Thermal Compensation Experience in LIGO

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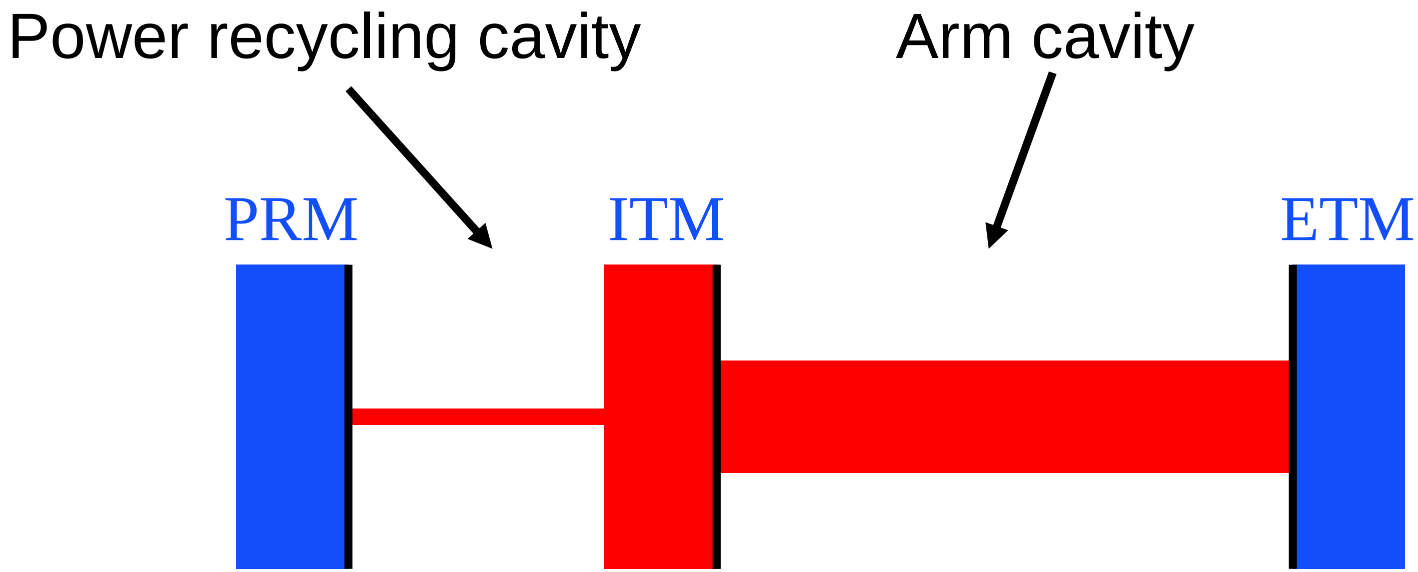
Virgo/LSC Meeting, Cascina, May 2007

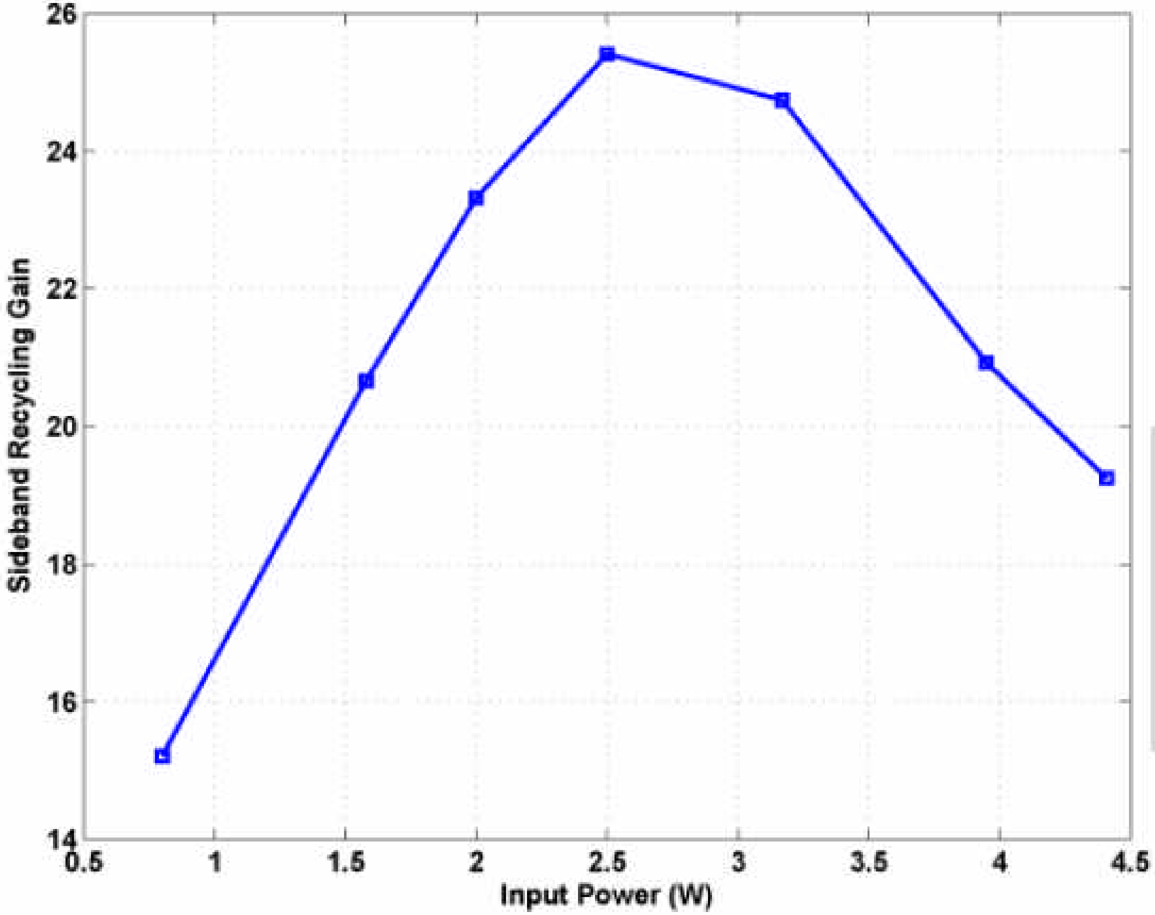
LIGO-G070339-00-Z

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.

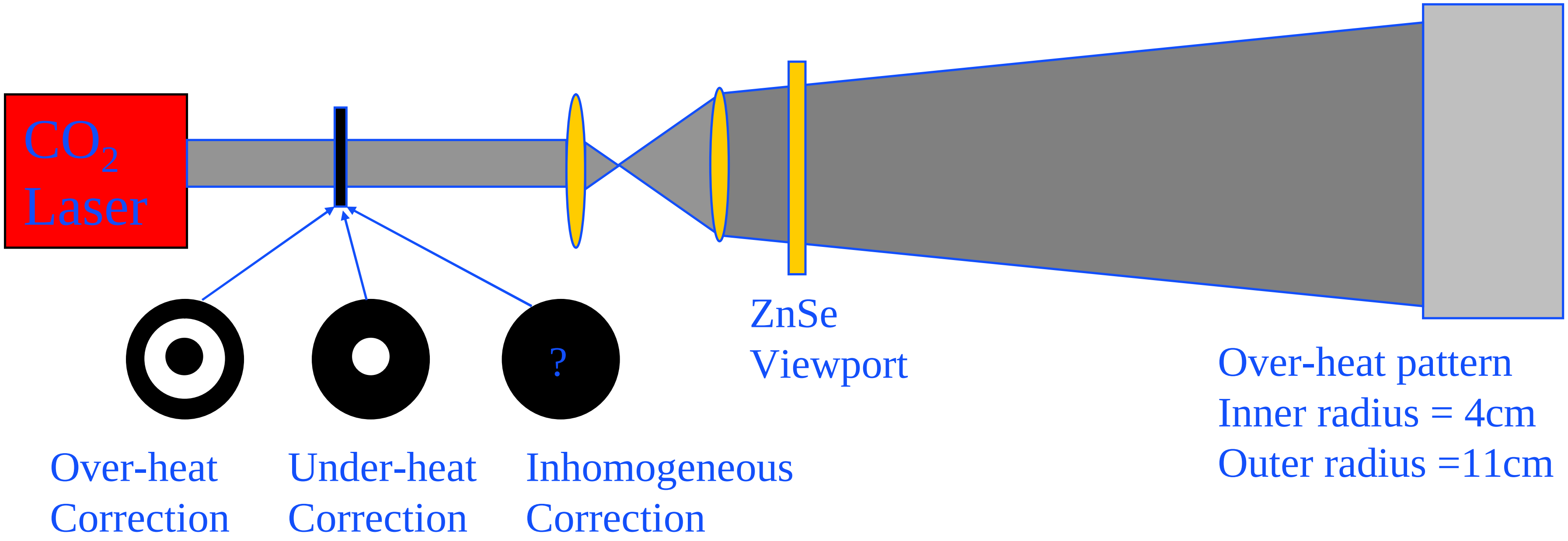
Sideband recycling gain



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

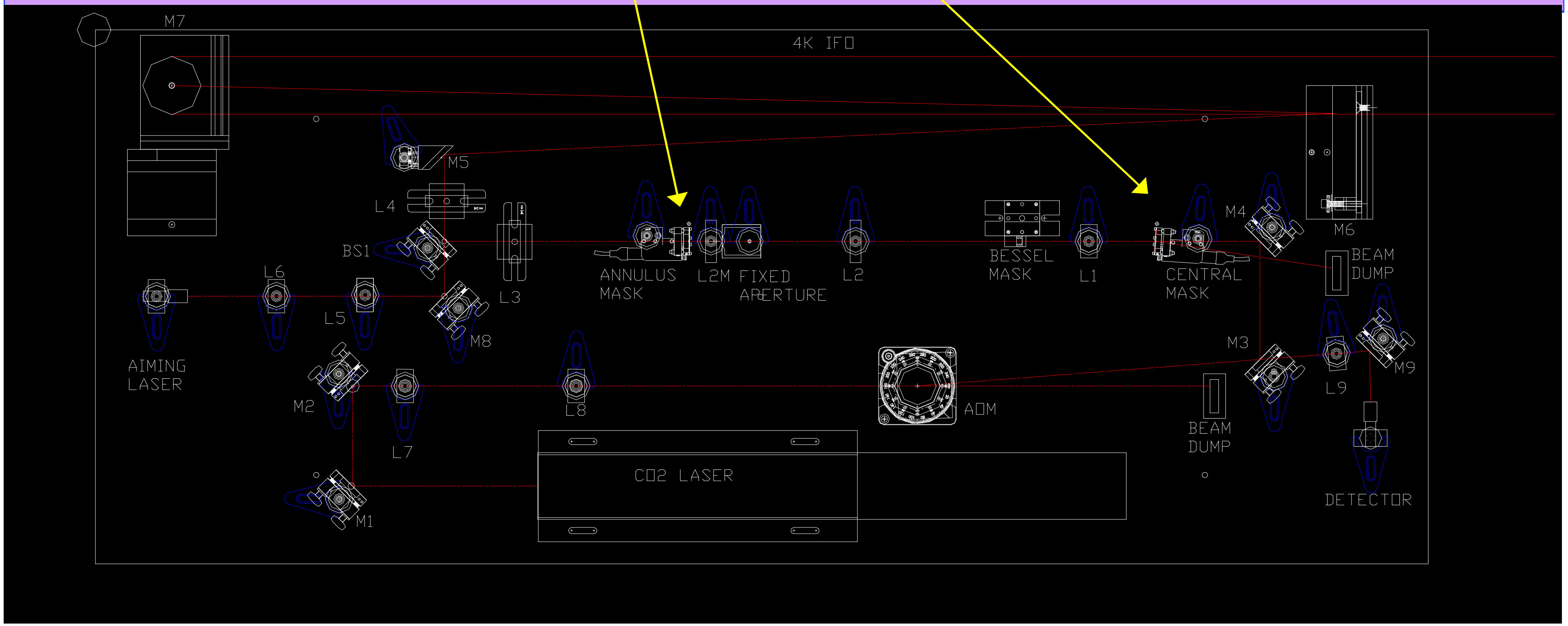
•Modeling suggests a centering tolerance of 10 mm is required

CO_2 Laser Projector Layout

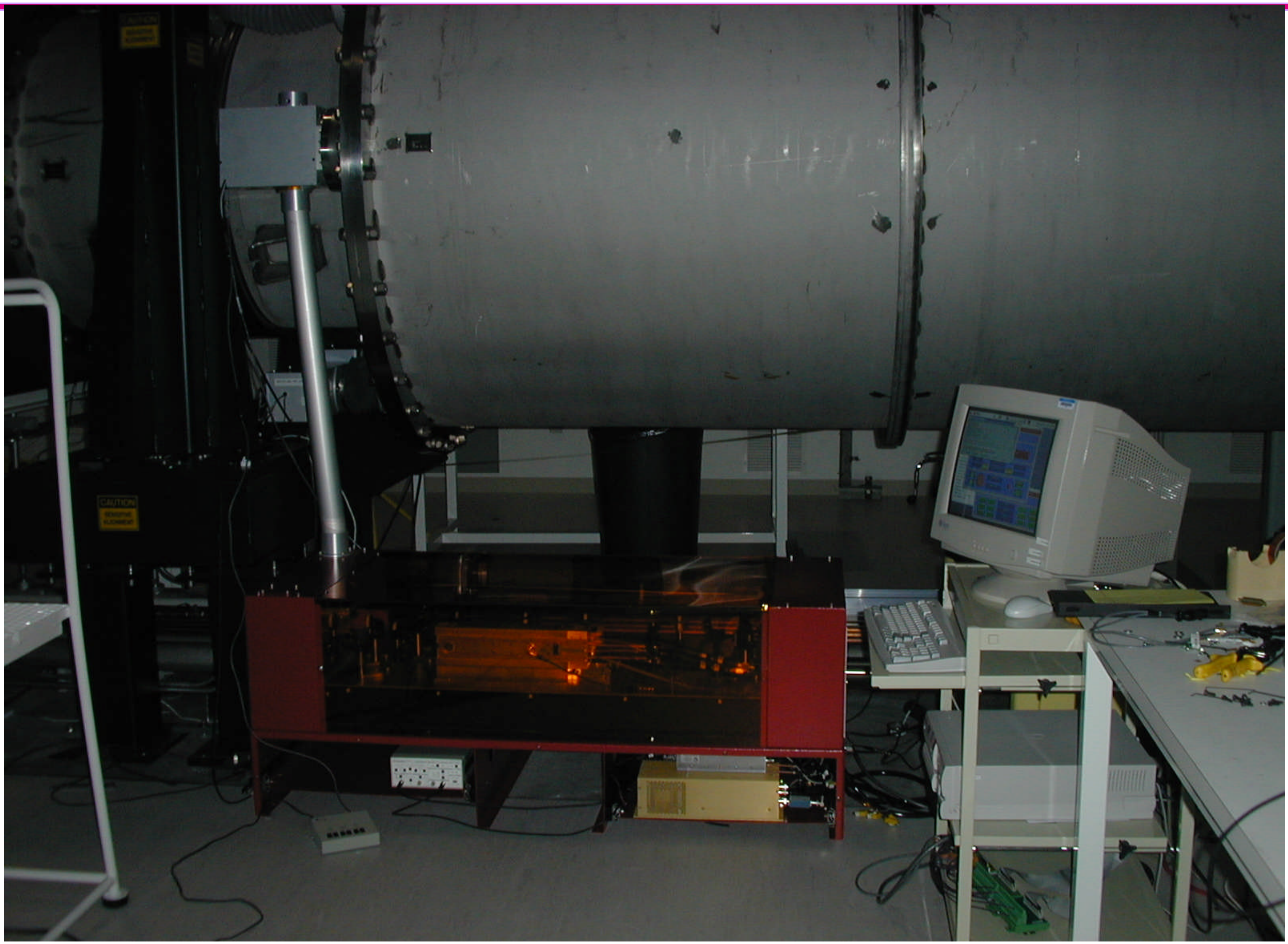
- Image planes here, here, and at ITM HR face

over-heat correction

under-heat correction

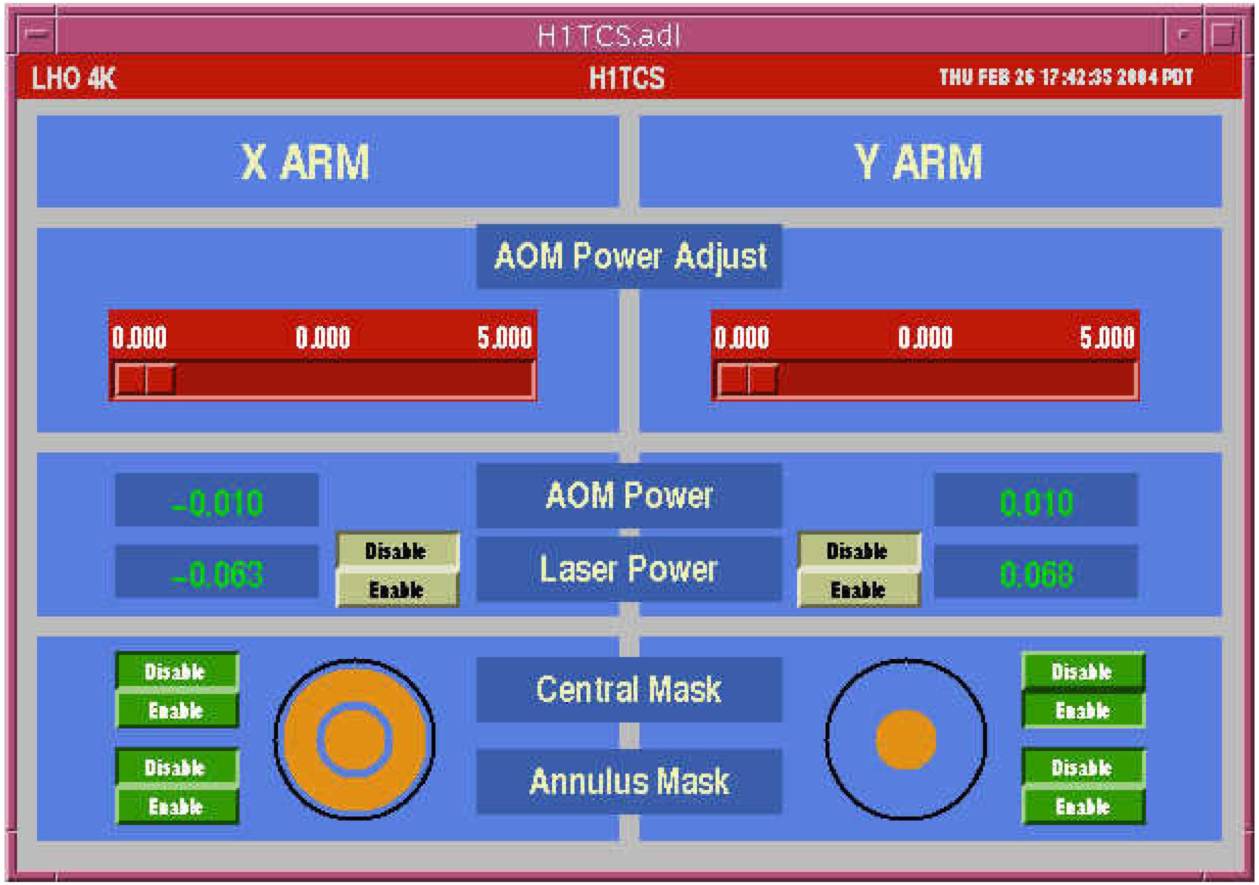


Thermal Compensation as Installed

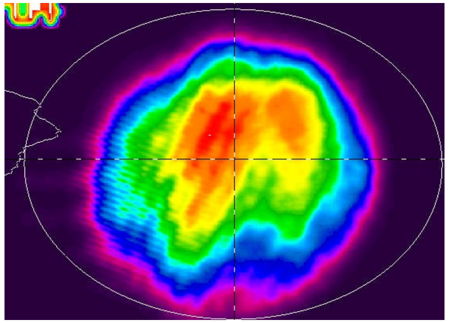


TCS Servo Control

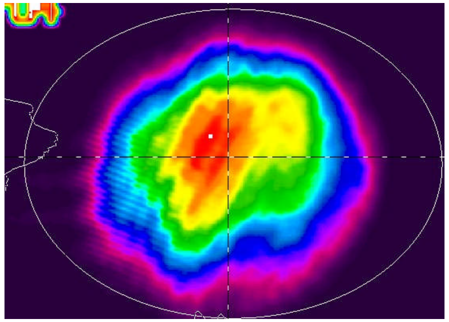
Thermal Compensation Controls



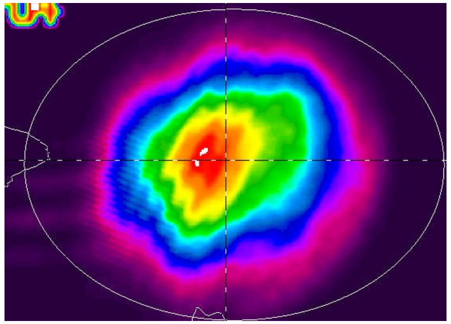
Heating Both ITMs in a Power-Recycled Michelson



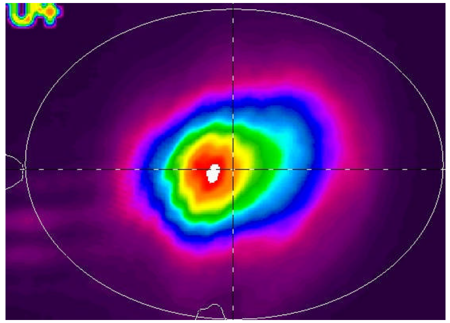
No Heating



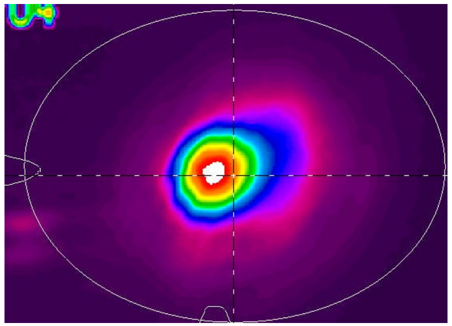
30 mW



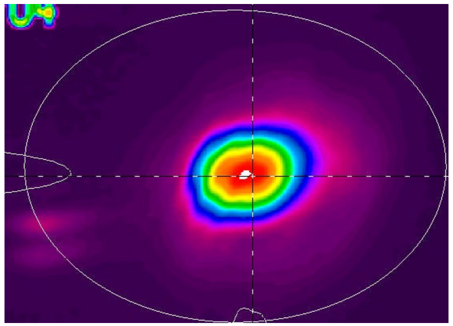
60 mW



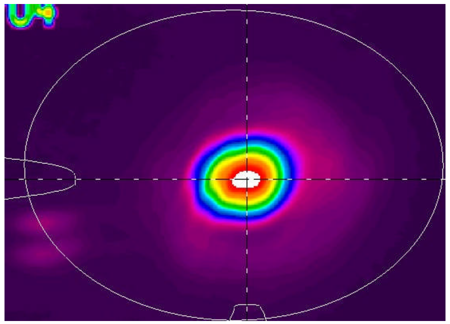
90 mW



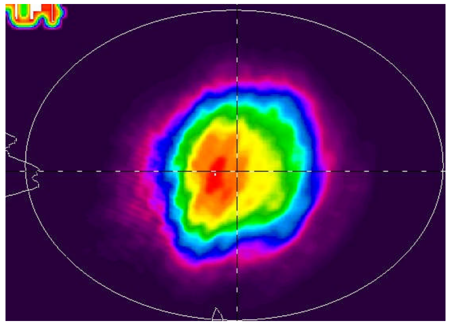
120 mW



150 mW

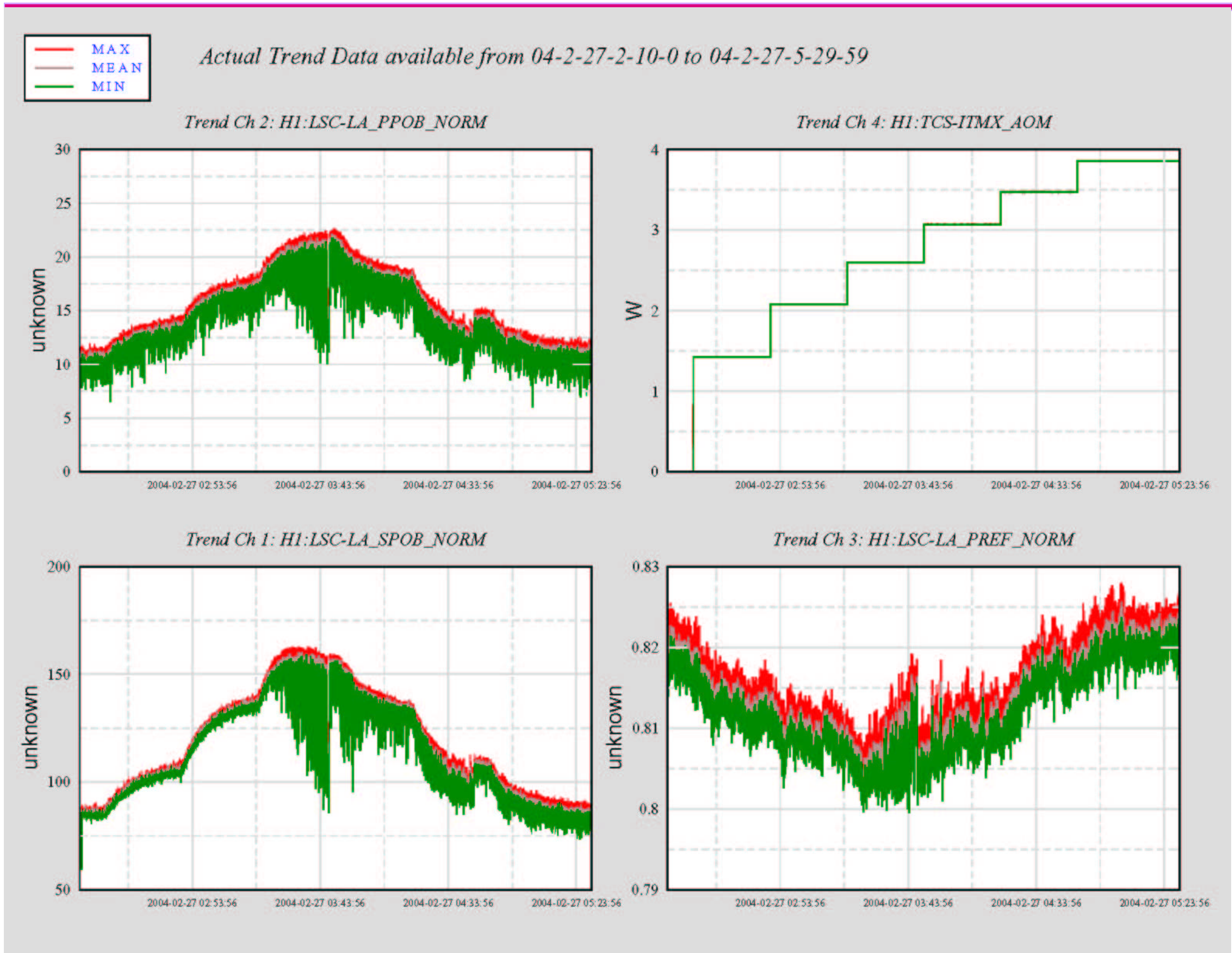


180 mW



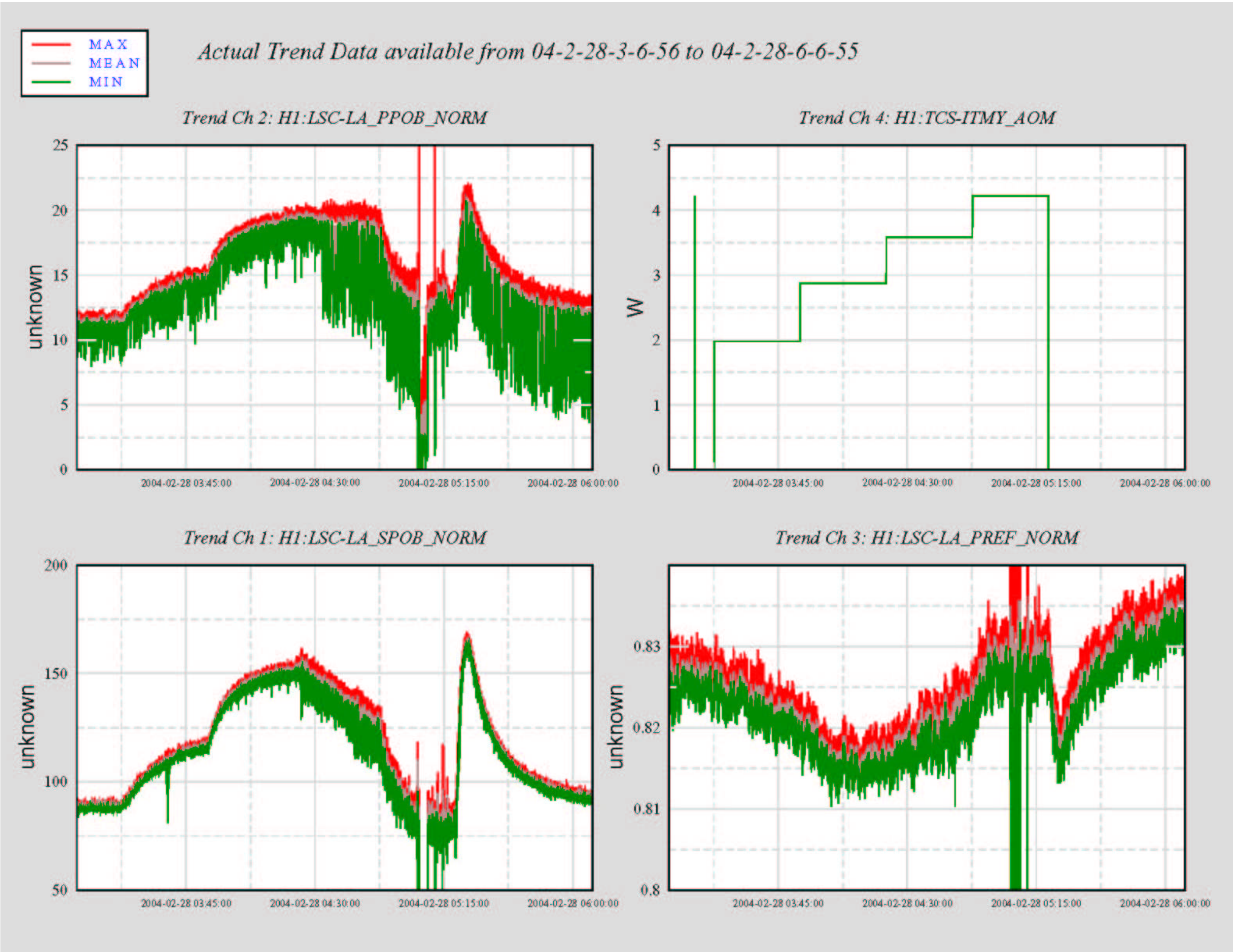
Carrier

RF Sideband Power Buildup



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

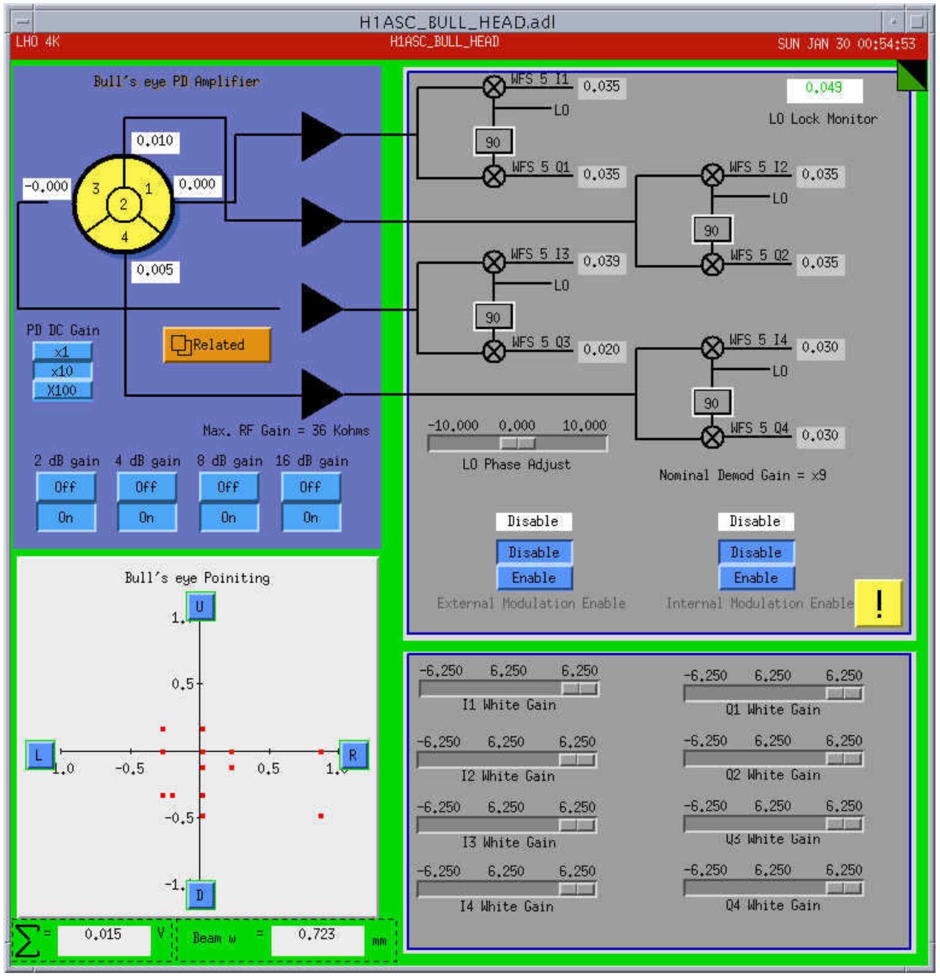
RF Sideband Power Buildup



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

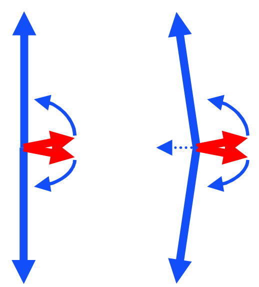
Common-mode Bulls-eye Sensor

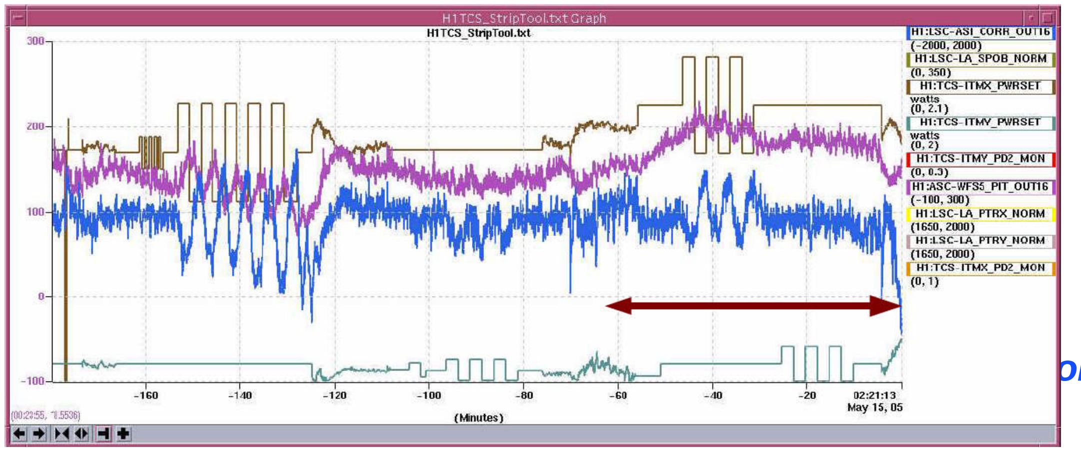
- Good mode overlap of RF sideband with carrier determines optimal thermal compensation- so we measure the RF mode size to servo TCS.
- Sensor output is proportional to LG10 mode content of RF sidebands.



Differential TCS- Control of 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.

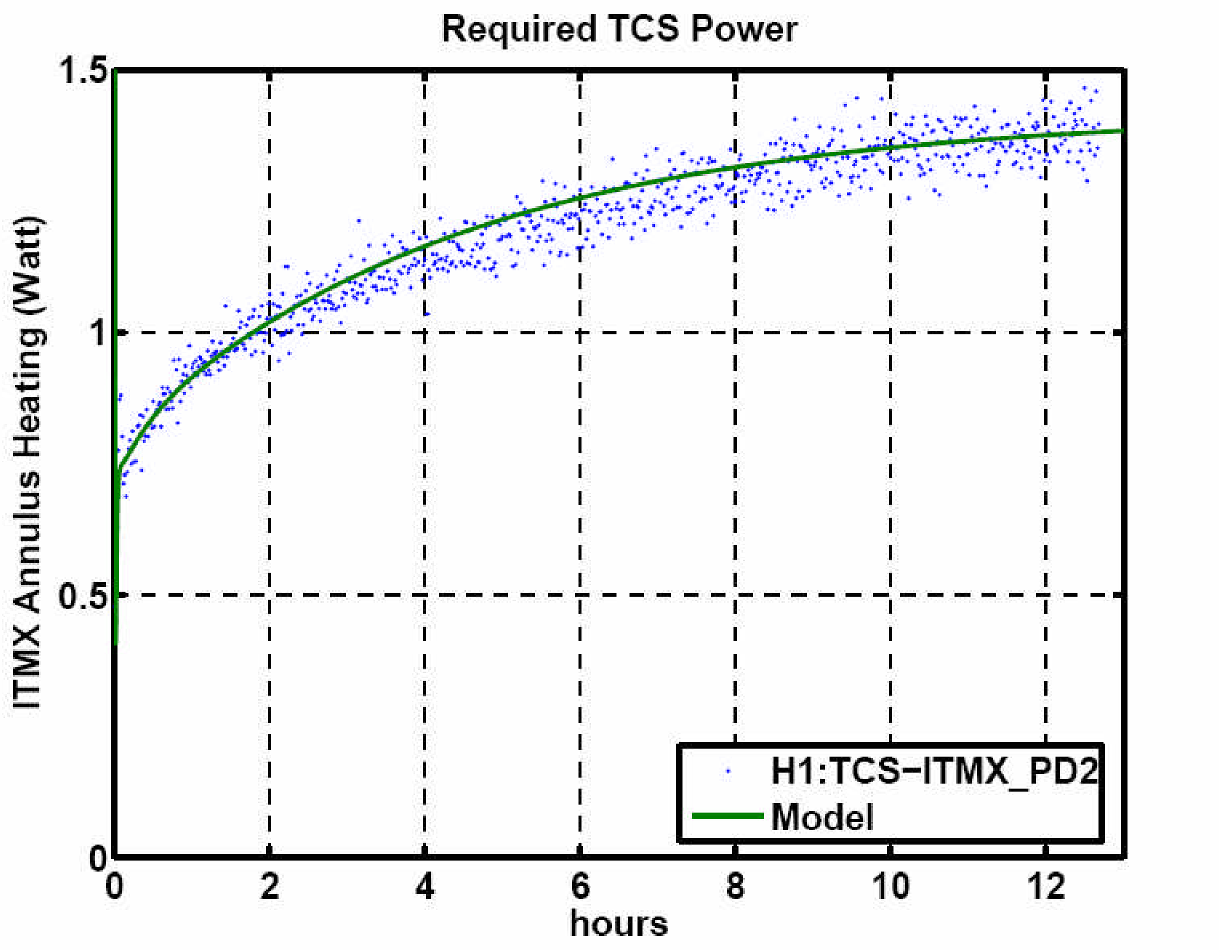
Yet, this signal dominates the RF photodetection electronics!

--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

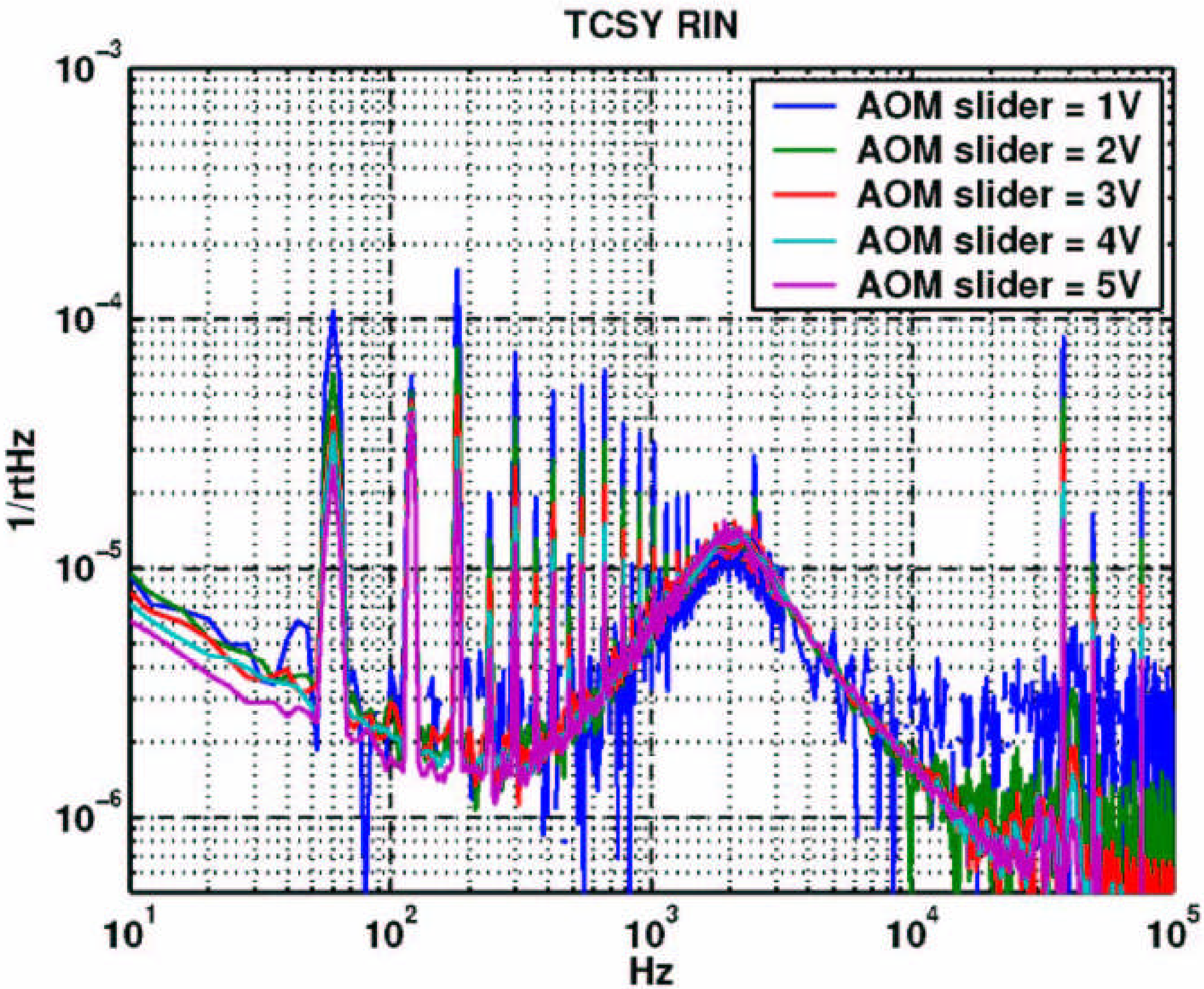


After locking at high power, the heat distribution in the ITM continues to evolve for hours. To maintain constant thermal focusing power requires varying TCS power.

In practice, constant TCS power is often enough.

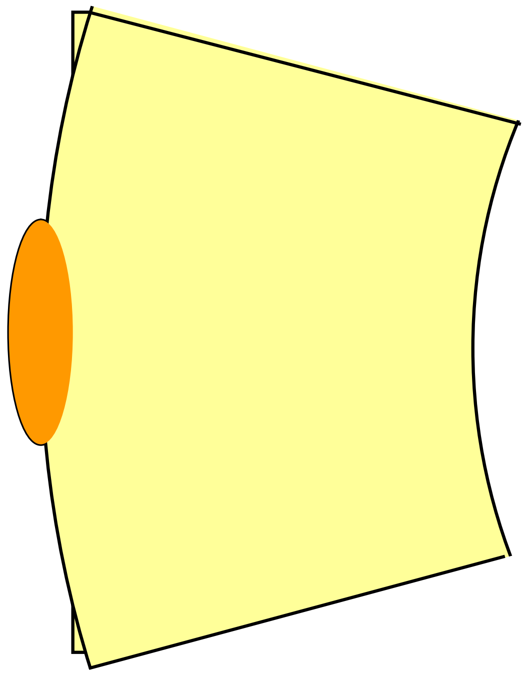
TCS Noise Issues

RIN of TCS-Y CO_2 Laser



TCS Noise Coupling Mechanisms

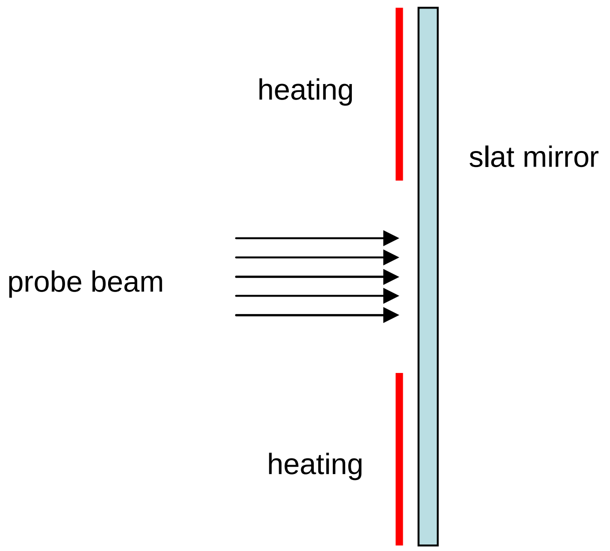
- Thermoelastic (TE)- fluctuations in locally deposited heat cause fluctuations in local thermal expansion
- Thermorefractive (TR)- fluctuations in locally deposited heat cause fluctuations in local refractive index
- Flexure (F)- fluctuations in locally deposited heat cause fluctuations in *global*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

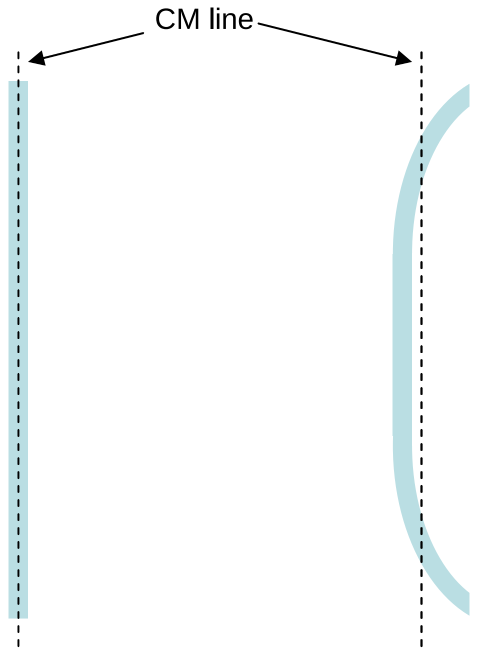


$$\langle \triangle z \rangle = \frac{P}{2\pi f C\rho} \left(\qquad \right) \mathrm{RIN}$$

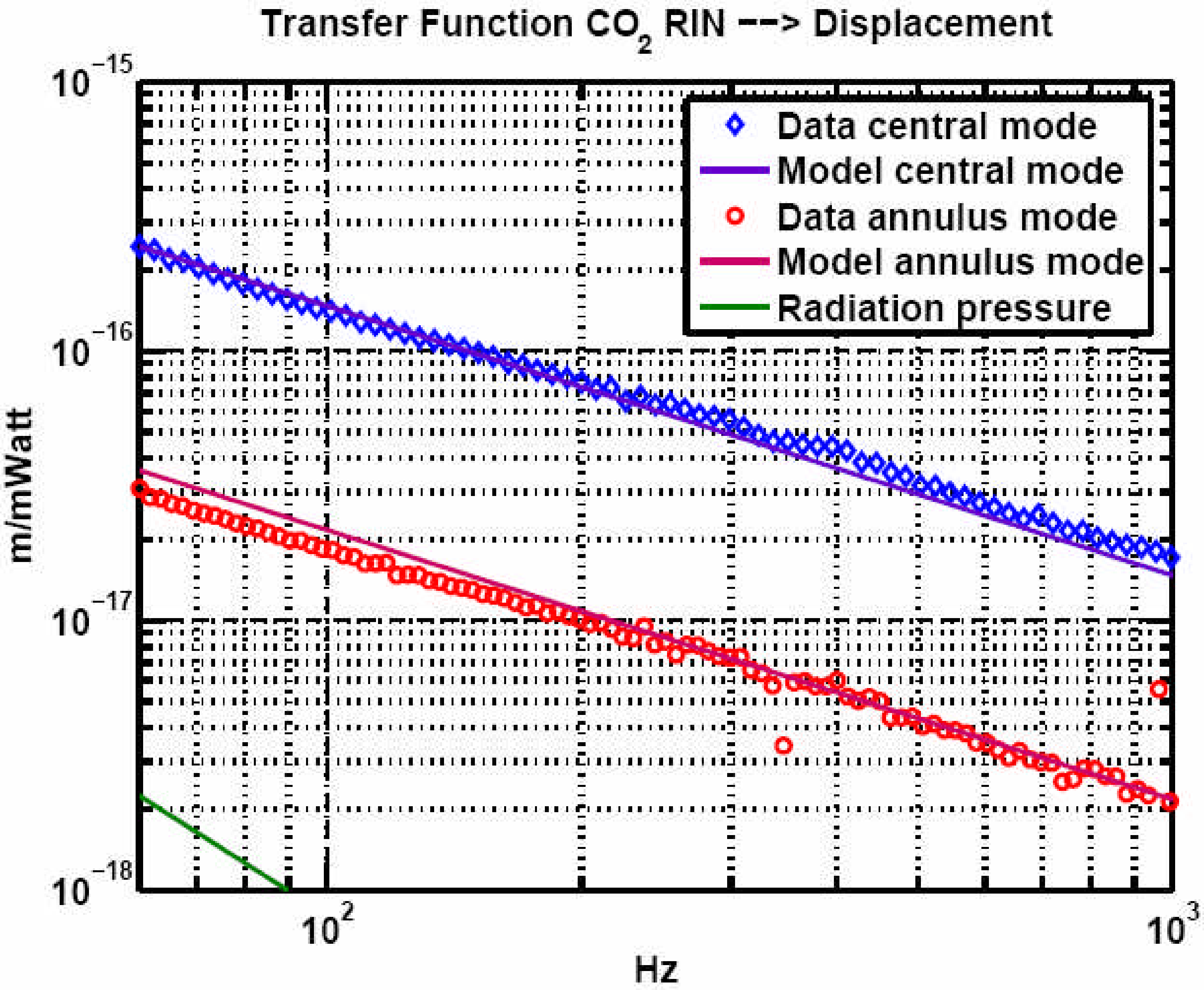
Flexure Noise- A Simple Model

A very skinny mirror
with ‘annular’ heating



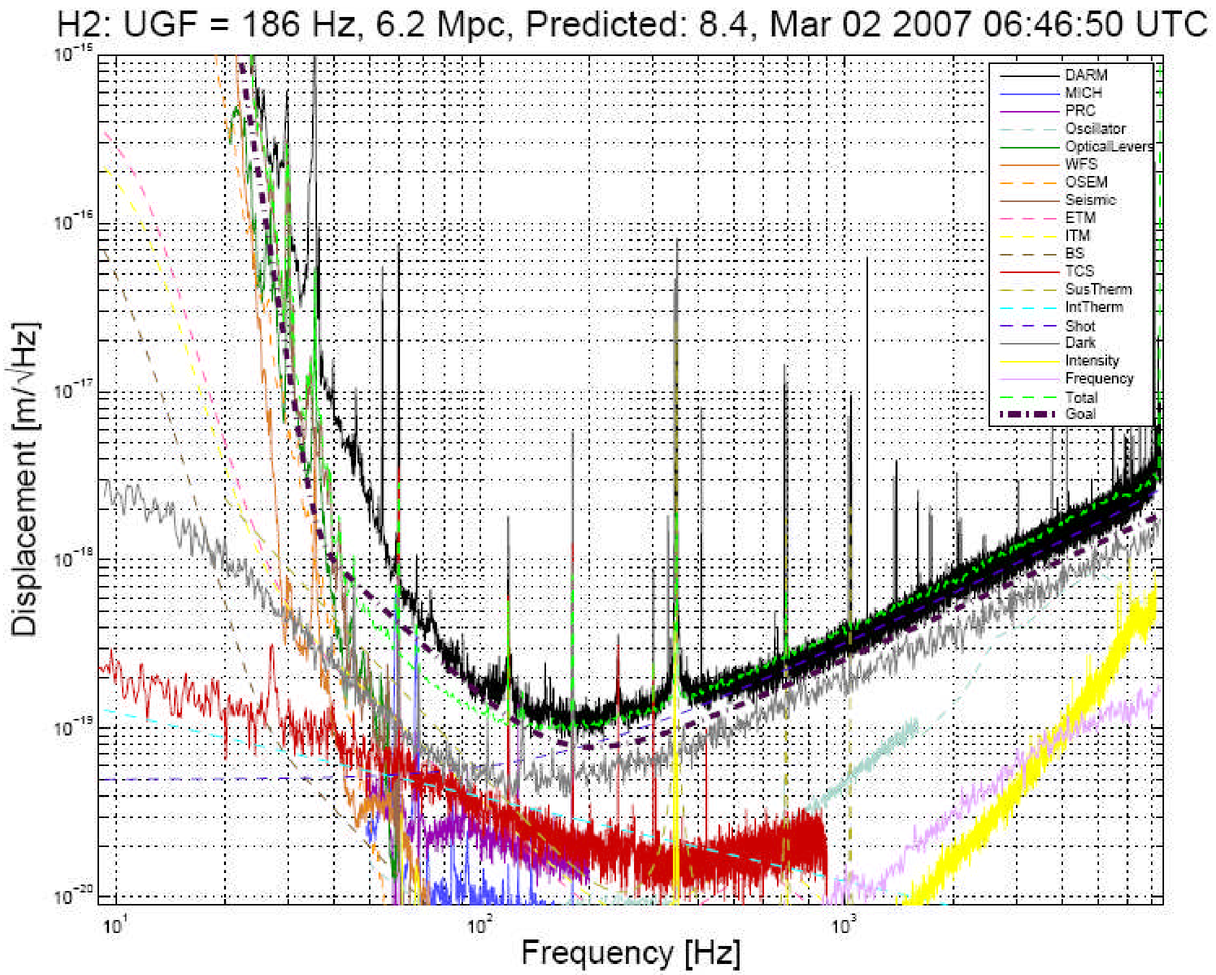


The probe beam sees the mirror move at the center due to wiggling far from center



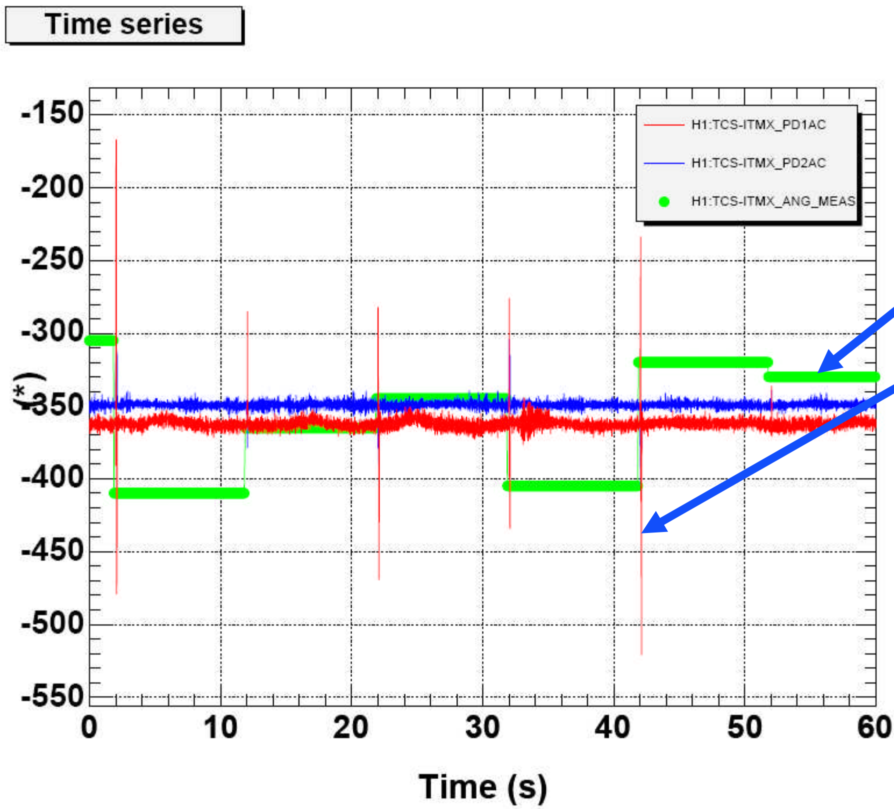
Transfer Function CO_2 RIN --> Displacement
10^{-15}
10^{-16}
10^{-17}
10^{-18}
m/mWatt
10^{2}
10^{3}
Hz
Data central mode
Model central mode
Data annulus mode
Model annulus mode
Radiation pressure

TCS Injected Noise Spectrum



TCS-Induced Transients

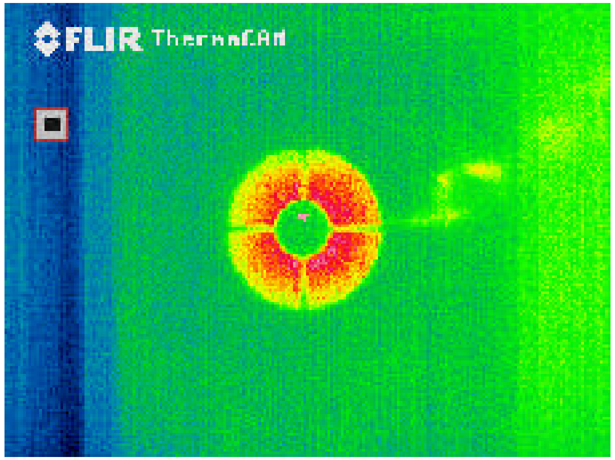
Impulses in TCS output can produce impulsive signals in the interferometer output: laser switching, mode transitions, and more obscure sources of noise…



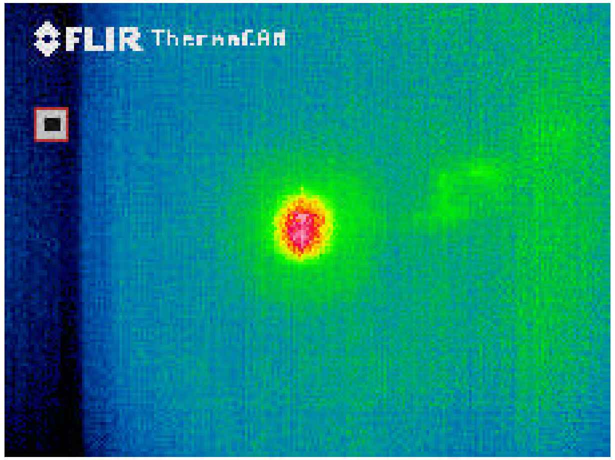
- Upgraded TCS controllers use rotating polarizers to adjust power.
- Every 10 seconds, the polarizers reorient.
- Every 10 seconds a glitch appears in TCS.
- Most glitches are well below LIGO sensitivity.
- After discovering this mechanism, polarizer stage motion was smoothed.

Quality of Compensation

Projector Heating Patterns



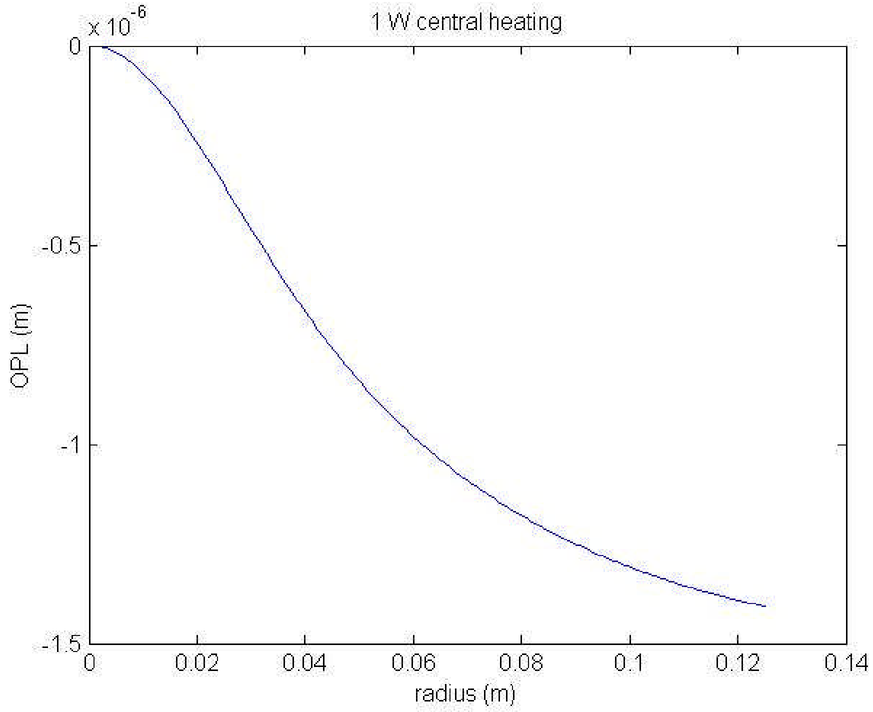
Annulus Mask



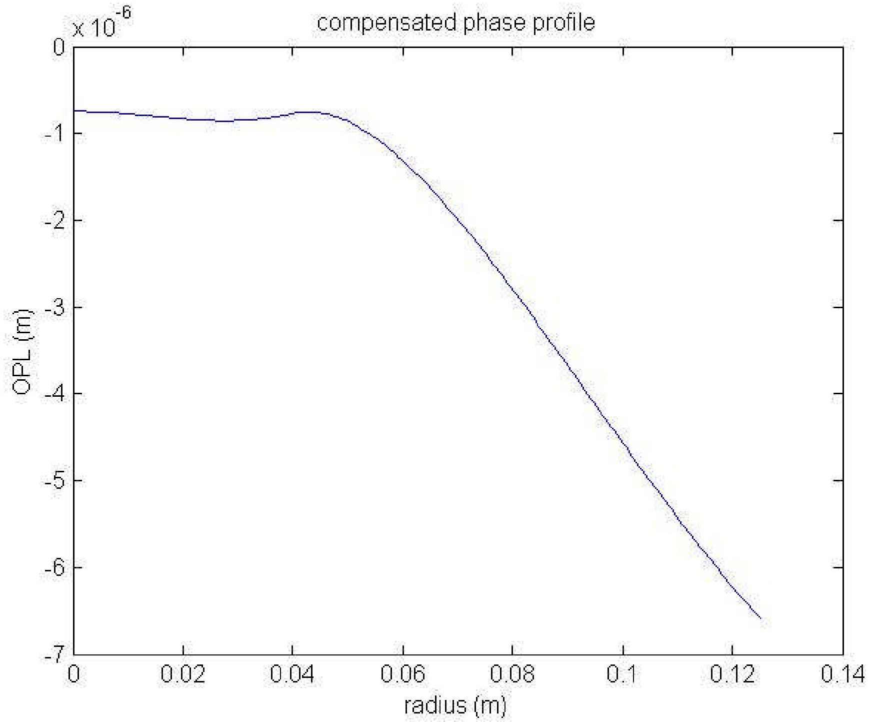
Central Heat Mask

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

Expected Profile of Thermal Lens

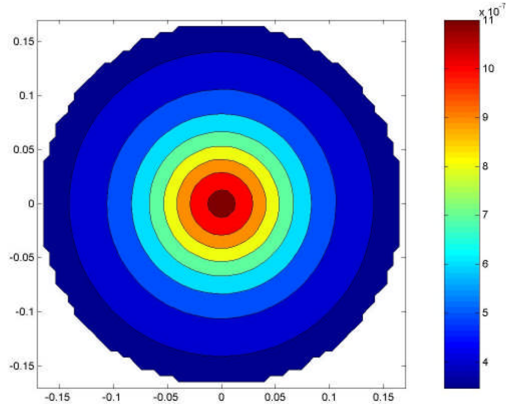


Expected uncompensated phase profile.

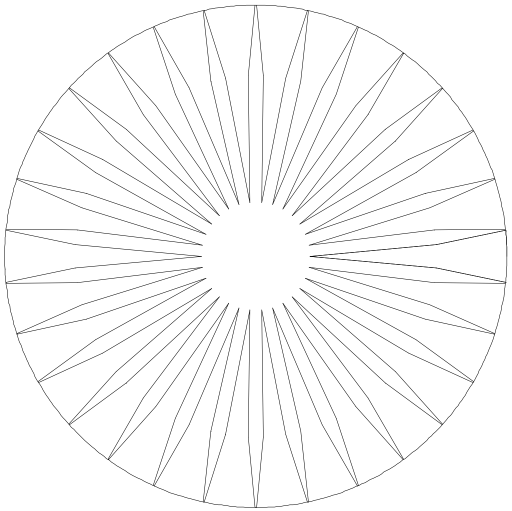


Expected compensated phase profile.

Actual Profile of Thermal Lens



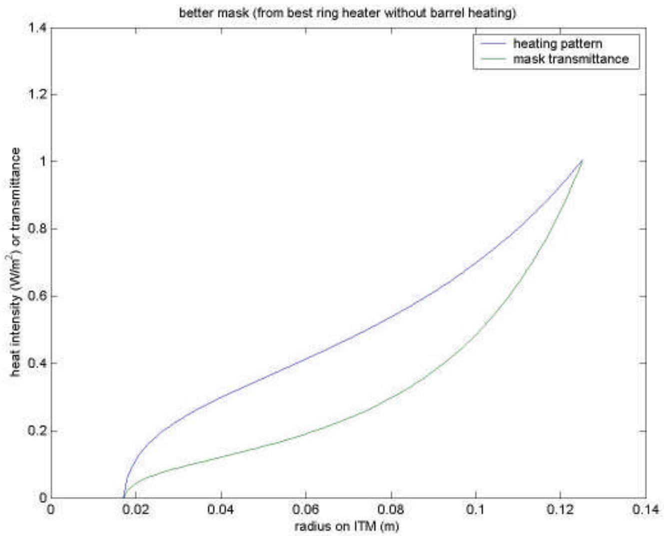
‘Gold Star’ Mask Design

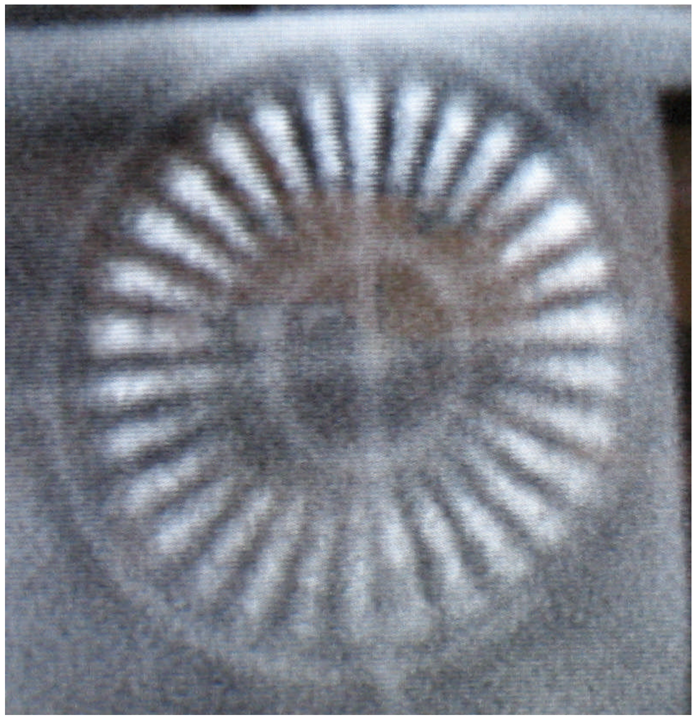


“star”- from hole pattern

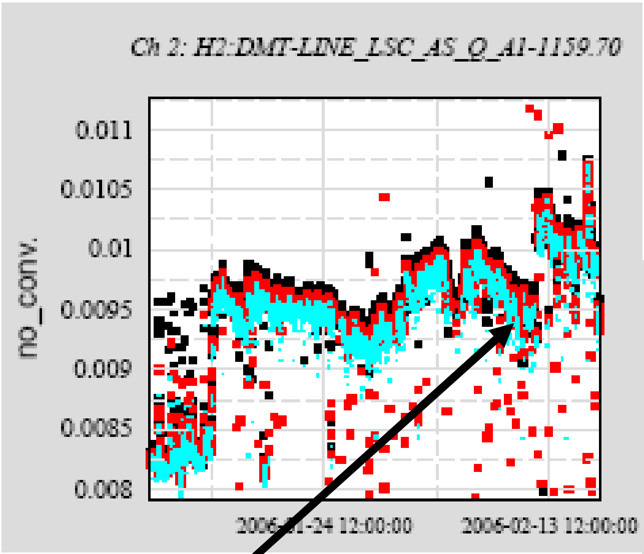
“gold”- gold coating to reduce power absorption

Hole pattern is clearly not ideal but diffraction and heat diffusion smooth the phase profile

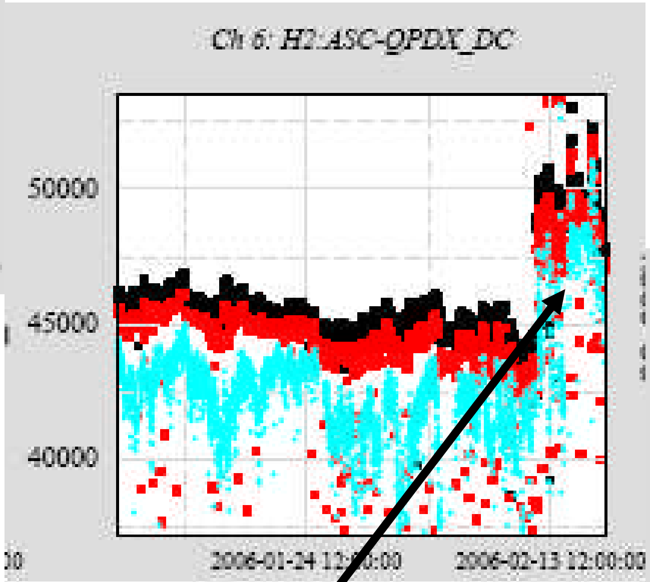




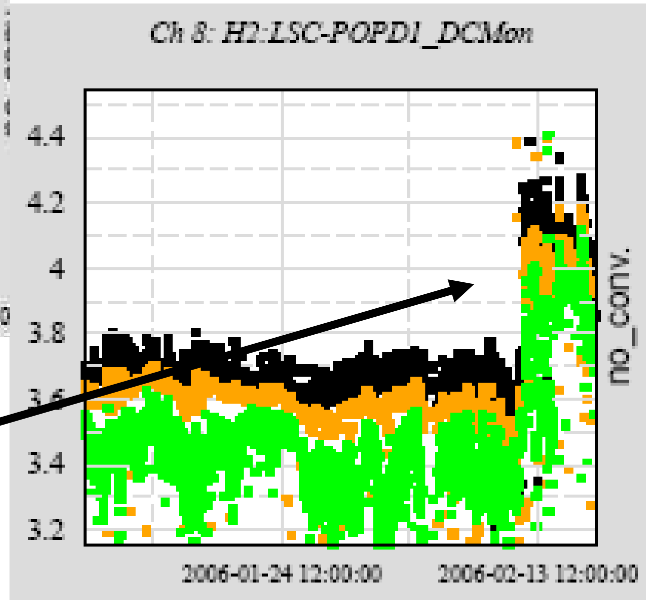
Improved Carrier Power with Gold Star Mask



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



optical gain up 5%



Note: no similar improvement in the sideband power was observed

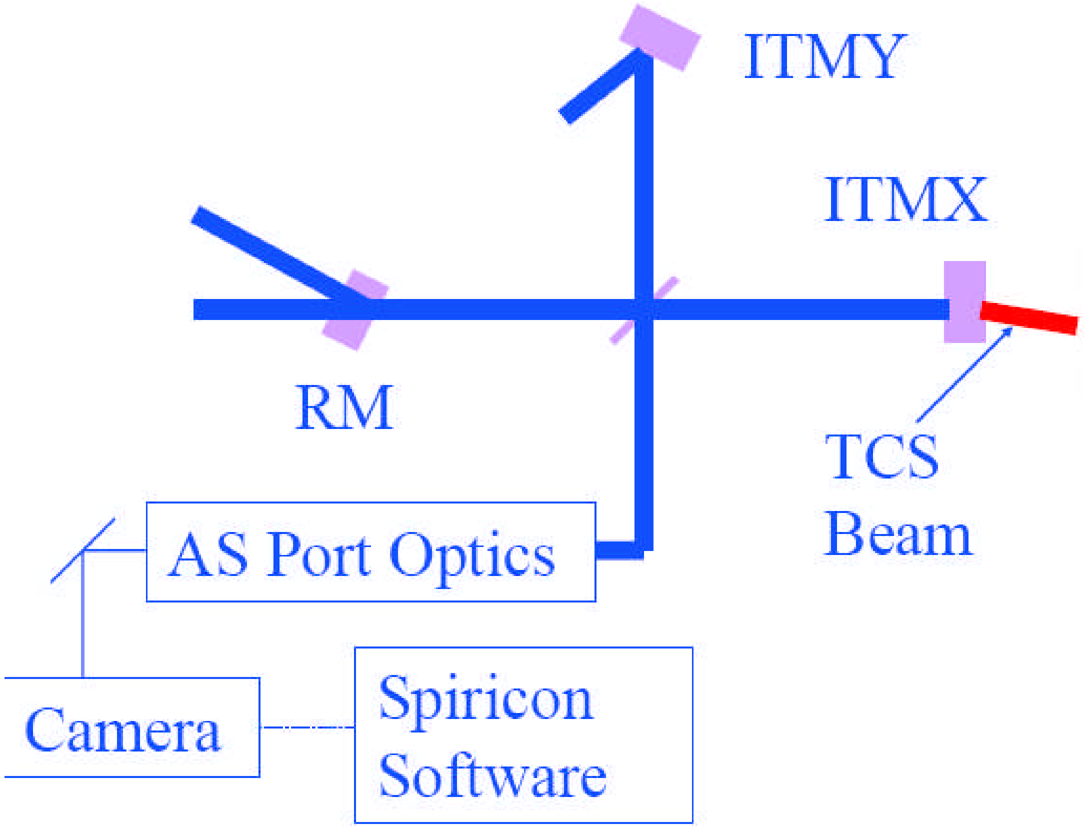
carrier recycling gain up 10%

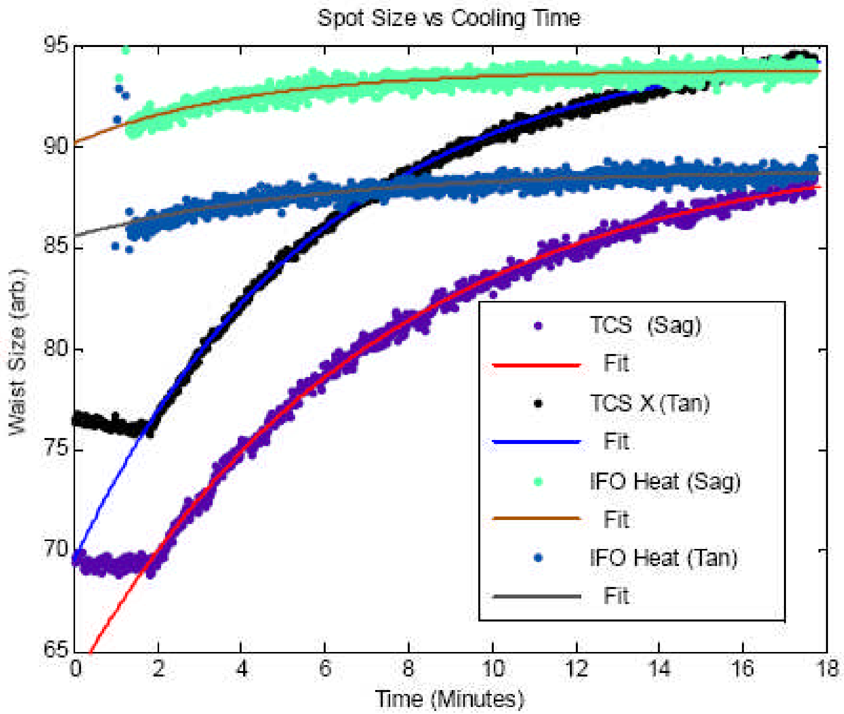
Enhanced LIGO TCS

Our Need for Power

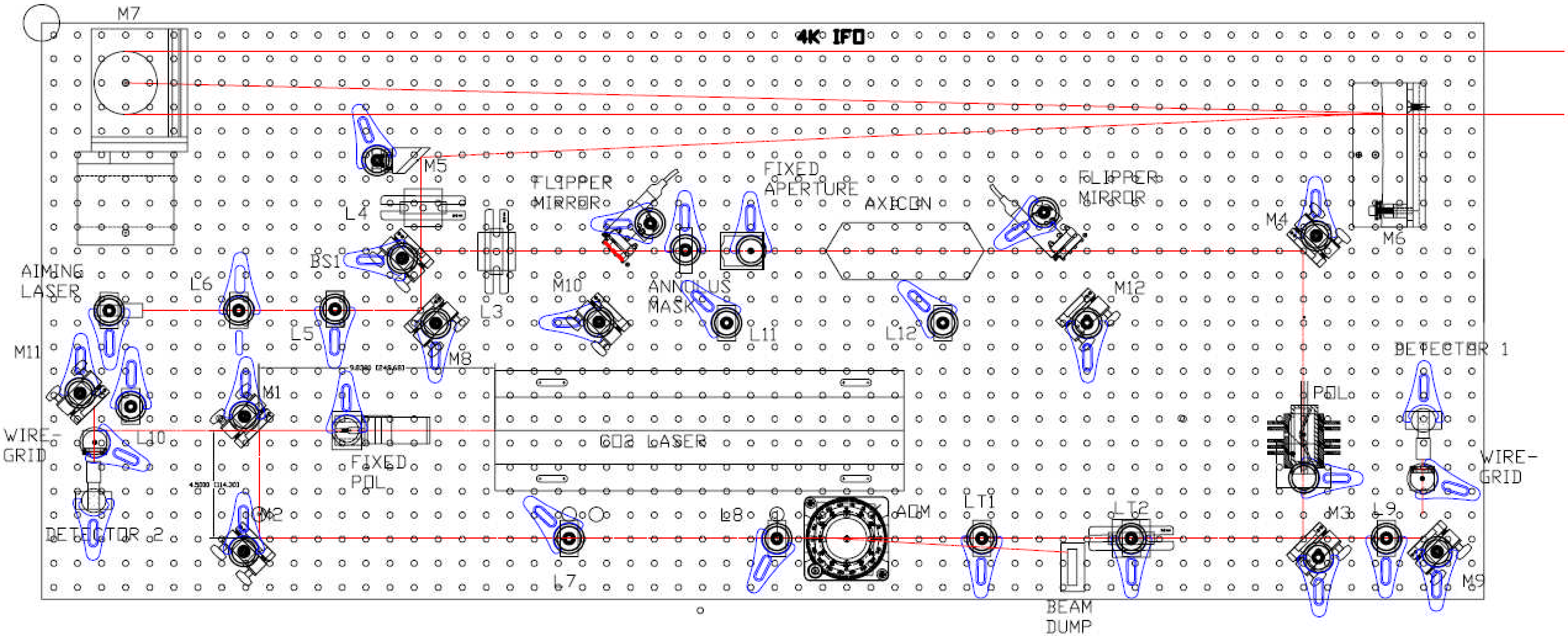
- Initial LIGO runs at ~7W input power
- Enhanced LIGO will run at ~30W input power
  - » 4-5x more absorbed power
  - » Naively, ~4-5x more TCS power needed
  - » Practically, more power even than this may be needed since LIGO point design is meant to make TCS unnecessary at 6W
  - » Or less power, if we can clean the mirrors
  - » Correction of static mirror curvature errors clouds this picture
- Our current projectors are not adequate

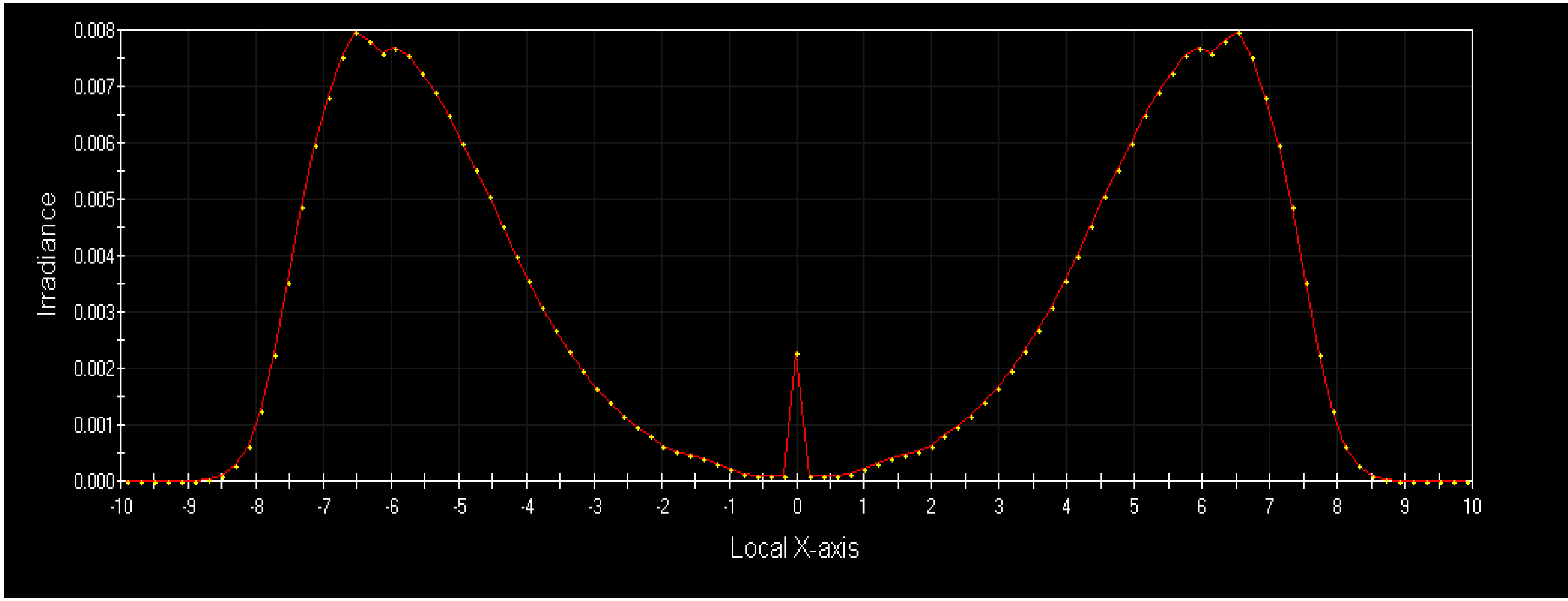
Test Mass Absorption Measurement Technique-Spot Size





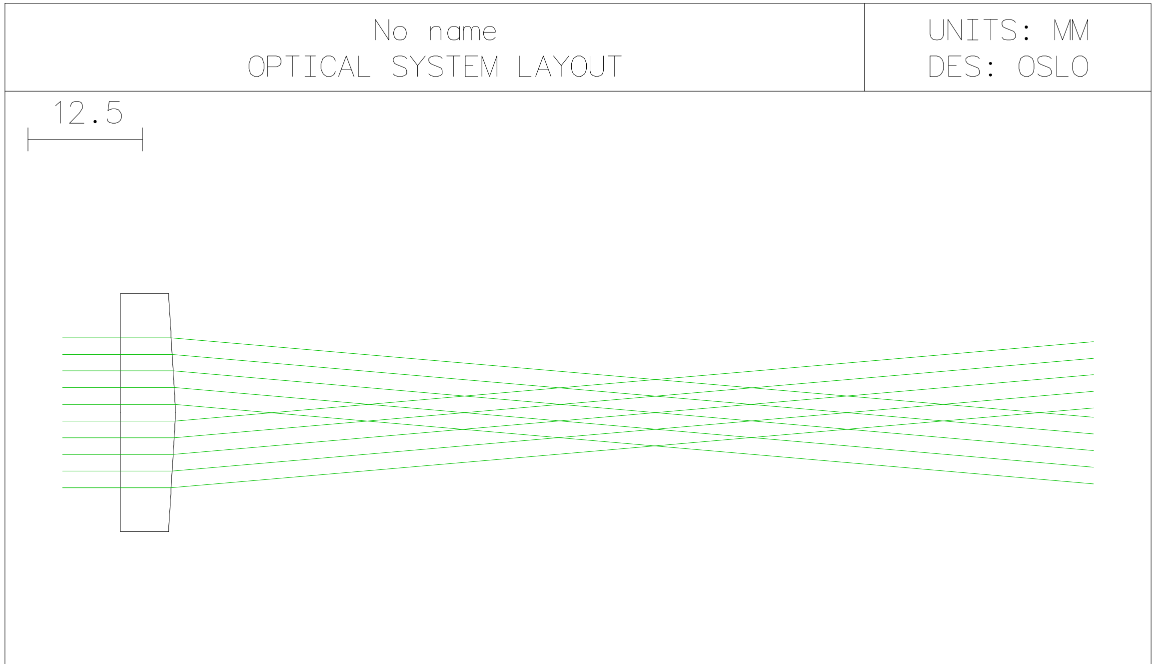
Enhanced LIGO TCS Projector





Axicon design proposed by II-VI for Enhanced LIGO

The Axicon



Conclusions

- TCS becomes essential instantly after it is installed.
- TCS works even though thermal lens is poorly known.
- TCS is flexible (all three IFOs have different installations).
- The external projector design is flexible and easy to maintain.
- Unexpected behaviors and uses (e.g. AS_I, carrier arm coupling, static correction) appear during commissioning.
- Noise couplings and injections can be rich but are predictable, measurable, not fatal.