Radiation Pressure Experiments at MIT

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Outline

- Goals of experiments
  - Explore radiation pressure effects
    - Ponderomotive squeezing
    - Optical spring / parametric instability
- Path to goals
  - Phase I experiment – completed!
    - See some RP effects.
  - Phase II experiment – almost completed!
    - See extreme RP effects.
  - Phase III – ongoing.
    - See ponderomotive squeezing.

The principle

- Use radiation pressure as the squeezing mechanism
  - Consider an optical cavity with high stored power and a phase sensitive readout
  - Intensity fluctuations (radiation pressure) drive the motion of the cavity mirrors
  - Mirror motion is then imprinted onto the phase of the light
  - Correlation between phase and intensity quadratures is squeezing

The experimental concept

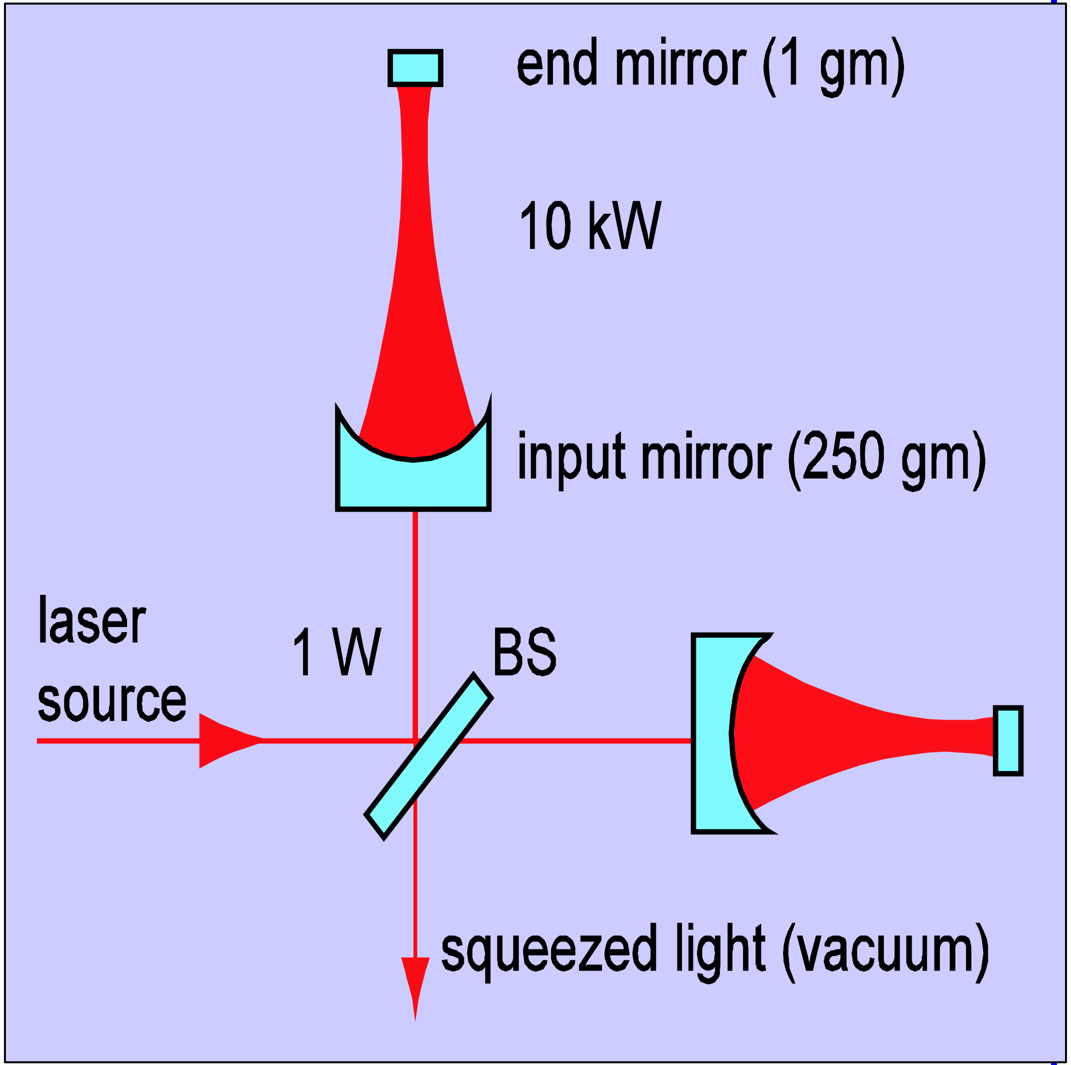
- A “tabletop” interferometer to generate squeezed light as an alternative to nonlinear optical media and to explore radiation pressure effects
- Relies on intrinsic quantum physics of optical field–mechanical oscillator correlations
- Squeezing produced even when the sensitivity is far worse than the (free mass) SQL
  - Due to noise suppression of optical springs

A table

The ponderomotive interferometer

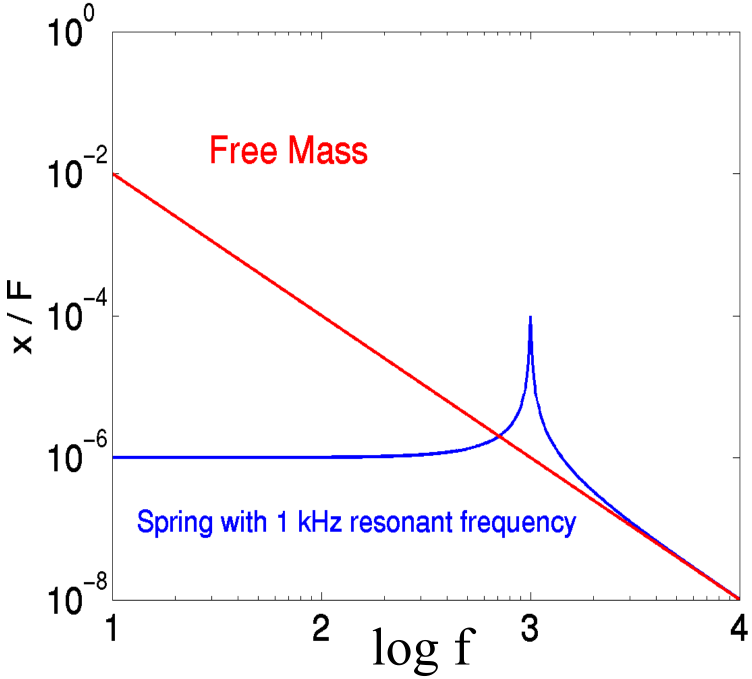
Key ingredients:

- Low mass, low noise mechanical oscillator mirror – 1 g with 1 Hz resonant frequency
- High circulating power – 10 kW
- High finesse cavities - 8000
- Differential measurement – common-mode rejection to cancel classical noise
- Optical spring – noise suppression and frequency independent squeezing



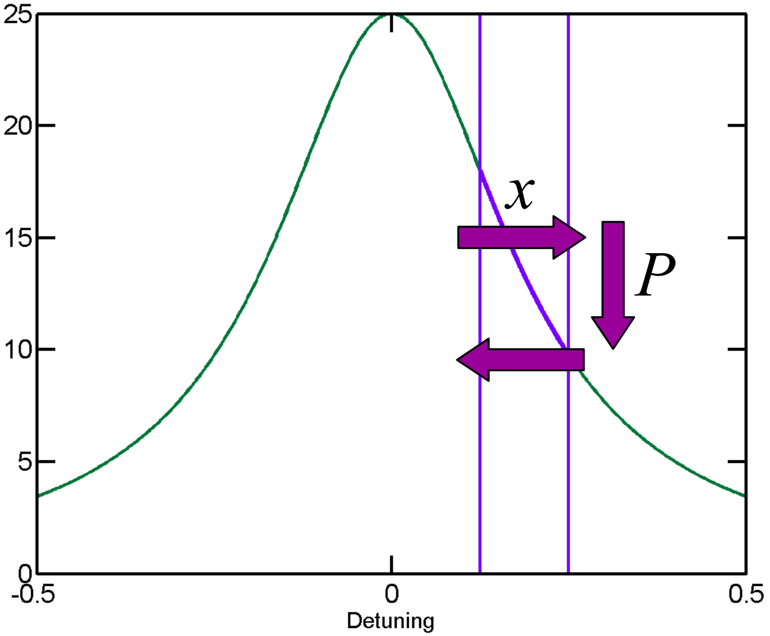
Optical Springs

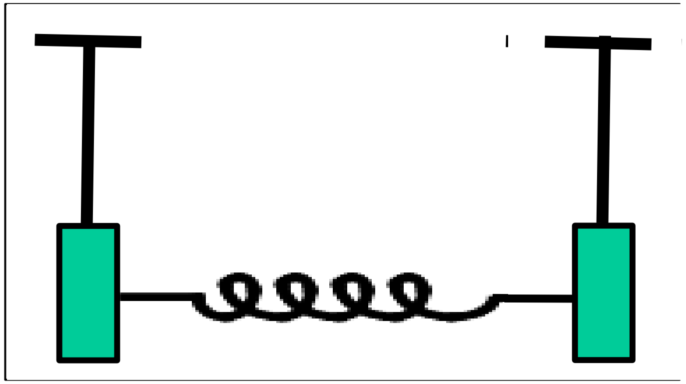
- Modify test mass dynamics
- Suppress displacement noise (compared to free mass case)
- Why not use a mechanical spring?
  - Displacements due to thermal noise introduced by the high frequency (mechanical) spring would destroy the effects of squeezing
- Connect low-frequency mechanical oscillator to (nearly) noiseless optical spring
- An optical spring with a high resonant frequency will not change the thermal force spectrum of the mechanical pendulum
  - Use a low resonant frequency mechanical pendulum to minimize thermal noise
  - Use an optical spring to produce a flat response out to higher frequencies



How to make an optical spring?

- Detune a resonant cavity to higher frequency (blueshift)
  - DC radiation pressure balanced by control system
  - Detuning increases
  - Cavity becomes longer
  - Power in cavity decreases
  - Radiation-pressure force decreases
  - Mirror ‘restored’ to original position
  - Cavity becomes shorter
  - Power in cavity increases
  - Mirror still ‘restored’ to original position





Optical rigidity model

- Power inside cavity in steady state is
  - δ is detuning
  - γ is linewidth

$$P = \frac{4P_0/T_i}{1+(\delta/\gamma)^2}$$

- Radiation pressure force is 2P/c, so optical spring constant is:

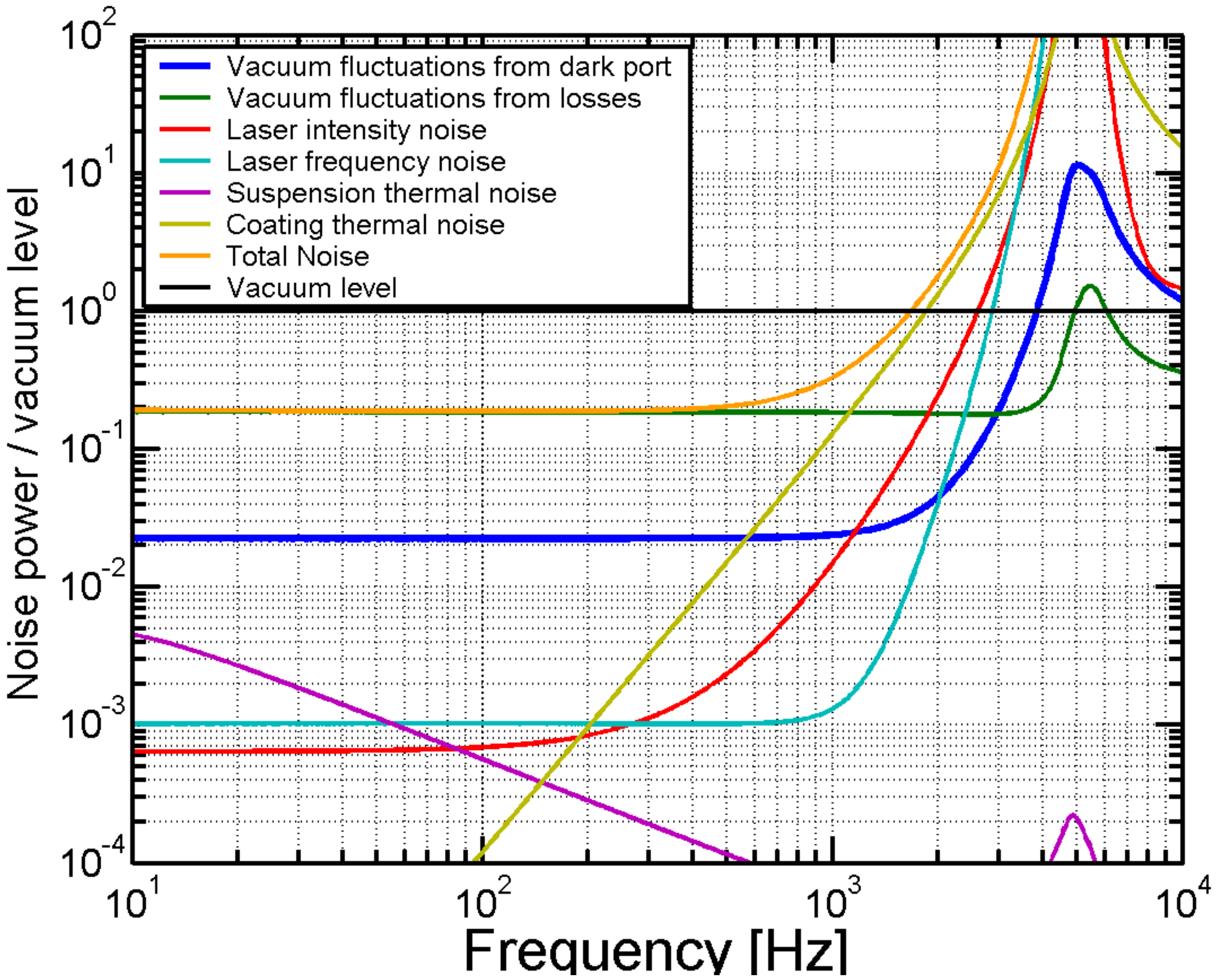
$$k_{opt,0} = \frac{2}{c}\frac{dP}{dx} = \frac{128\pi P_0}{c T_i^2 \lambda_0} \frac{(\delta/\gamma)}{[1+(\delta/\gamma)^2]^2}$$

- This determines the frequency shift of mechanical modes.
- When the finite response time of the cavity is included:

$$k_{opt} = k_{opt,0} \frac{1+(\delta/\gamma)^2}{(1+i\Omega/\gamma)^2+(\delta/\gamma)^2}$$

Imaginary spring constant gives viscous forces, leading to unstable optical spring, as well as PI and cold damping effects.

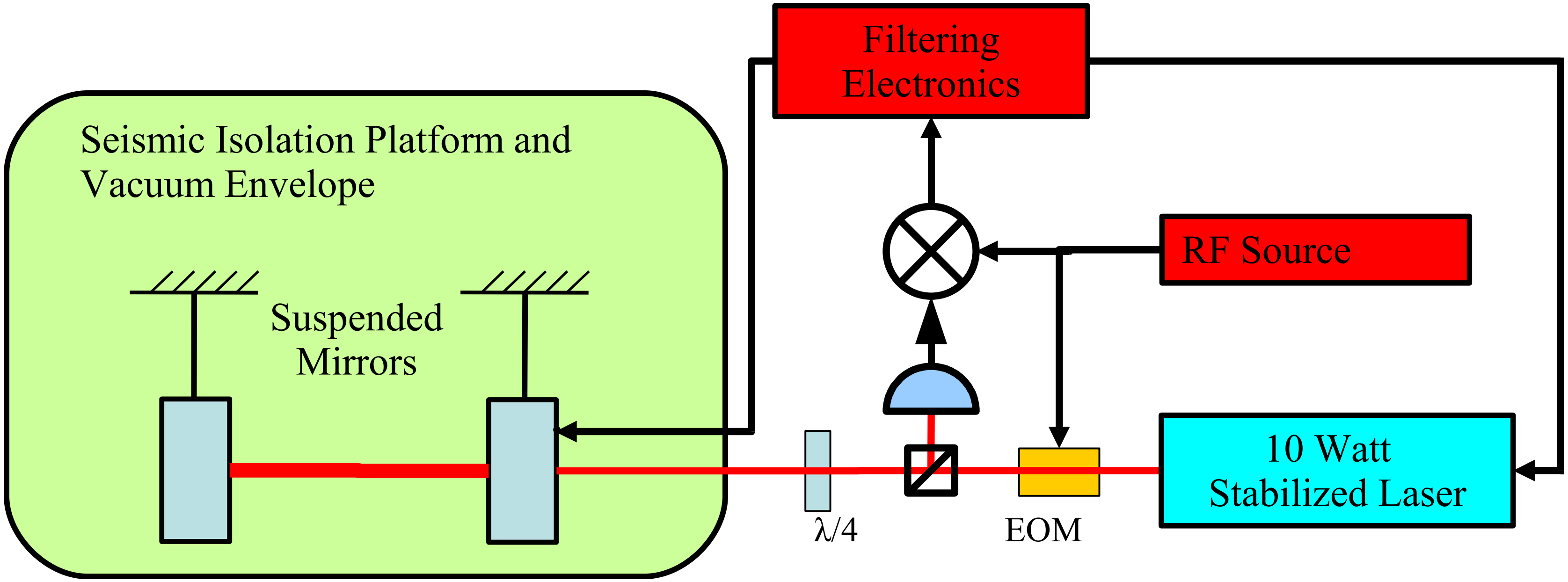
Noise budget



Experimental progress

- Experiment carried out in three phases
  - Phase I → linear cavity with two 250 g suspended mirrors, finesse of 1000, ~5 W of input power
  - Phase II → cavity with one 250 g and one 1 g suspended mirror, finesse of 8000, ~5 W of input power.
  - Phase III → two identical cavities and Michelson interferometer
- Ultimate goal – quantum-limited radiation pressure for ponderomotive squeezing interferometer

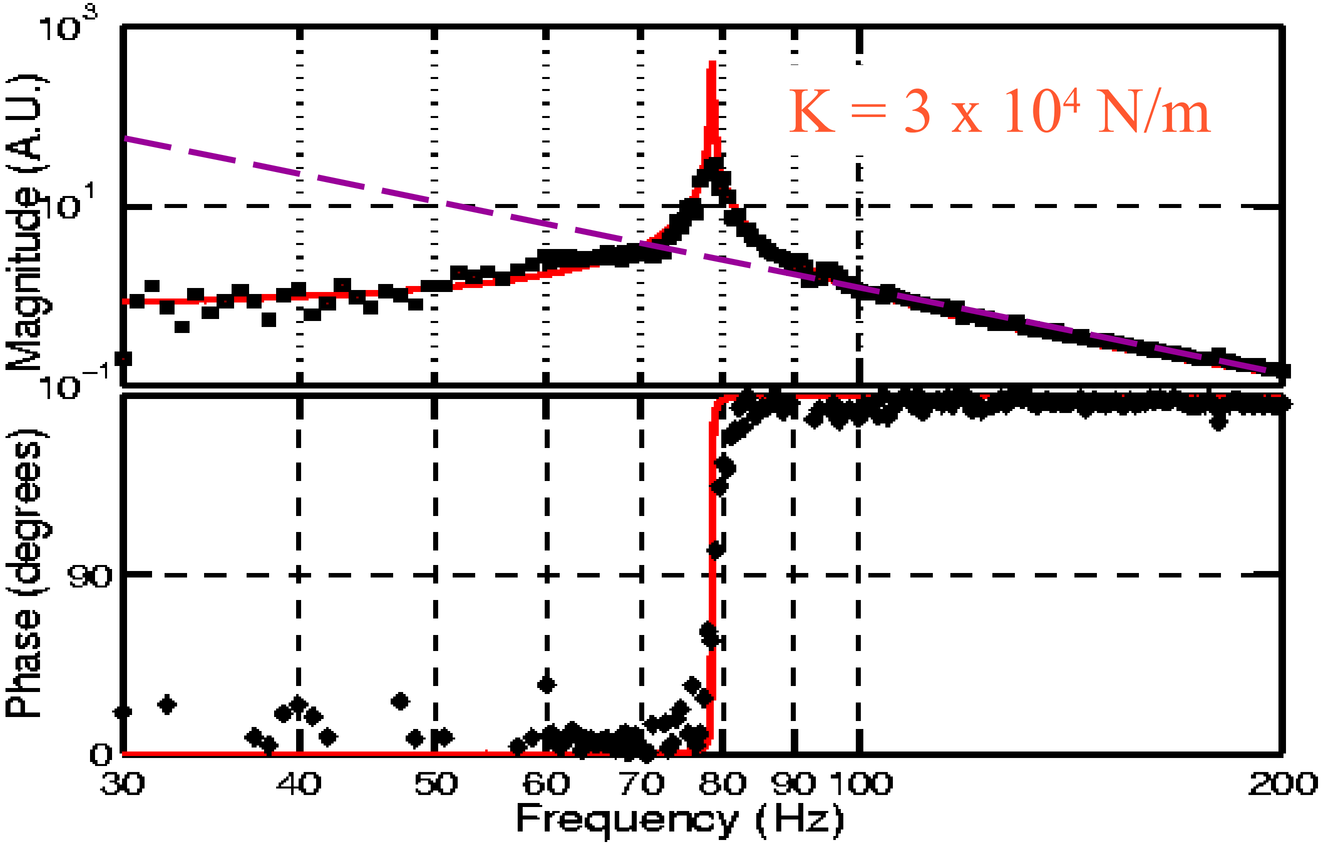
Phase I Experiment



Detuned by inserting offset into PDH error signal, limited to detunings ~ half linewidth.

Optical Spring Measured

- Phase increases by 180˚, so resonance is unstable!
- But there is a lot of gain in our servo at this frequency, so it doesn't destabilize the system.
- Stiffness is approximately the same as if the two mirrors were connected by a wood beam with same dimensions as the optical field.



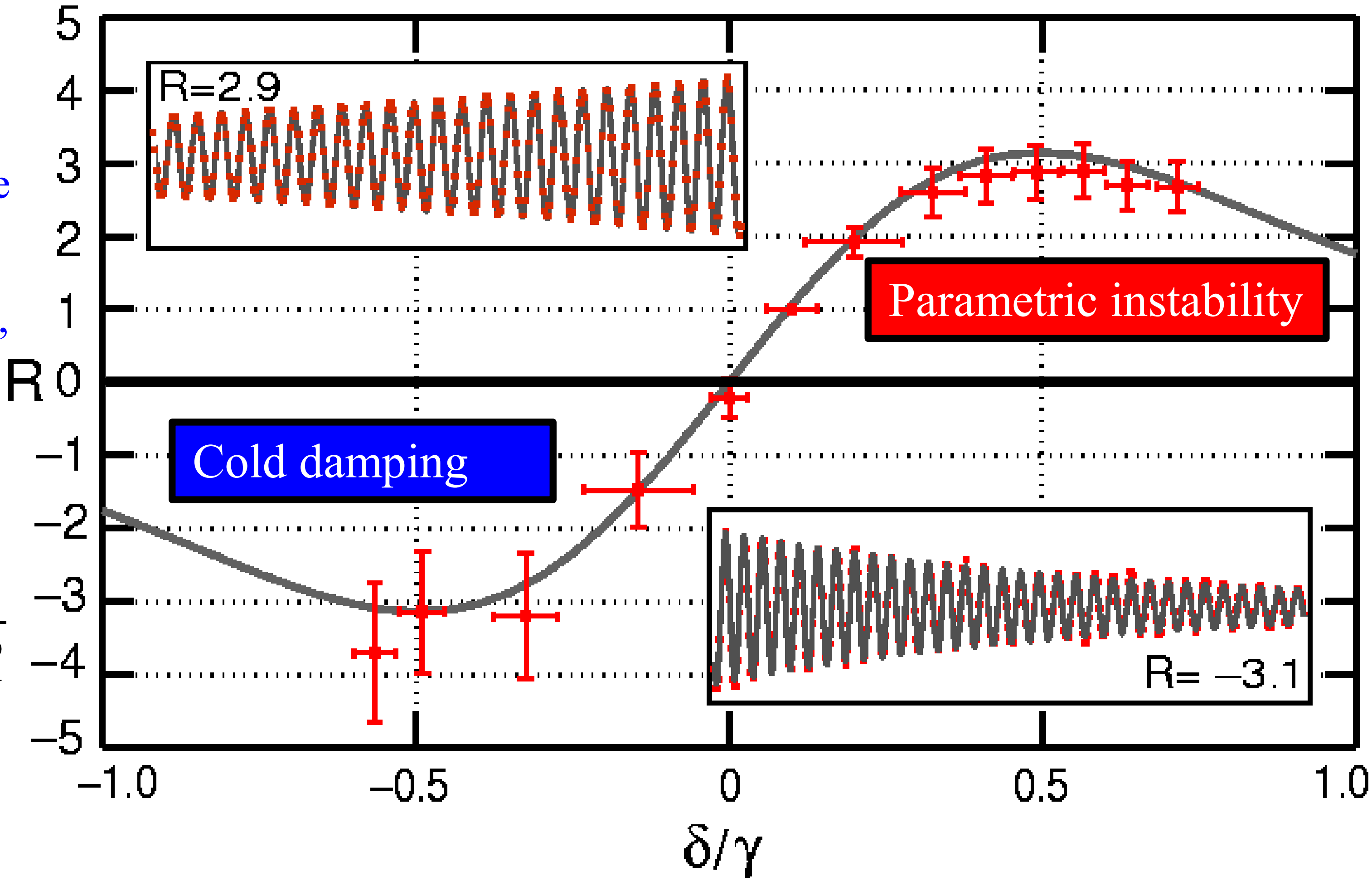
Parametric instability observed and damped!

Acoustic drumhead mode of one mirror became unstable when detuned at high power. The viscous radiation pressure force drives the mode to become unstable – PI! Also when detuned to opposite direction, the Q of the mode is decreased – cold damping!

The mode was stabilized through feedback to the frequency of the laser.

If not stabilized, the mode rings up until cavity loses lock.

$$\tau_{eff} = \frac{\tau}{1-R}$$

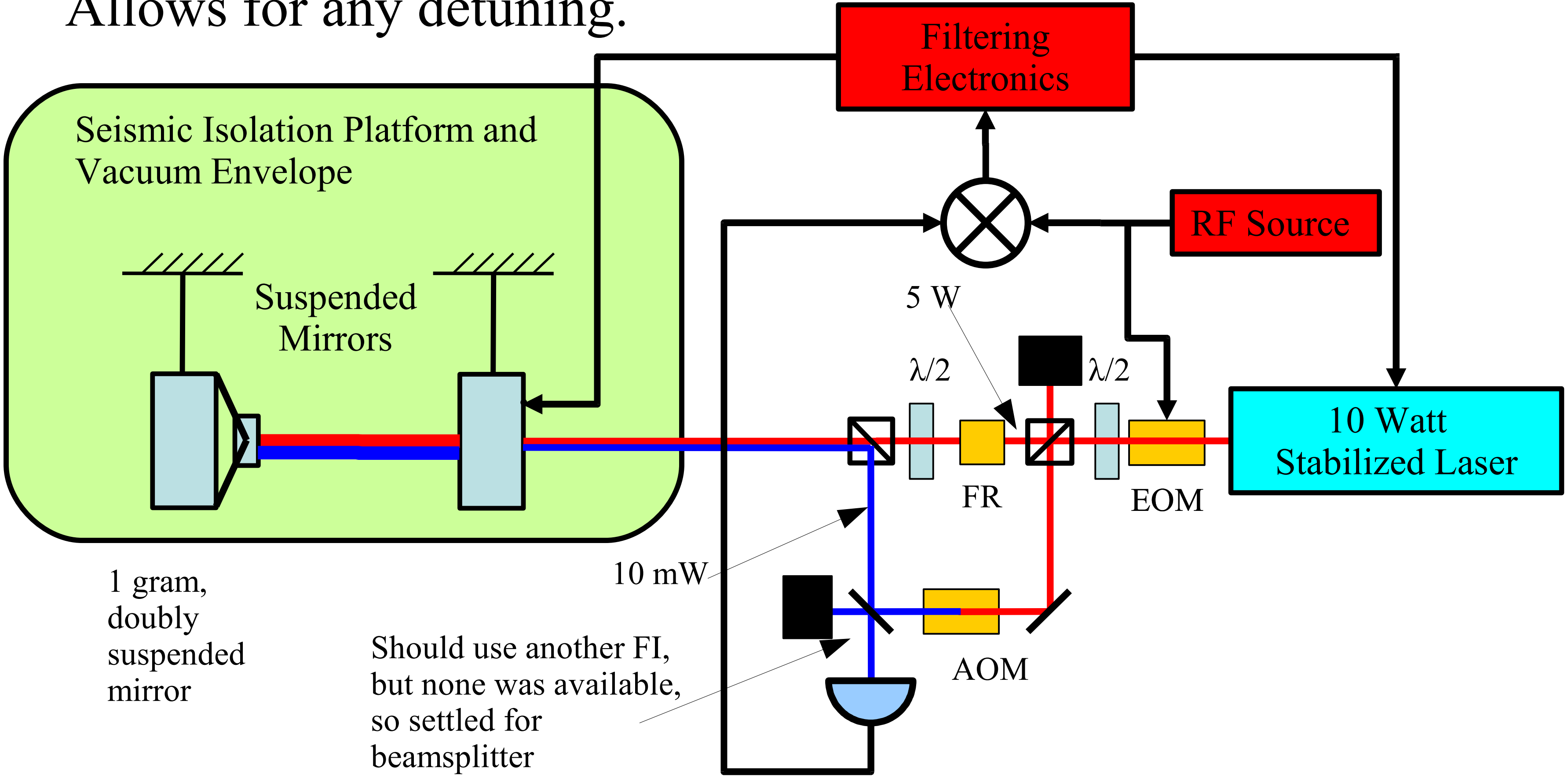


Phase II Cavity

- Use 250 g input and 1 g end mirror (same mirrors to be used in Phase III) in a suspended 1 m long cavity with goal of
  - PI R < 100 at full power
  - <1 MW/cm^2 power density
  - Optical spring resonance at > 1 kHz
  - Same performance as single cavity of Phase III
- Final (low thermal noise) suspension for 1 g mirror was not ready, so
  - Double suspension
- Goals for this stage
  - See noise reduction effects
  - Get optical spring out of the servo bandwidth
  - See instability directly and damp it

Phase II Experiment

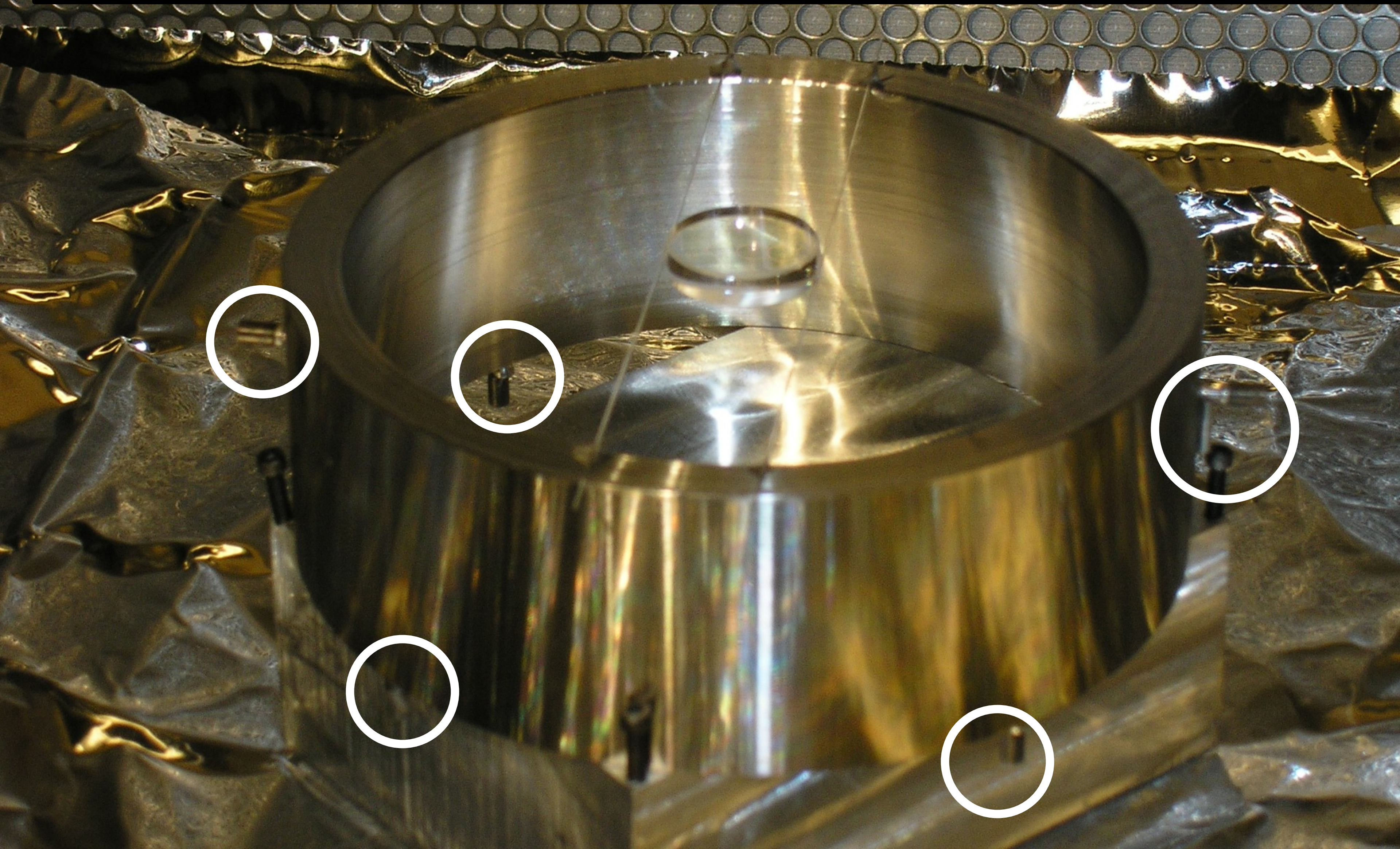
Frequency shifted light (by 1 FSR) is always locked on resonance. By controlling the frequency shift, we detune the pump beam, but frequency shifted light stays on resonance! Allows for any detuning.



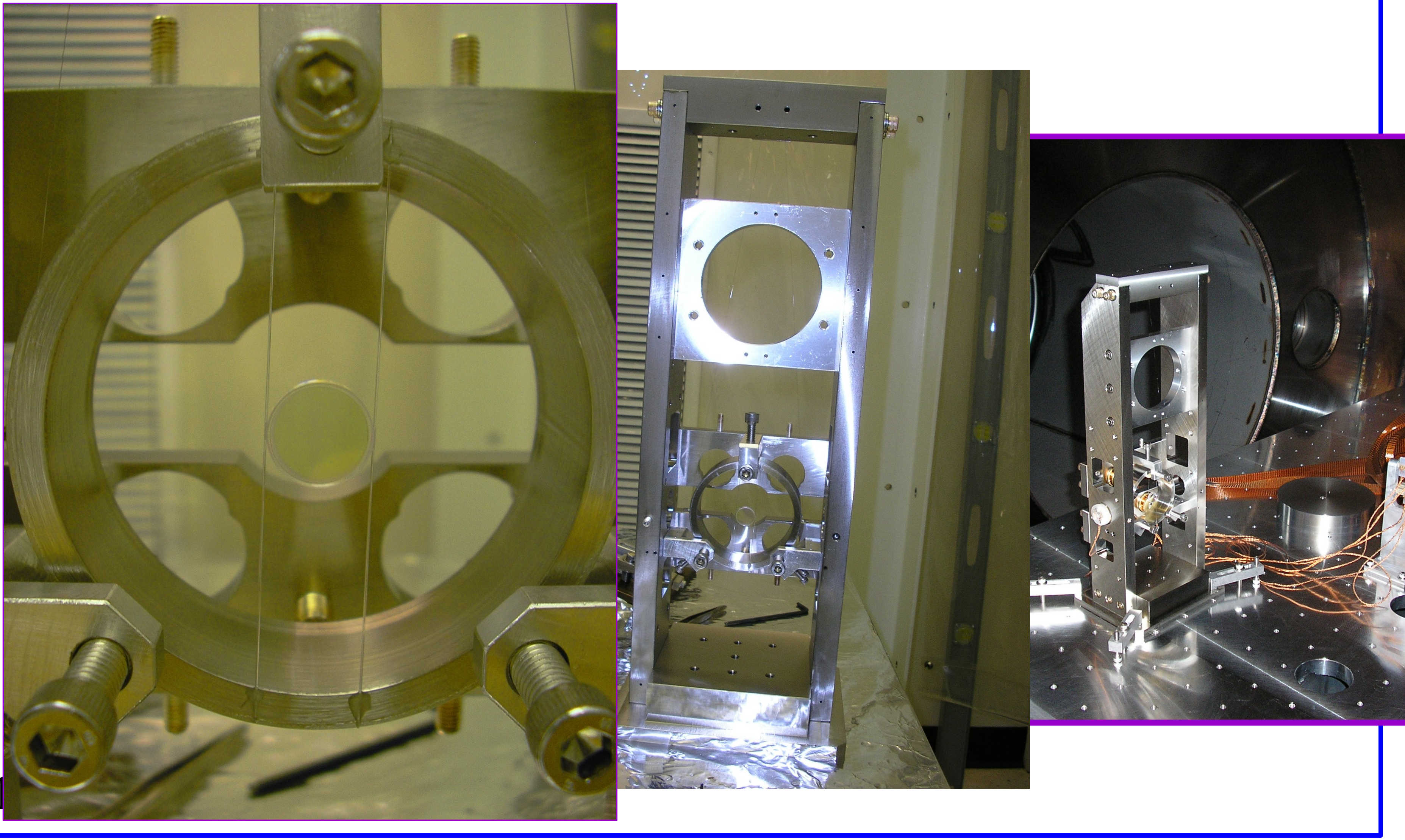
1 gram, doubly suspended mirror

Should use another FI, but none was available, so settled for beamsplitter

Steel shell with same diameter as small optics. Suspended as a small optic with magnets, standoffs, etc. Little mirror attached by two 300 micron fused silica fibers. All glued together.



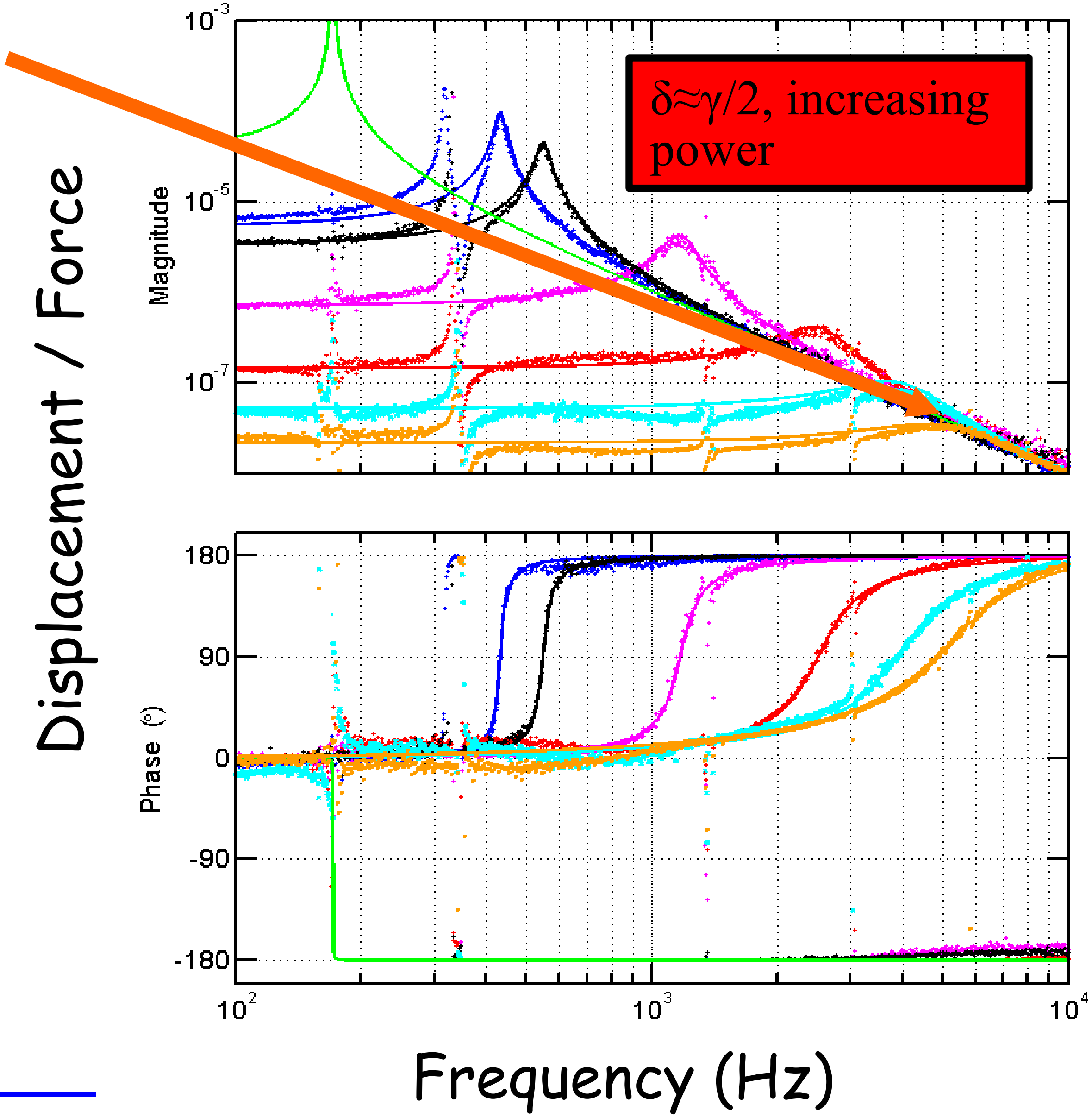
Double suspension for mini mirror



Noise suppression – response of cavity to external disturbance

5 kHz ➔K = 2 x 10^6 N/m (at DC)
Cavity optical mode - stiffest known material?

Twice as stiff as one would expect from a normal 5 kHz spring, due to cavity filtering of the optical rigidity.



δ≈γ/2, increasing power

How stiff is it...?

- Typical person weighs ~ 100 kg, so gravitational force is about ~ 1,000 N. Expected displacement for this force and stiffness is x = F / k = 0.5 mm.
- If one replaced the optical mode with a cylindrical beam with same radius (0.7mm) and length (0.92 m), it would need a Young's modulus of:
  - Cavity mode: ***1.2 TPa***
  - Compare to:
    - Steel: ~0.16 Tpa
    - Diamond: ~1 TPa
    - Single walled carbon nanotube: ~1 TPa (fuzzy)
- Very stiff, but also very easy to break. Maximum force it can withstand is only ~ 100 μN, or about 1% of the gravitational force on the little mirror.
- Optical rigidity is about the same as planned for Advanced LIGO, but operated on a mass 10^4 times smaller. Lessons from extreme case should be useful.

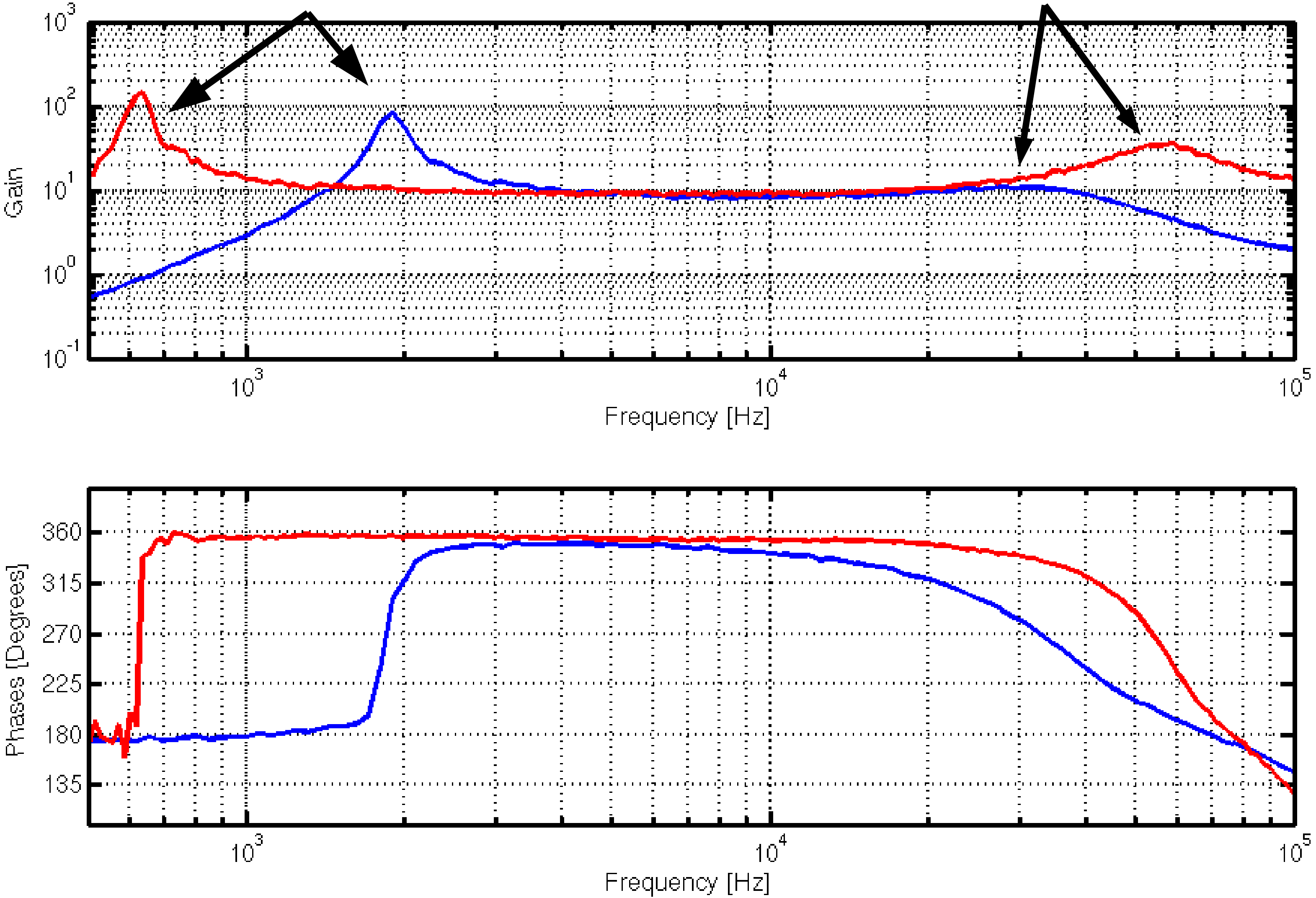
Doubly resonant cavity

Detuning = 30,60 kHz, Linewidth = 11 kHz

Optical spring resonance

Optical resonance

Optical gain



Some interesting numbers

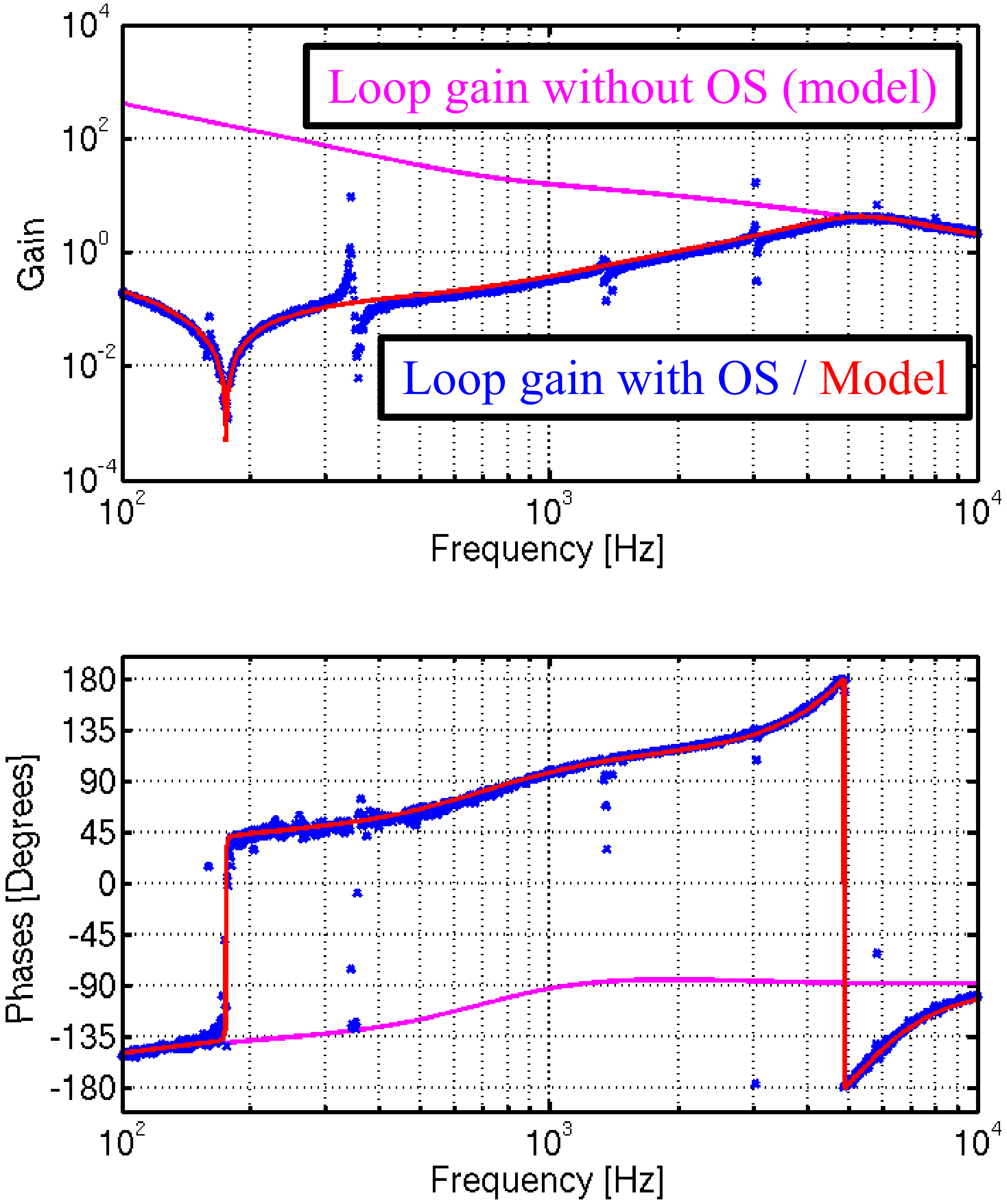
- Max circulating power ~ 25 kW.
- Power density on mirrors ~ 1 MW/cm^2.
- Constant radiation pressure force / gravitational force on little mirror is about 1%.
  - Higher finesse and smaller mirrors... levitated mirrors?
- Ringup time of stiffest optical spring in absence of damping: ~ 60μs.
- Q of drumhead mode of ITM is only 10^4 (in Phase I it was nearly 10^6).. what happened?
  - Works to our benefit since it avoids PI, otherwise we could see PI of nearly 100 in some cases. Very hard to stabilize. As it is, we see only a small PI at highest powers.
- We routinely operate at power levels that exceed the requirements for our ponderomotive squeezer. If we didn't have so much noise (laser and thermal), we could see squeezing now. Laser noise requires the IFO, thermal noise requires the new suspension.

Practical lesson

Optical rigidity makes cavity rigid to both force and frequency fluctuations. This can wreak havok on your control system! Our servo is overwhelmed by the optical stiffness.

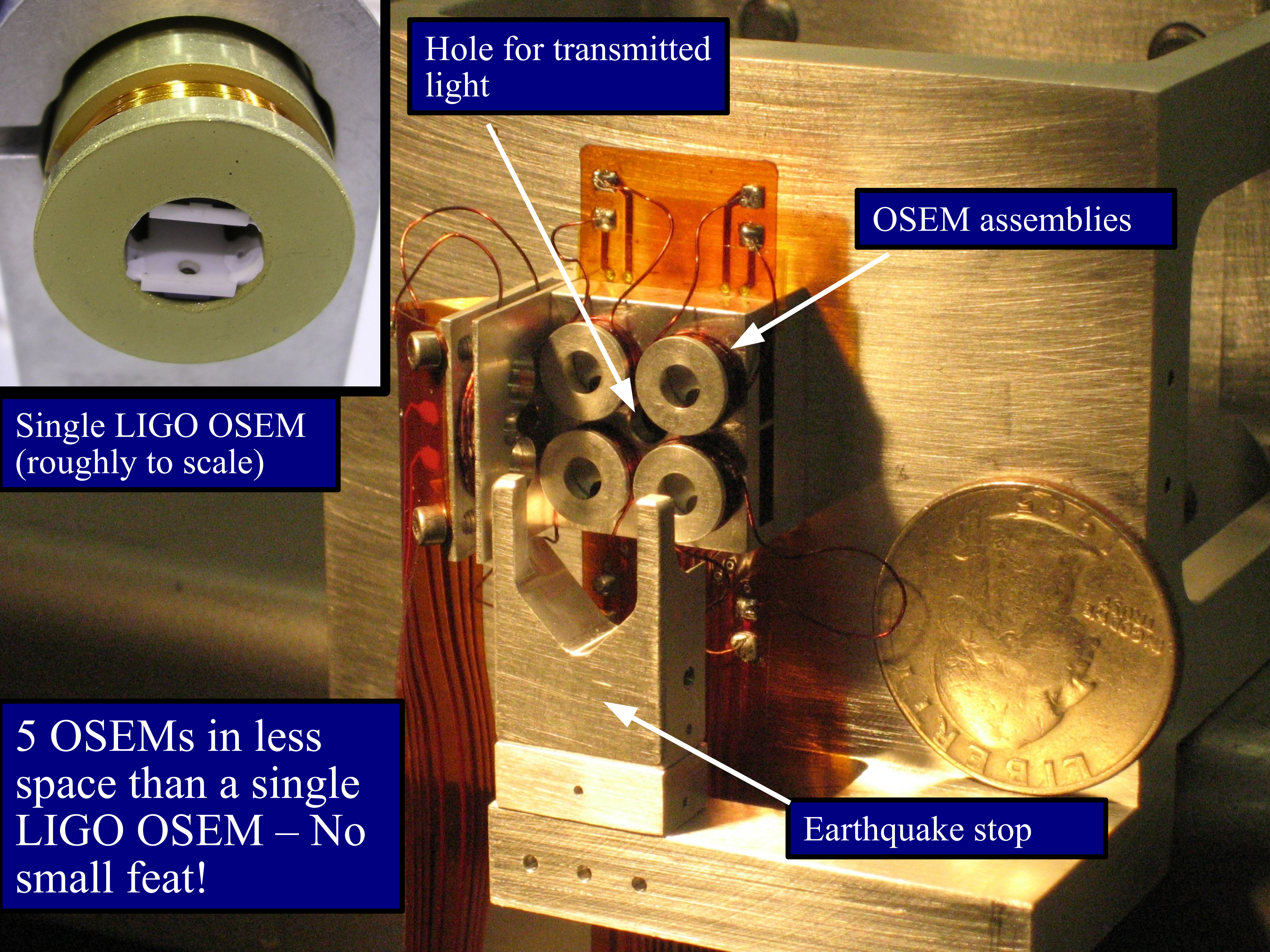
But this is actually a good thing, since the cavity becomes more stable, and the servo won't interfere with the dynamics – which is essential for ponderomotive squeezing.

Servo open-loop gain



What's next?

- Some remaining work for Phase II cavity
  - Low frequency instabilities (angle?)
  - Noise characterization
- Buildup to full IFO to begin in next few months.
  - Suspension of mini-optic is extremely difficult, but possible, and will happen.
  - Biggest remaining challenge to reach ponderomotive squeezing will be noise reduction.



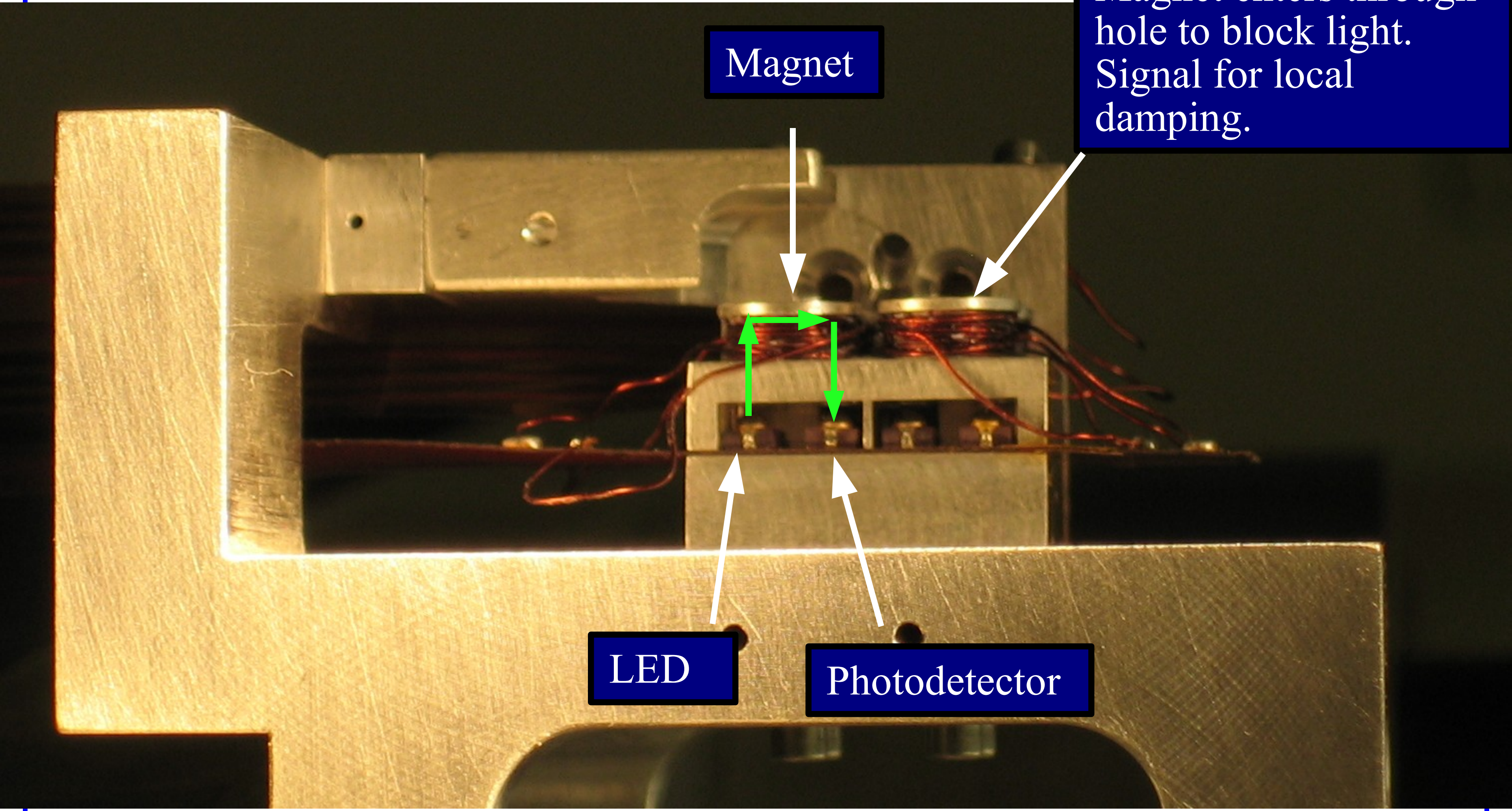
Single LIGO OSEM (roughly to scale)

Hole for transmitted light

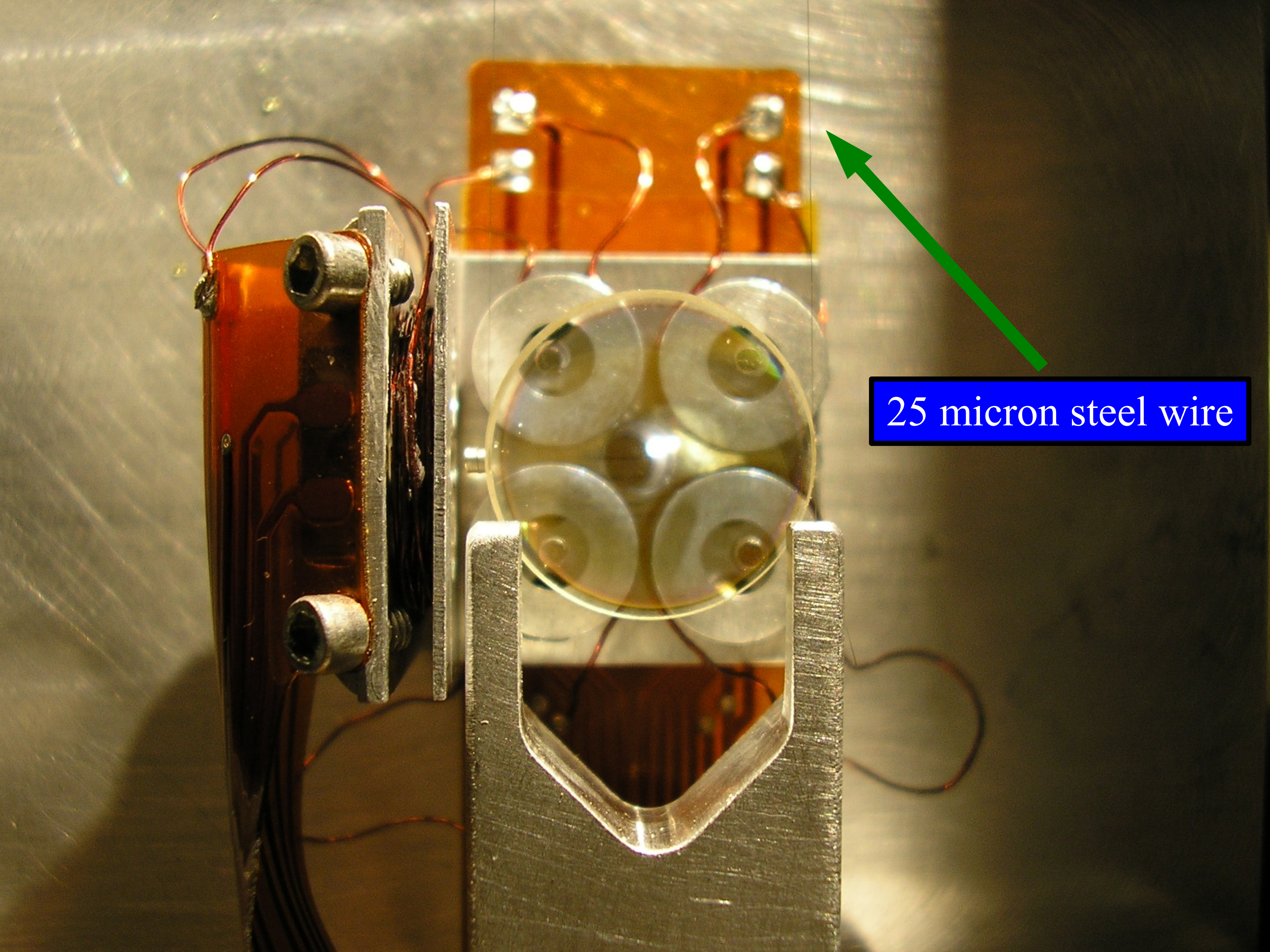
OSEM assemblies

Earthquake stop

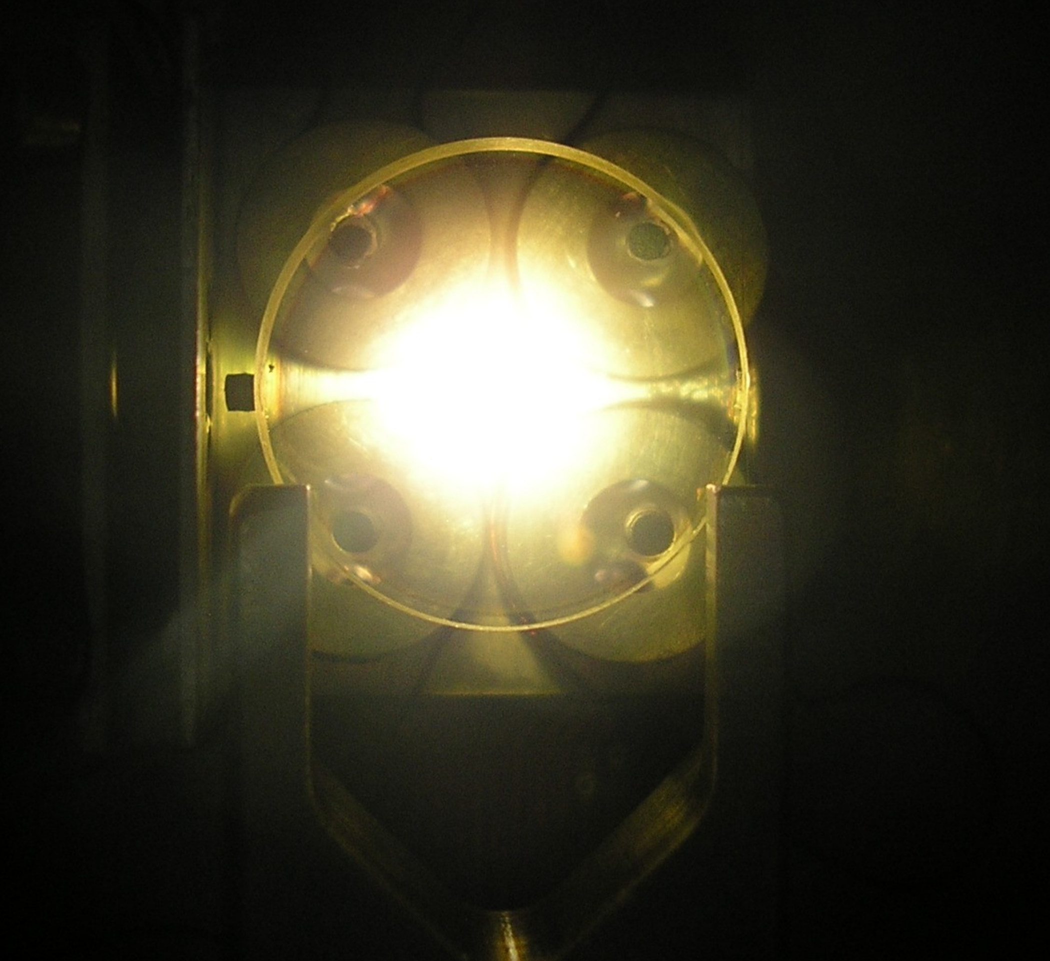
5 OSEMs in less space than a single LIGO OSEM – No small feat!



Inside surface of structure is curved and polished to reflect the light from the LED. Magnet enters through hole to block light. Signal for local damping.



25 micron steel wire



Why is this interesting/important?

- Optical systems that are radiation pressure dominated
    - Study modified mirror oscillator dynamics
    - Manipulate optical field quadratures
- Test of low noise optical spring
    - Suppression of thermal noise
- First ever demonstration of ponderomotive squeezing
- Probes quantum mechanics of optical field-mechanical oscillator coupling at 1 g mass scales (MACROscopic quantum measurement)
- Role of feedback control in these quantum systems

Conclusions

- Radiation pressure effects observed and characterized
    - Optical spring
    - Parametric instability
- Techniques for future experiments explored
    - Damping of extremely unstable OS
    - Control system interaction with OS and PI
    - Locking detuned cavities
    - Testing extremely high power (densities) on small mirrors
        - Nothing has blown up or melted (yet).
    - Operating a system that behaves as the ponderomotive squeezer will behave, at a higher noise level.