Thermal Compensation in LIGO

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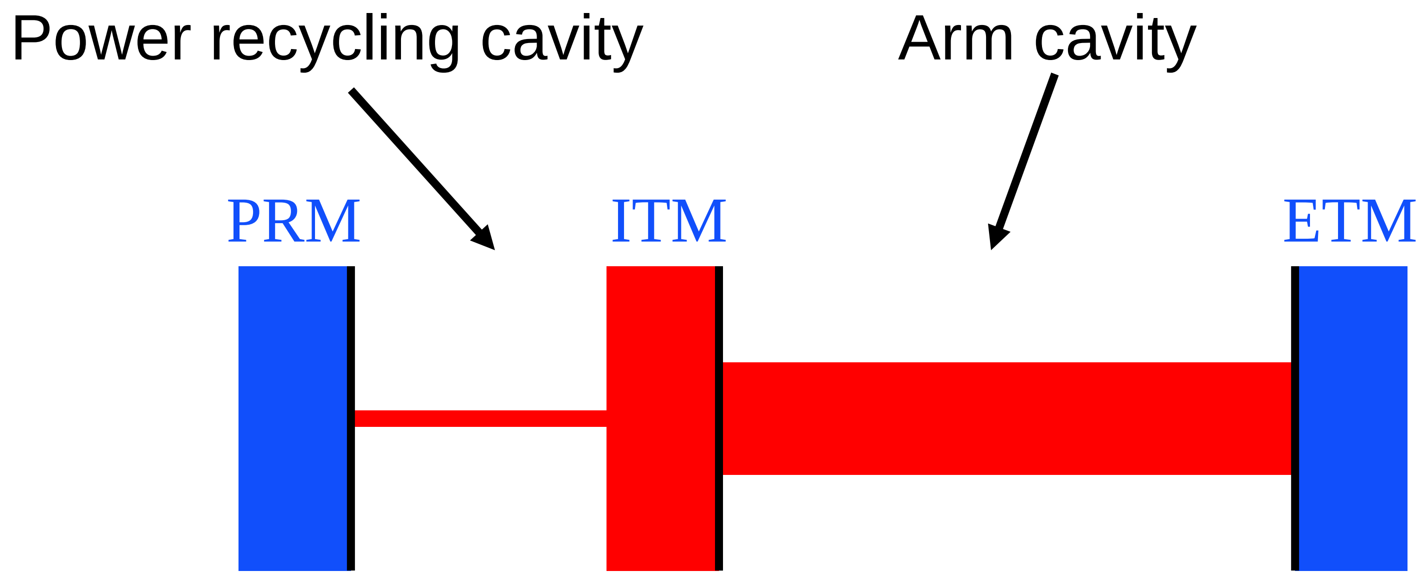
Baton Rouge LSC Meeting, March 2007

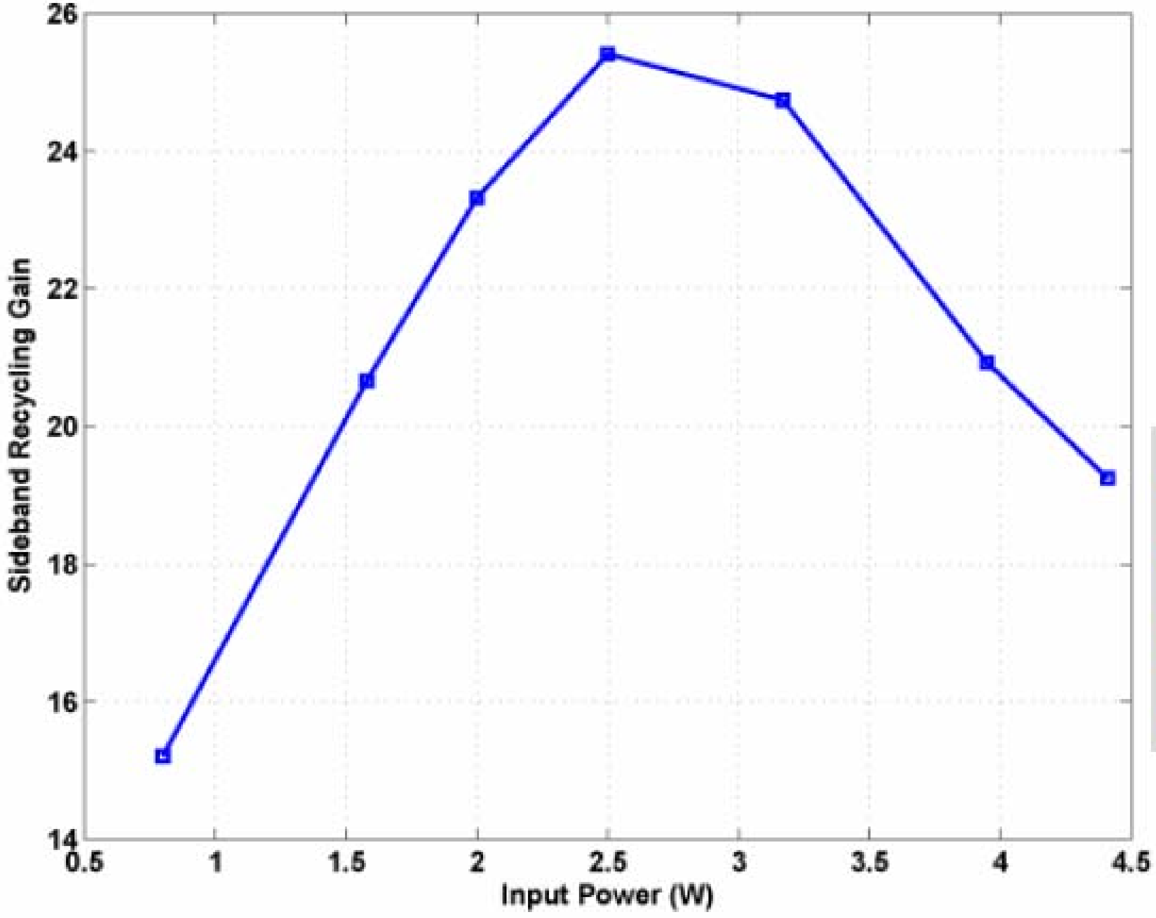
LIGO-G070146-00-Z

The Essence of the Problem, and of its Solution



Add optical power to the ITM to erase the thermal gradient, leaving a uniformly hot, flat-profile substrate.

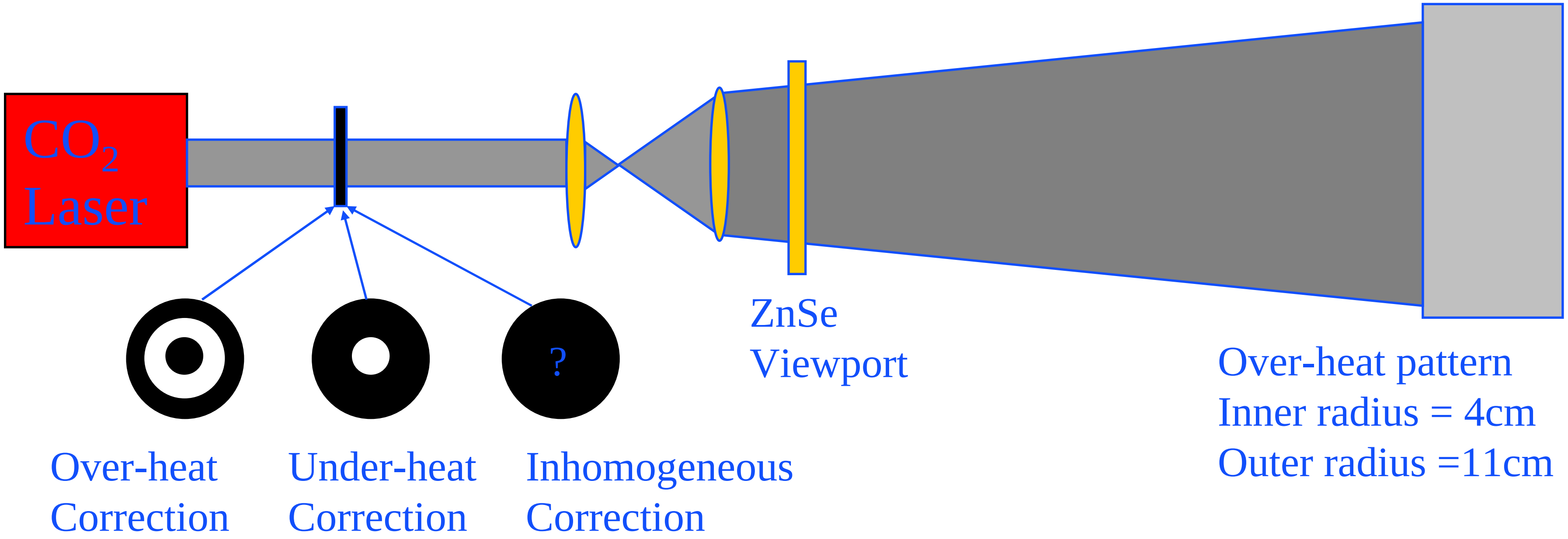
Sideband recycling gain



Expected gain:
G_{sb} = 35, based
On T_{RM} = 2.7%
& T_{MI} = 2.72%

Absolute numbers scaled from G_{sb} = 7.1 for cold PRM

LIGO CO_2 Laser Projector Thermal Compensator



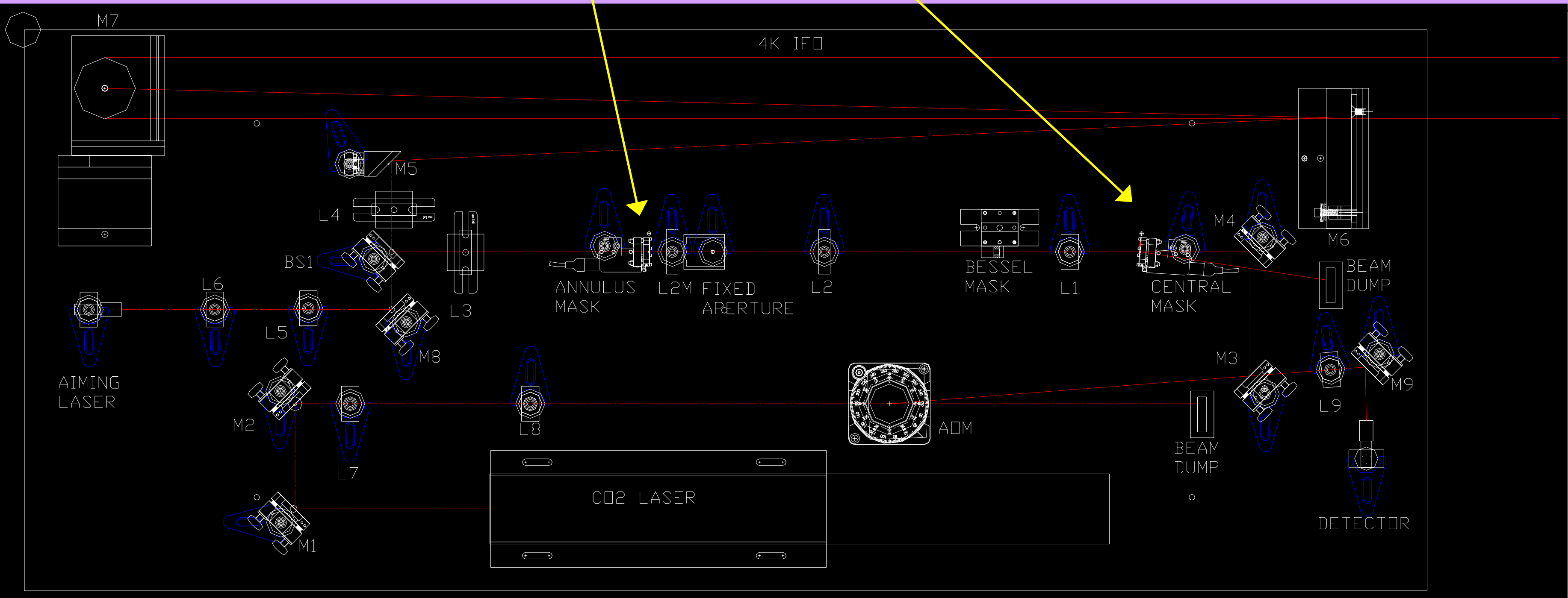
- Imaging target onto the TM limits the effect of diffraction spreading
- Modeling suggests a centering tolerance of 10 mm is required

CO_2 Laser Projector Layout

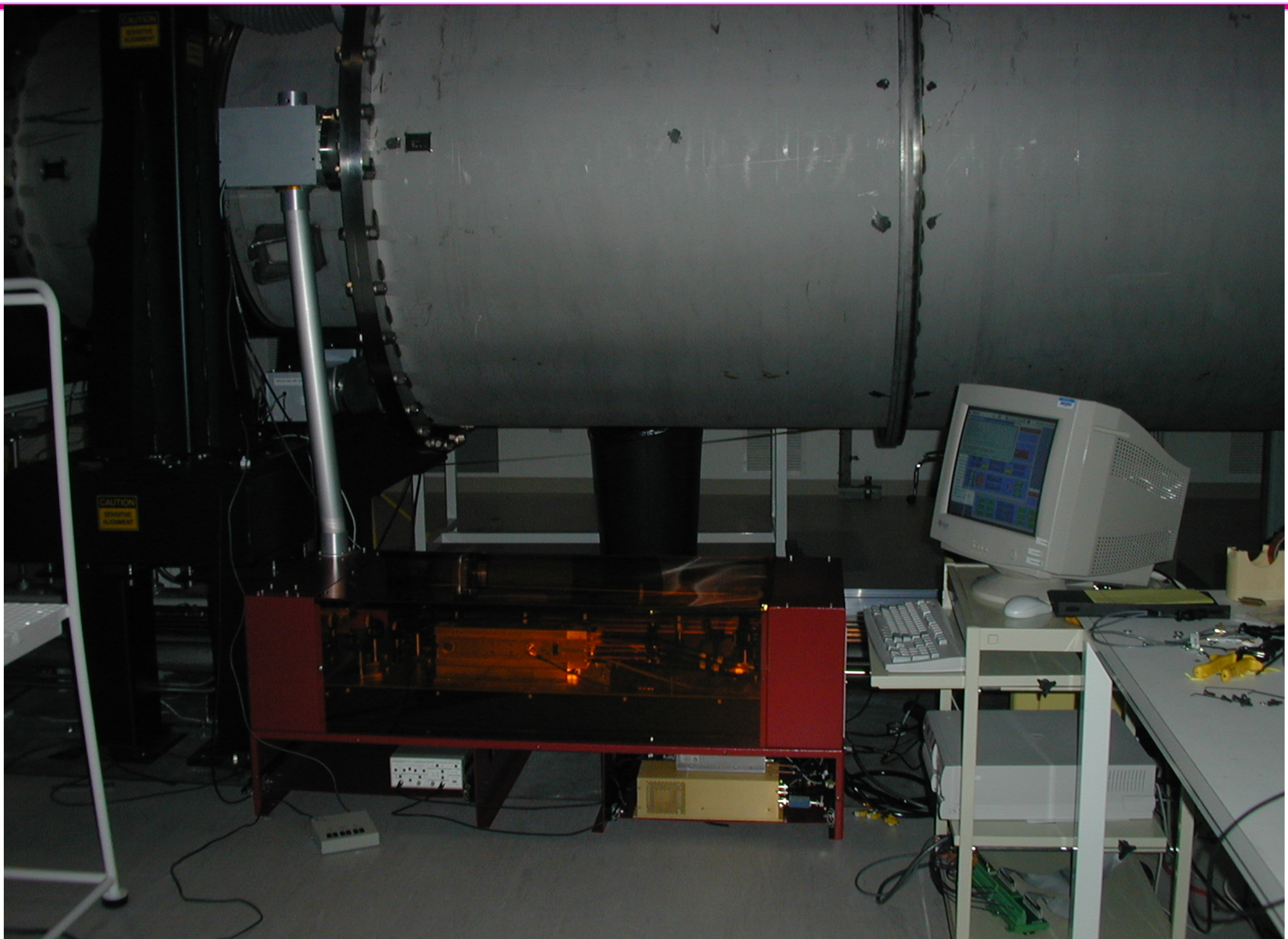
- Image planes here, here, and at ITM HR face

over-heat correction

under-heat correction

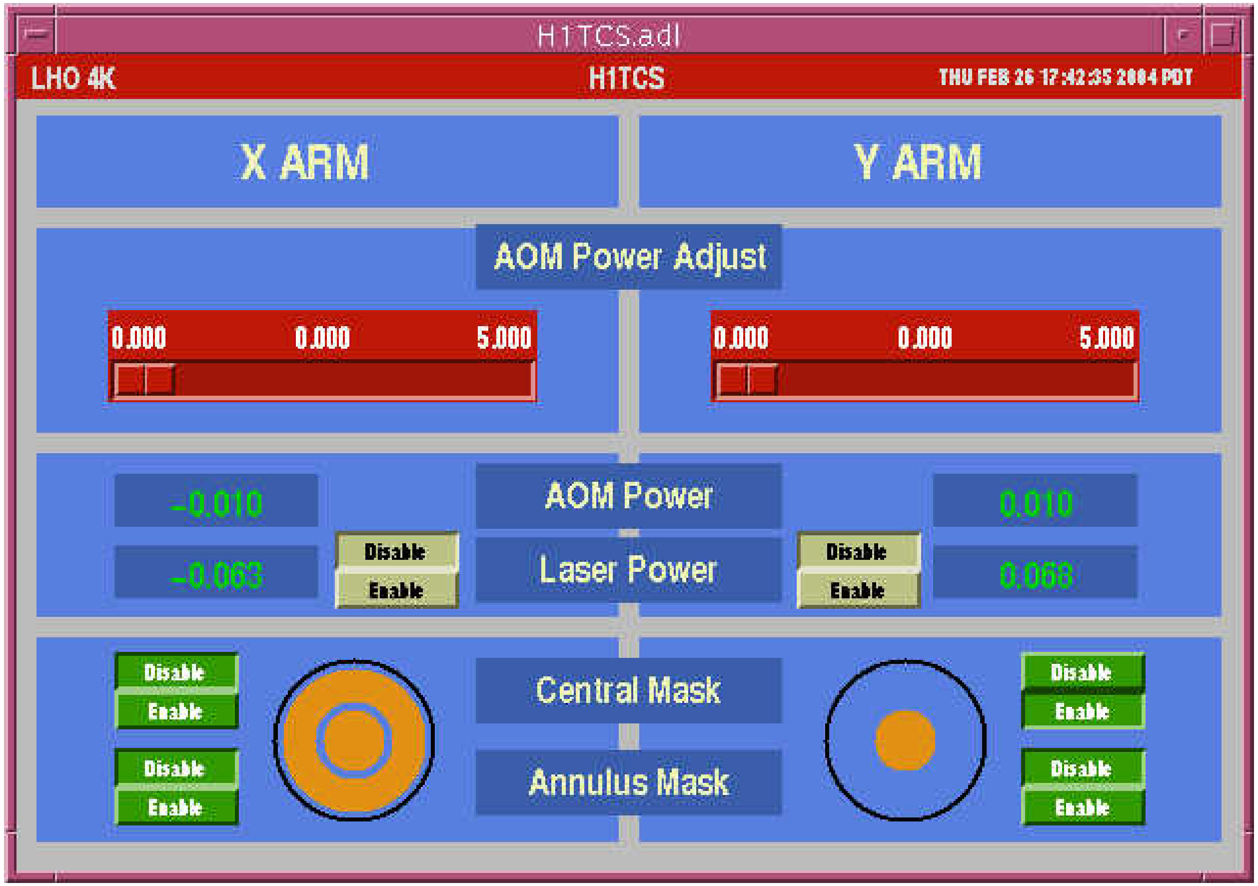


Thermal Compensation as Installed

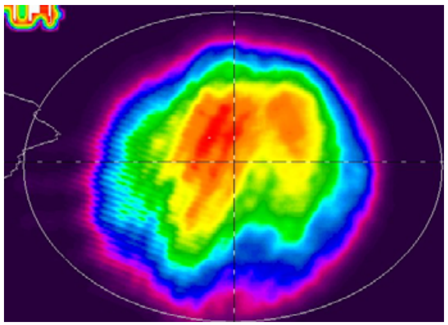


TCS Servo Control

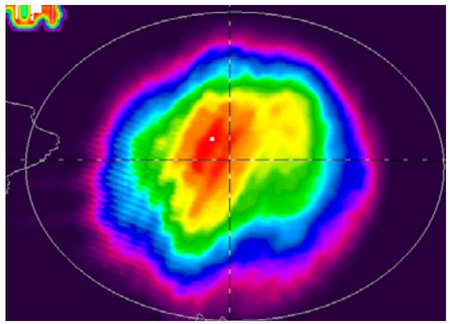
Thermal Compensation Controls



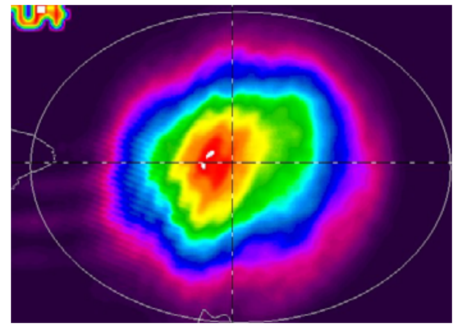
Heating Both ITMs in a Power-Recycled Michelson



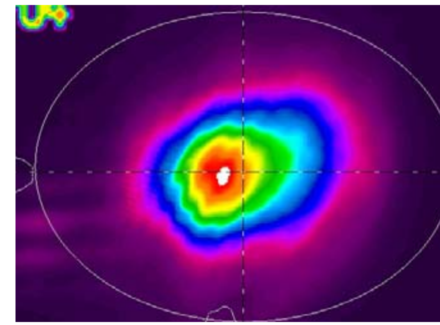
No Heating



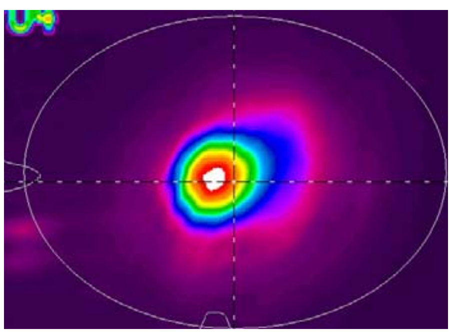
30 mW



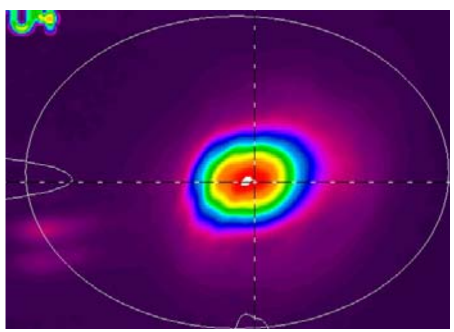
60 mW



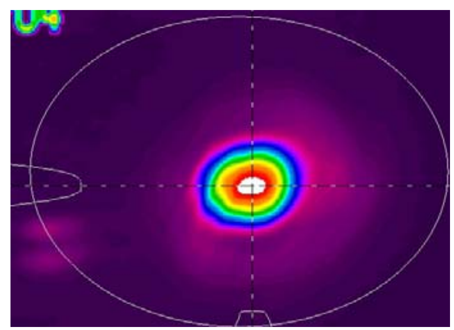
90 mW



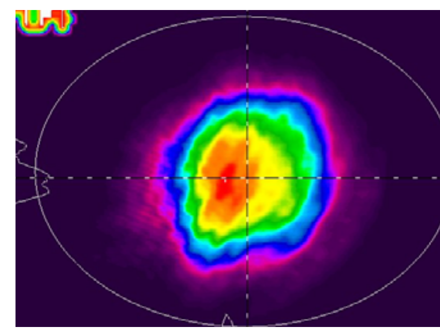
120 mW



150 mW

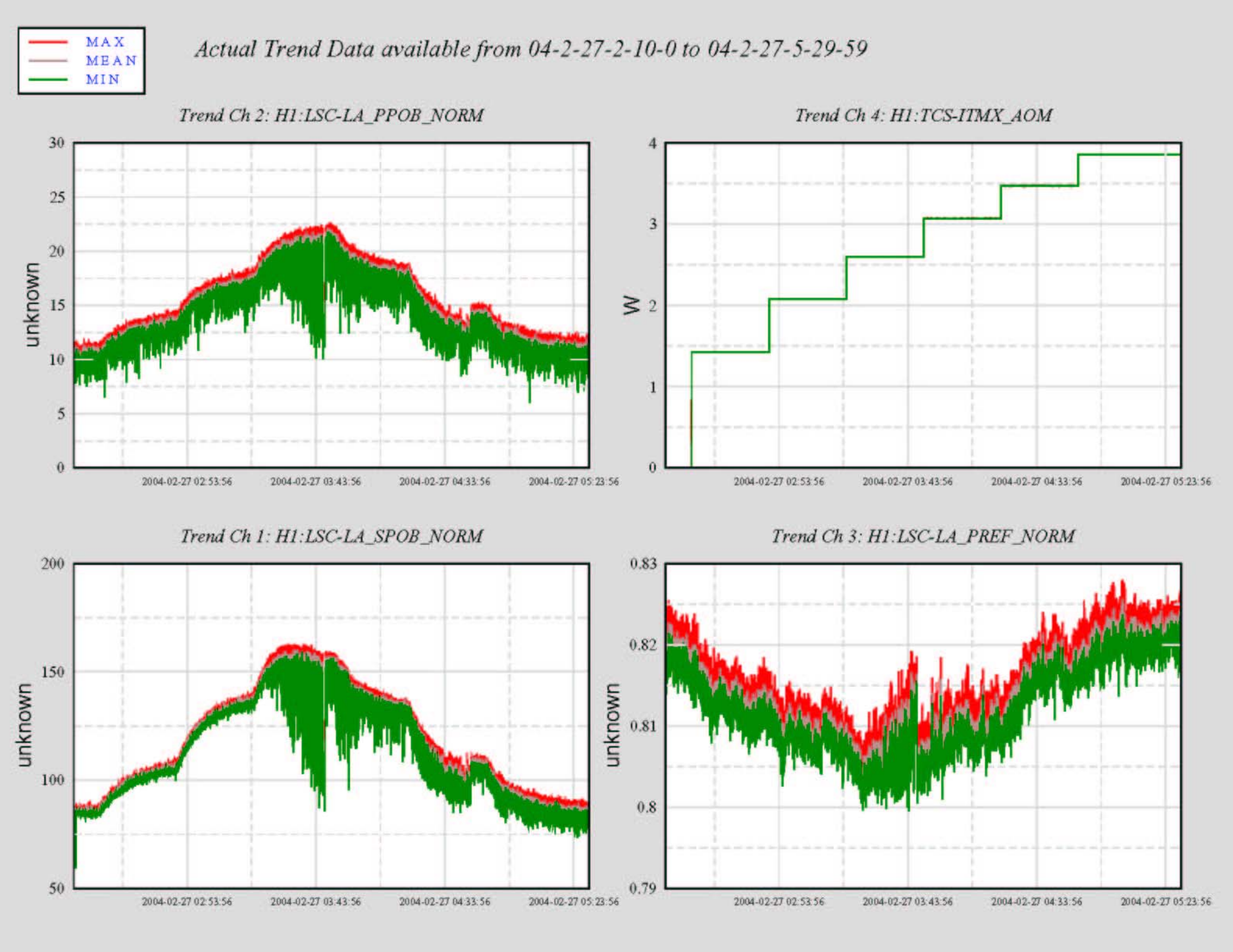


180 mW



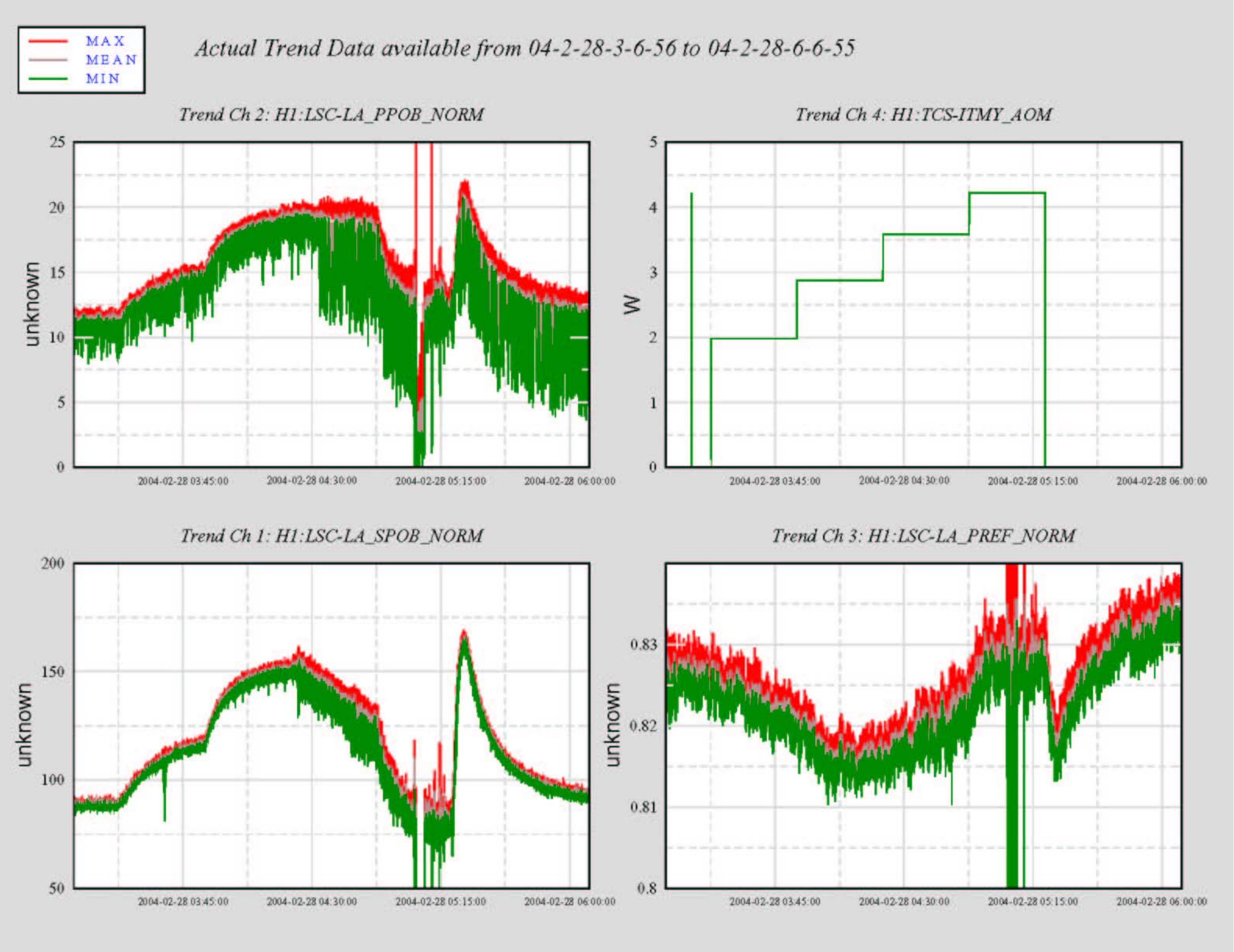
Carrier

RF Sideband Power Buildup



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

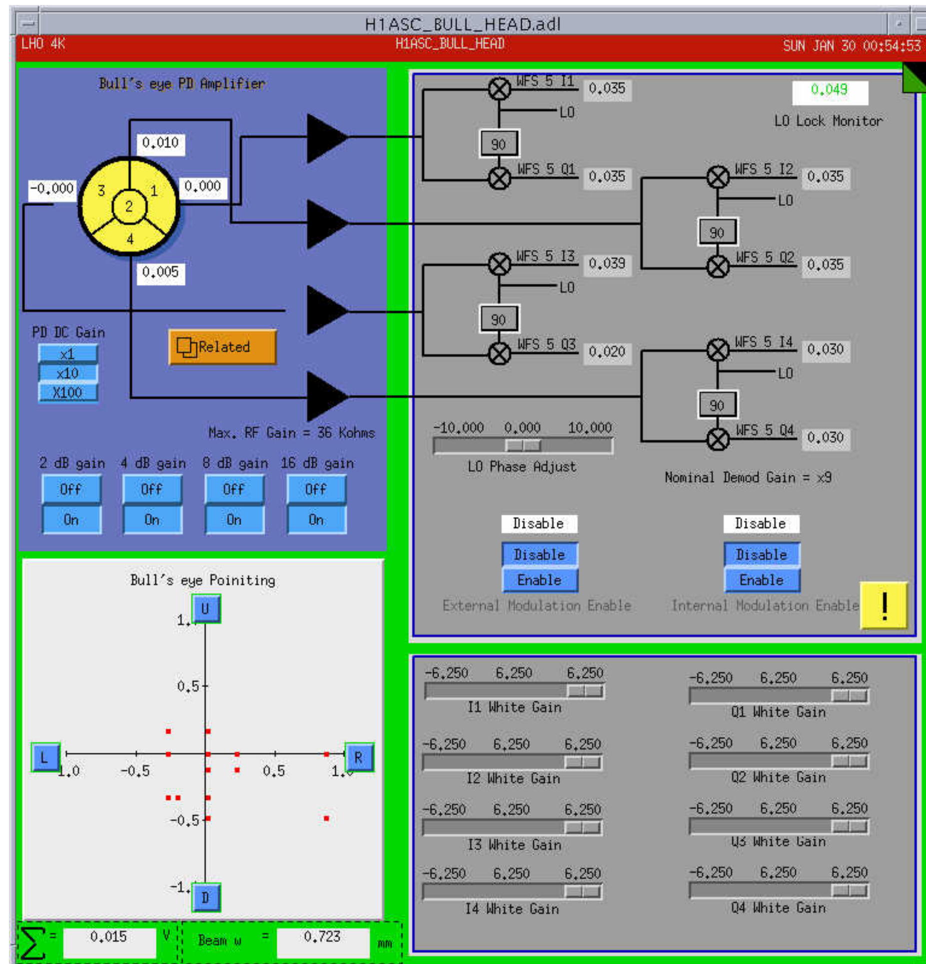
RF Sideband Power Buildup



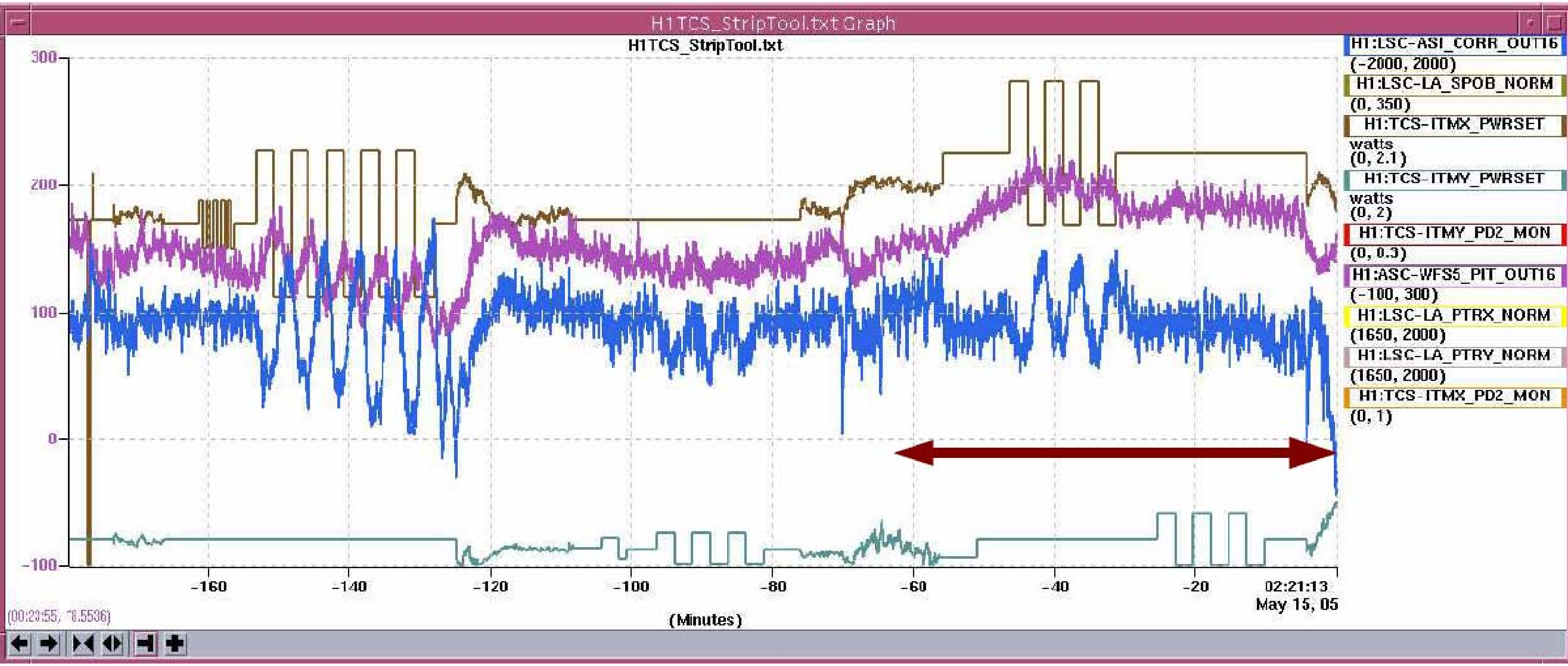
- Only ITMy heated
- Maximum power with 120 mW total heat
- Same maximum power as when both ITMs heated

Common-mode Bulls-eye Sensor

- Good mode overlap of RF sideband with carrier determines optimal thermal compensation- so we measure the RF mode size to servo TCS.

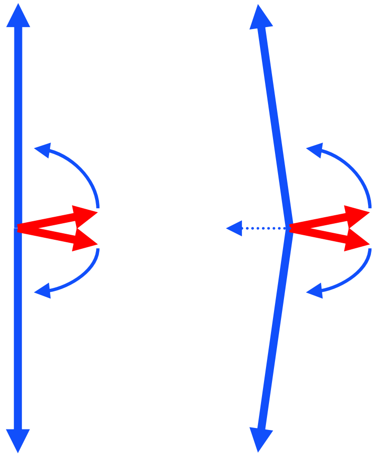


Differential TCS- Control of AS_I



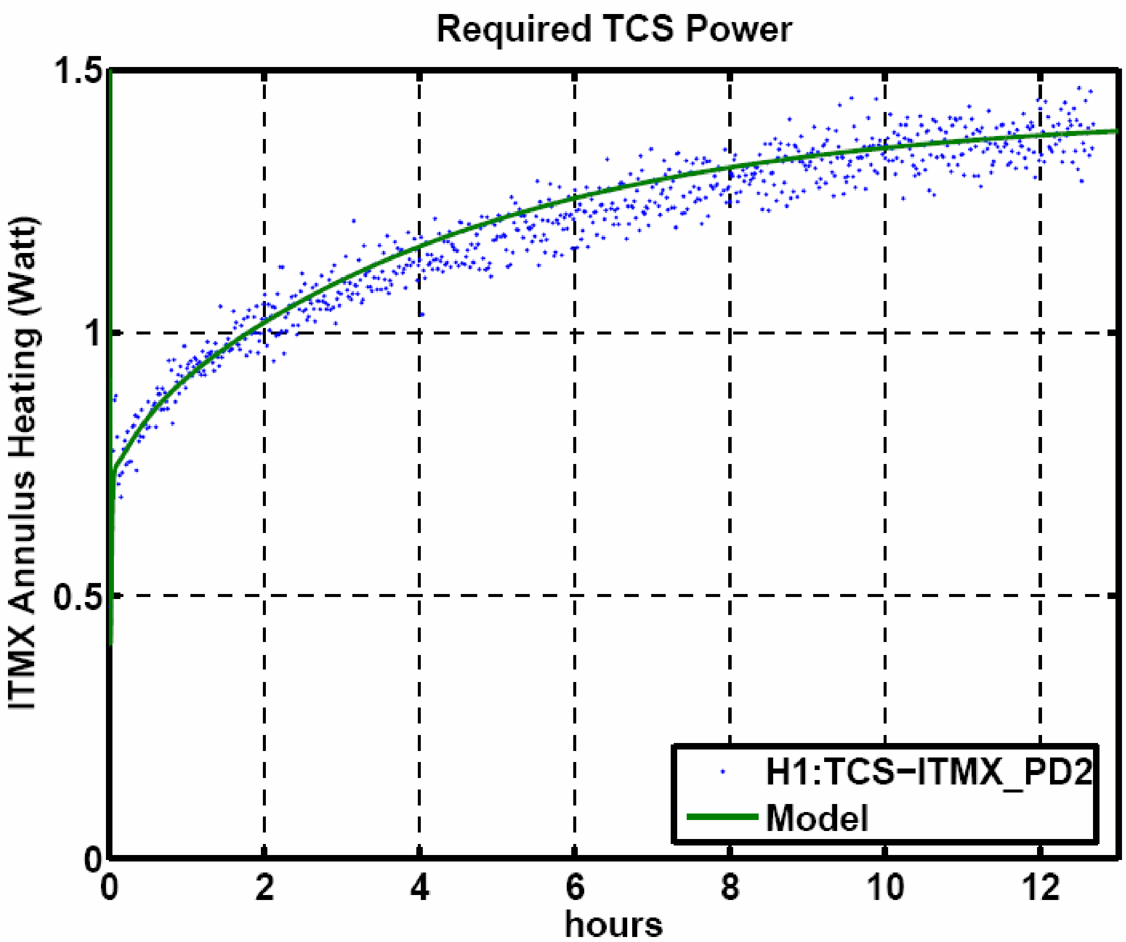
What Is AS_I?

- AS_Q: RF sidebands at dark port create swinging LO field- when arm imbalance detunes carrier from dark fringe signal appears at quadrature phase



- AS_I: dark fringe means no carrier, RF sideband balance means no LO at this phase- there should be no signal.
- Yet, this signal dominates the RF photodetection electronics!
  - --there must be carrier contrast defect
  - --there must be RF sideband imbalance
  - --apparently, slightly imperfect ITM HR surfaces mismatch the arm modes, creating the contrast defect. TCS provides the cure.

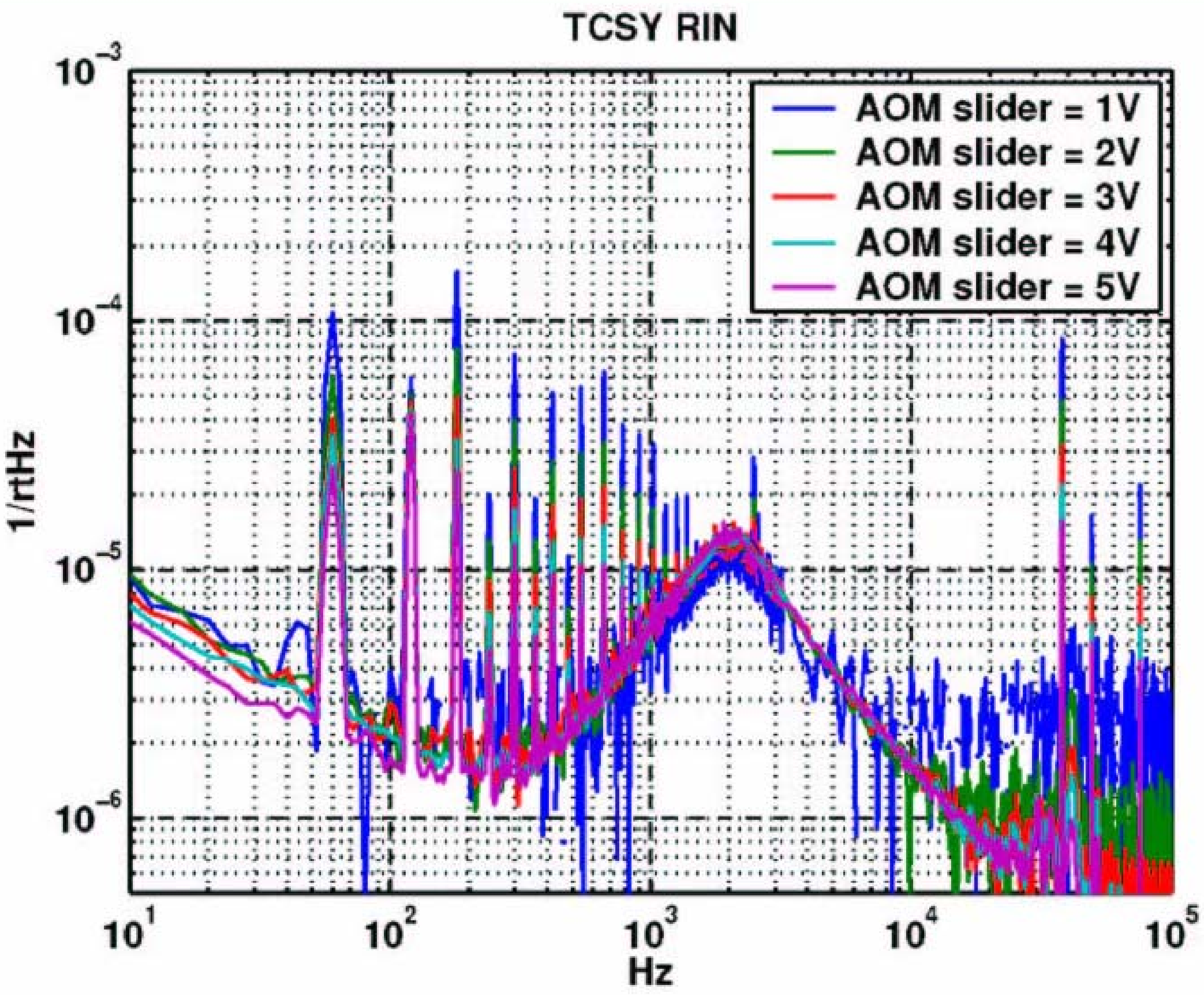
Thermal Time Scales



After locking at high power, the heat distribution in the ITM continues to evolve for hours. To maintain constant thermal focusing power requires varying TCS power.

TCS Noise Issues

RIN of TCS-Y CO_2 Laser



TCS Noise Coupling Mechanisms

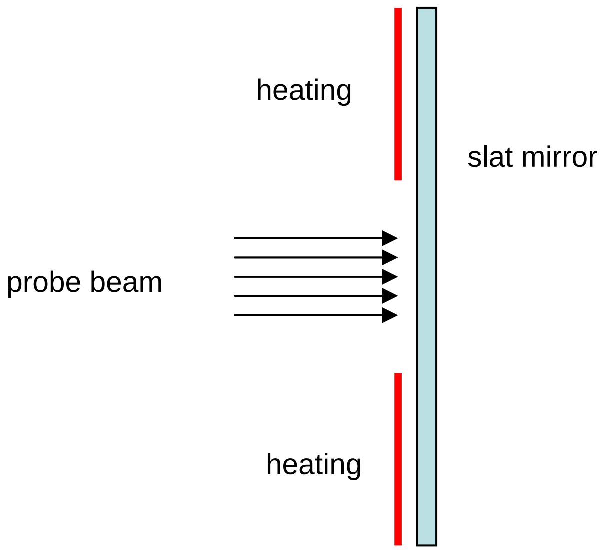
- Thermoelastic (TE)- fluctuations in locally deposited heat cause fluctuations in local thermal expansion
- Thermorefractive (TR)- fluctuations in locally deposited heat cause fluctuations in local refractive index
- Flexure (F)- fluctuations in locally deposited heat cause fluctuations in *global*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

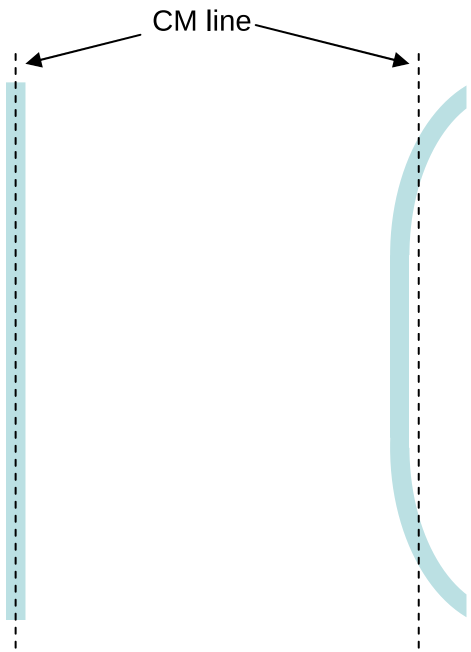
TE → $(1+\eta)\alpha$ TR → $\frac{\pi}{2\mathcal{F}}\frac{dn}{dT}$ F → $\frac{6\alpha}{h^2}C^{\rm cen}_{\rm num}$

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

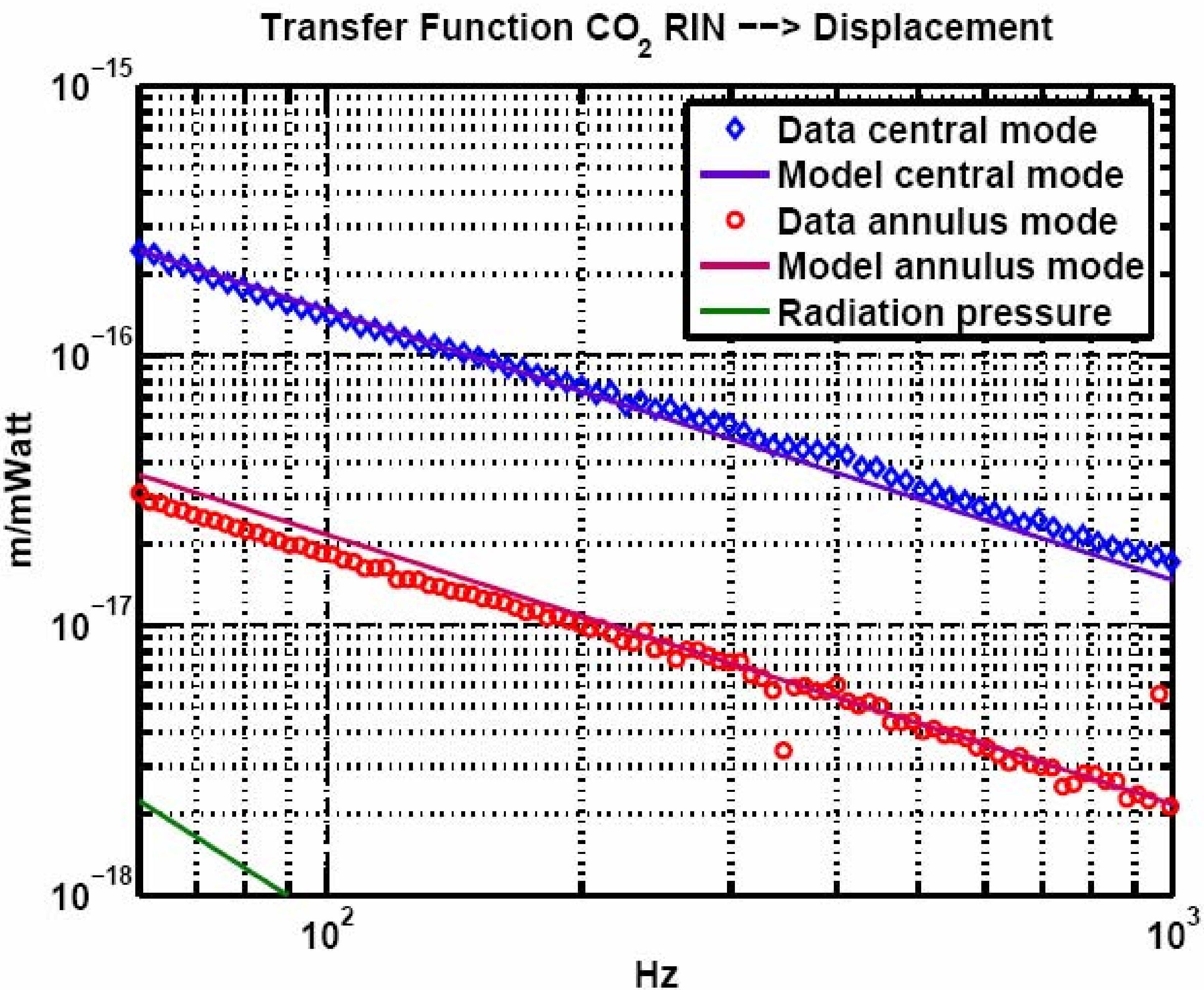
Flexure Noise- A Simple Model

A skinny LIGO mirror with 'annular' heating



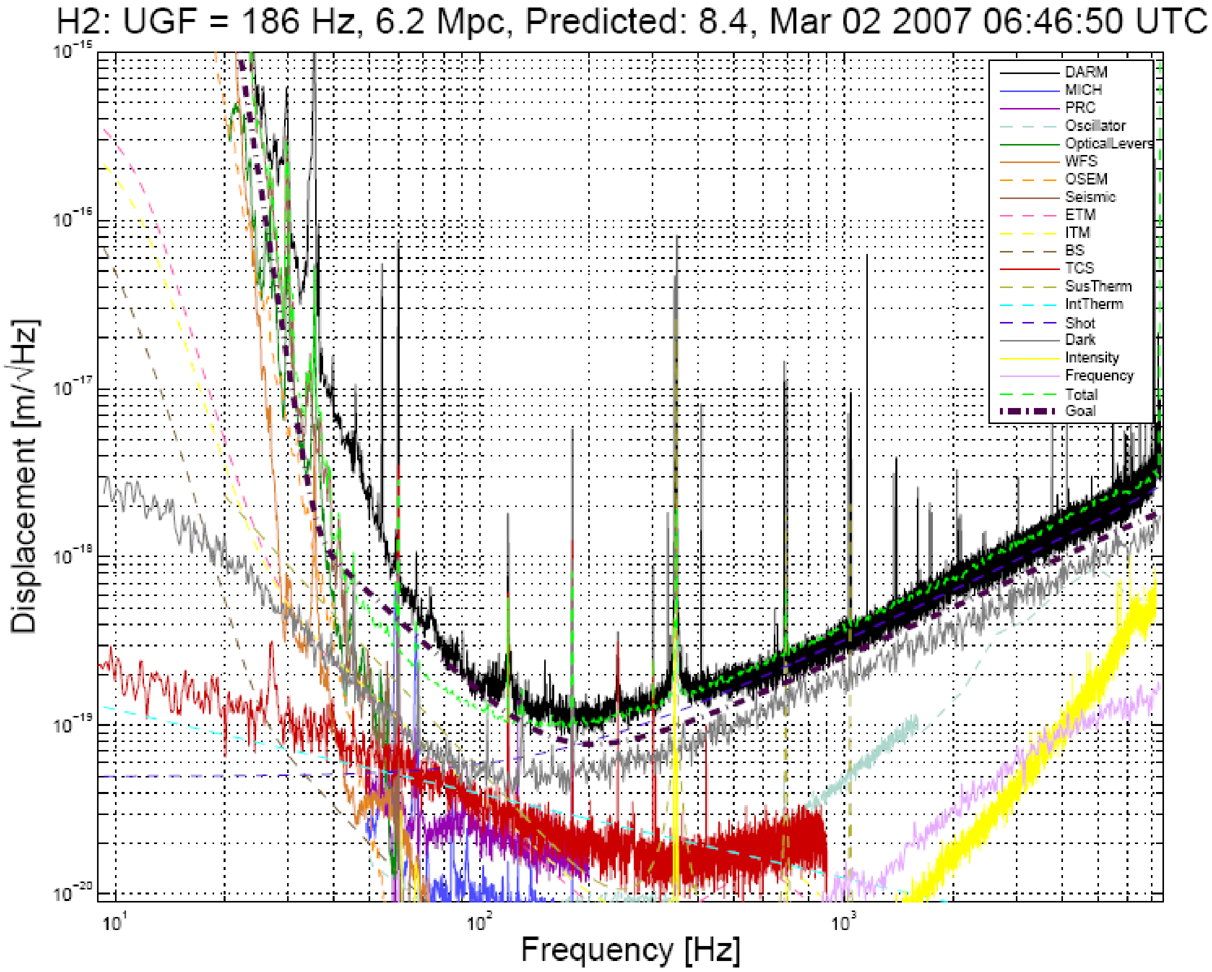


The probe beam sees the mirror move at the center due to wiggling far from center



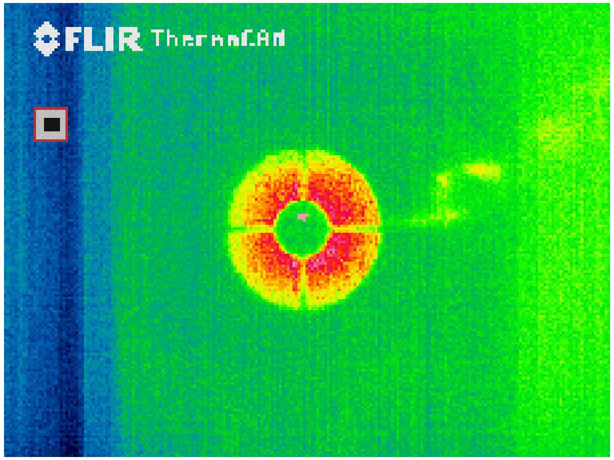
Transfer Function CO2 RIN --> Displacement
10^-15
10^-16
10^-17
10^-18
m/mWatt
10^2
10^3
Hz
Data central mode
Model central mode
Data annulus mode
Model annulus mode
Radiation pressure

TCS Injected Noise Spectrum

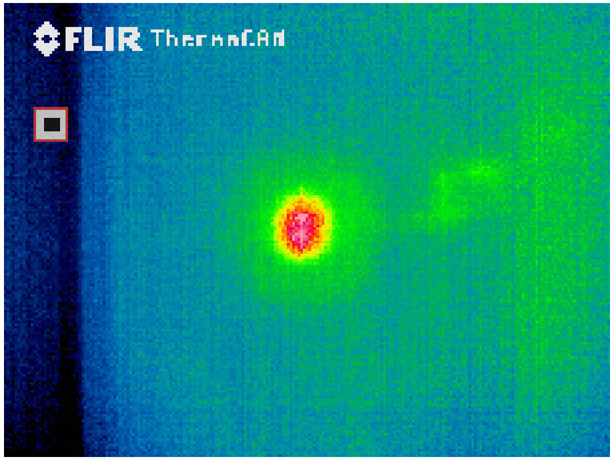


Quality of Compensation

Projector Heating Patterns



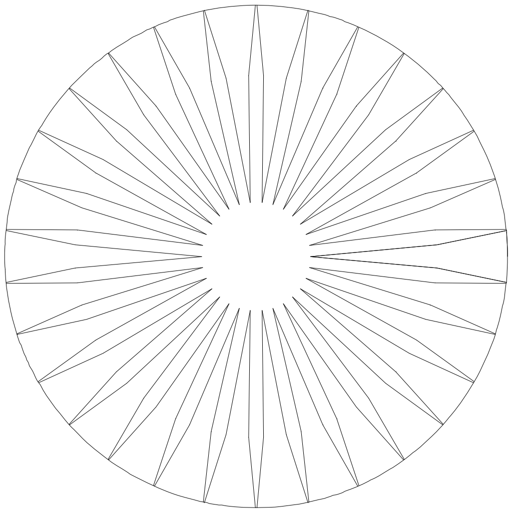
Annulus Mask



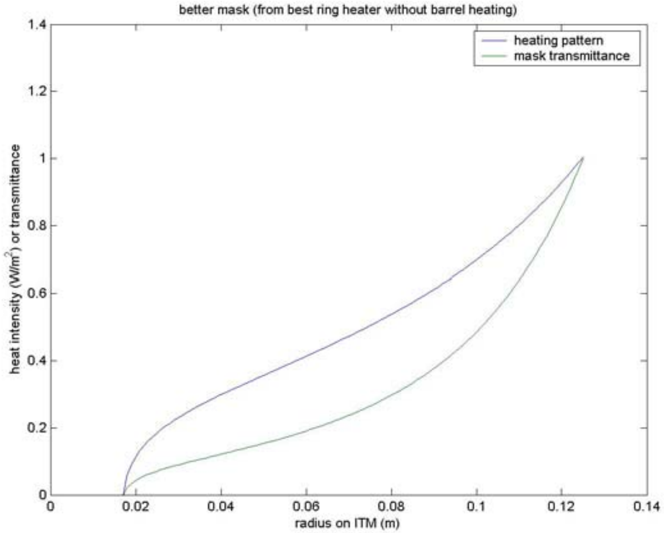
Central Heat Mask

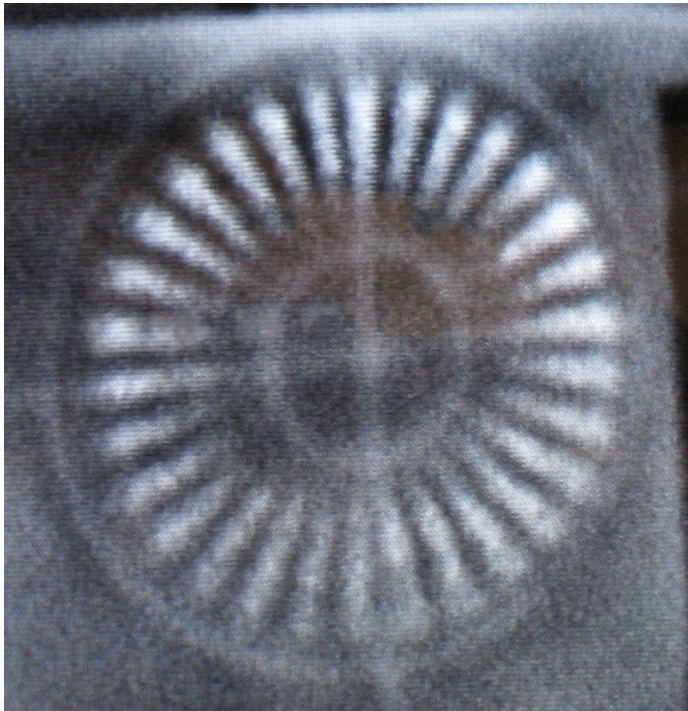
- Intensity variations across the images due to small laser spot size
- Projection optics work well

‘Gold Star’ Mask Design



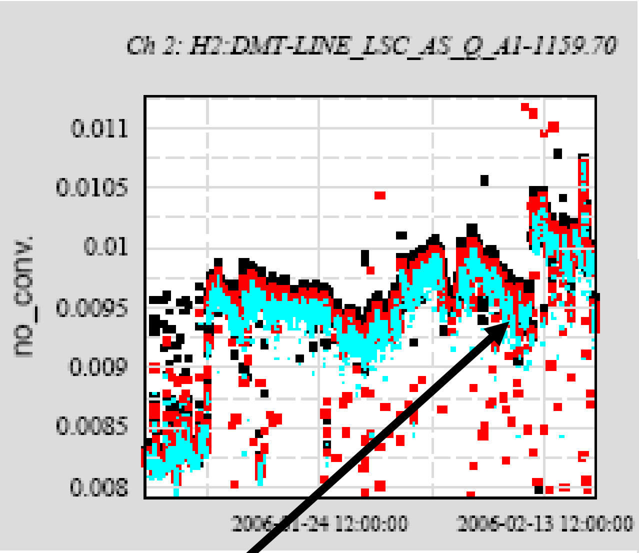
- “star”- from hole pattern
- “gold”- gold coating to reduce power absorption
- Hole pattern is clearly not ideal but diffraction and heat diffusion smooth the phase profile



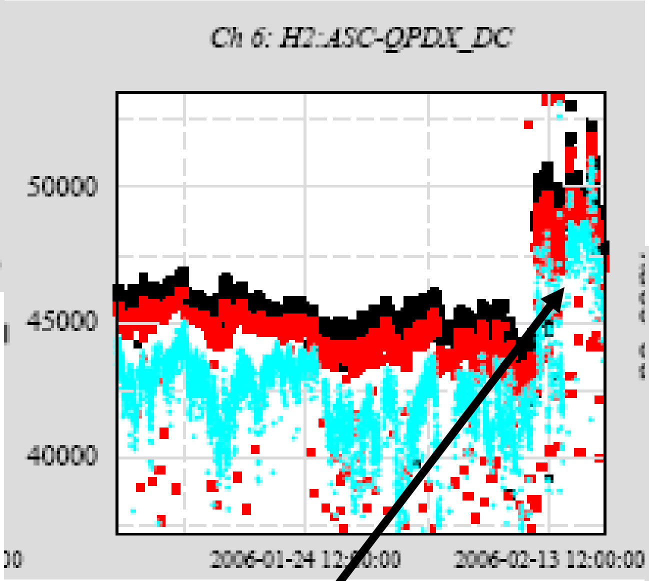


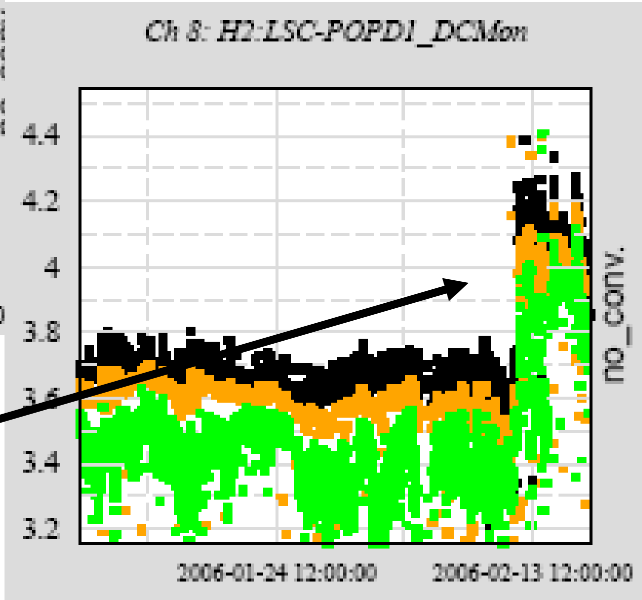
Improved Carrier Power with Gold Star Mask

Why this helps the carrier is mysterious, but we'll take it



optical gain up 5%





carrier recycling gain up 10%

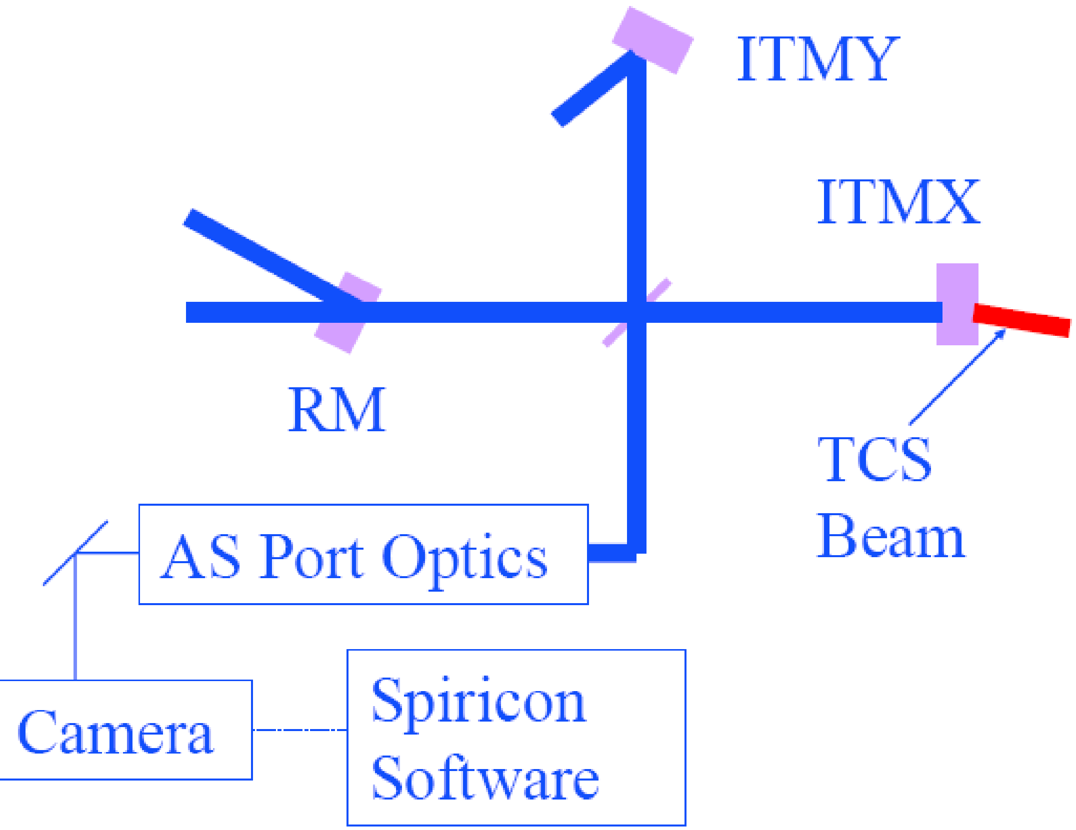
LIGO Laboratory

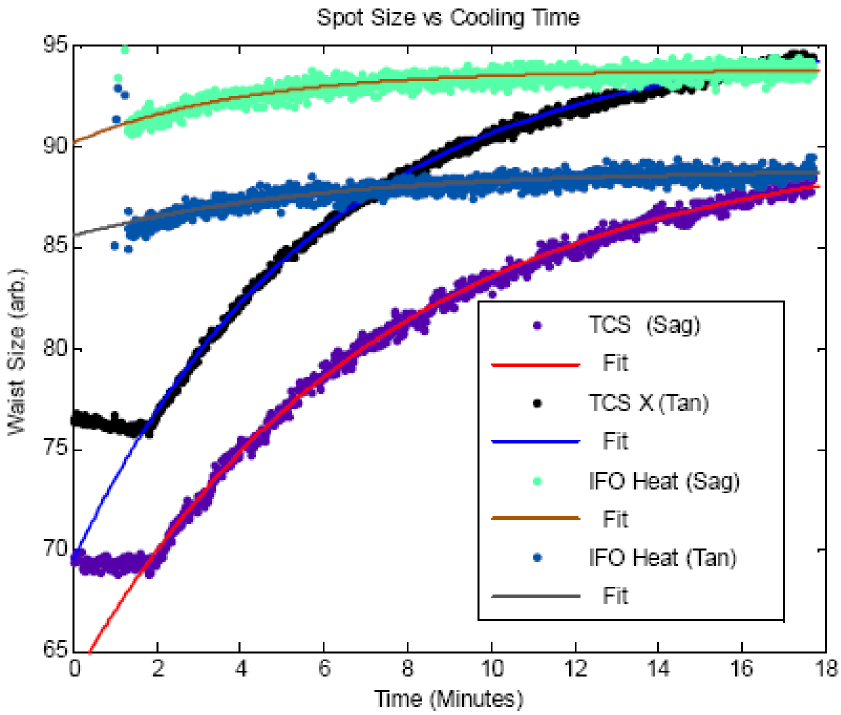
Enhanced LIGO TCS

Our Need for Power

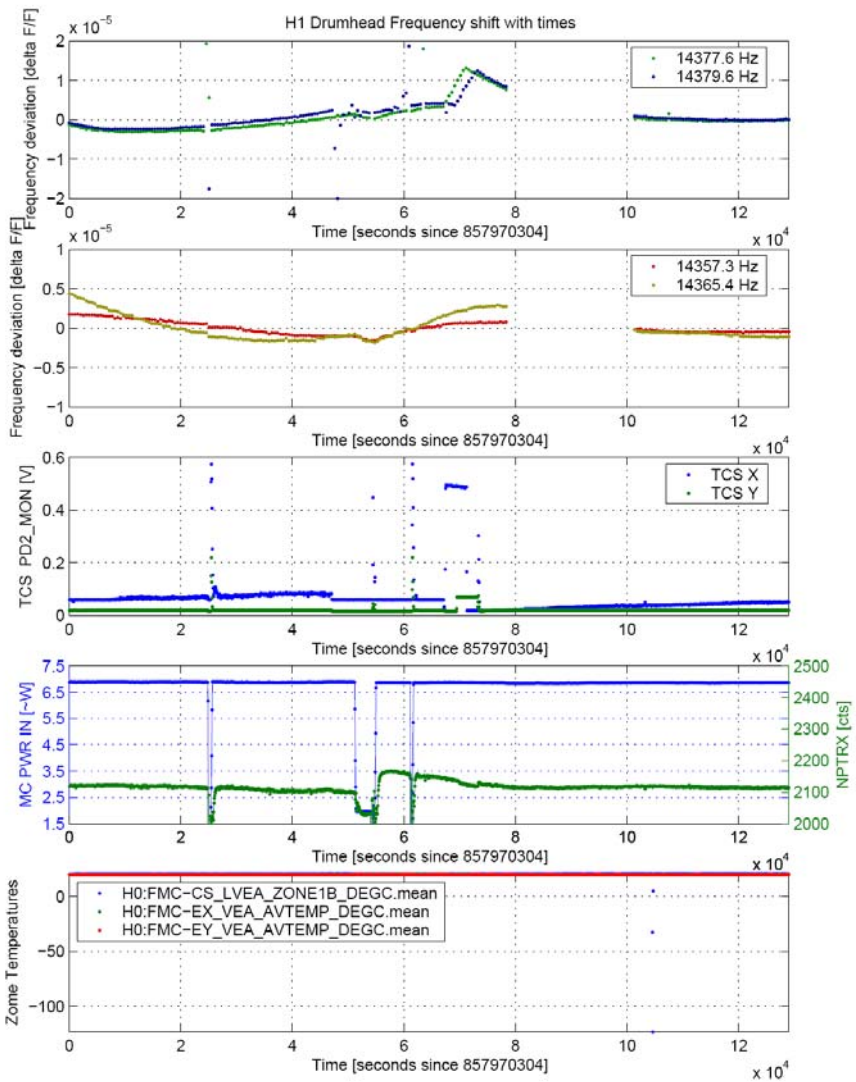
- Initial LIGO runs at ~7W input power
- Enhanced LIGO will run at ~30W input power
  - » 4-5x more absorbed power
  - » Naively, ~4-5x more TCS power needed
  - » Practically, more power even than this may be needed since LIGO point design is meant to make TCS unnecessary at 6W
- Our current projectors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

Test Mass Absorption Measurement Technique-Spot Size





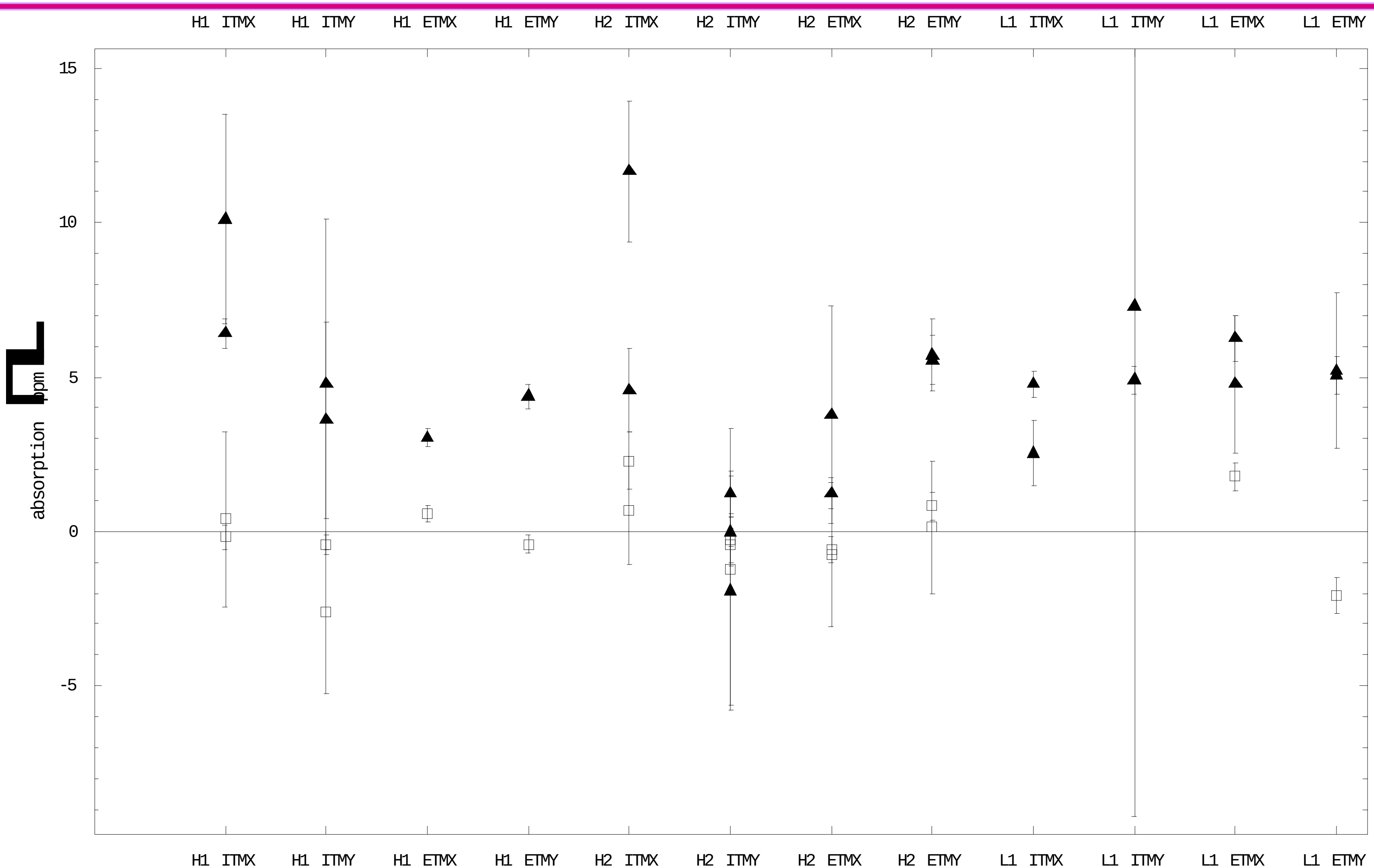
Test Mass Absorption Measurement Technique-Acoustic Frequencies



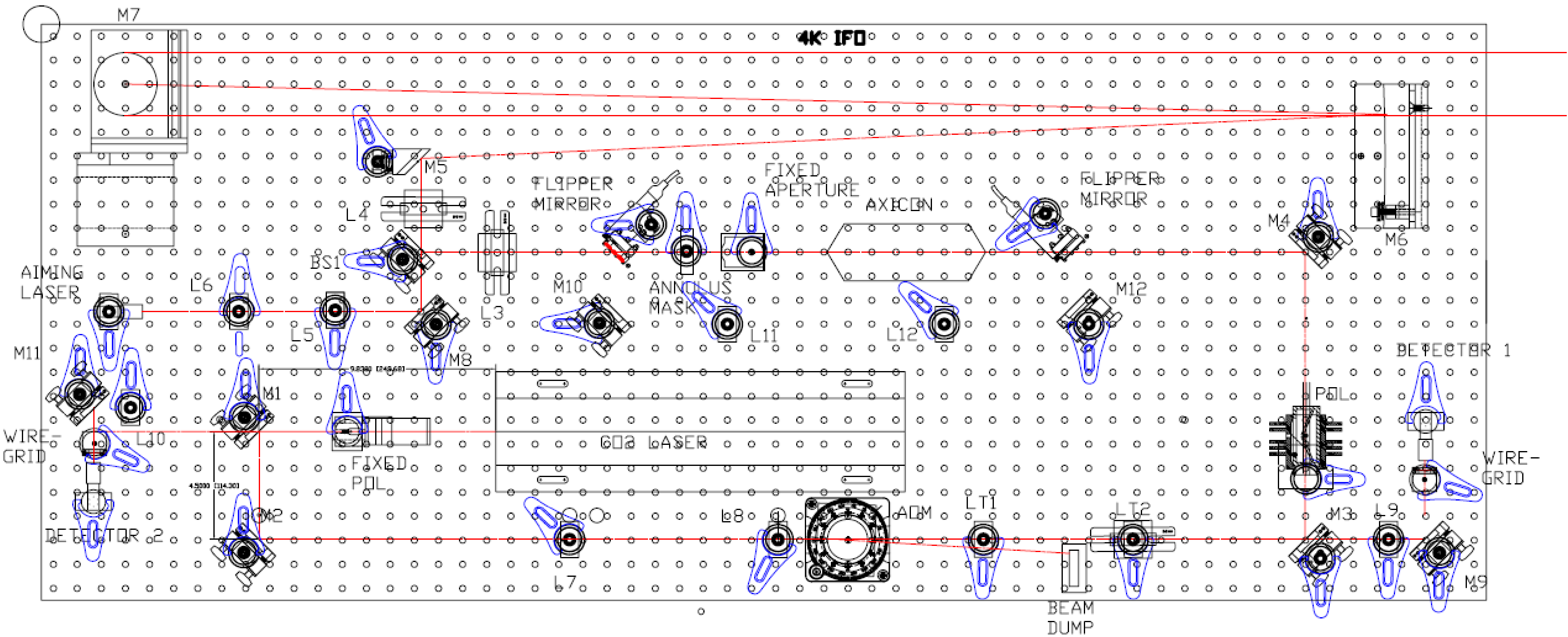
- test mass acoustic frequencies vary with temperature, so monitor their drift as the IFO power is varied
- requires no additional optics
- measures all ITMs and ETMs simultaneously

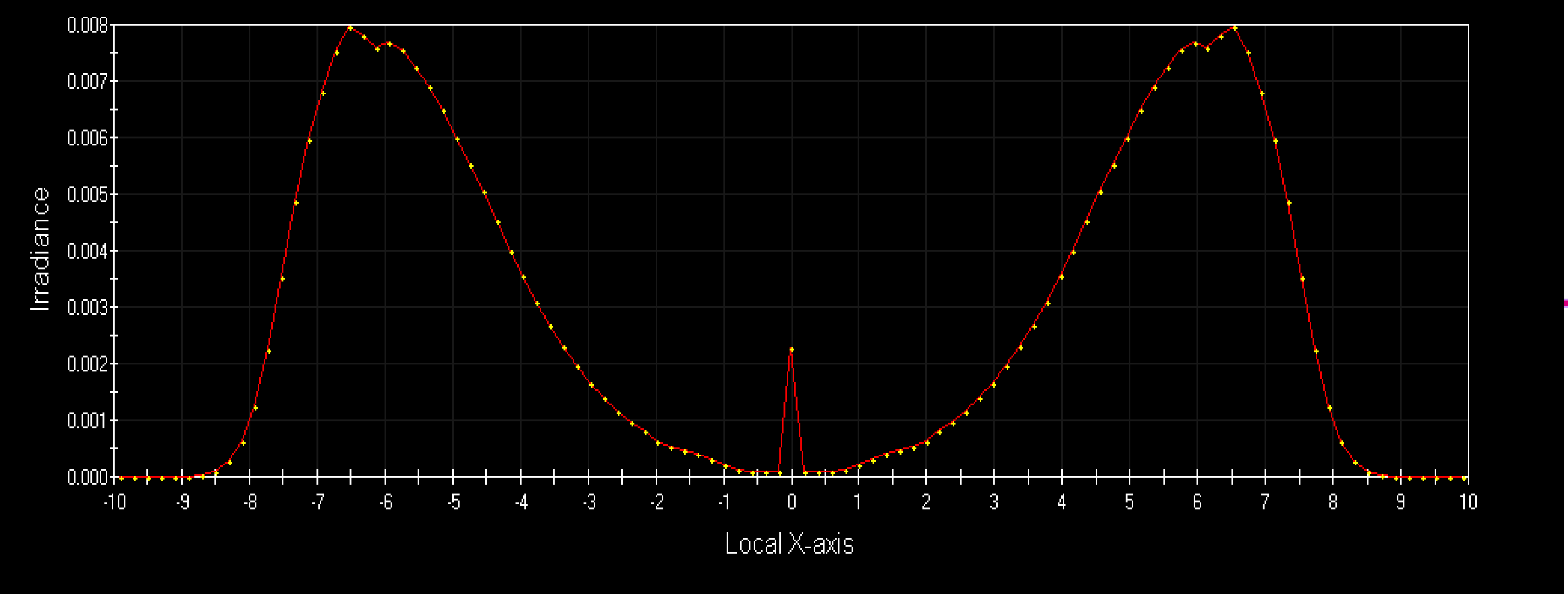
Many thanks to Alessio Rocchi & Viviana Fafone from Virgo for showing us this could work

Measured Test Mass Absorption



Enhanced LIGO TCS Projector





Axicon design proposed by II-VI for Enhanced LIGO

The Axicon