Enhanced and Advanced LIGO TCS

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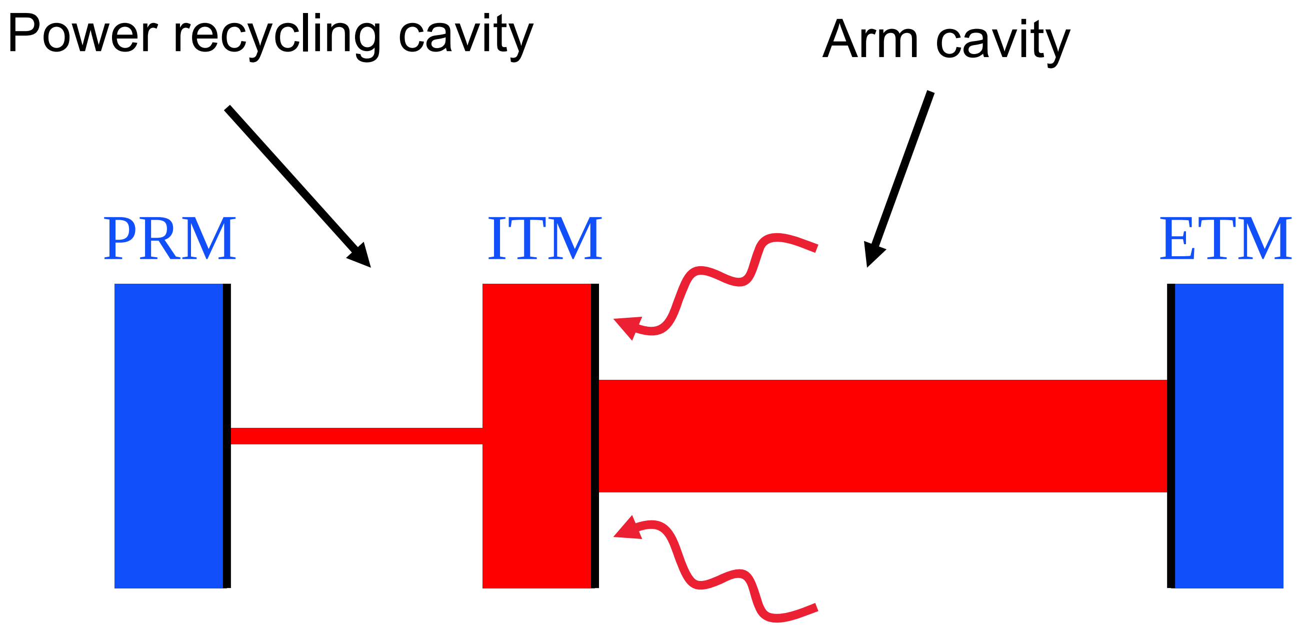
Hannover LSC-VIRGO Meeting, October 2007

LIGO-G070634-00-Z

Initial LIGO TCS

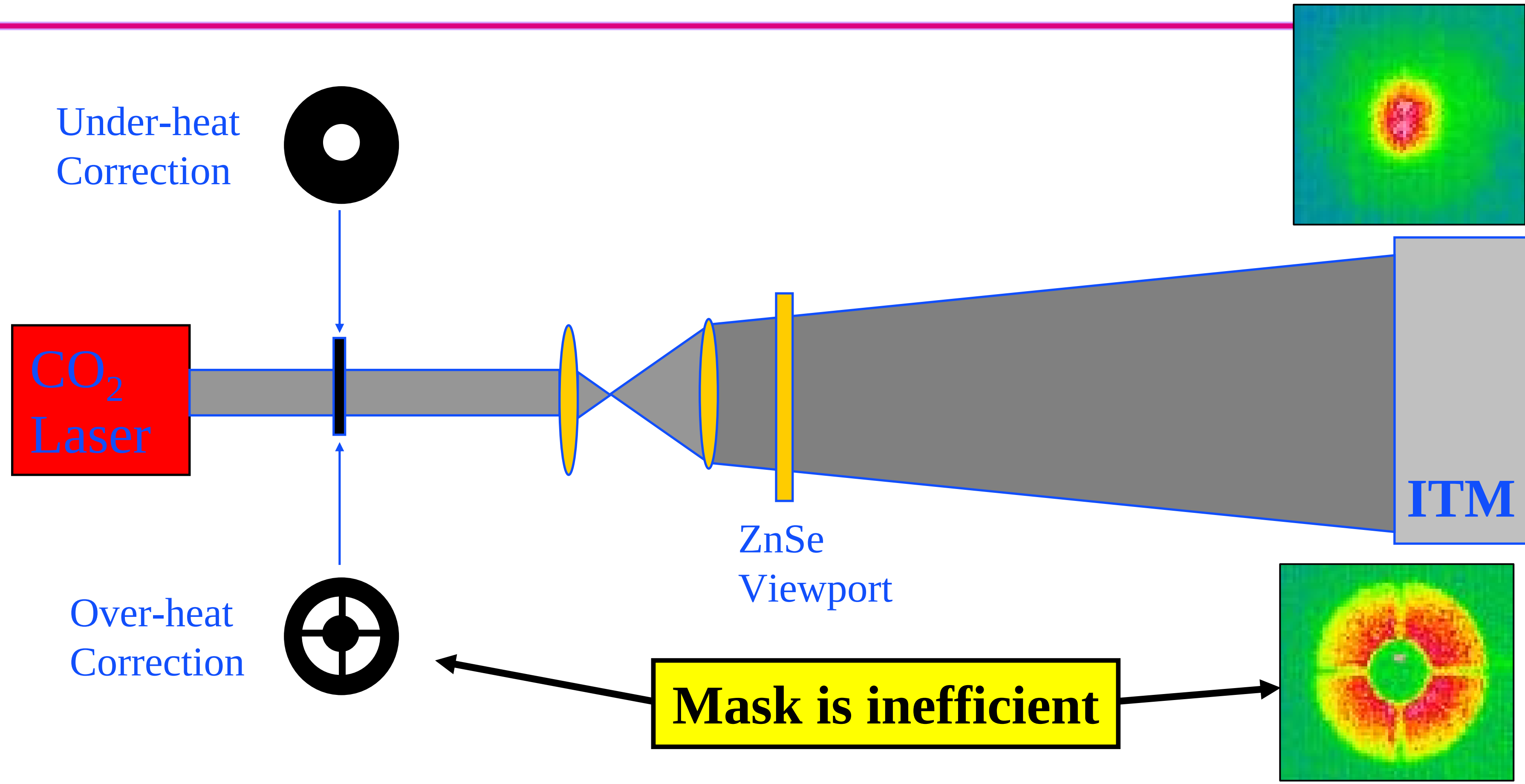
Initial LIGO

The Essence of the Problem, and of its Solution



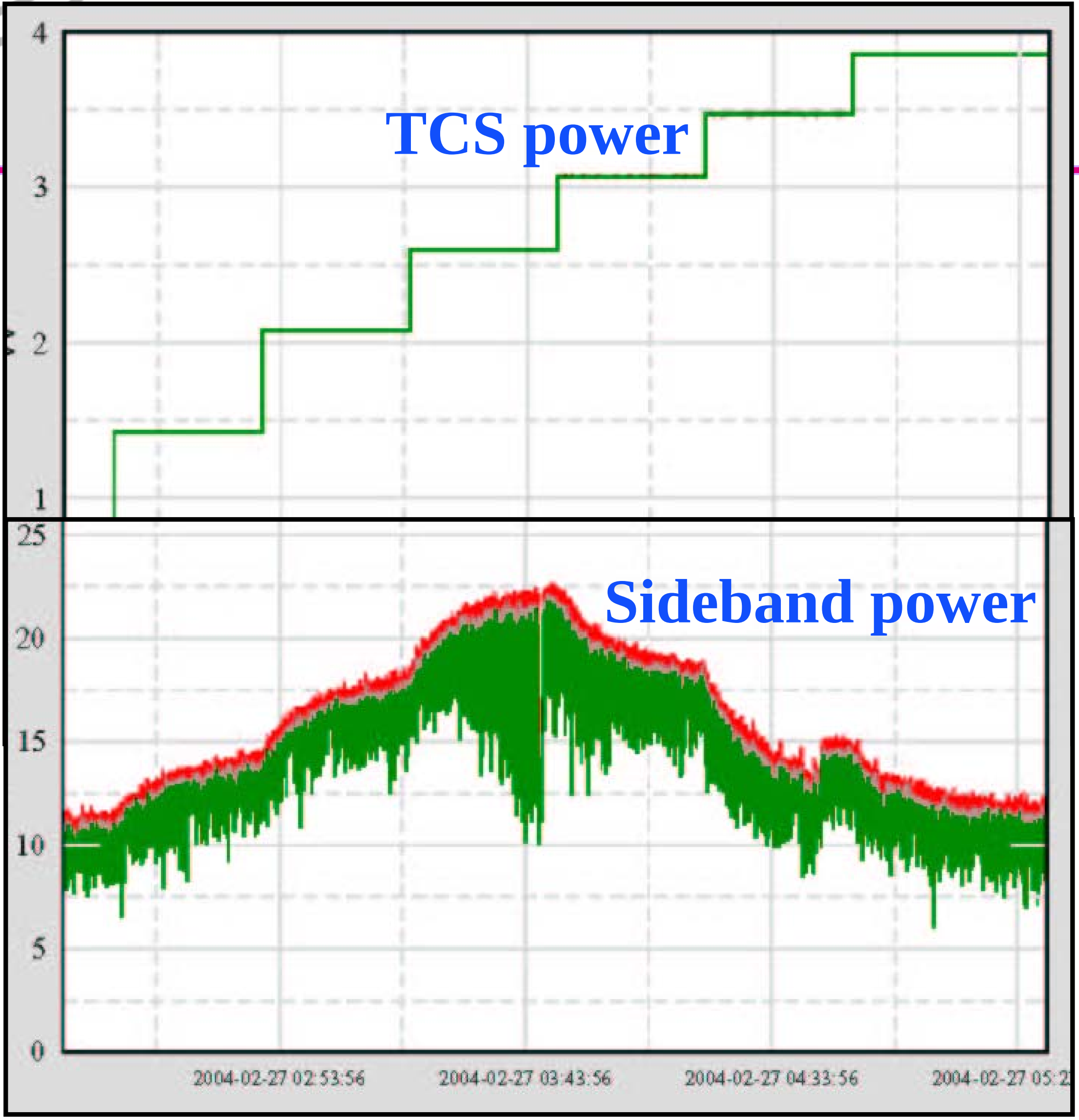
Optical power absorbed by the ITM creates a thermal lens in the (marginally stable) recycling cavity, distorting the **RF sideband** fields there.

LIGO CO_2 Laser Projector Thermal Compensator



- Imaging target onto the TM limits the effect of diffraction spreading

RF Sideband Power Buildup



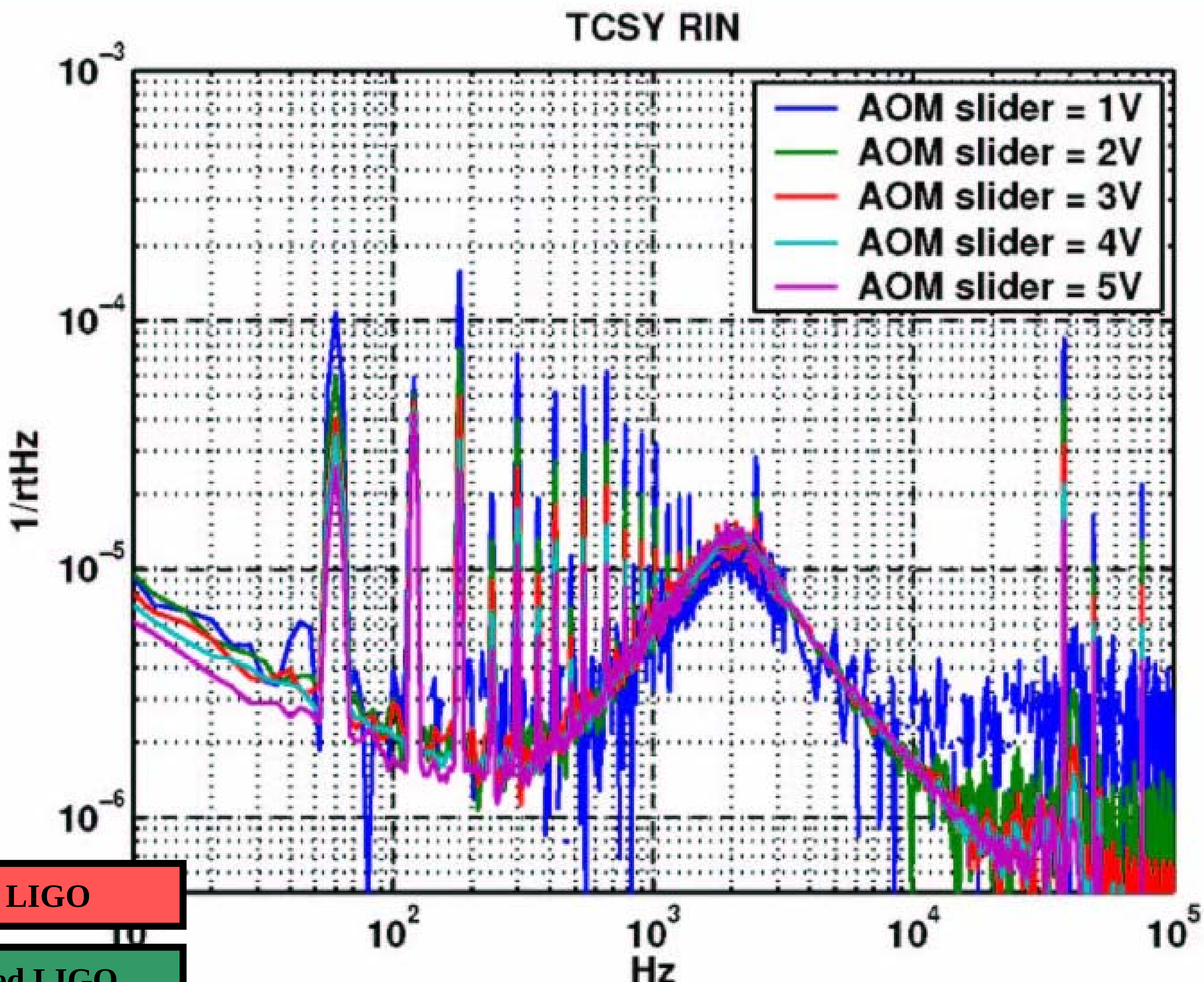
- Both ITMs heated equally
- Maximum power with 180 mW total heat

TCS Noise Issues

Initial LIGO

Enhanced LIGO

RIN of TCS-Y CO_2 Laser



Initial LIGO

Enhanced LIGO

TCS Noise Coupling Mechanisms

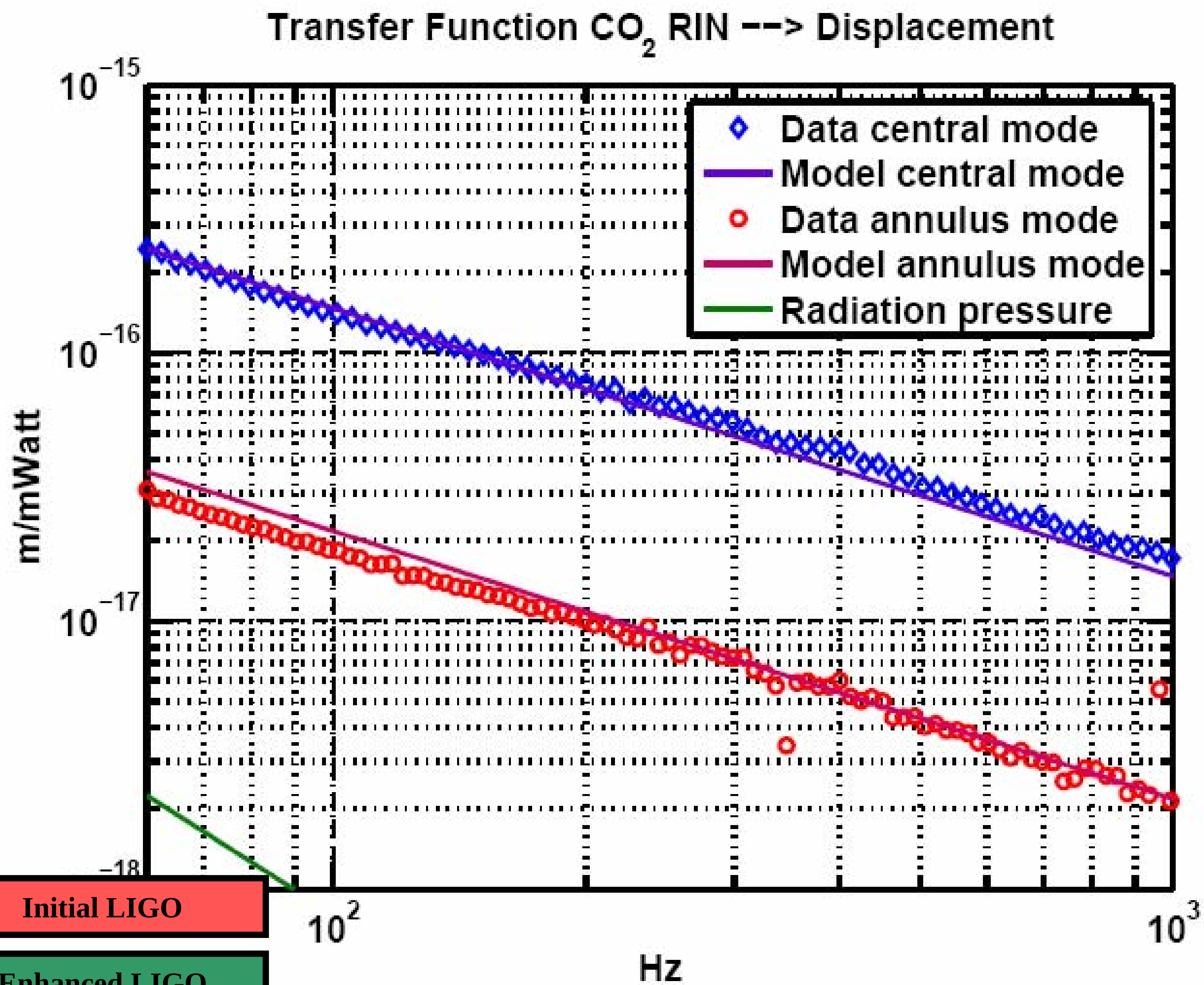
- Thermoelastic (TE)- fluctuations in locally deposited heat cause fluctuations in local thermal expansion
- Thermorefractive (TR)- fluctuations in locally deposited heat cause fluctuations in local refractive index
- Flexure (F)- fluctuations in locally deposited heat cause fluctuations in *global* shape of optic

TE, TR, F

$$\langle \triangle z \rangle = \frac{P}{2\pi f C \rho}\left(\frac{1}{\pi w^2}\left[(1+\eta)\alpha\left(1-\frac{\pi}{2\mathcal{F}}(n-1)\right)-\frac{\pi}{2\mathcal{F}}\frac{dn}{dT}\right]+\frac{6\alpha}{h^2}C^{\rm cen}_{\rm num}\right)\mathrm{RIN}$$

Initial LIGO

Enhanced LIGO



Initial LIGO

Enhanced LIGO

Enhanced LIGO TCS

Upgrading from Initial LIGO

Enhanced LIGO

Summary of upgrades

- Increase in TCS CO_2 laser power
  - » 30W input into cavity vs 7W input
  - » 35W Synrad lasers
- Intensity stabilization of laser **
  - » PD - AOM Servo loop
  - » Better electronics
- More efficient annulus **
  - » Previous: mask ≈ 30% efficient annulus
  - » Now: axicon ≈ 99% efficient annulus
- Chillers
  - » Quieter and more remote locations
- "Optical lever wavefront sensor" ? **
  - » Thermo-elastic surface deformation measurement using OL

Summary of Upgrades
Intensity Stabilization

Schematic of CO2 Intensity Stabilization Servo

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Intensity Noise Coupled into Displacement Noise

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Summary of Upgrades

More efficient annulus

The Axicon: 99.99% Efficient Annulus Production

Conical lenses

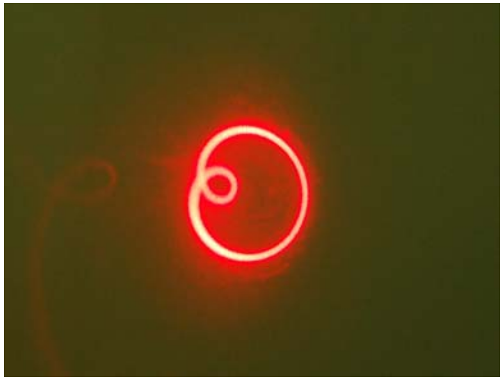
<u>Pros</u>

- Nearly 100% efficient annulus production
- Easy to adjust major and minor radii of annulus

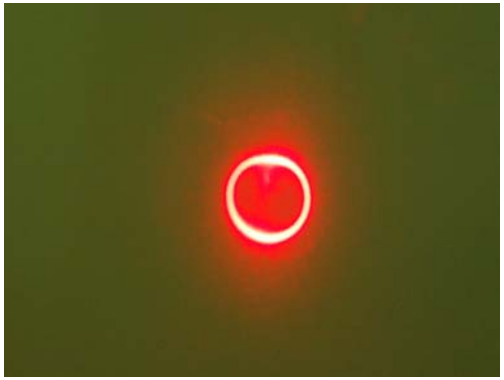
<u>Cons</u>

- Very sensitive to mis-alignment

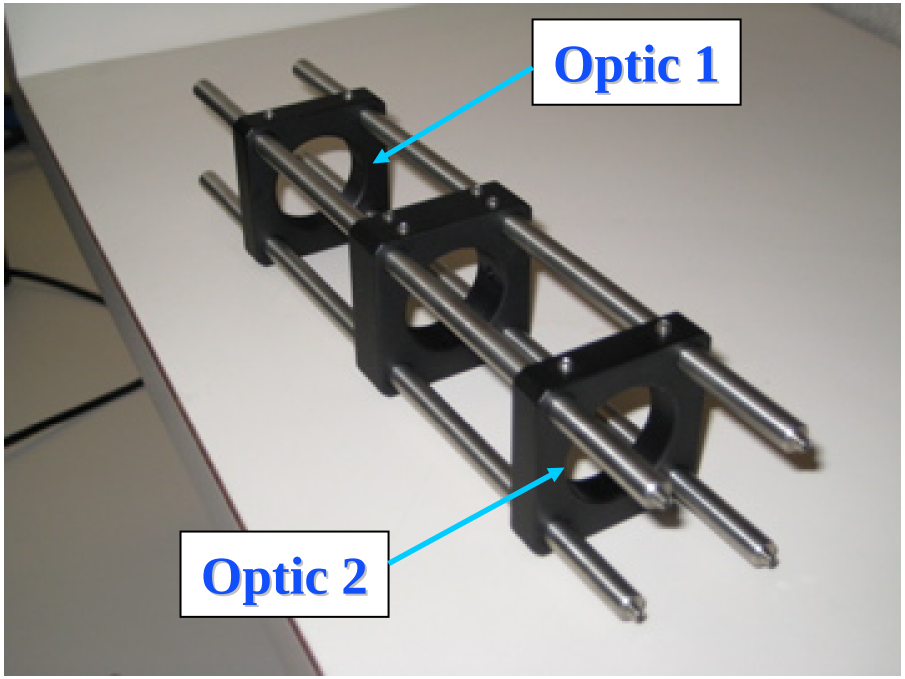
The Axicon: Alignment issues



Mis-aligned



Aligned (mostly)

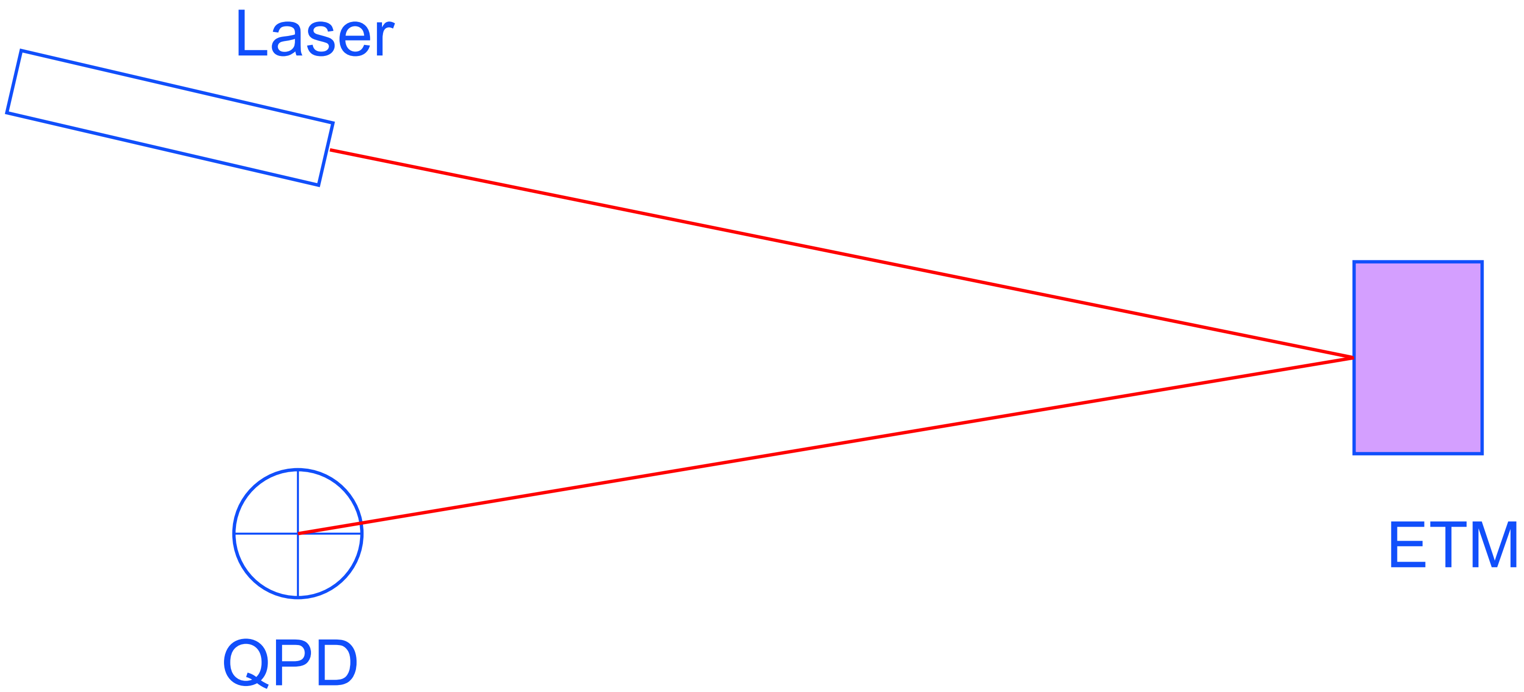


Mount for the axicon

Summary of Upgrades

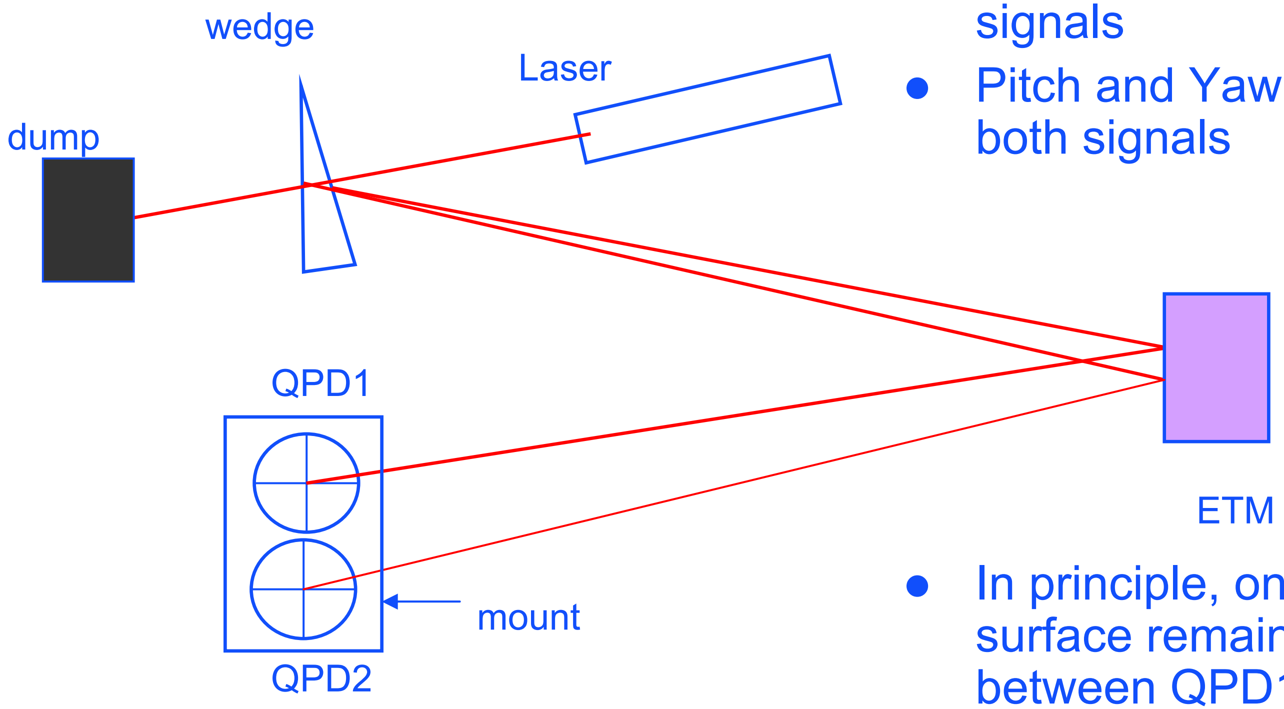
Sensing with Optical Levers?

What about the Optical Levers?



- Used to measure PITCH and YAW of the optics

Optical Lever Wavefront Sensor



- Seismic noise common to both QPD signals
- Pitch and Yaw of optic common to both signals
- In principle, only curvature of ETM surface remains in difference between QPD1 and QPD2

Advanced LIGO TCS

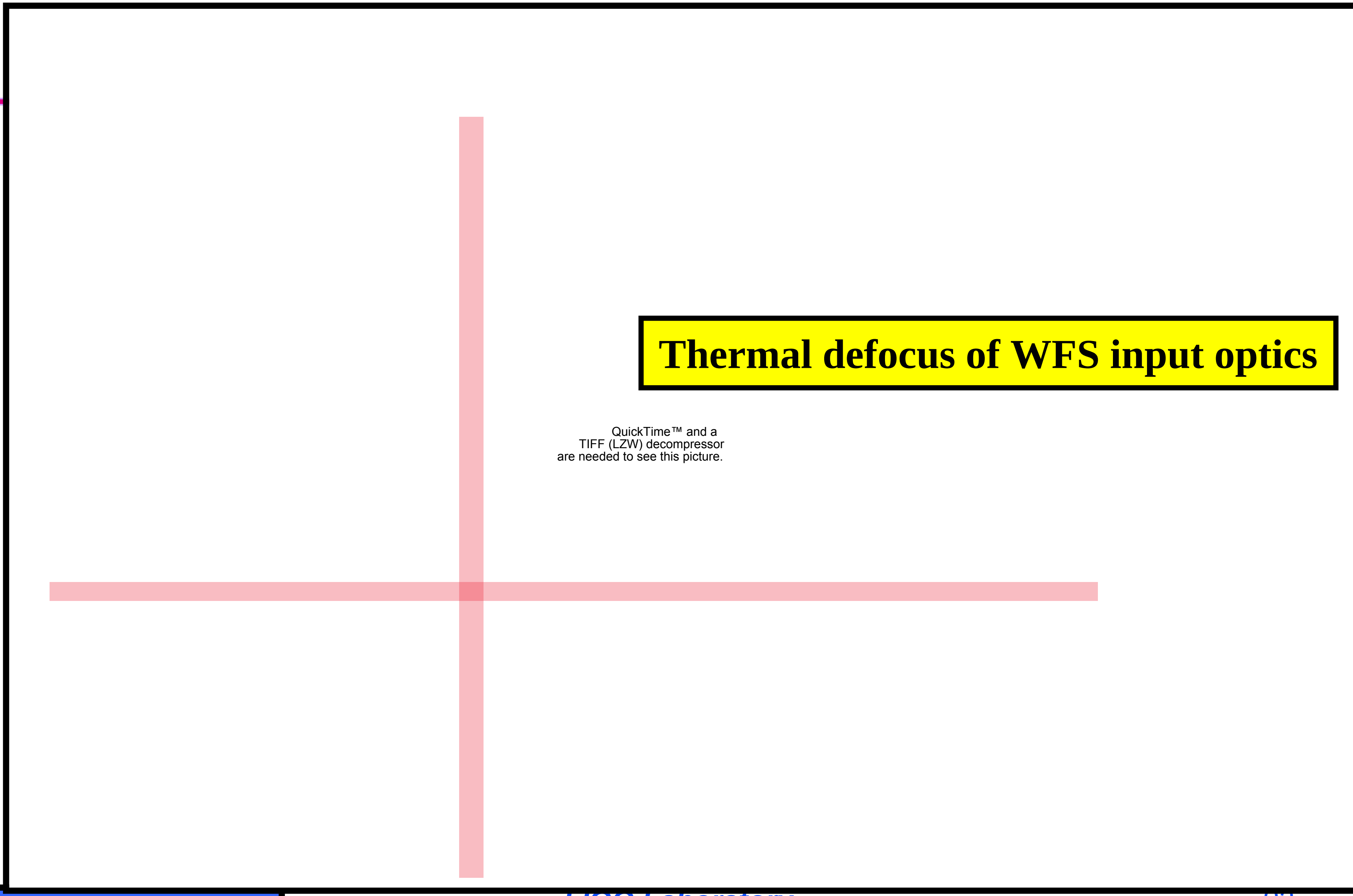
Sensing and Control

Advanced LIGO

Summary of AdvLIGO TCS

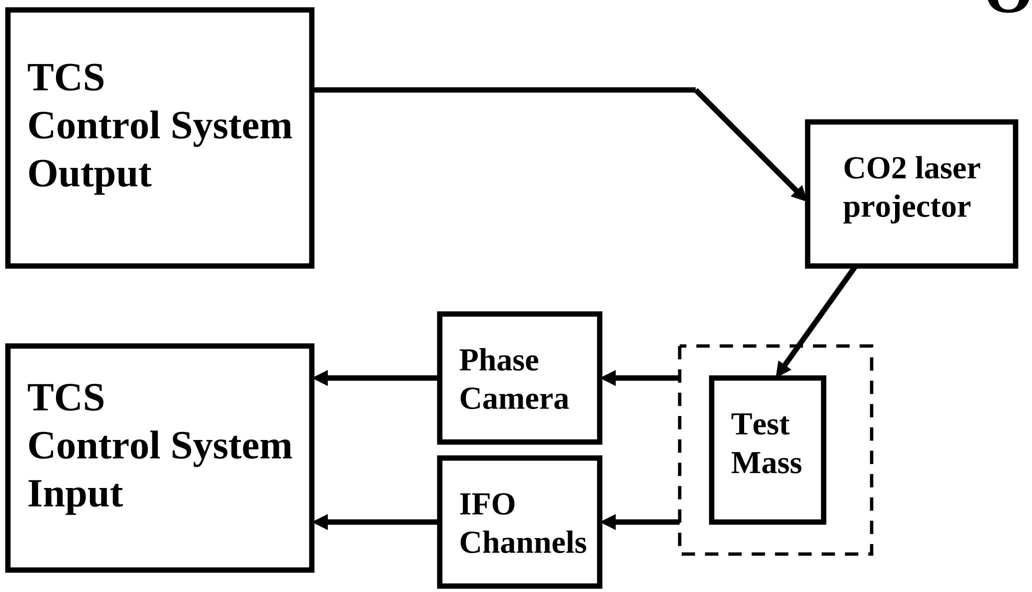
- Actuators - greater arsenal
  - Ring heaters
  - CO2 lasers
  - Compensation plates
- Sensors for each optic
  - Hartmann Wavefront Sensor
- Issues with design
  - Heating of ITMs by compensation plates
  - Thermal defocussing of relay optics

Advanced LIGO TCS schematic



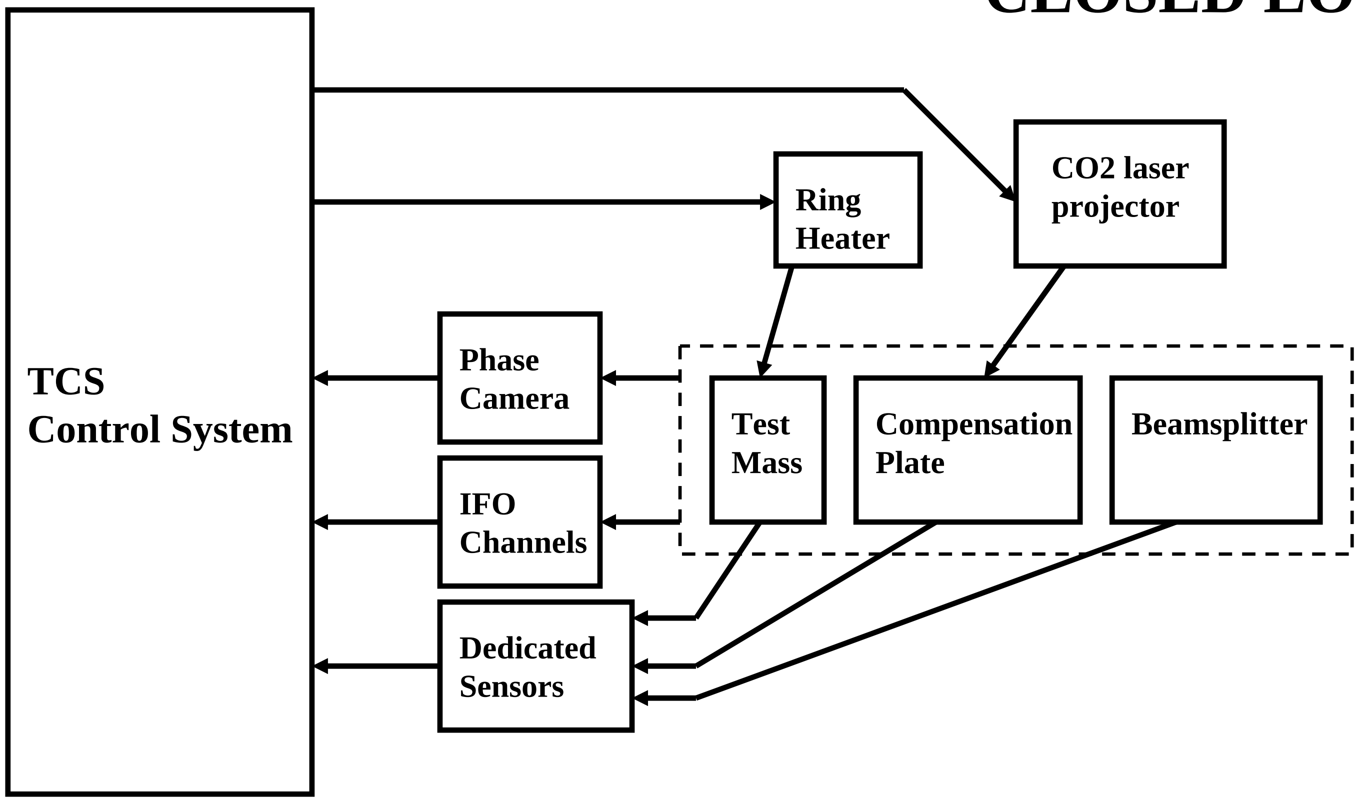
Sensing and Control Servo

OPEN LOOP



Sensing and Control Servo

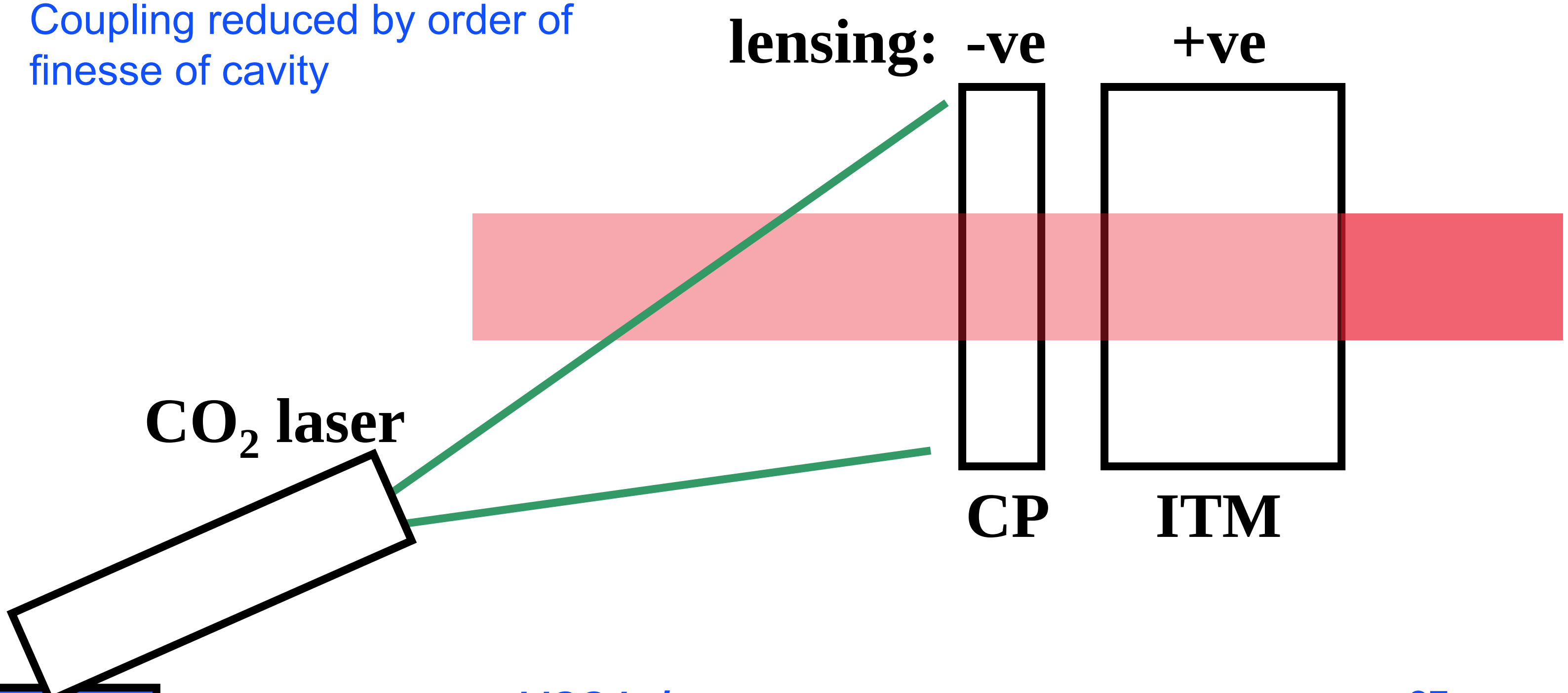
CLOSED LOOP



Actuators
Compensation Plate

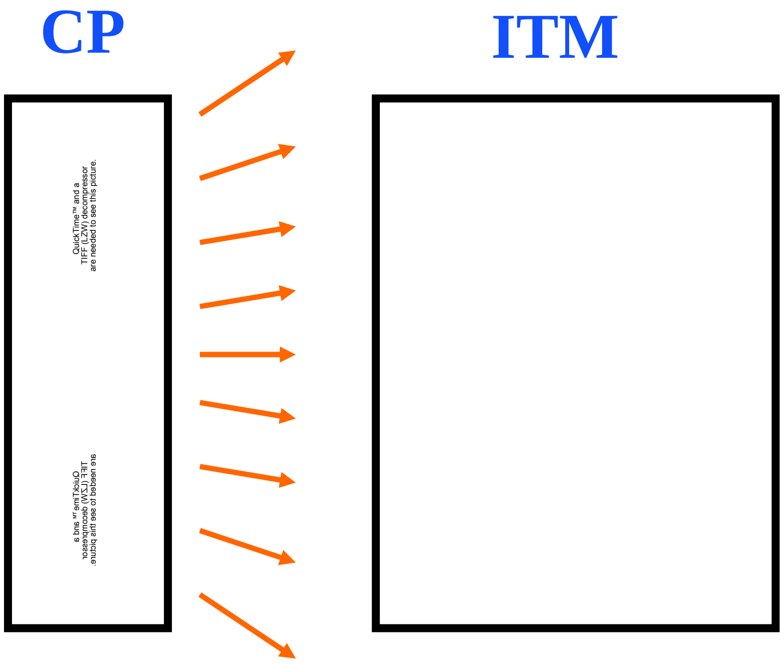
Compensation Plate (CP)

- Not acting on reflective optic
- Flexure noise is no longer an issue
  - » Coupling reduced by order of finesse of cavity



Heating of ITM by CP

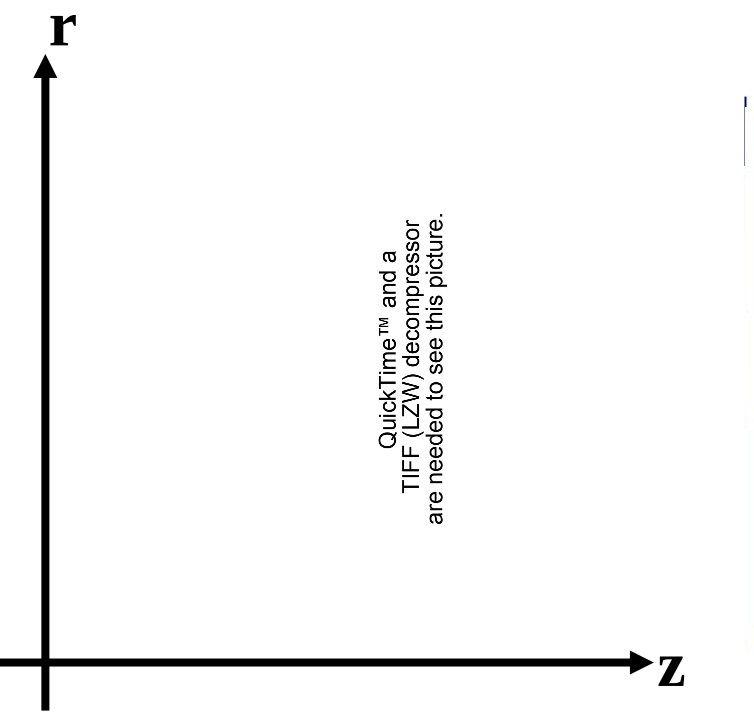
- CP gets hot
- Radiates onto ITM
- Induces positive thermal lens in ITM
- As much as 40% additional thermal lensing

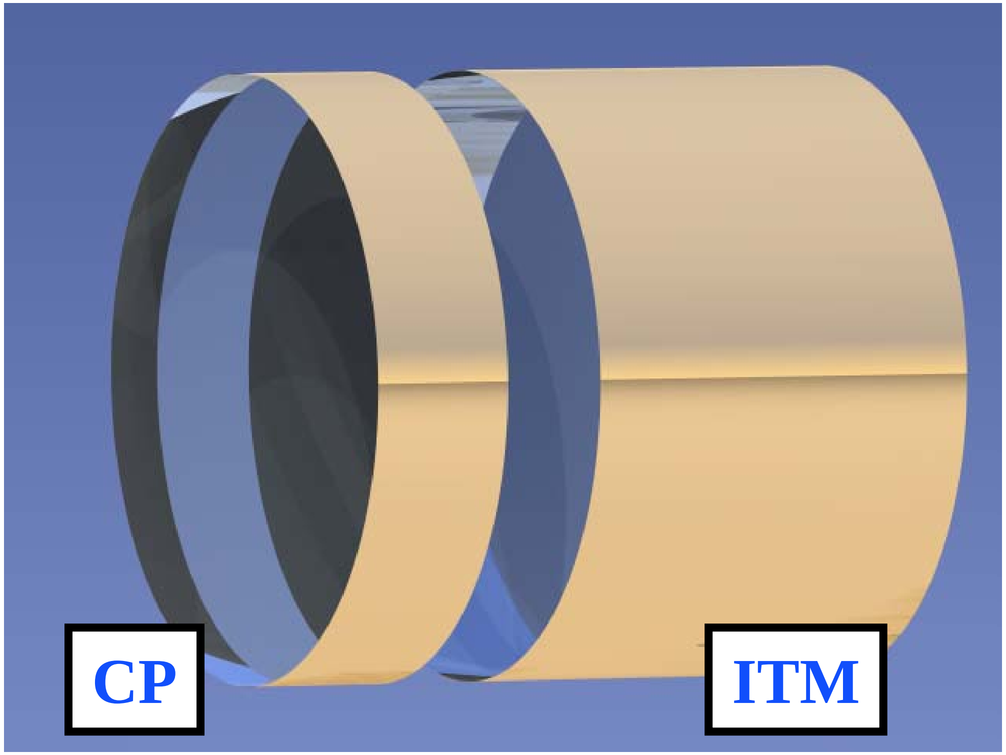


![LIGO]

ITM with barrel coating?
Heating from CP

Induced ITM thermal profile

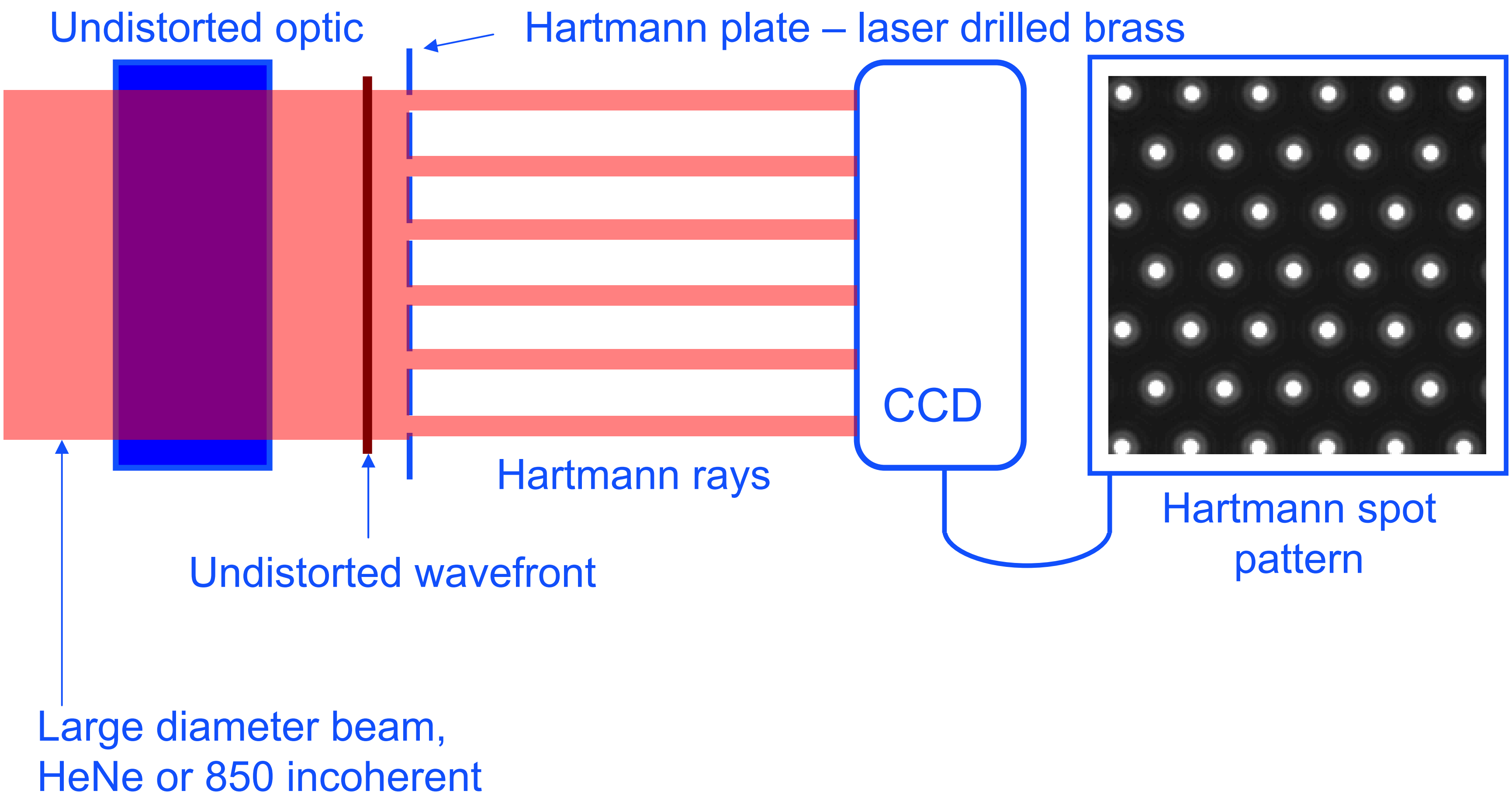




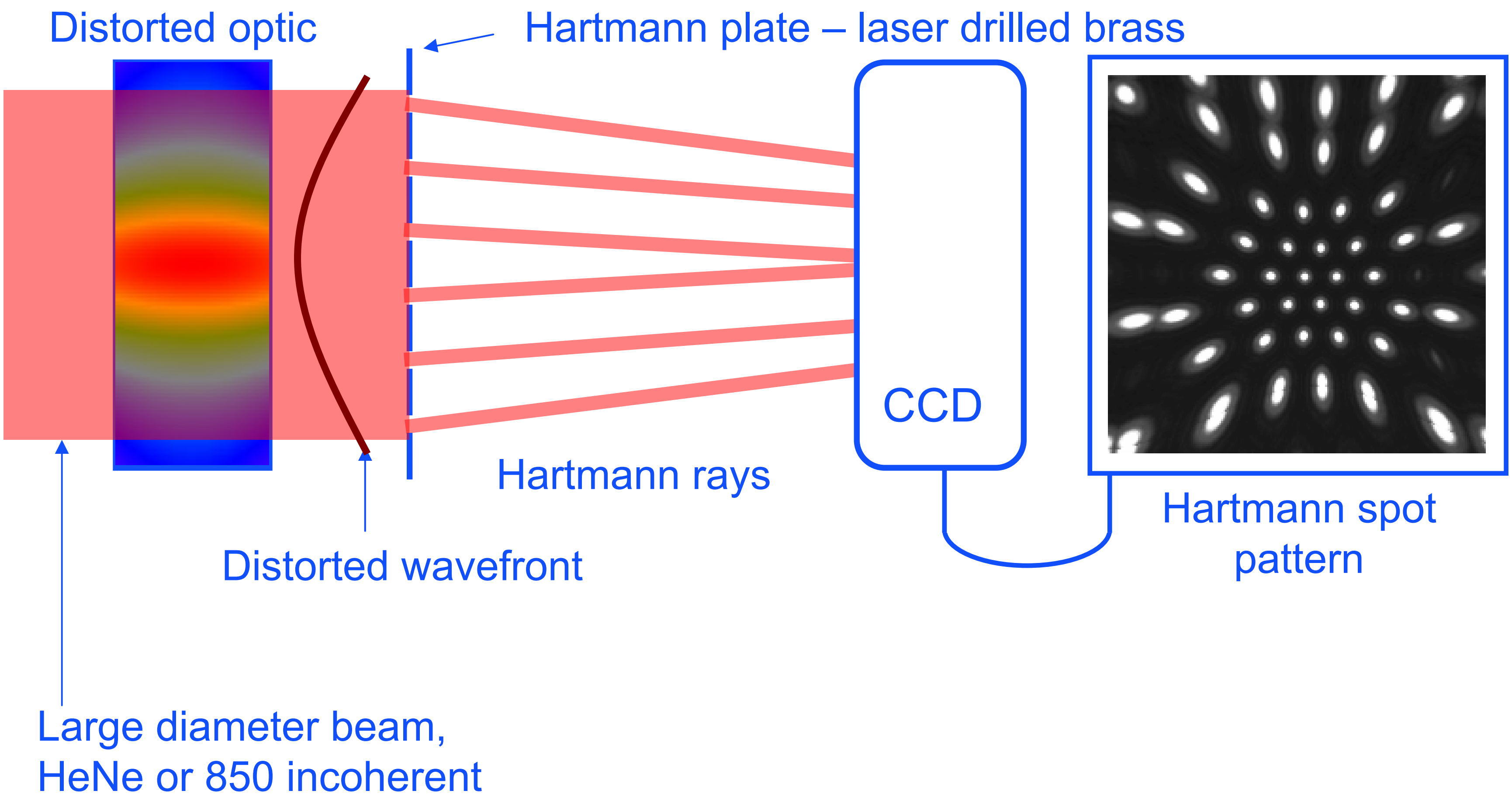
LIGO

Sensors
Hartmann Wavefront Sensor

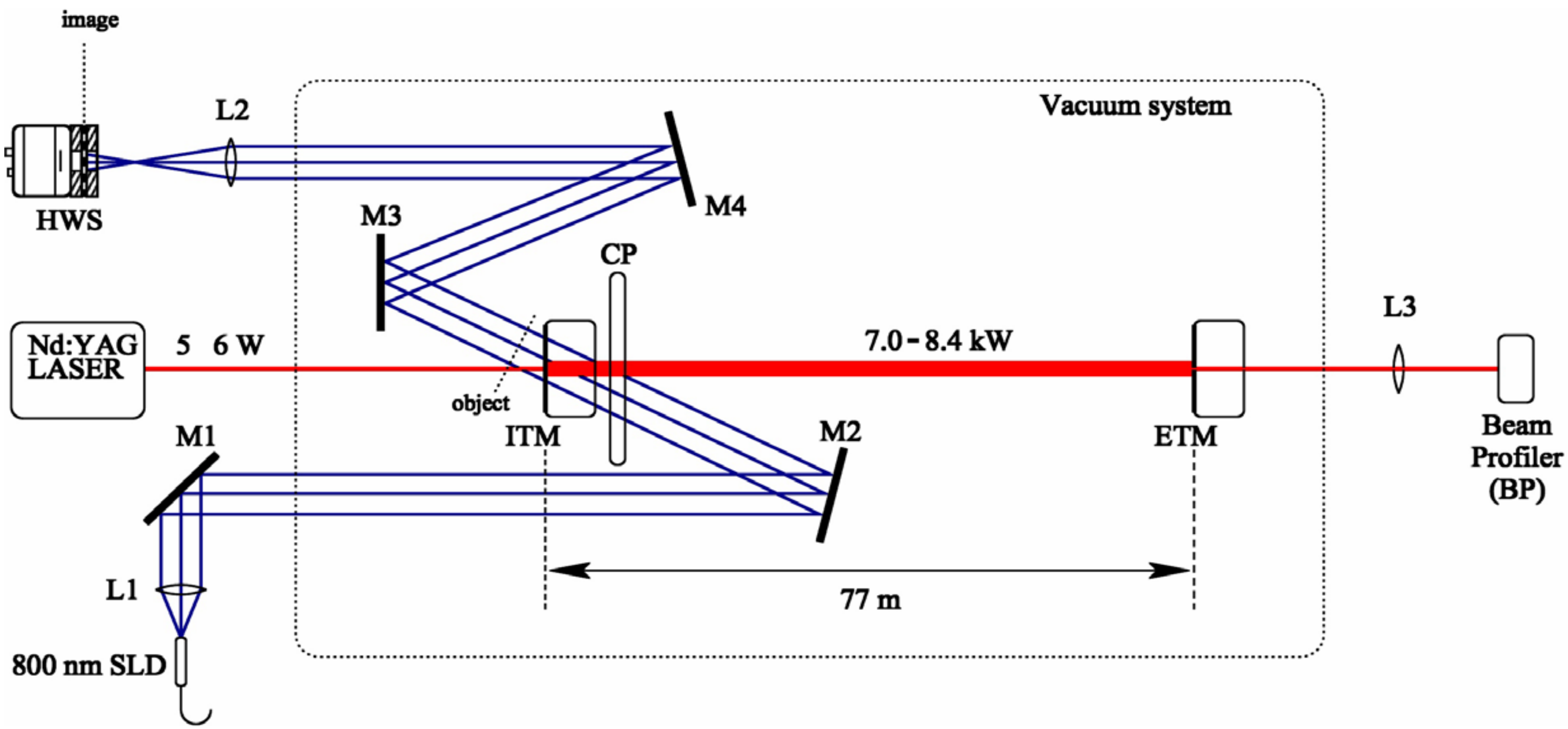
What is a Hartmann Wavefront Sensor?



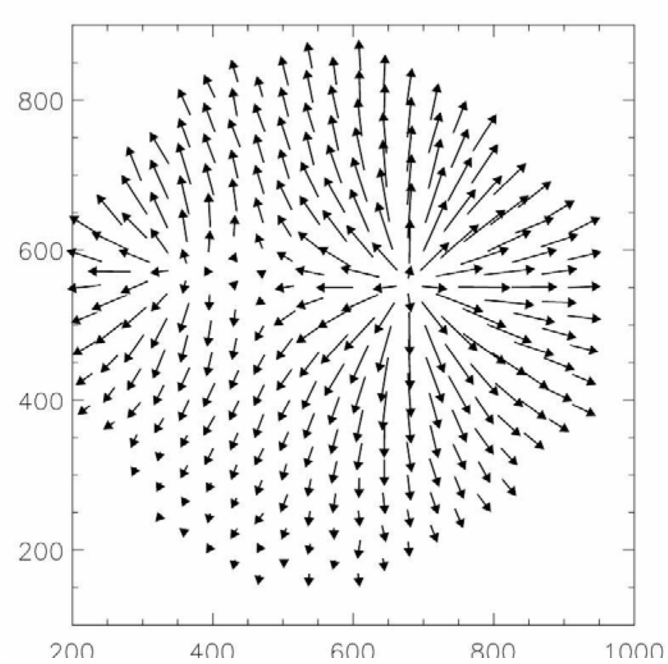
What is a Hartmann Wavefront Sensor?

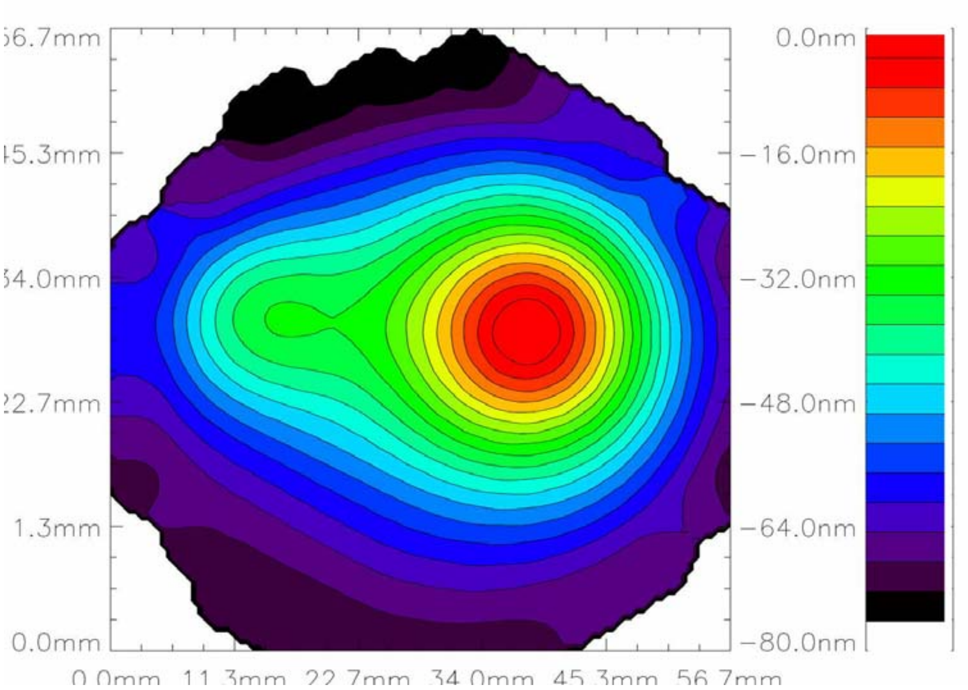


HWS + Fabry-Perot cavity



Measured HWS profile.
Cavity mode ON for 300s





Hartmann Sensor Beam Size Prediction

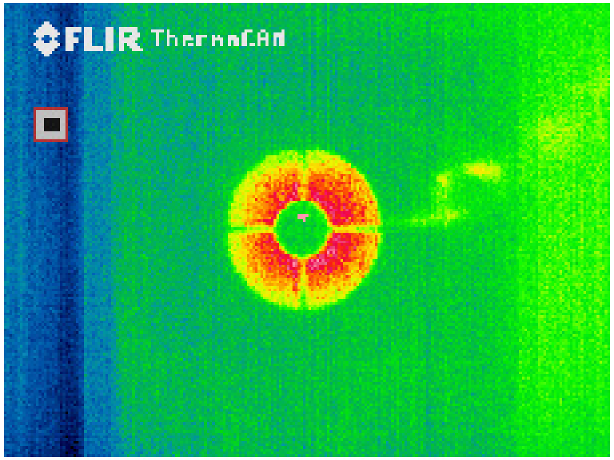
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Summary

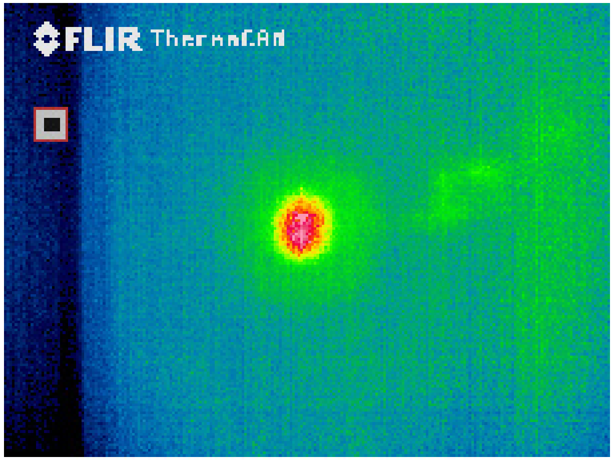
- TCS worked well for Initial LIGO
- Demands on TCS increase for eLIGO
  - » Current upgrades address these demands
    - – Axicon
    - – Intensity stabilization
    - – Increased power
- aLIGO TCS R&D is underway
  - » Primary design pretty mature
  - » Secondary design problems are being addressed
  - » HWS shown to be very effective

Supplementary Slides

Projector Heating Patterns



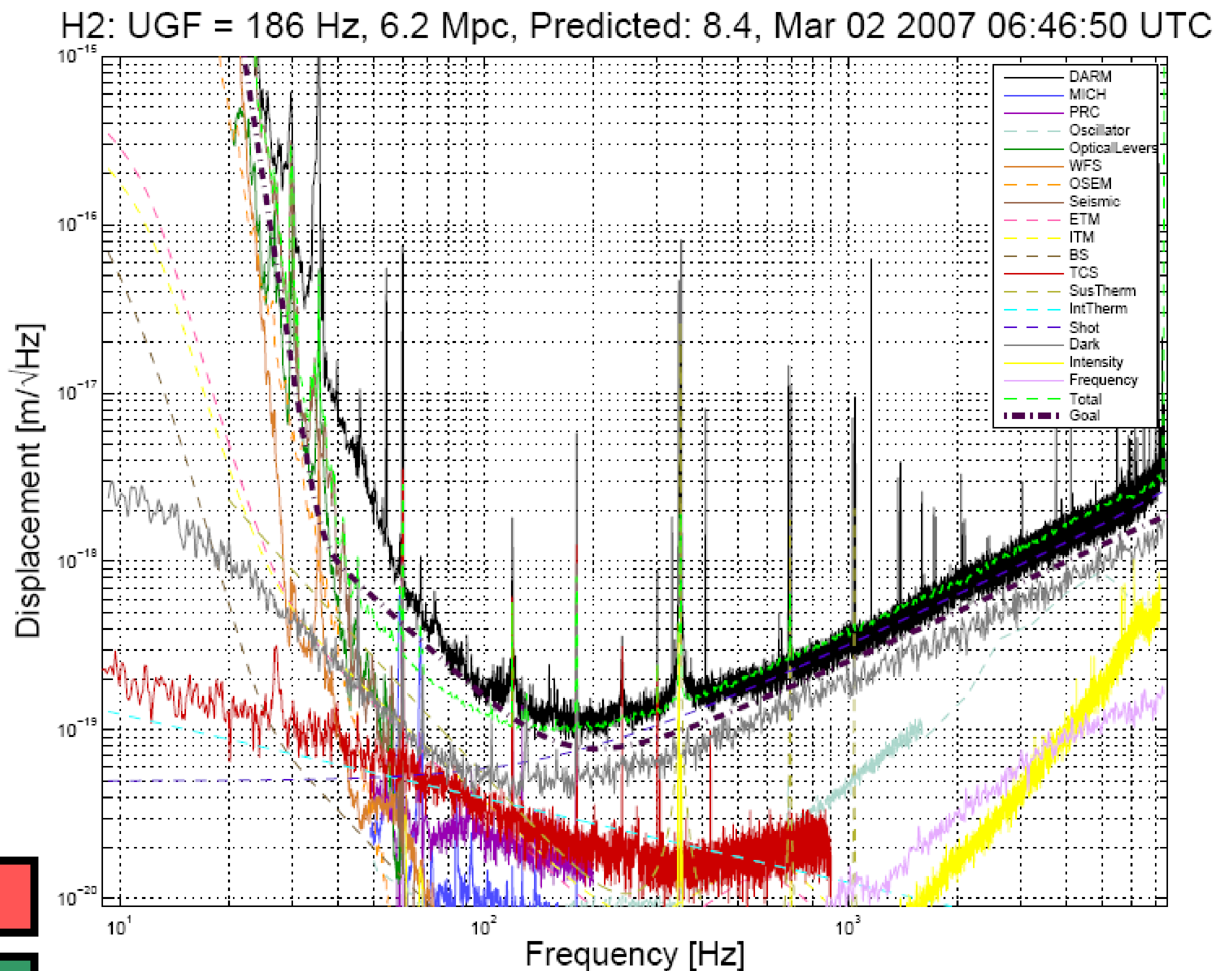
Annulus Mask



Central Heat Mask

- Intensity variations across the images due to small laser spot size
- Projection optics work well

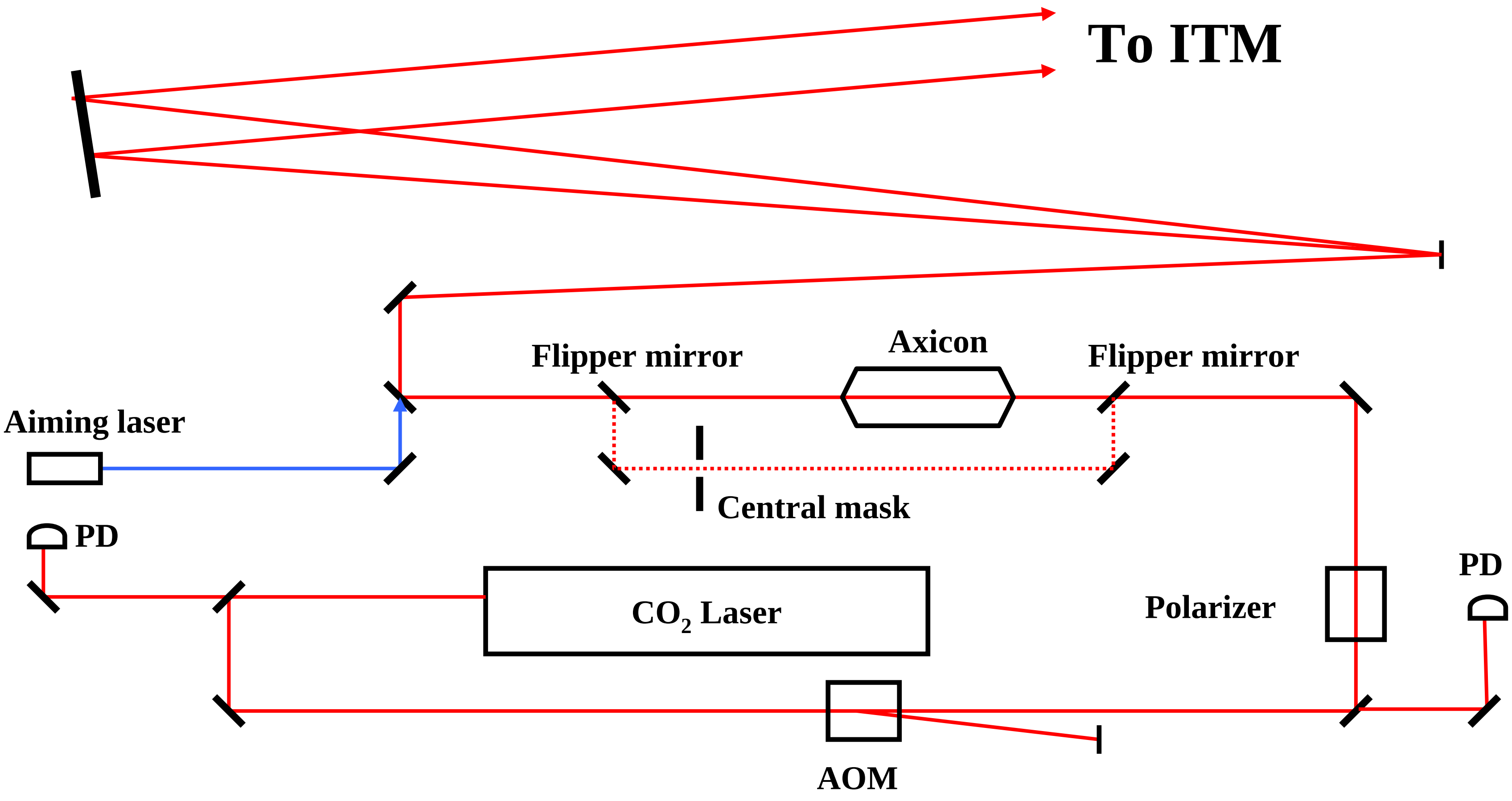
TCS Injected Noise Spectrum



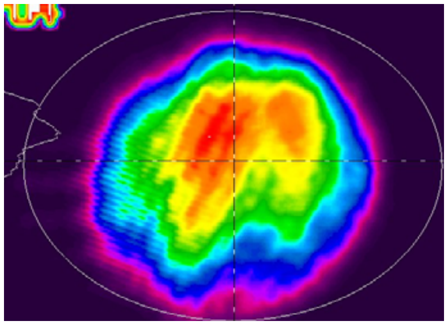
Initial LIGO

Enhanced LIGO

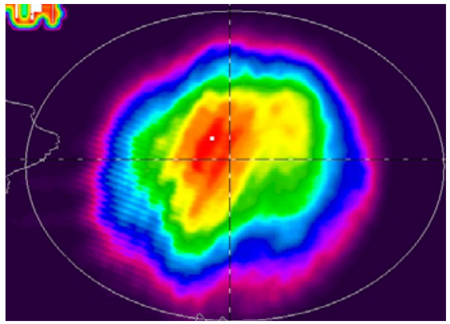
Enhanced LIGO TCS Projector



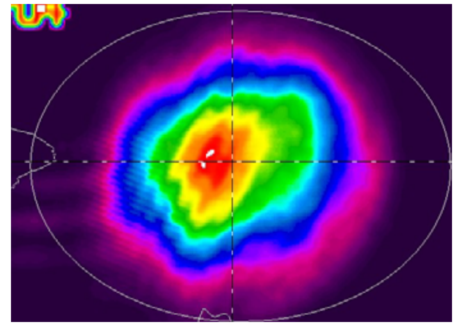
Heating Both ITMs in a Power-Recycled Michelson



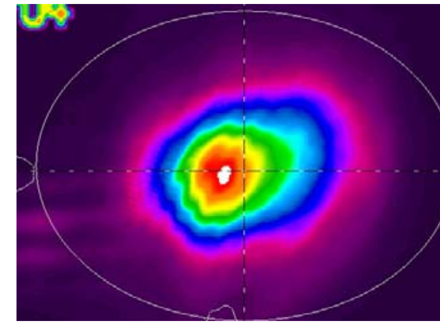
No Heating



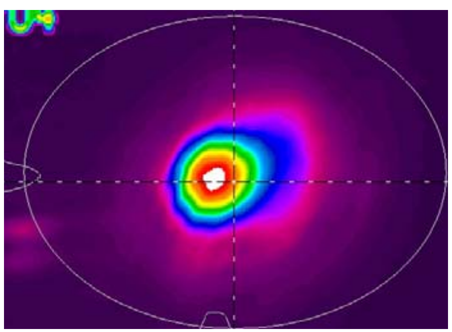
30 mW



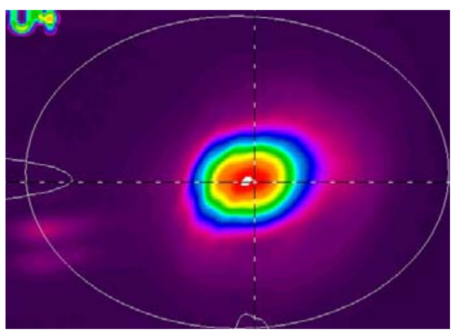
60 mW



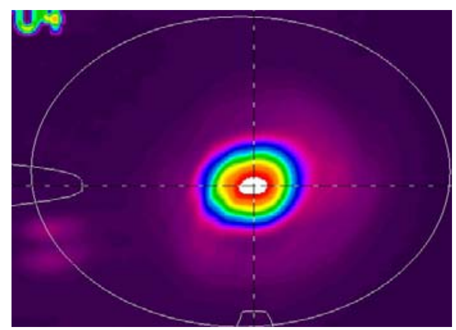
90 mW



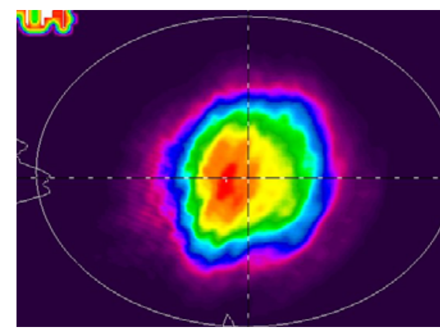
120 mW



150 mW



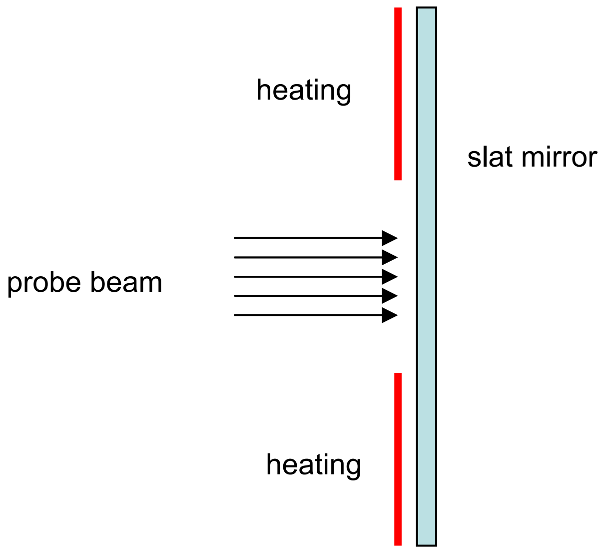
180 mW

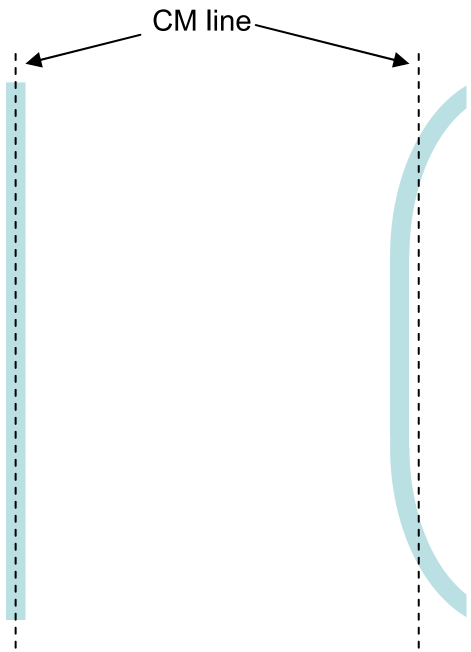


Carrier

Flexure Noise- A Simple Model

A skinny LIGO mirror with ‘annular’ heating





The probe beam sees the mirror move at the center due to wiggling far from center

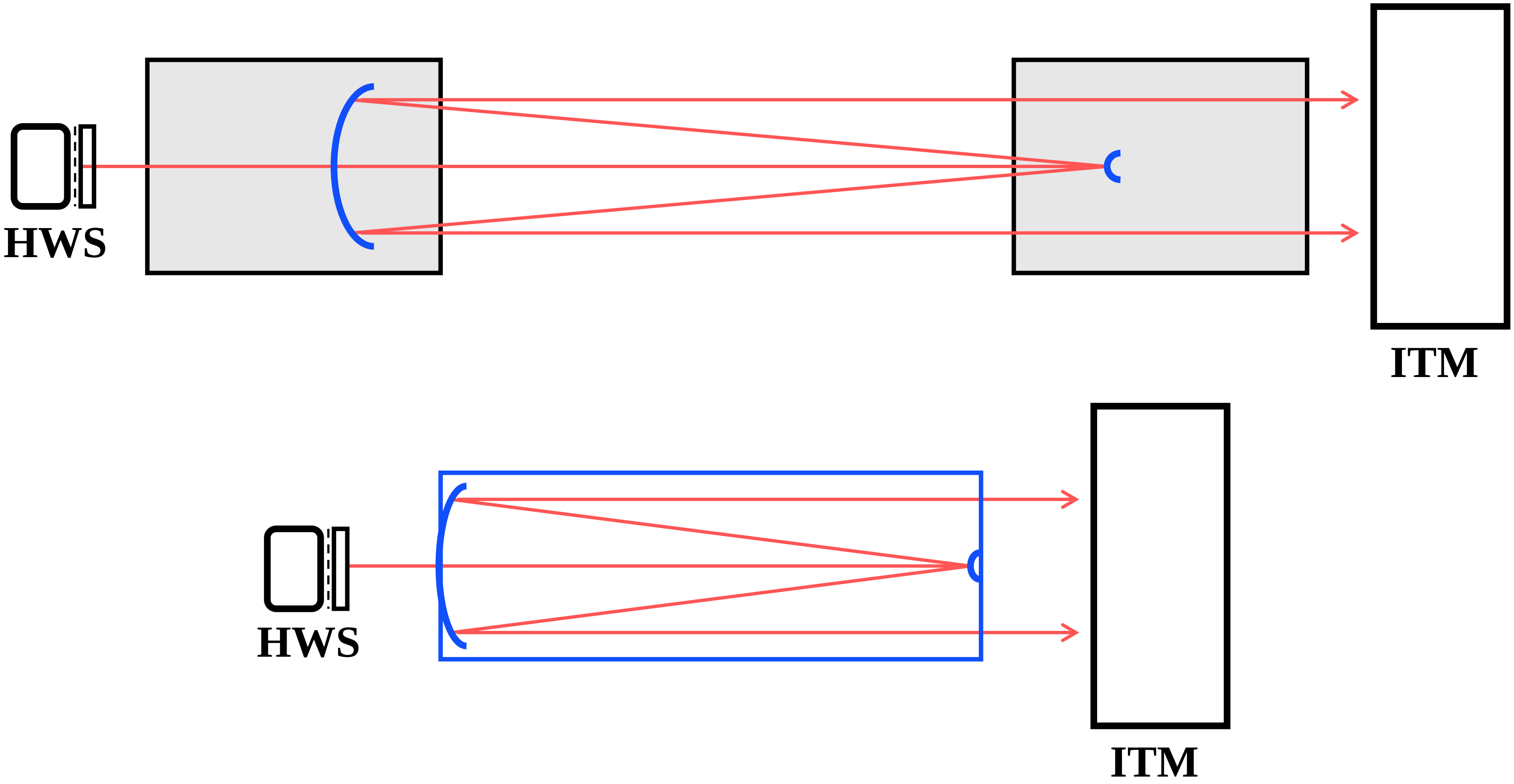
Initial LIGO

Enhanced LIGO

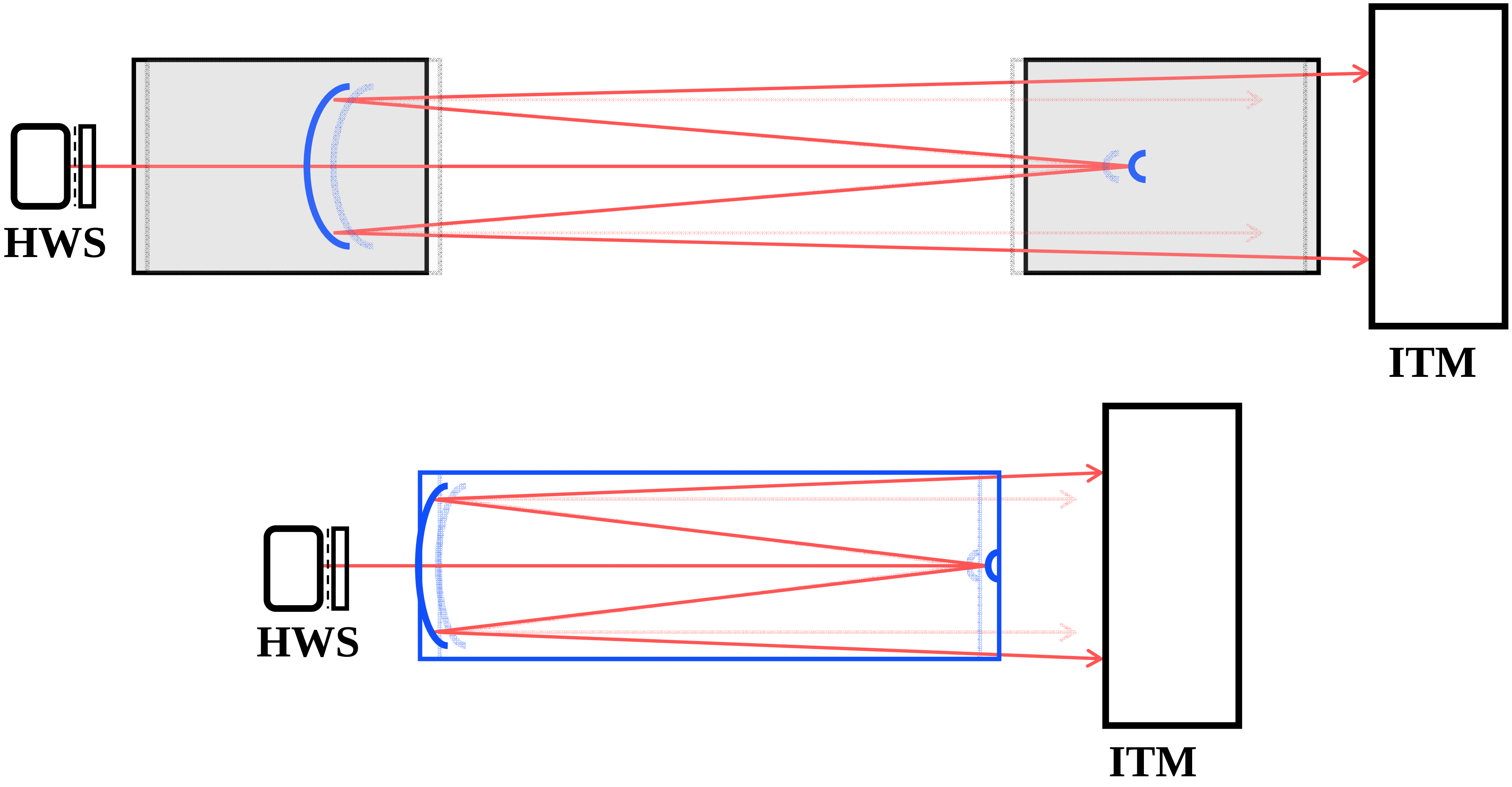
Our Need for Power

- Initial LIGO runs at ~7W input power
- Enhanced LIGO will run at ~30W input power
  - » 4-5x more absorbed power
  - » Naively, ~4-5x more TCS power needed
  - » Practically, more power even than this may be needed since LIGO point design is meant to make TCS unnecessary at 6W
- Our current projectors are not adequate

Thermal defocus



Thermal defocus



Is image relay without contamination feasible?

- Single material design?
  - » Zerodur
  - » ULE glass
- Heat shield for uniform distribution of temperature changes
- Measurement/actuation of displacement between optical tables
  - » Brian Lantz - Stanford