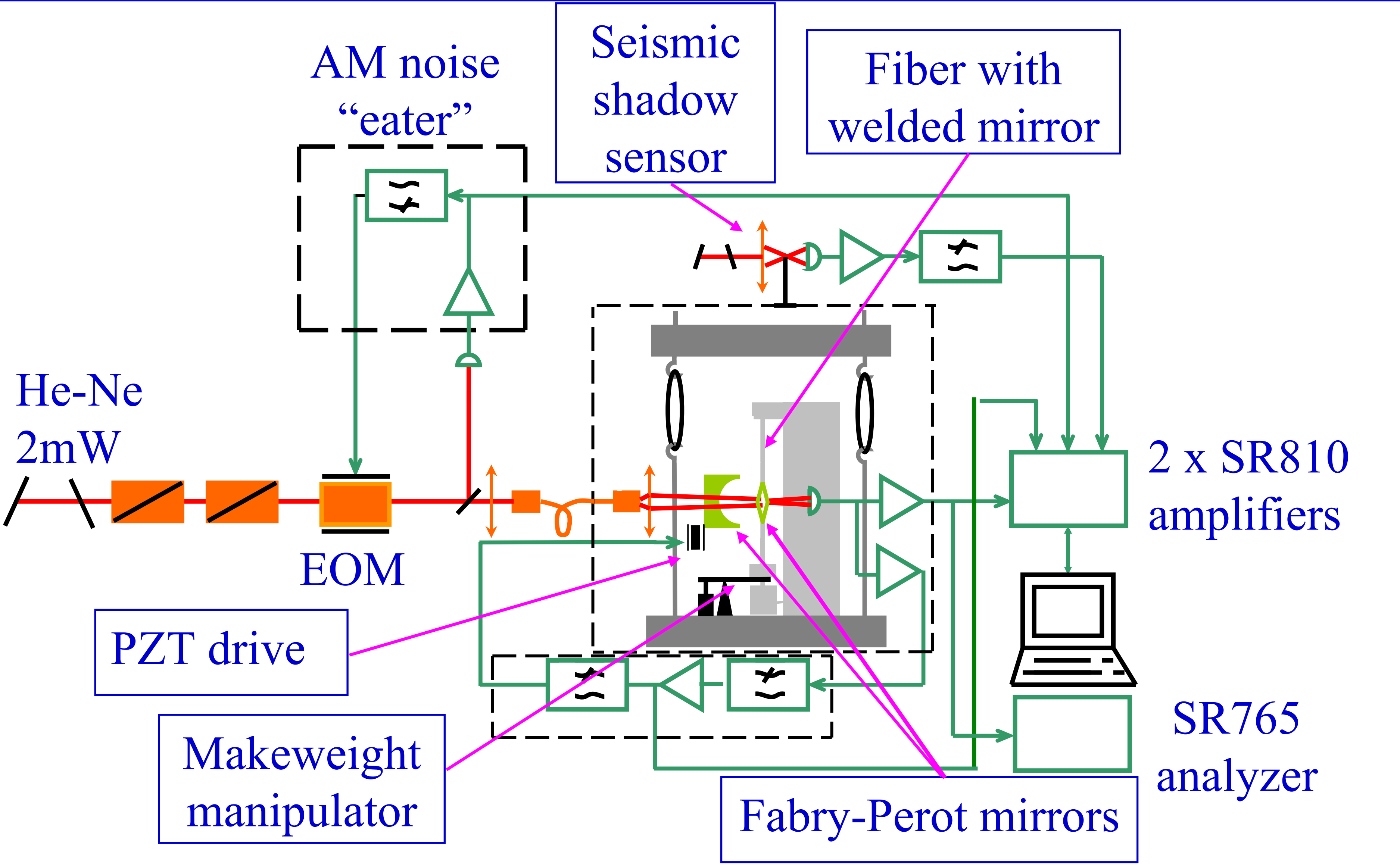
$$Q = 1 \times 10^{5} \div 3 \times 10^{6}$$

Mirror-swinging mode:

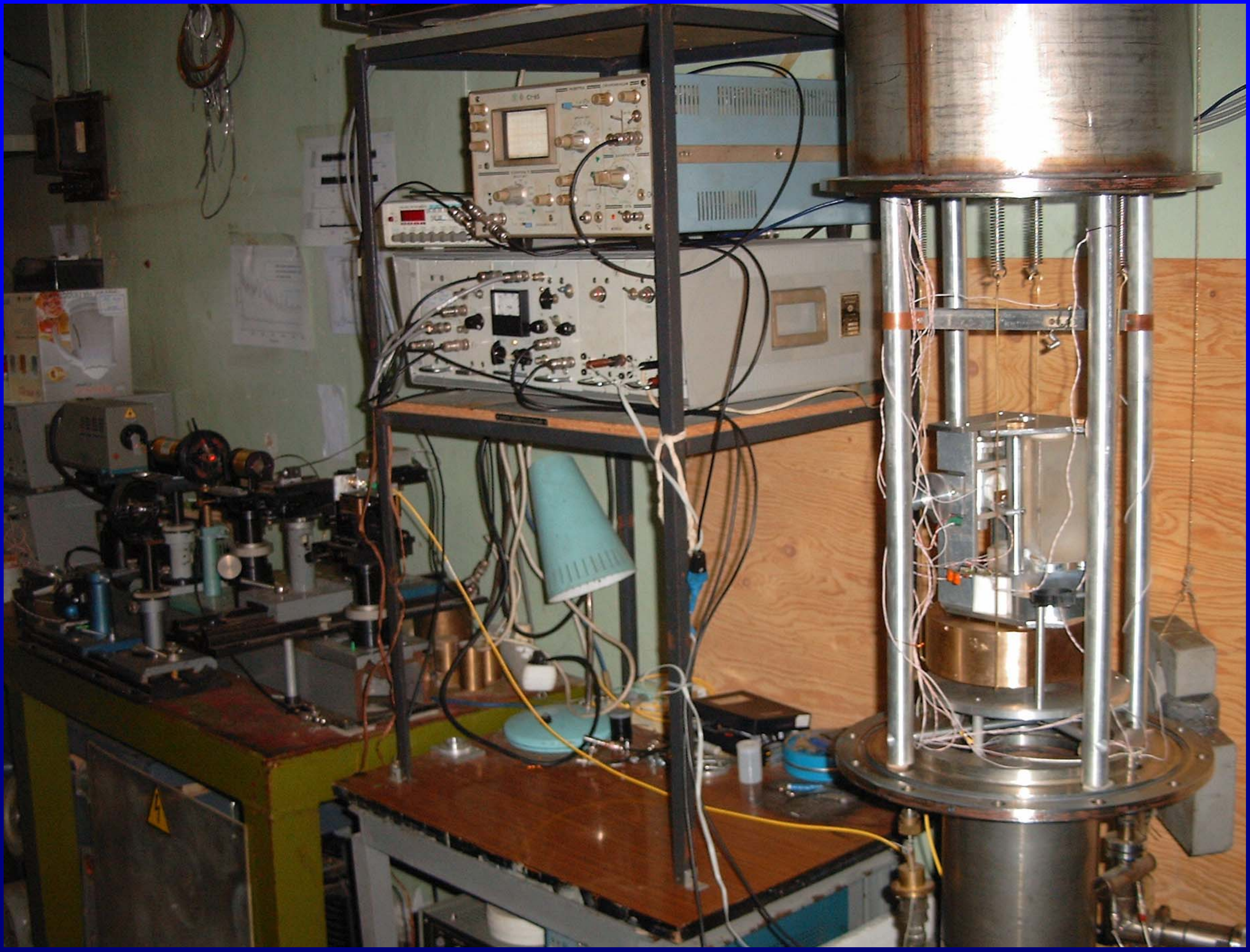
$$f = 1 \div 2\, kHz$$

$$Q = 5 \times 10^{6} \div 2 \times 10^{7}$$

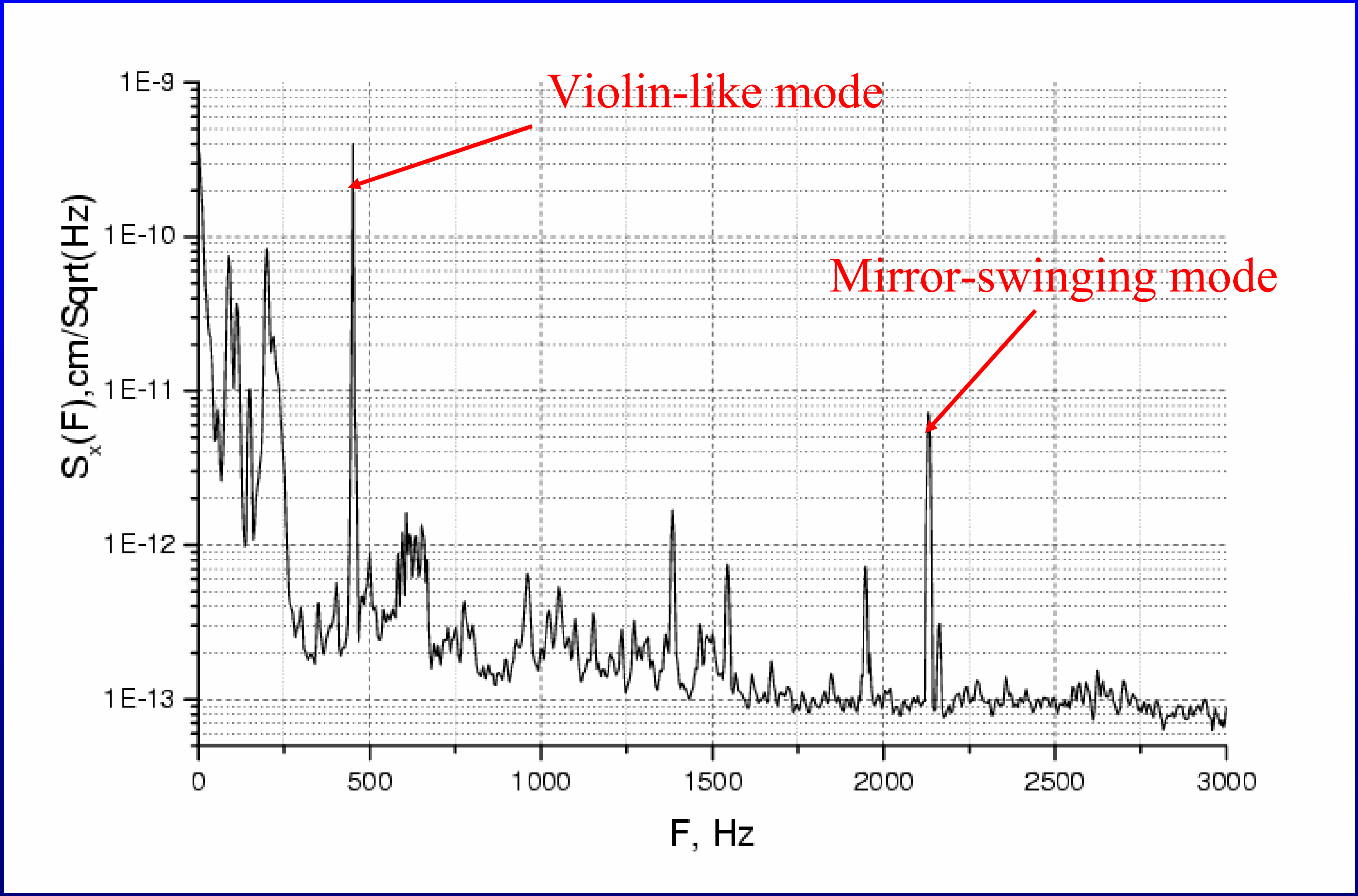
Installation diagram



Installation picture



Typical mirror oscillations spectrum (analyzer binwidth 4 Hz).



Measurements results

- Best obtained sensitivity:

$$S_x^{\min} \cong 9 \times 10^{-14}\, cm/\sqrt{Hz} \qquad (f \geq 2\, kHz)$$

- Sensitivity in the violin-like mode domain:

$$S_x^{500\,Hz} \leq 10^{-12}\, cm/\sqrt{Hz}$$

- Relaxation time for violin-like mode:

$$\tau^{*} \approx 600\, s \qquad \left(Q_0^{silica} \approx 10^{6}\right)$$

Minimum amplitude variations measured over $t = 0.1\, s$

corresponds to: $\Delta E_{\min} \approx 0.01 kT$

Sample management

1. Fabrication (welding)

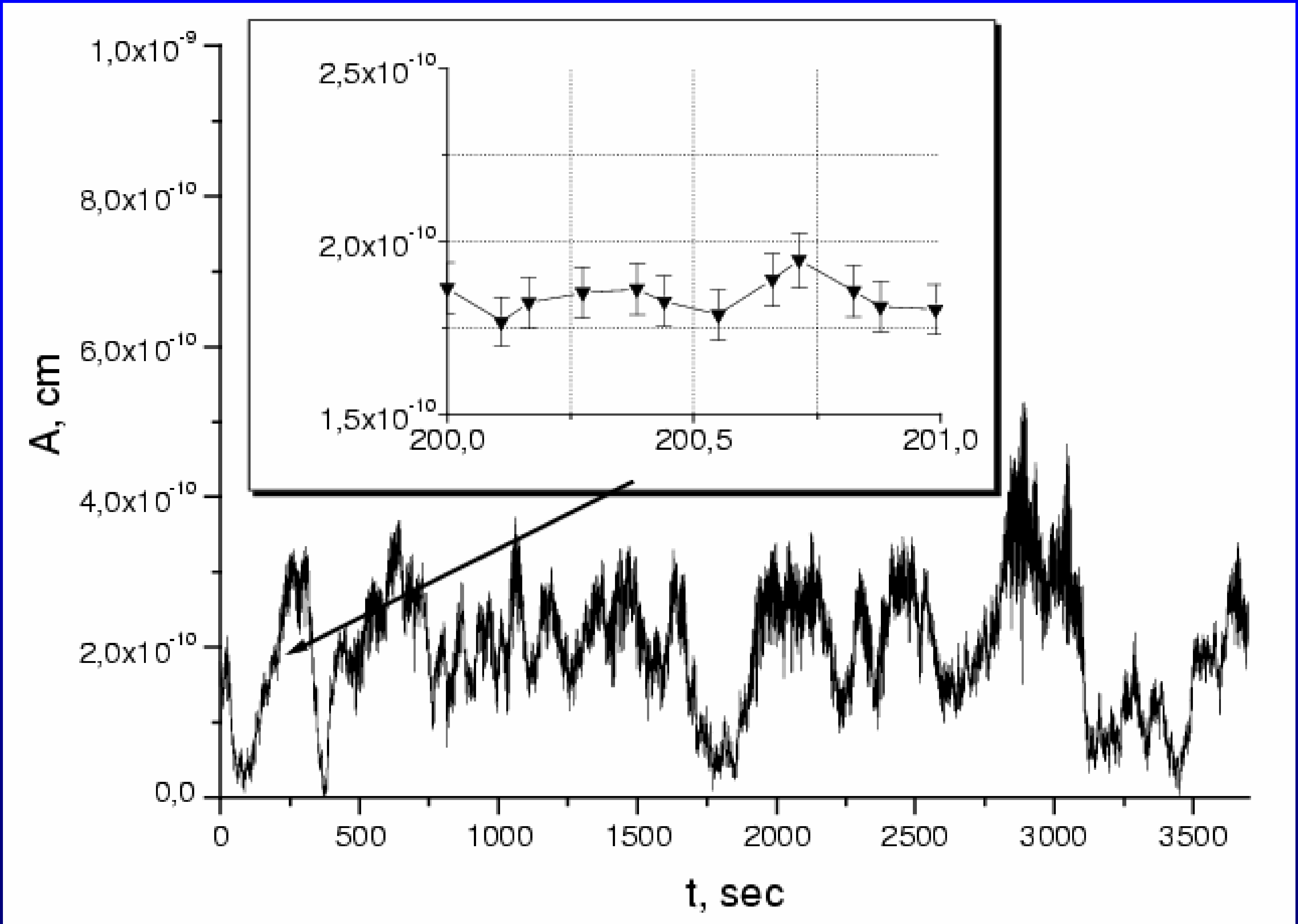
2. Installation, optic adjustment, pumping out the tank

3. Data recording (night time, record length 1-5 h, up to 10 records/sample)

4. Applying the makeweight (for some samples), more data recording

5. Sample tensile testing

Record example



Data processing procedure

1. Obtaining signals proportional to the amplitudes of selected modes.

2. Filtering and digitizing with sample rate 100 *1/s*, averaging with t = 0.1 *s*

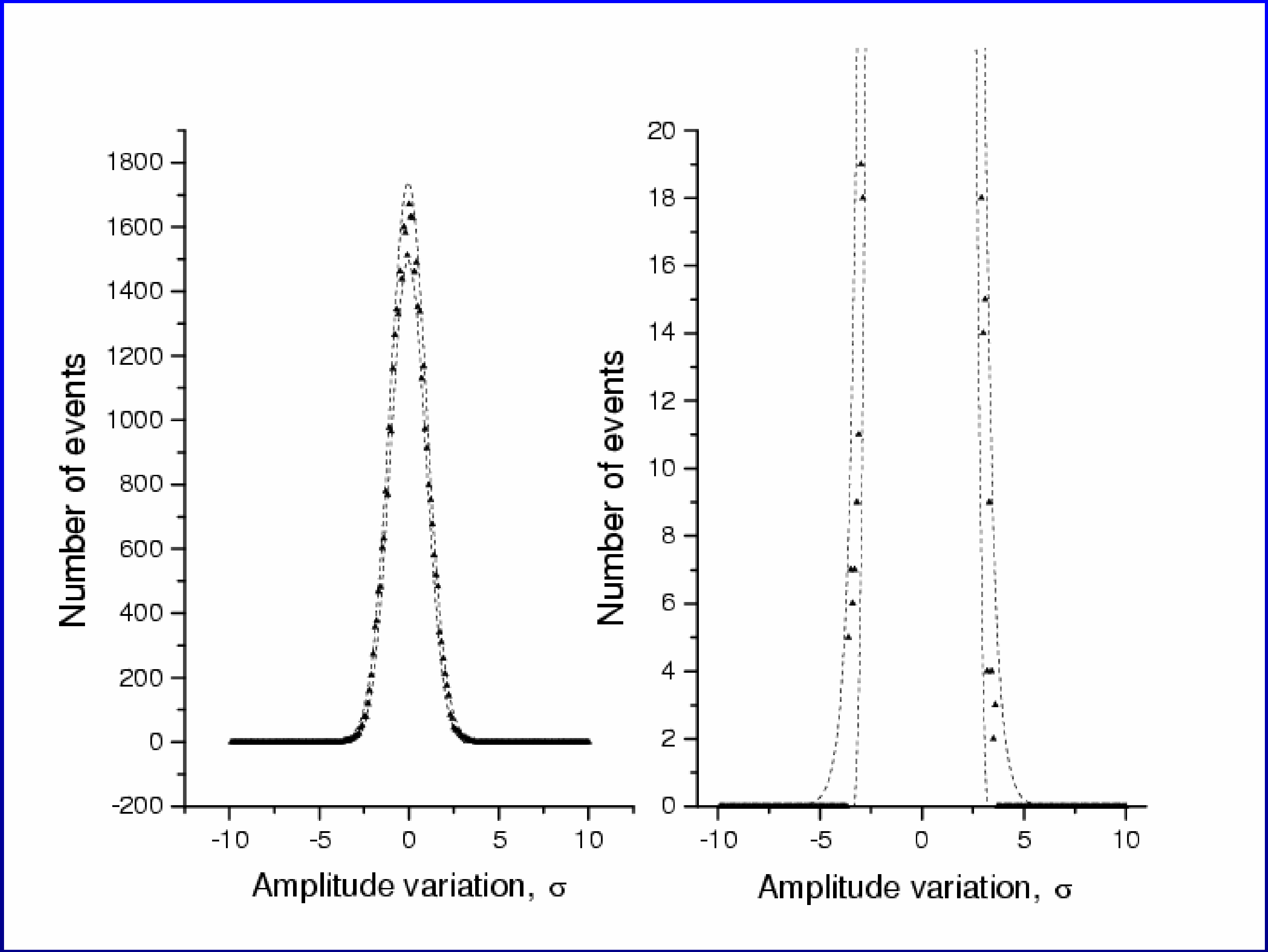
3. Applying the “veto” using the local seismometer information

4. Estimation of the average amplitude variation over 0.1 *s*, plotting a distribution

5. Selection of the “candidate evens”, test for coincidence with control channels, replotting distribution

Obtained: 90 hours of “clear” records for 9 samples from 50 to 180 μm in diameter stressed from ~4% to ~50% from breaking value.

Amplitude variations distribution



Record on sample Q21:

$$N_0 = 45986$$

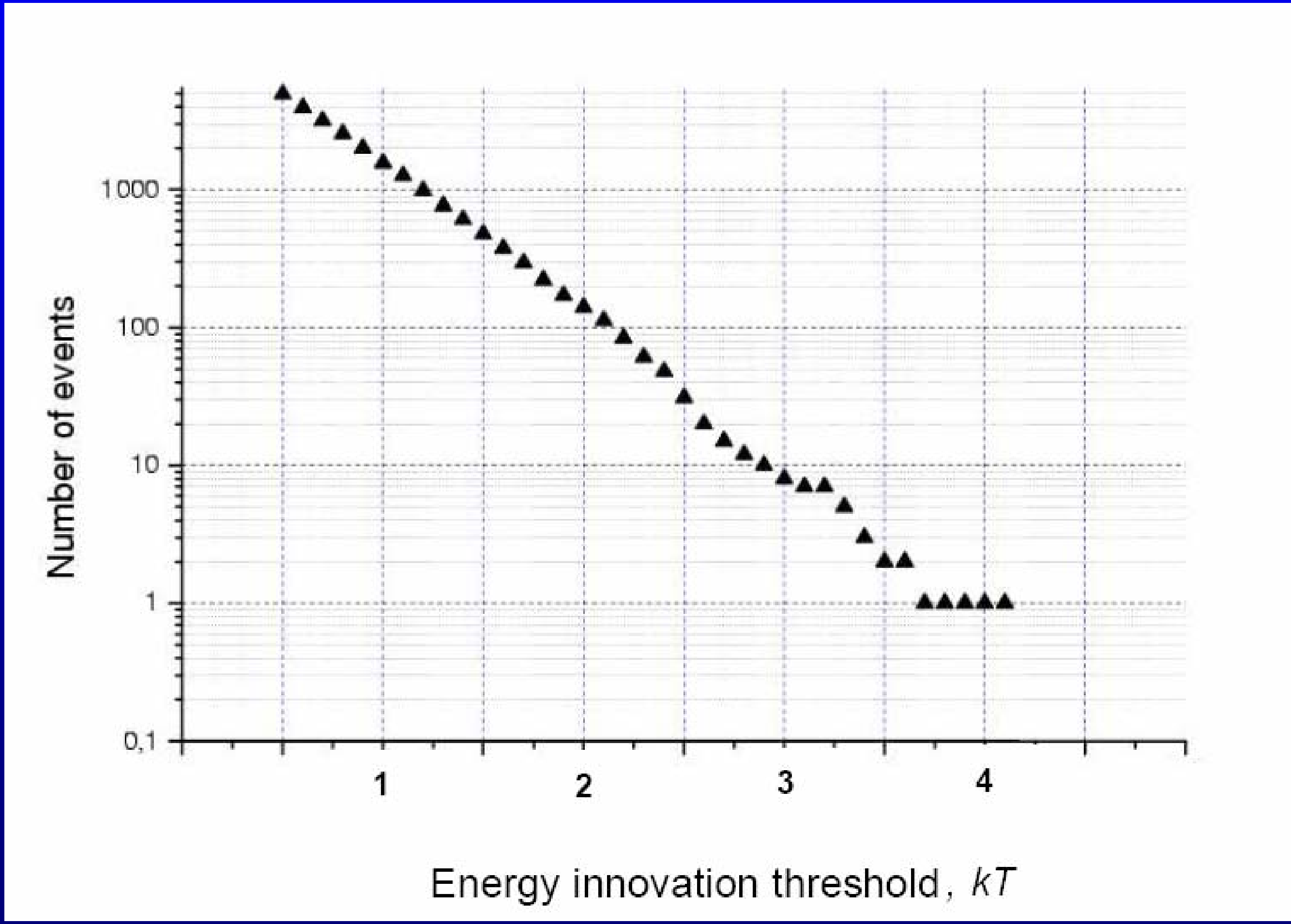
$$\Delta x = \sigma / 10$$

$$A_t = A_i - A_{i-1} \qquad P[A_t] = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{A_t^2}{2\sigma^2}\right) \qquad \sigma = \sqrt{\overline{A_t^2}}$$

Alternative representation – *Energy innovation* histogram

pair of quadrature amplitude have to be recorded:

$$\eta_i^2 \equiv \left[A1_i - A1_{i-1}\right]^2 + \left[A2_i - A2_{i-1}\right]^2$$



A1,A2 record made on sample Q21 for comparision porpose

Results summary

Test set Nr.	Sample code	Diameter and applied load(% of breaking stress for this sample)	Mode freq. $[Hz]$ and type	Quality factor	Obs. time (sec)	Noise floor	Nr. of can-didate events	Nr. of excess events proved
1	Q2	$180\,\mu m, 4\%$	1087m	2×10^6	17000	5×10^{-2}	62	0
2	Q4	$120\,\mu m, 8\%$	762v	3.4×10^6	7450	1.5×10^{-2}	7	0
3			2319m	1×10^7	31300	4×10^{-2}	48	0
4	Q5	$90\,\mu m, 15\%$	1538m	7.4×10^6	14400	4×10^{-2}	26	0
5	Q6	$70\,\mu m, 19\%$	1932m	2×10^7	23600	1×10^{-2}	0	0
6	Q9	$85\,\mu m, 16\%$	748v	1.4×10^6	6700	3×10^{-2}	17	0
7			1980m	1×10^7	5050	5×10^{-2}	1	0
8	Q9	$85\,\mu m, 19\%$	759v	1.9×10^6				
			2197m	1.3×10^7	33450	5×10^{-2}	0	0
9	Q11	$70\,\mu m, 24\%$	1600m	1.4×10^7	16750	2×10^{-2}	0	0
10	Q11	$70\,\mu m, 29\%$	1747m	1.3×10^7	18250	2×10^{-2}	0	0
11	Q11	$70\,\mu m, 35\%$	1946m	9×10^6	16500	3×10^{-2}	0	0
12	Q11	$70\,\mu m, 42\%$	2083m	5×10^6	15850	6×10^{-2}	0	0
13	Q20	$75\,\mu m, 20\%$	624v	8.2×10^5	2400	3×10^{-2}	2	0
			1852m	8.5×10^6	2400	5×10^{-2}	0	0
14*	Q20	$75\,\mu m, 21\%$	627v	8.0×10^5	4800	3×10^{-2}	5	0
			1861m	8.5×10^6	4800	5×10^{-2}	0	0
15	Q21	$60\,\mu m, 33\%$	450v	1.3×10^5	28200	2×10^{-2}	28	0
			2130m	5×10^6	28200	6×10^{-2}	2	0
16	Q25	$50\,\mu m, \sim 50\%^{**}$	404v	1×10^5	8750	1×10^{-2}	3	0
			1811m	8.5×10^6	8750	9×10^{-2}	0	0
17*	Q25	$50\,\mu m, > 50\%^{**}$	413v		14550	1×10^{-2}	11	0
			1860m		14550	9×10^{-2}	0	0

Conclusions

- ✓ Affordable installation for investigation of mechanical noise in fused silica fiber has been designed. Best displacement sensitivity is:

$$S_x^{\min} \cong 9\times10^{-14}\, cm/\sqrt{Hz}$$

- ✓ Non-Gaussian (excess) mechanical noise hasn't been observed at the achieved sensitivity level.

- ✓ Extrapolation of this result to the Advanced LIGO suspension shows promise that this type of noise will not affect the detector sensitivity at the level:

$$\Delta x_{gr} > A_L \approx \overline{A}\sqrt{\frac{2t}{\tau^*}}\frac{m_m}{M_L} \cong 1\times10^{-17}\, cm$$

- ✓ In order to investigate the noise in the suspension with better resolution both, the quality factor of violin-like mode and the sensitivity of the readout system should be improved