Radiative Cooling Thermal Compensation for Gravitational Wave interferometer mirrors.

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High power interferometers

- The main Fabry Perot mirrors of advanced interferometers will be subject to almost a MW of standing laser light over a Gaussian spot size of ~6 cm radius
- high reflectivity coatings absorb >0.25 ppm
- The mirrors receives 0.25 ~ 0.5 W of heating
- The deposited power distribution matches the stored beam profile

Thermal lensing problem

- Thermal lensing impede the performance of the interferometer
- Problem already present in Virgo and LIGO at lower power, due to the higher absorption of their mirrors

Present solution

- Thermal Compensation System (TCS)
- shape an annular CO_2 laser beam and project it on the mirror periphery
- generate counter thermal lensing

- Problem for Advanced interferometers:
- Radiation pressure and thermoelastic noise on test mass affect the GW signal

Advanced solution

- Hot ring on a compensation plate
- Generates negative thermal lensingon an optical element that does not otherwise affect the interferometer performance
- Technique tested on main mirrors by GEO

Advanced Virgo problem

- Very difficult to implement compensation plate

Alternative solution

- Directional cooling of the stored beam spot
- Passive, no forces on the test mass

Directional Radiative Cooling (DRC) working principle

- Image a cold surface on the laser spot
- The thermally radiated heat from the spot is absorbed by the cold target
- The cold target, being colder, returns less heat to the laser spot

DRC basics

- DRC takes advantage of the heat emitted by the spot BECAUSE it is at room temperature

- Simply balances the laser deposited power with robbed thermal power

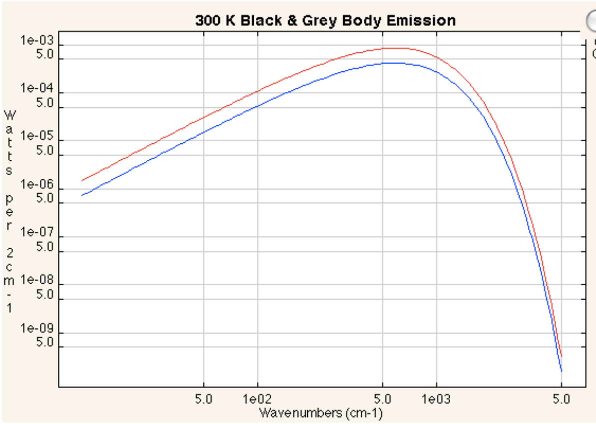
- DRC applied in absence of stored power would generate a cold spot on the mirror

DRC Facts

- The mirror is subject to less thermal radiation radiation pressure
- actually quieter than without cooling
  - (no practical advantage though)

Feasibility of DRC

- At room temperature a black body emits 146W/sr-m^2
- Fused silica emissivity is close to that of a black body 0.93 engineering toolbox http://www.engineeringtoolbox.com/
- A 6 cm radius spot emits 1.64W/sr
- Black Body Emission Calculator http://infrared.als.lbl.gov/calculators/bb2001.html
- 0.25-0.5 sr coverage sufficient to rob the 0.25—0.5W deposited by the laser spot



DRC required temperature

- Liquid nitrogen cooled black bodies emit only 0.4% thermal radiation than a room temperature body

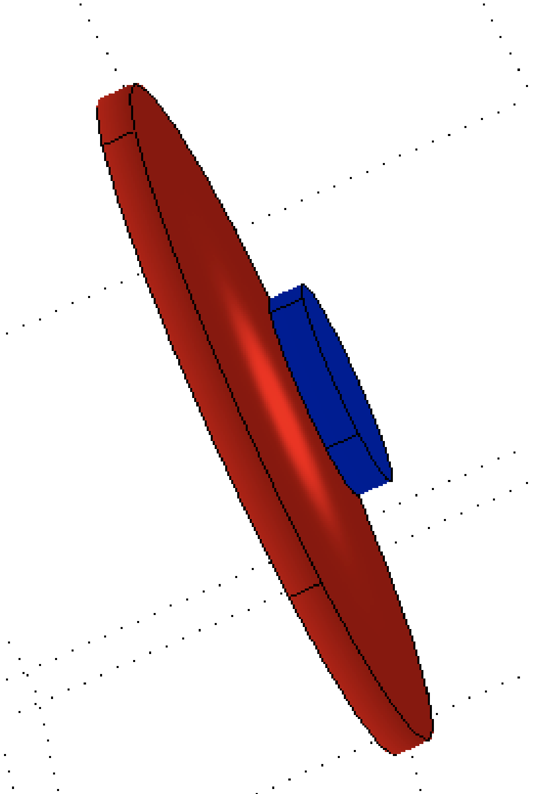
- Li-N_2 targets would be 99.6% efficient

How to “direct” radiative cooling

- Proximity cooling
- Baffled cooling
- Imaging cooling

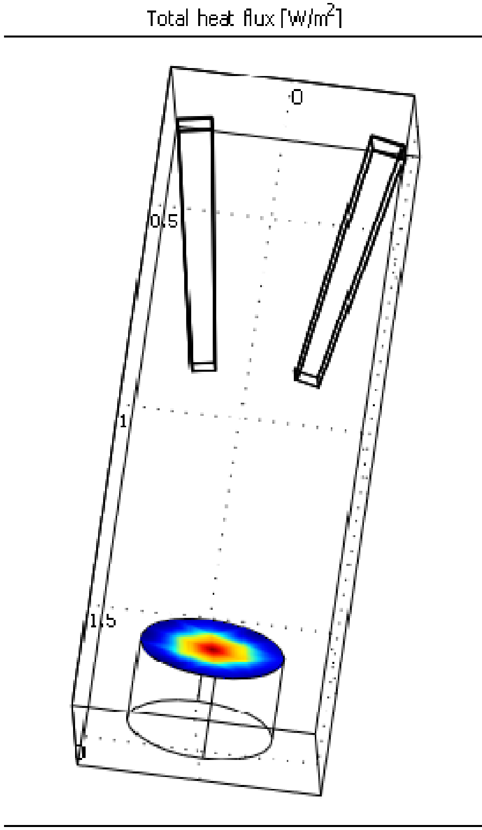
Proximity DRC

- A 6.2 cm radius, liquid-nitrogen-cooled disk placed in front of the test mass would suck out 5.1 W
- Advantages:
  - simple solution
- Disadvantages:
  - Obstruct the stored light beam
  - Suck out too much power



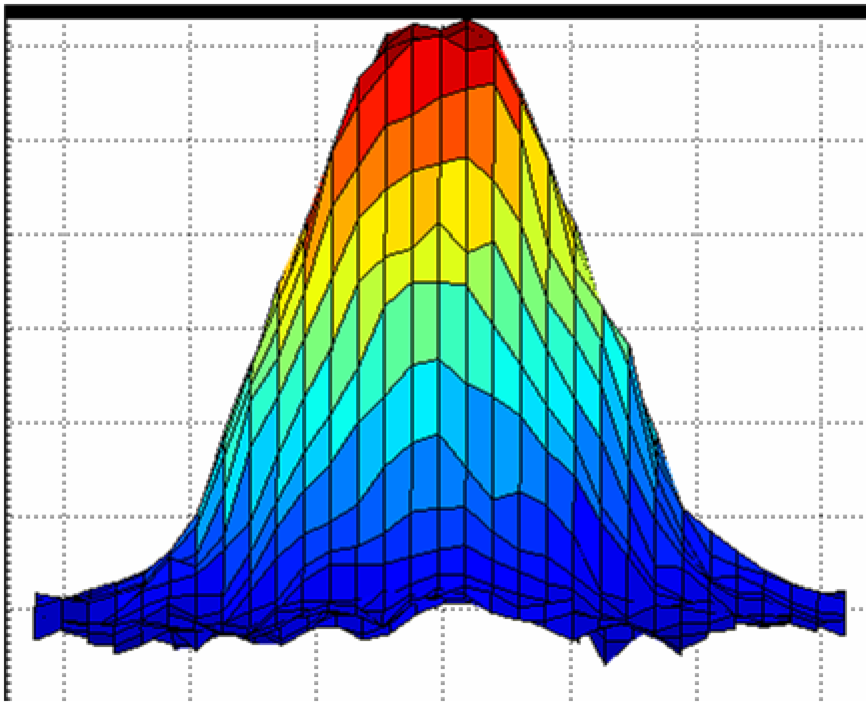
Baffled DRC

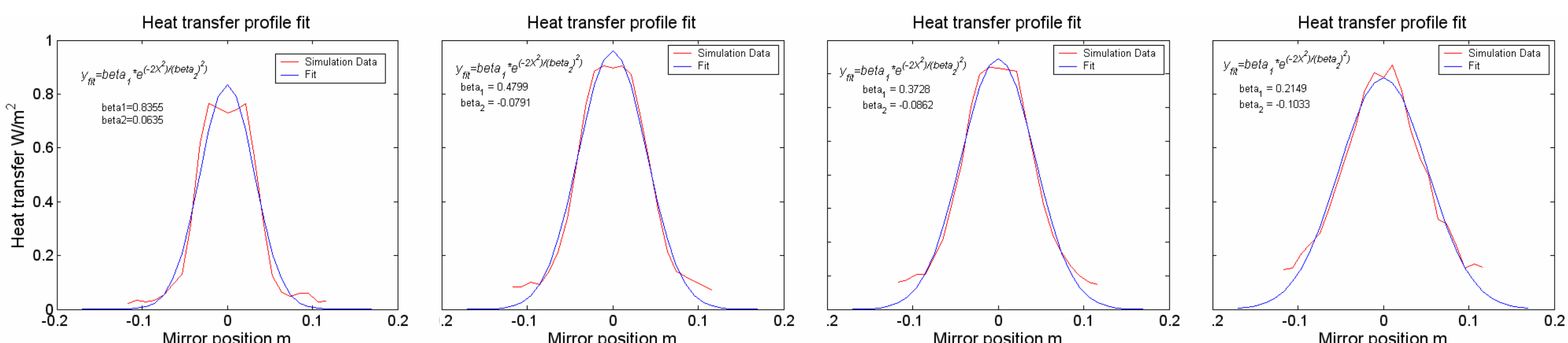
- A large Li-N_2 target is used
- Pyramidal Baffles restrict the line of view of the cold target to the stored beam spot
- Pyramids can be located outside the beam line outer envelope



Baffled DRC de-focussing

- Cooling spot can be defocussed to mimic a Gaussian by playing with longitudinal positioning of the baffles



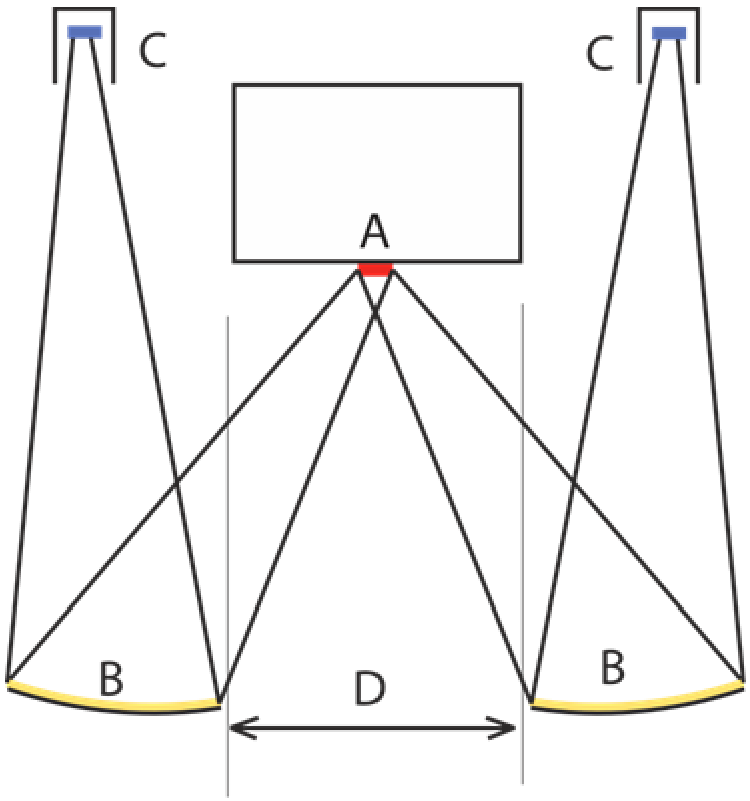


Baffled DRC disadvantages

- Advantages
  - Large cooled surface acts as cryo-pump for organics
- Disadvantages
  - Bulky baffle array,
  - Large Li-N_2 cooled target
  - Large cooling power requirement, potentially mechanically noisy

Mirror focused DRC

- One or two small Li-N_2 cooled targets focused with Au plated spherical mirrors on stored beam spot
- Mimic Gaussian spot profile by moving cold targets out of focus



Controlling DRC power

- Three methods
  - Iris control
  - Target temperature control
  - Hot resistor power balance

Iris DRC power Control

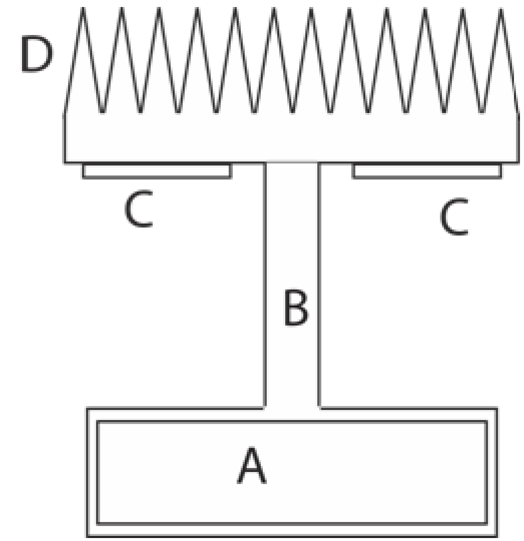
- The DRC cooling power is directly proportional to the cold target area used.
- An iris placed in front of each target would naturally tune the cooling power
- Disadvantage:
  - Mechanical parts in vacuum

Iris DRC power Control

- Advantage:
  - A fixed iris can be used for static cooling power controls, to match the absorption of individual coatings and minimizing the dynamic range of active power controls

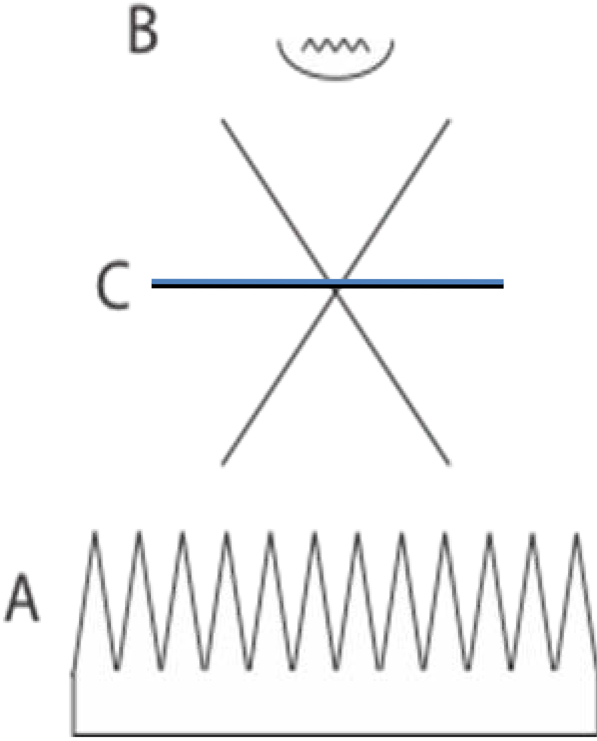
Target temperature Control

- The cold target "D" is separated from the Li-N_2 cooling bath "A" by a thermal resistor "B"
- The cold target temperature is controlled by a resistor "C" mounted on the cold target
- Disadvantages:
  - Reaction time of several seconds
  - Dumps power in thermal bath
- Advantages:
  - Can be used for small corrections

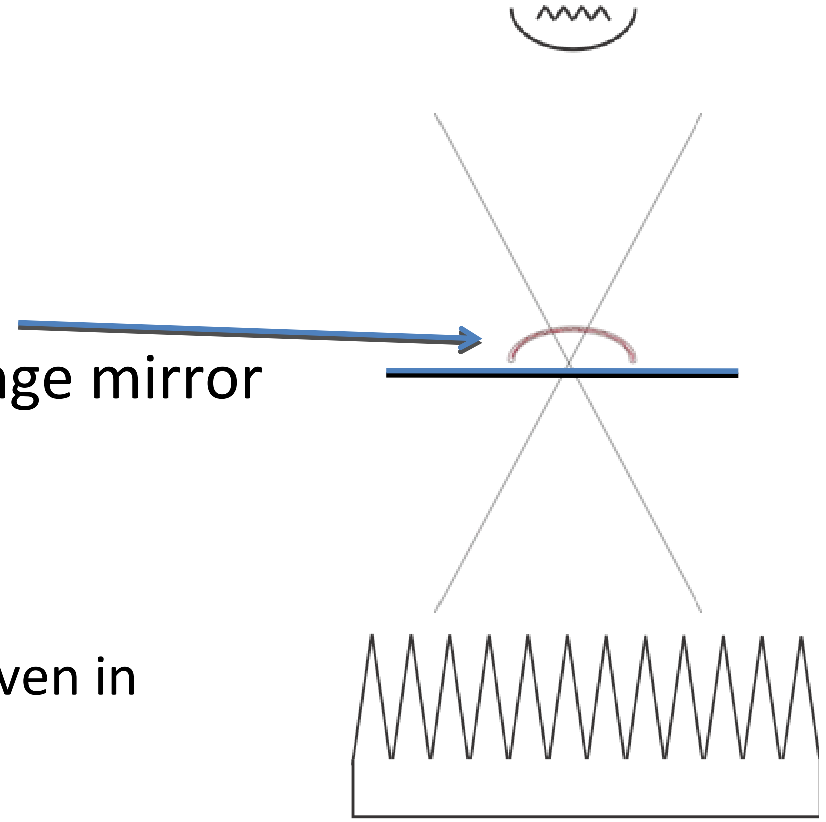


Hot resistor DRC power Control

- The cold target "A" is placed behind the mirror focal plane "C"
- A back shielded resistor "B" is placed in front of the focal plane
- Both defocused to generate Gaussian profile, the heating modulatable
- Disadvantages:
  - Heating power fluctuations can generate thermo-elastic noise on the main mirror,
    - can use with interferometer off,
    - need to limit the resistor applied power
- Advantages:
  - Fast reaction times (low resistor heat capacitance)
  - Does not dump power in thermal bath



Focused RTC further option

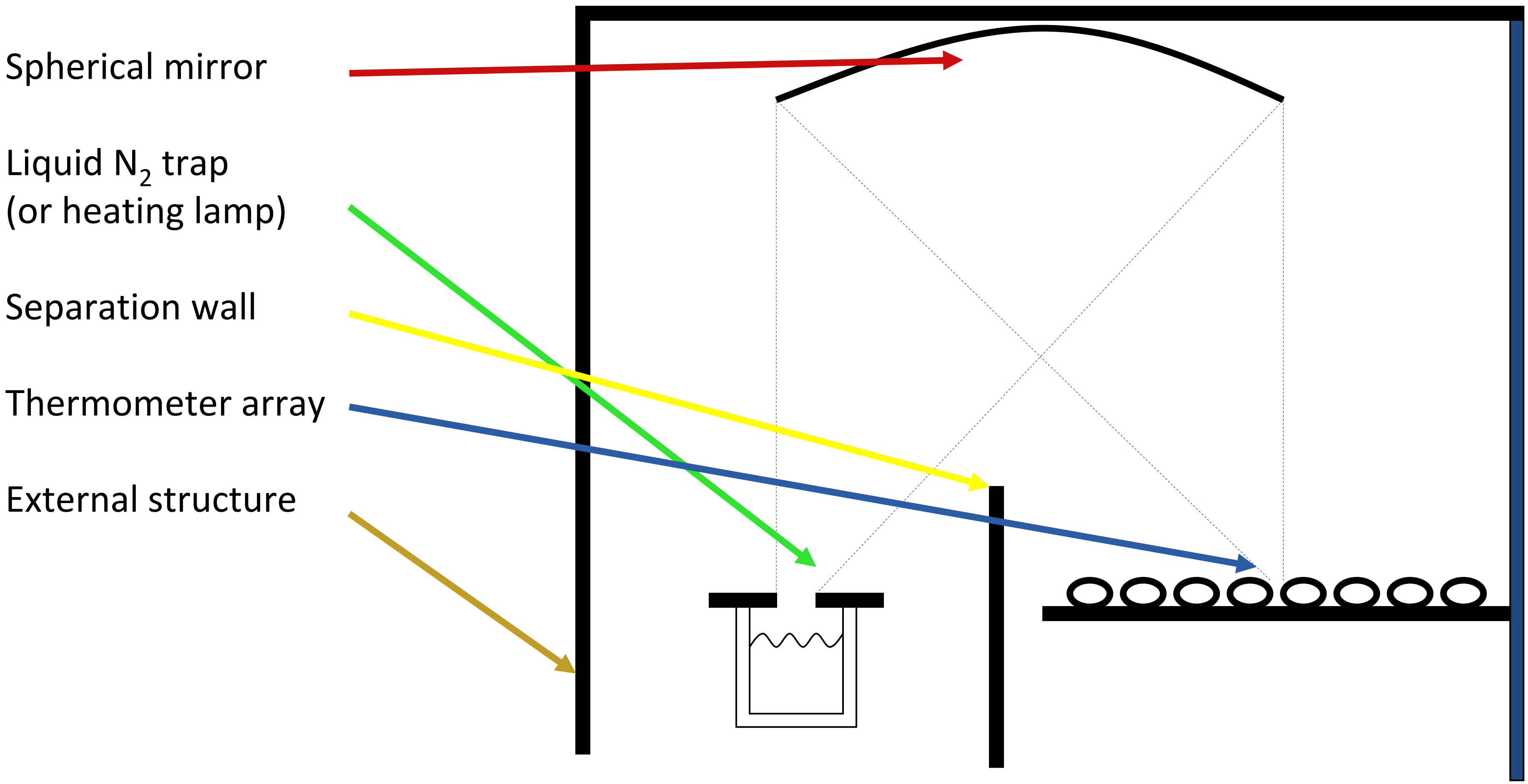


- Hot ring placed in focal plane
  is imaged on the mirror, can change mirror focal length

- Advantage:
  - Fine mirror focal length controls even in absence of beam power
- Disadvantage:
  - Possible thermo-elastic noise
    - Useful with interferometer off

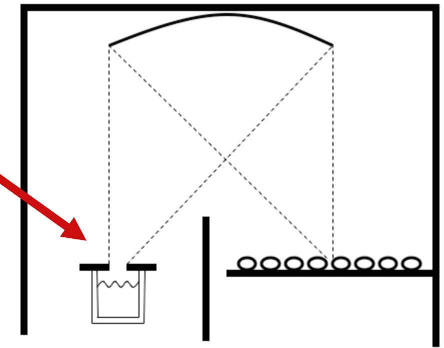
Experimental measurements

Experimental Setup schematics



LIGO

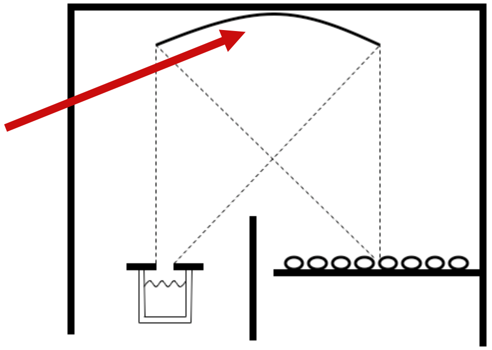
Liquid Nitrogen trap



62.5mm diameter orifice

Dewar

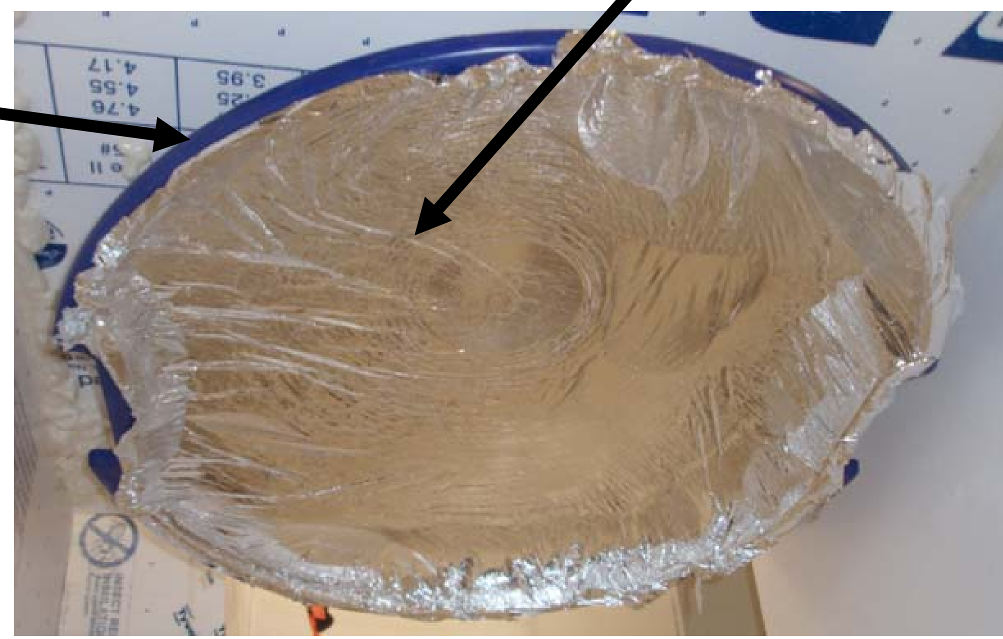
Parabolic mirror



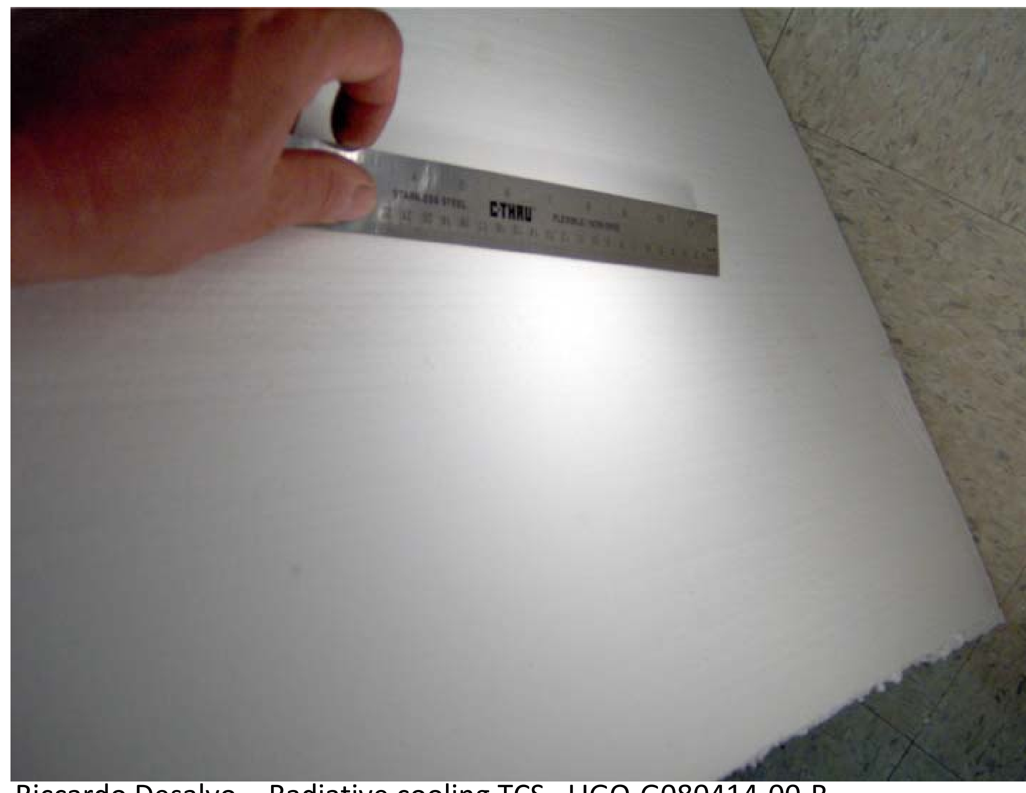
We made the parabolic mirror with super insulation foil glued on a circular sled as support.

Super insulation foil

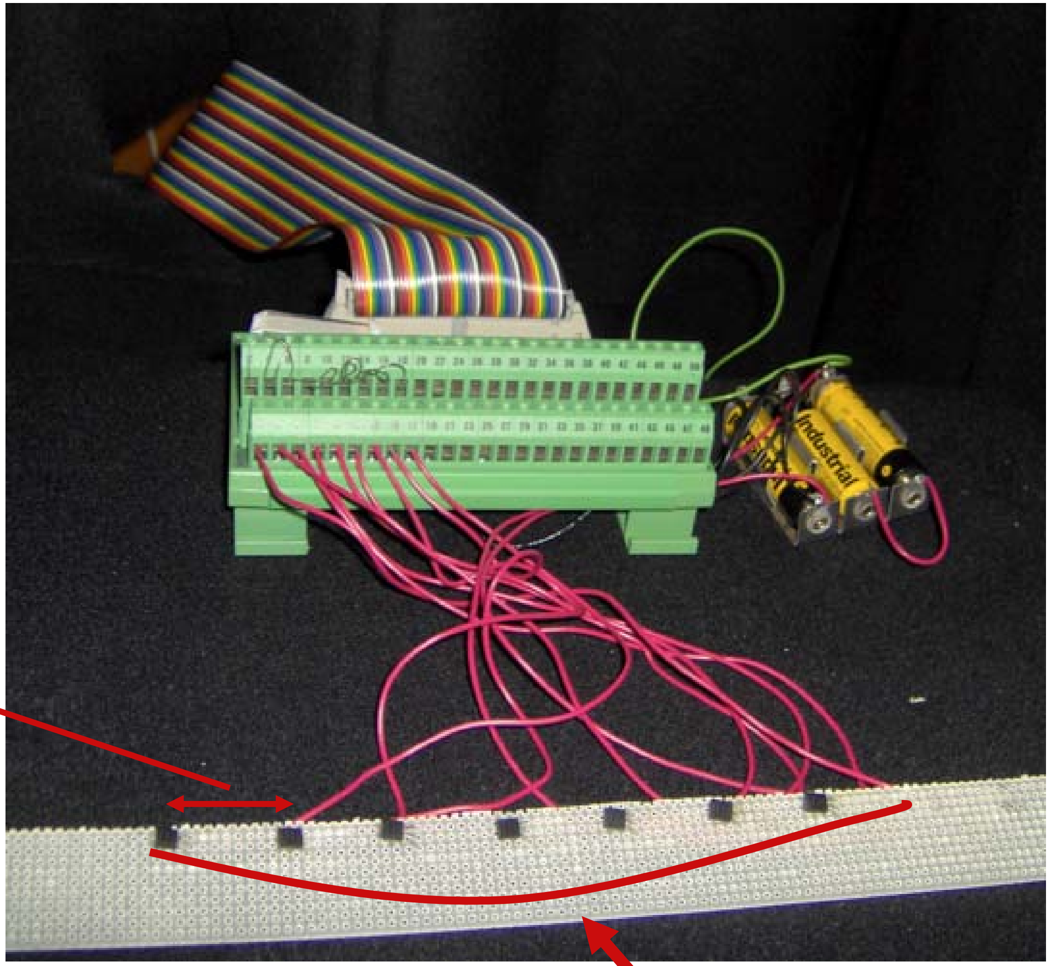
Circular sled

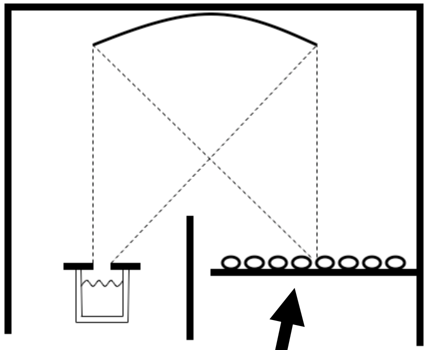


Building and testing the mirror



Thermal sensors



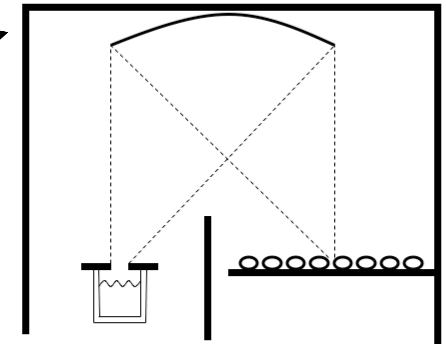


Thermometer array (LM19)

2.5cm

There were 8 thermal sensors, one broke half way. At the end only 7 thermal sensors left.

Building the box



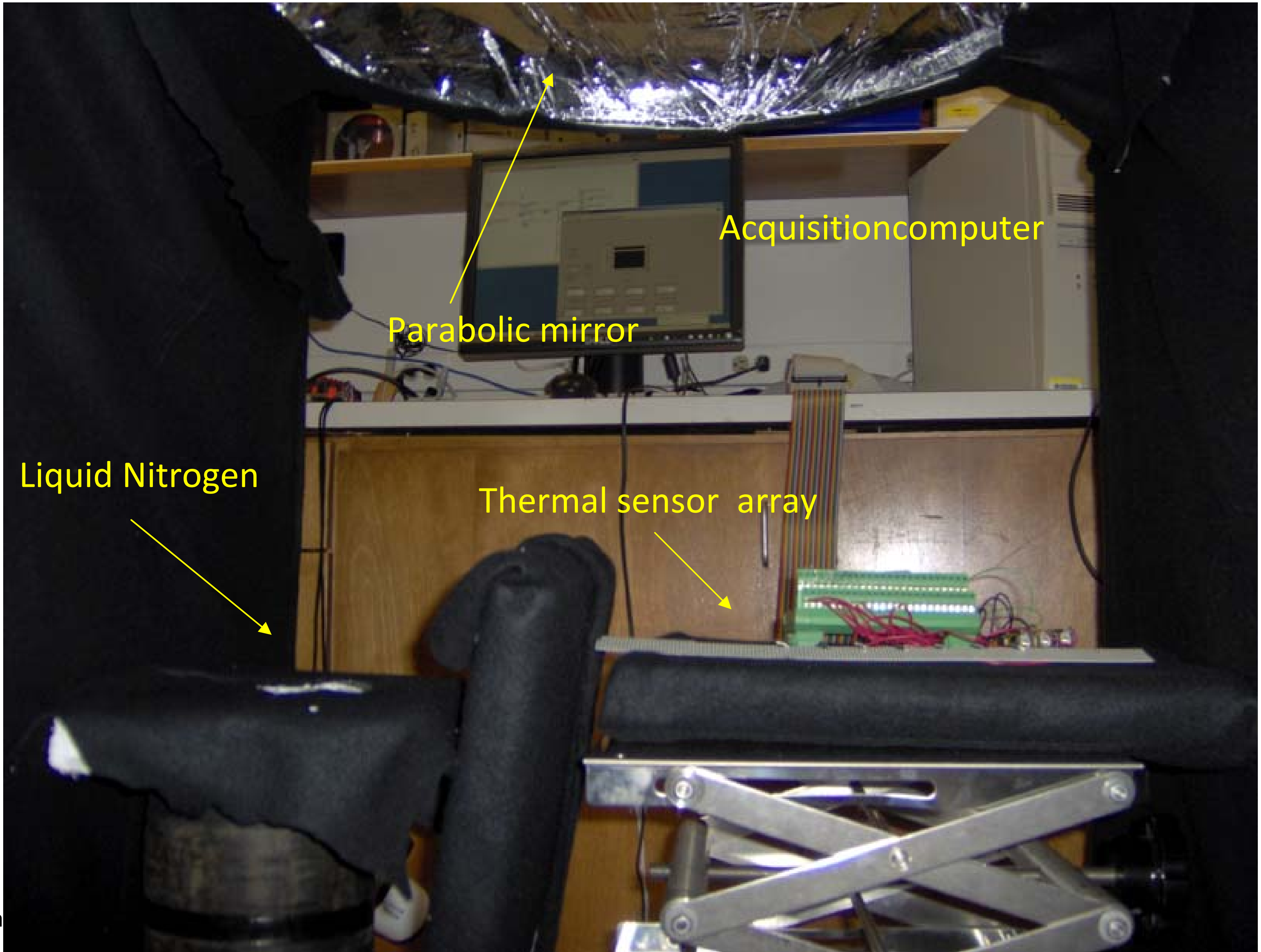
Lined with black
Felt to absorb
Diffused radiation

Before lining

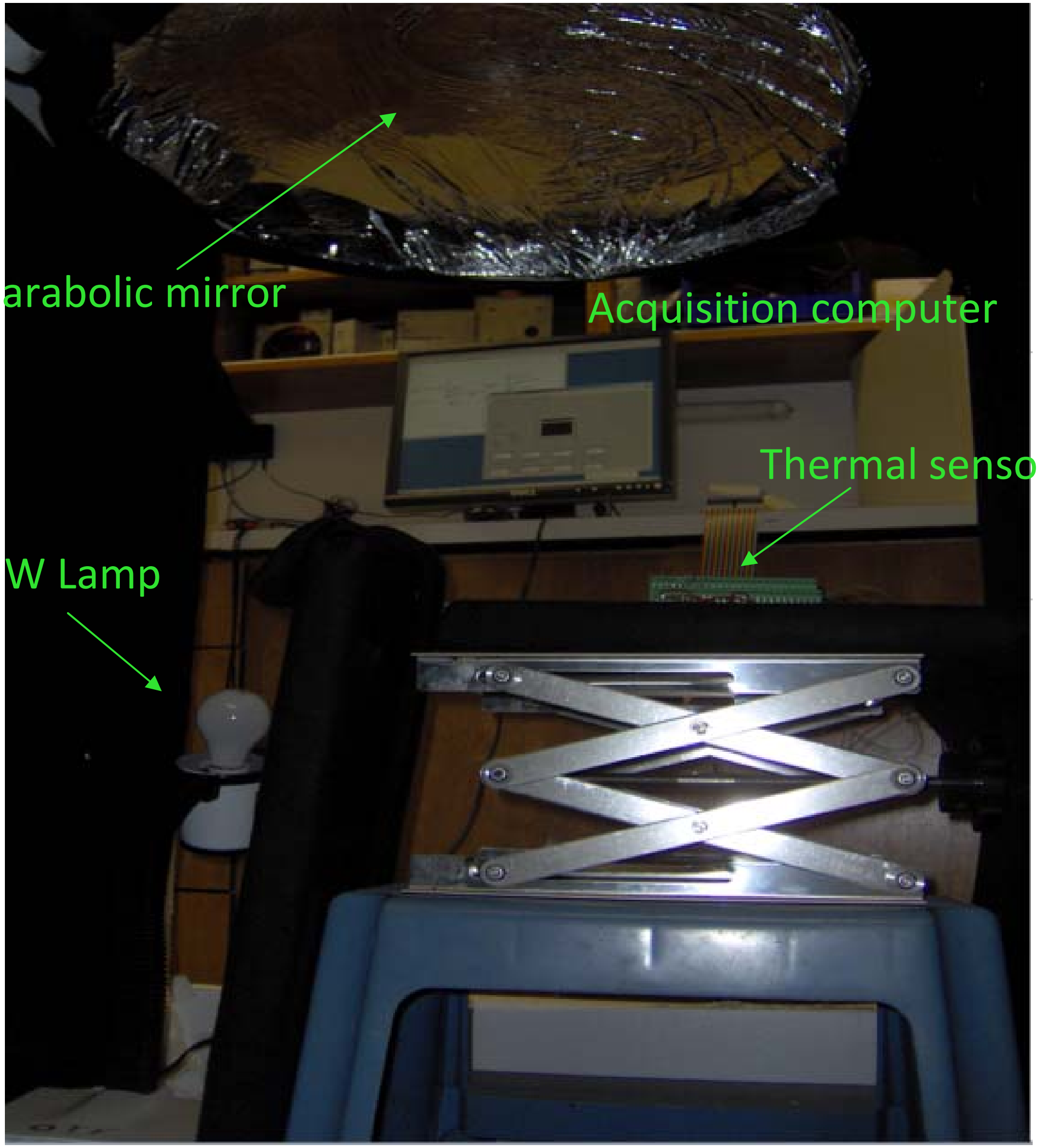
Pasa

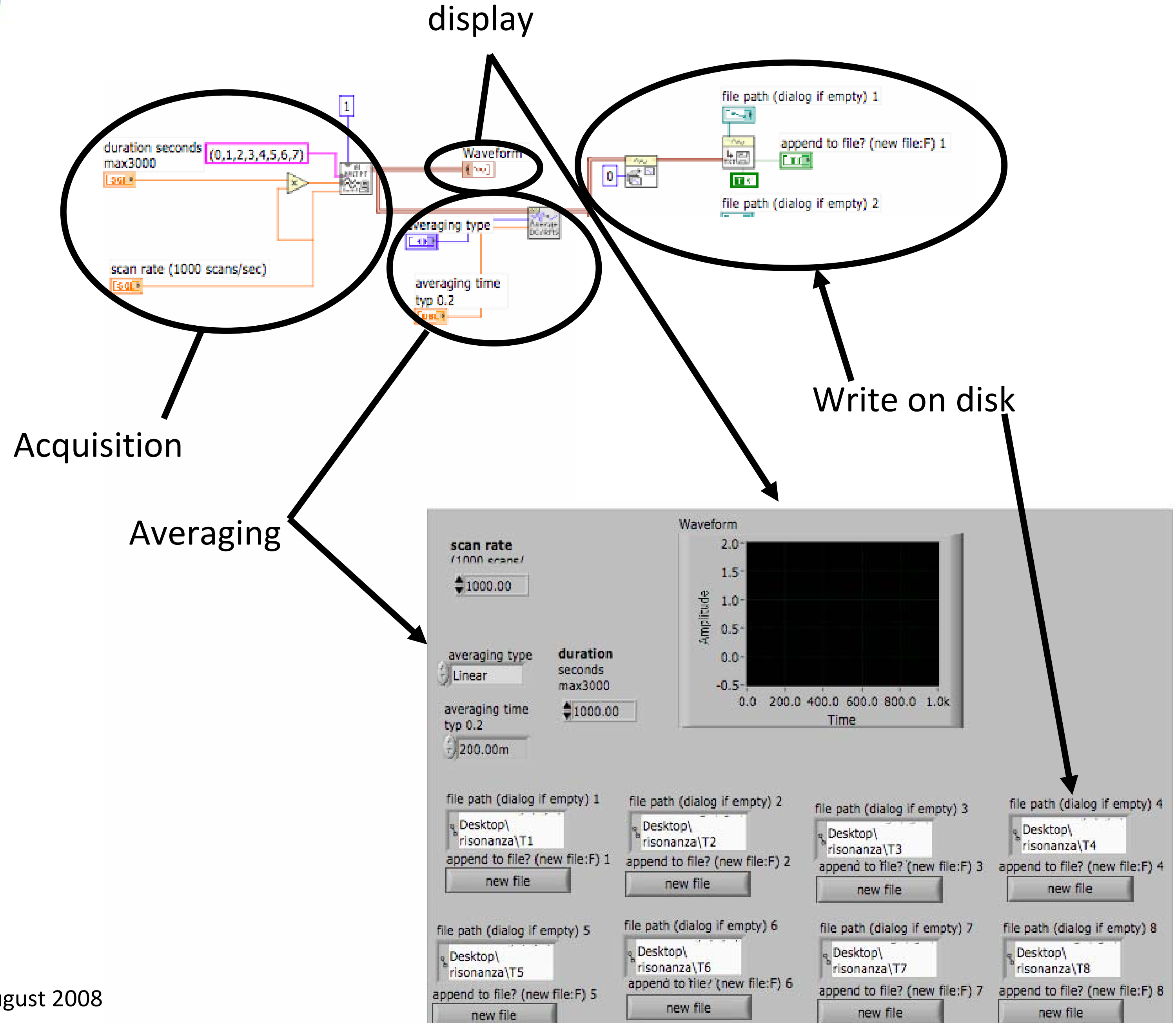
Hinata

Cold trapset-up



40 W heater Lamp setup

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Acquisition
Averaging
Write on disk
duration seconds
max3000
(0,1,2,3,4,5,6,7)
1
scan rate (1000 scans/sec)
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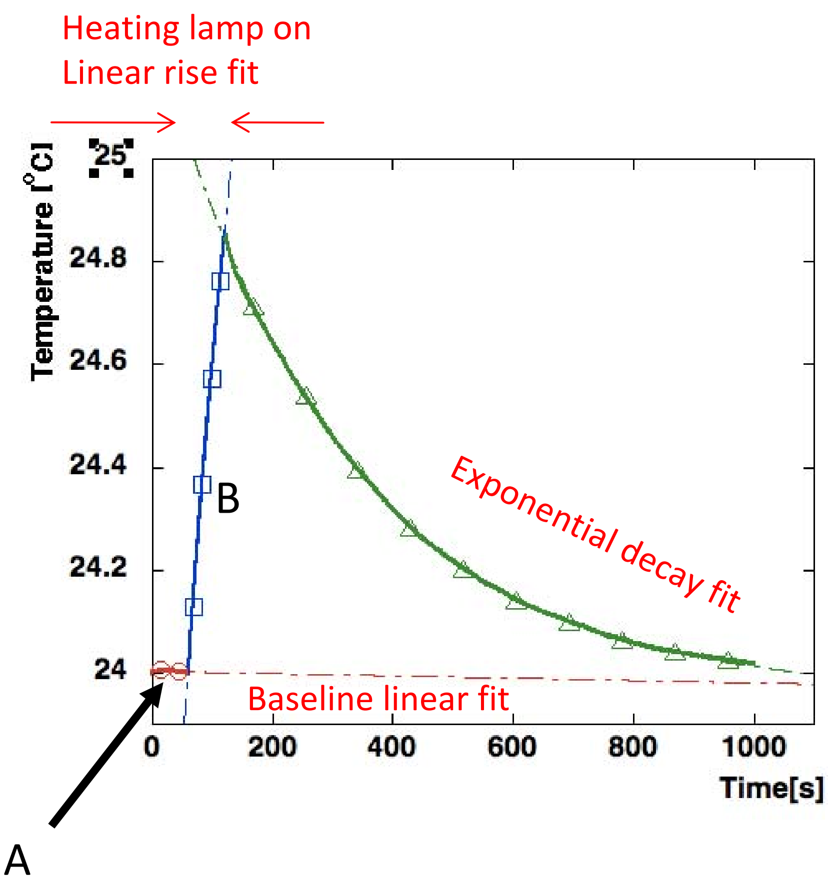
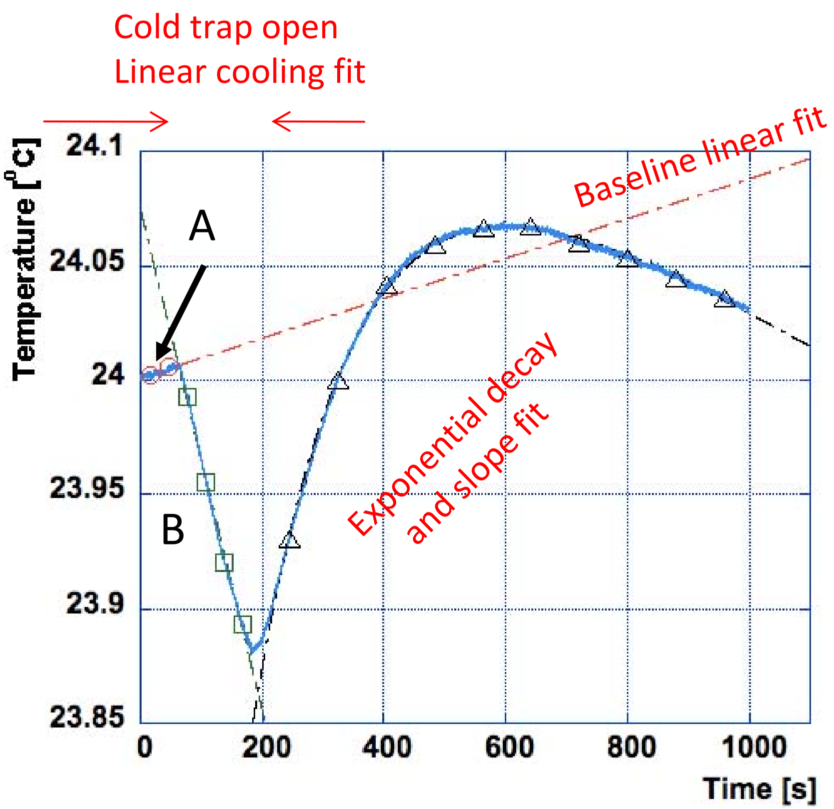
Warming and cooling cycle

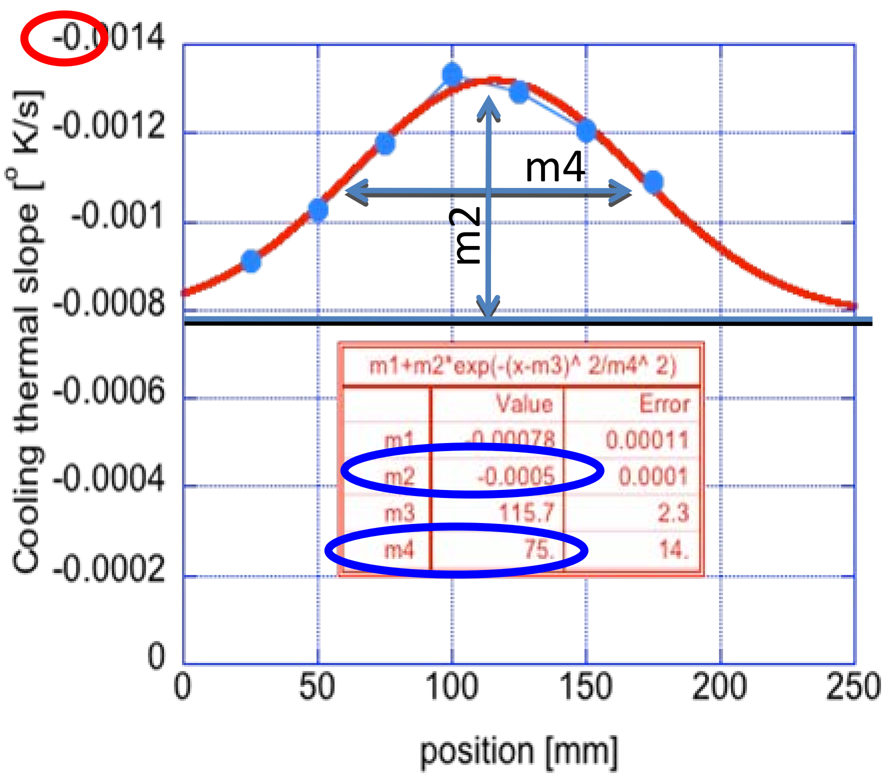




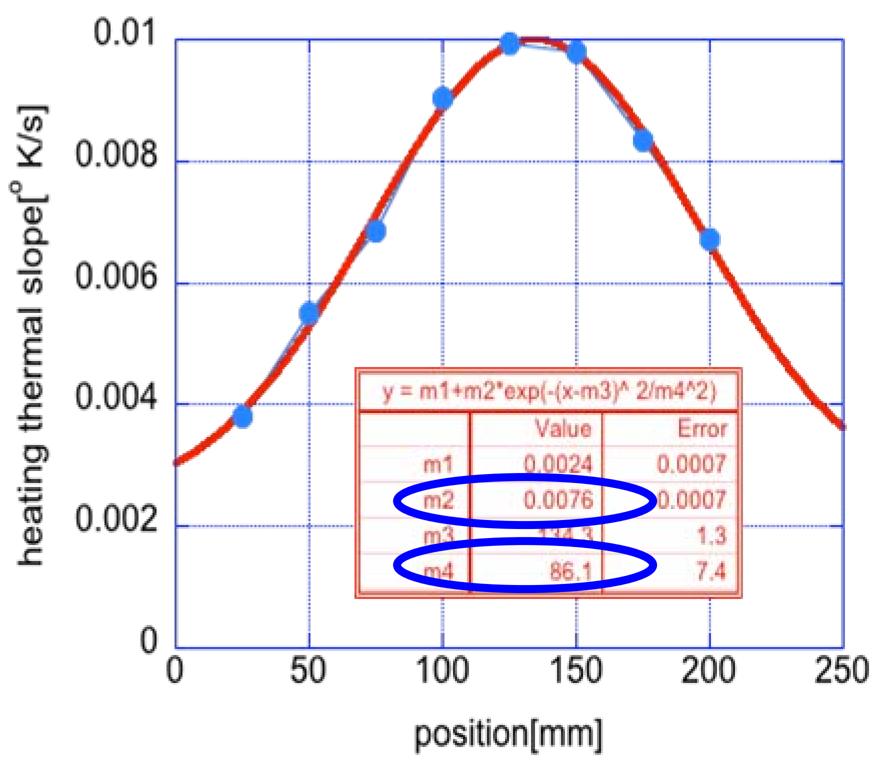
Thermal Power= slopeA - slopeB [oC/s]

Energy deposition/extraction

cooling



heating



Exchanged power = Gaussian spot surface S = m2*m4

Results

- Gaussian fit area results
  - 1.9W heating => S = 0.685±0.02
  - Li-N_2 cooling => S = 0.056±0.028
- Cooling power
  - Measured

    1.9 [W] x (0.685/0.056) = 155±78±39 mW
  - Theoretical (all $\sum$= 1) 262 mW

Conclusions

- Demonstrated the feasibility of

focused radiative cooling

- Directly suck heat from mirror laser spot
- Passive and remote operation (low risk)
- Neutralize thermal lensingwithout perturbing the test masses
- Remote mirror focal length tuning capabilities
- Cryo pumping of organics impurities