Cryogenic interferometer ideas

Cryo-LIGO

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- LIGO Mechanical limitations.
- Present LIGO
  - Limited by metallic suspensions
- Advanced LIGO
  - Limited by fused silica thermal noise
- Cryo-LIGO
  - Will use crystals (sapphire)
  - Reduce thermal noise by
    - Reducing KT (T°K-$^{1/2}$ only!! Gain of 10 at 3 °K)
    - Take advantage of higher Q factors at low K
    - At cryogenic temperature thermo-eleasticity and other problems fade away

- Present LIGO
  - From 50-80 Hz up
- Advanced LIGO
  - From 10-20 Hz up
- Cryo LIGO
  - Below 10 Hz
    - Low frequency low power interferometer
      - Few Kelvins
    - High frequency high power interferometer
      - ~30^{o} Kelvins

- A Possible Option:
  - Referencing the mirror surface to a cold auxiliary test mass
    - Require cryogenic test mass close by
    - Require multiple beams to explore beam spot
    - High finesse beams, high specific power

- Simply displace problem
- Add complexity

• DISCLAIMER

- All the following ideas are Hypothetical
- Some tentative techniques have been identified
- None has been confirmed or validated
- Most are potential show stoppers

- Expect lots of basic R&D

- Lots of different groups collaborating
- Need to create specialized test labs

- Cryo-LIGO will be heat evacuation limited

- Radiative cooling is not an option because It behaves like T^4

- Heat conduction or heat extraction?

- Need both sequentially ! ! !

- To put things in perspective:

- A 1 ppm absorption mirror with 1 MW circulating power dissipates 1 W on mirror
- At cryogenic temperatures 1 W is problematic !!!
- Conducting it through the isolation system is daunting.
  - Classical conduction through ultra-pure and annealed copper or aluminum. But metals in contact with mirrors would destroy quality factor
- Must conduct all heat through crystalline struts
  - Need large cross sections for conductivity
  - Need thin flex joints for isolation and thermal noise
- All power must transit through flex joints

The LCGT test

- Used four 250 μm diameter 100 mm long sapphire fibers
- Extract of the order of 10 mW of power
- Thermal drop of order of 20^{o} K
- => Mirror above 25^{o} K
- If and only if can produce a mechanically quiet cold finger at $<4^{o}$ K
  - No Helium boiling, no thick heat conductors to ground

- Cryo-LIGO will be heat evacuation limited

- Waste heat reduction
  - Mirror coating losses reduction <0.1 ppm
  - Substrate losses reduction ~ ppm/cm
- Heat conductivity (from mirror)
  - Cube with temperature in crystals
  - Increasing with decreasing defect density
- Heat extraction technique
  - Metal conduction ?
  - Heat piping (Superfluid Helium) ?
  - Active extraction ?

First developments needed
Conservation !!

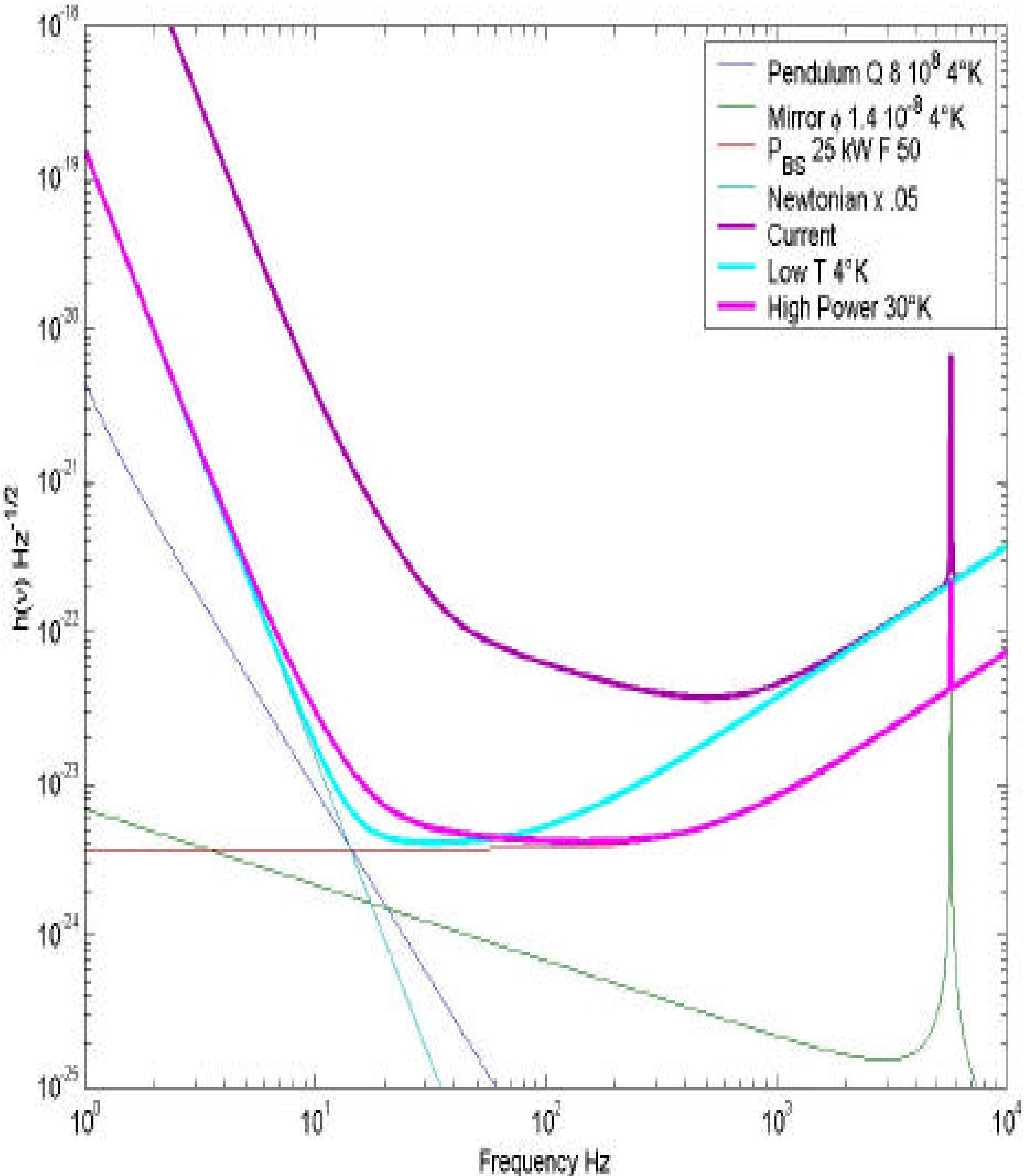
- Need a long term mirror coating R&D to develop lower mirror absorption
- Need long term crystal growth R&D to reduce bulk absorption

- Dual Frequency ranges
- Dual Cooling techniques

  - Low Frequency, local cooling
    - Optical chiller
  - High Frequency extensive conduction cooling
    - Superfluid Helium
  - Metal conduction
    - To boiling Helium

  - (Peltier pumps ruled out)

Sensitivity Options



With gravity gradient subtraction and suspension point interferometer

- In the low frequency range
  lower shot noise requirements
  - Can reduce circulating power by factors of 10 to 100
  - Can increase finesse and further reduce input power
  - Possibly use optical chilling after just one isolation stage

- In the high frequency range
  - Must use temperature drop to feed power across multiple isolation stages to noisy heat pipe.
  - Less isolation constraints
  - Can use shorter, thicker links for better conductivity

Comparative advantages of a low/high frequency, low/high power interferometer

- 4^oK/30^oK
- 1kW/25kW B.S. power
- 250/50 Finesse
- 250 kW/1.25MW circulating power
- 0.1 ppm coating absorption
- 3 ppm/cm bulk absorption
- 25+30 mW/125+750 mW deposited power
- Radiation Pressure Fluctuation / Shot noise limited
- Starts looking feasible

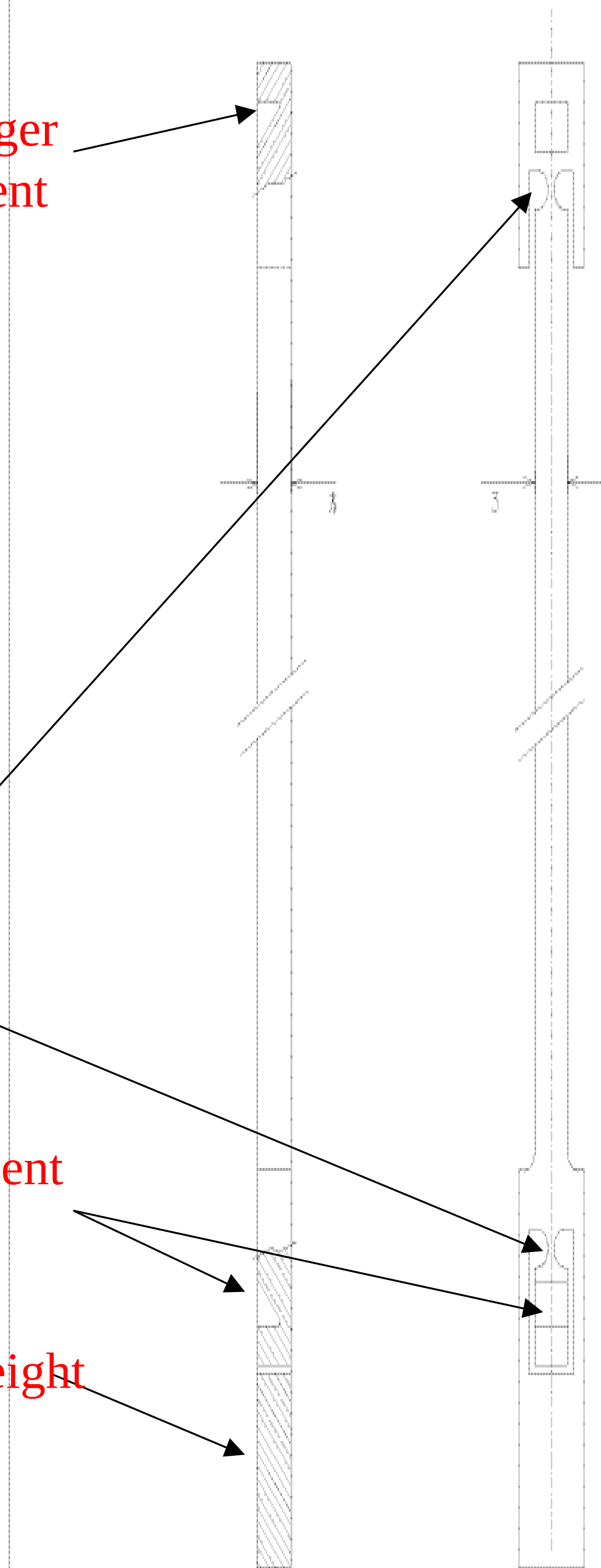
- In all cases
- need Sapphire suspensions from mirror leading to at least one recessed cooling stage.
  - Need cross section to carry heat
  - Need low defect crystals for higher conductivity

  - Fibers are ruled out
    - Wrong aspect ratio (LCGT test)
  - Will need rods with short flex joints
    - Mass of rods will limit isolation properties
  - Will need rods with counterweights

- How to make rods with
  - Counterweights and
  - Flex joints
  - Low defect crystal material

- UltraSound machining
- Ar-cluster polishing
- Crystal bull re-melting for defect reduction?
    - (Like in Silicon purification ovens?)

Shaping the flex joint links

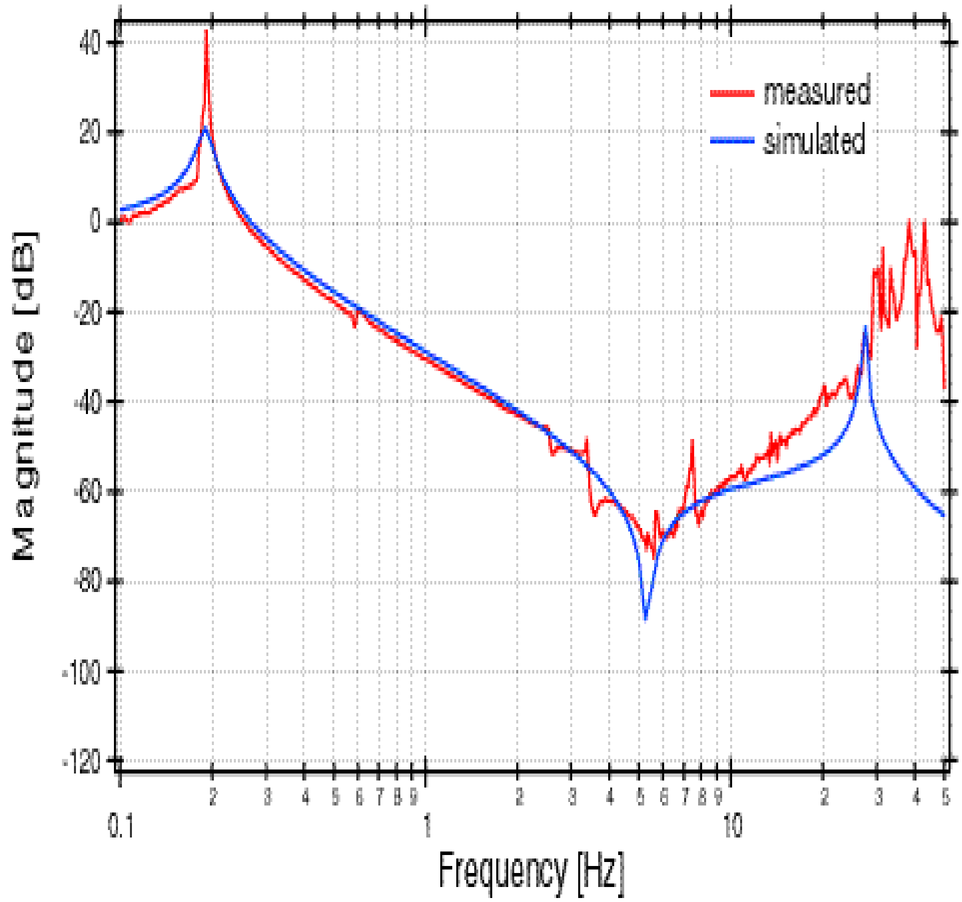


Advantages of flex joint links

- If 3x3 rods instead of 250 μm Φ fibers => Gain of 180 in cross section (conductance)
- Flex joint over < mm (instead of ~300 mm fibers) =>Gain of >300 in thermal resistance
- Low defect crystals
  => ballistic heat transport

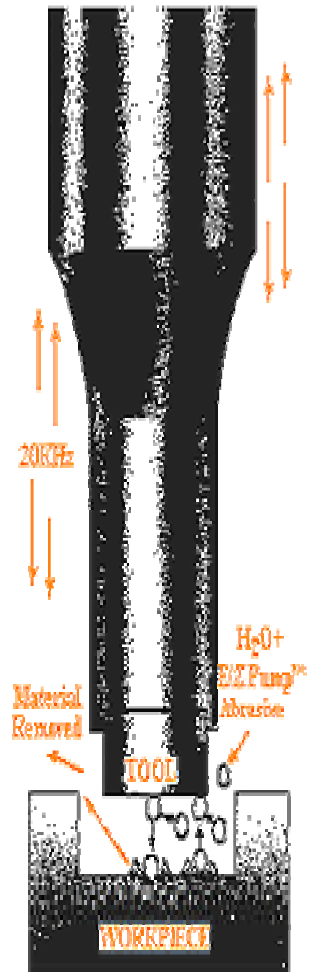
Shape of a flex joint link

- Counterweights will restore attenuation properties as in IPs



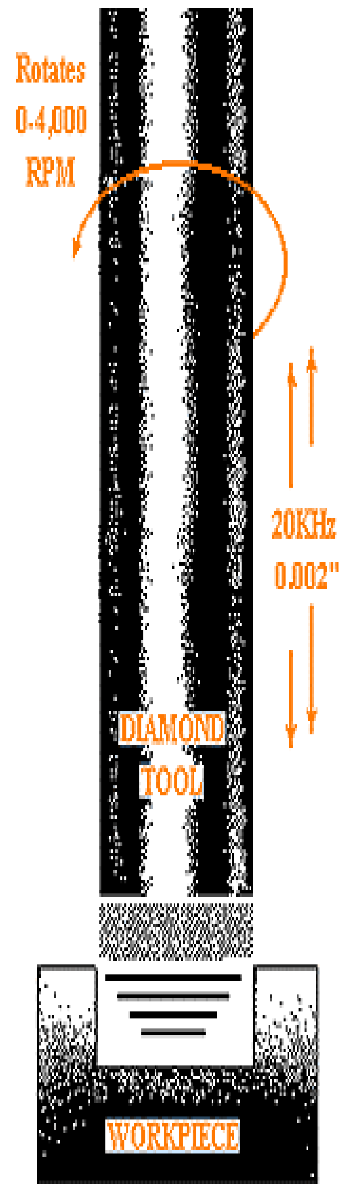
UltraSound machining of crystals

- Tool energized with U.S.
- Optical polishing powder carried in slurry
- Abrasive renewed by oscillating tool (static US machining) or



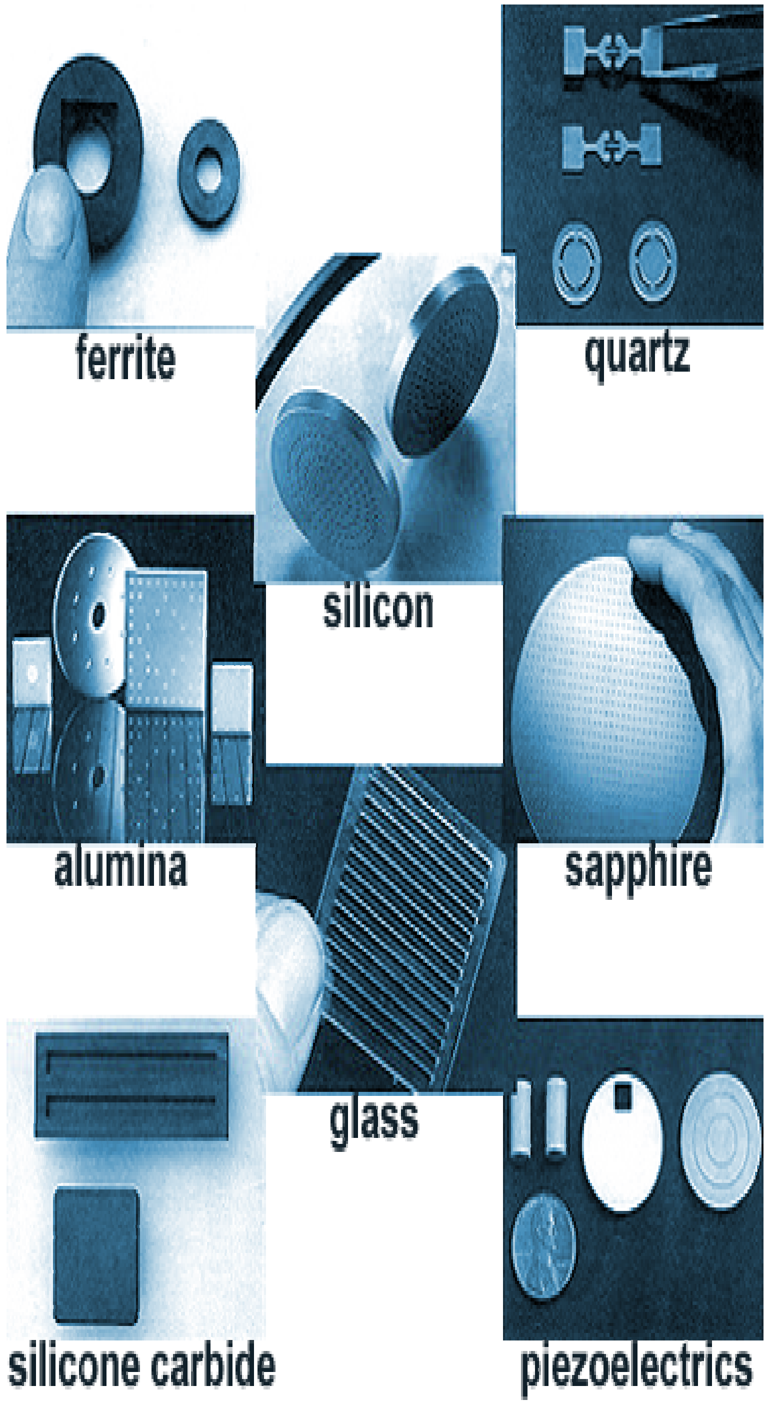
Ultrasound machining of crystals

- Abrasive renewed by rotating tool
- Examples:



Ultrasound machining of crystals

- More examples;

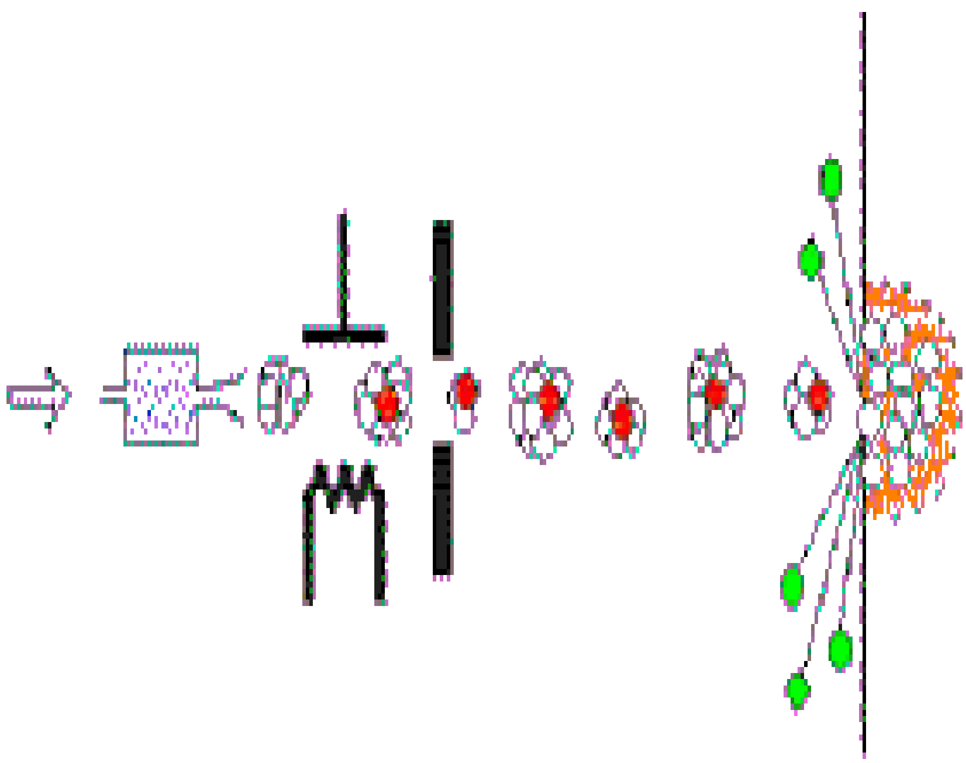


- How to remove possible machining induced surface defects?
  - US machining does not stress parts,
  - Uses same abrasives used in mirror coatings,
  - Can reach high polishing levels
- Still flex joints are thin,
- Small surface defects may induce fractures

- Need equivalent of flame polishing

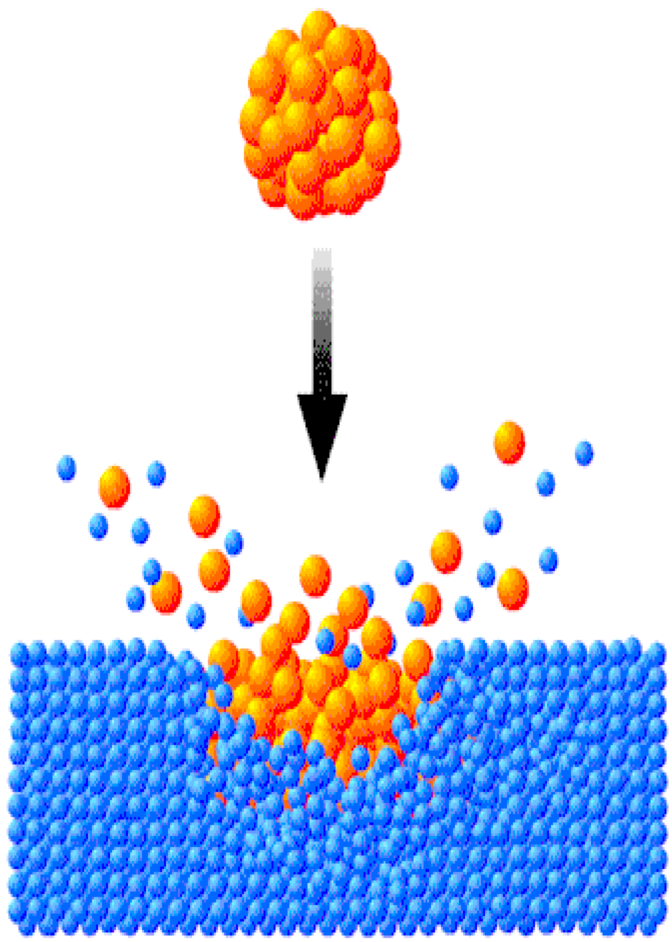
Ar- cluster polishing

- A jet of Argon droplets electrostatically accelerated abrades the surface

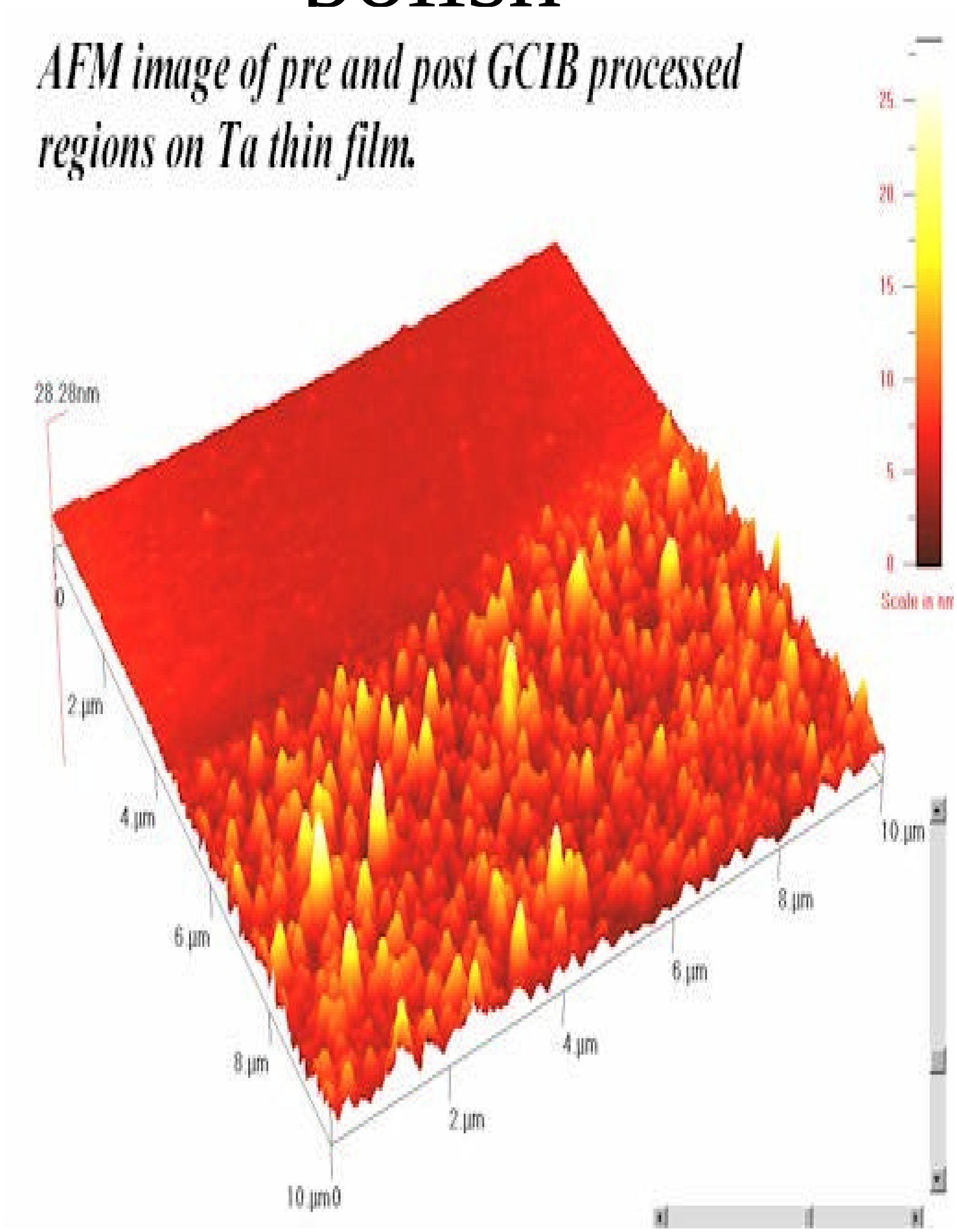


Ar- cluster polishing

- Argon cluster has effective high temperature
- Locally remelts material that then recrystallize (flame polishing equiv.)
- Mechanically remove excess material



Effects of Ar-cluster polish



Flex joints development line

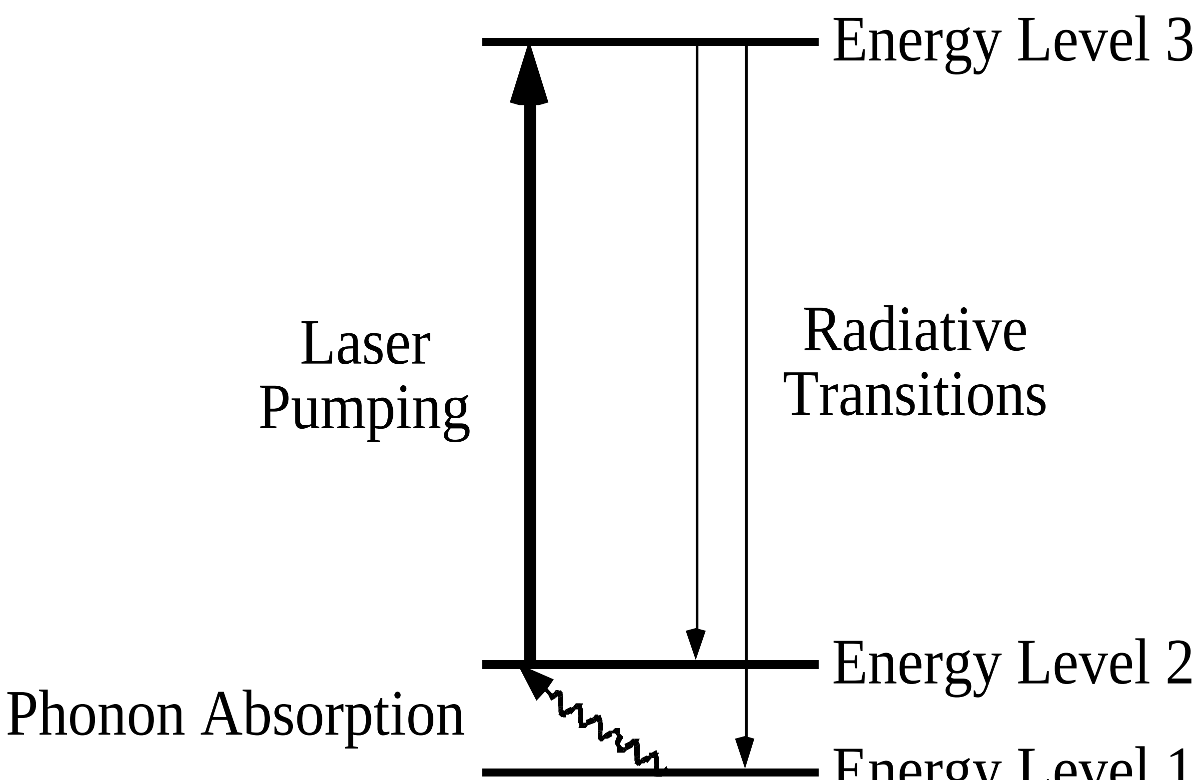
- Need prototyping (CIT) buying machine
- Need Q factor testing (SU)
- Need cryogenic Q factor testing
- Need cryogenic conductance tests
- Need long low defect Sapphire
- Need . . . .

How to evacuate the heat

- Options
- Optical chiller
  - (LASSOR proposed by Richard Epstein)
- Superfluid Helium

Basic Optical Refrigeration

Three-level "atom" in a transparent solid

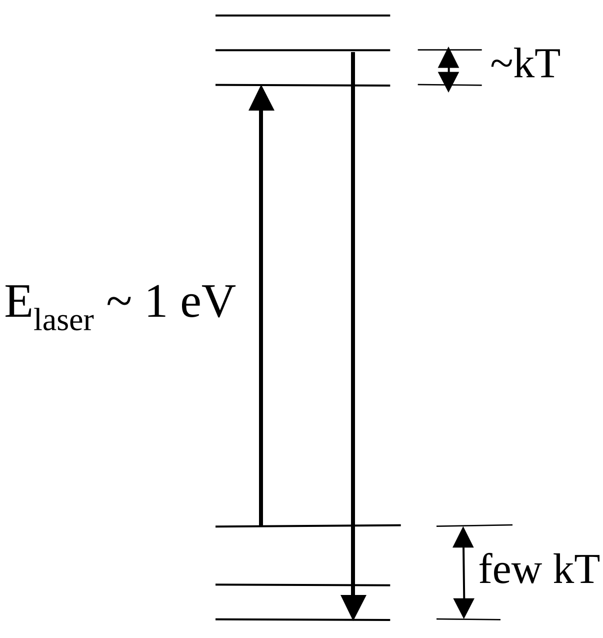


Radiative decay 3→1 followed by phonon absorption cools material

$$\textbf{Efficiency} \approx \frac{1}{2}\,\frac{\textbf{absorbed phonon energy}}{\textbf{laser photon energy}}$$

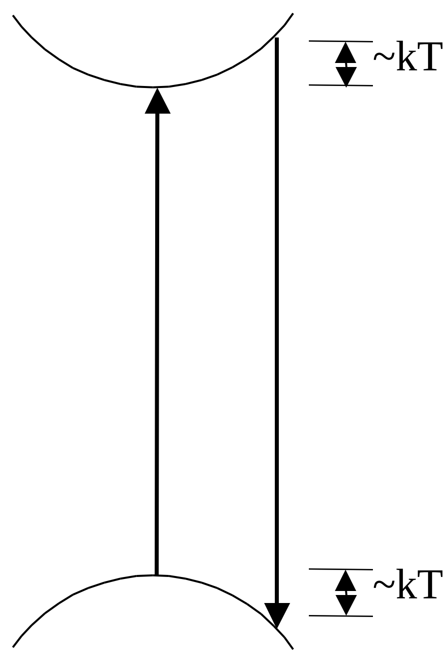
Practical Optical Refrigeration

Rare-earth-based Optical Refrigeration



Yb-, Tm- or Ho-doped glasses and crystals

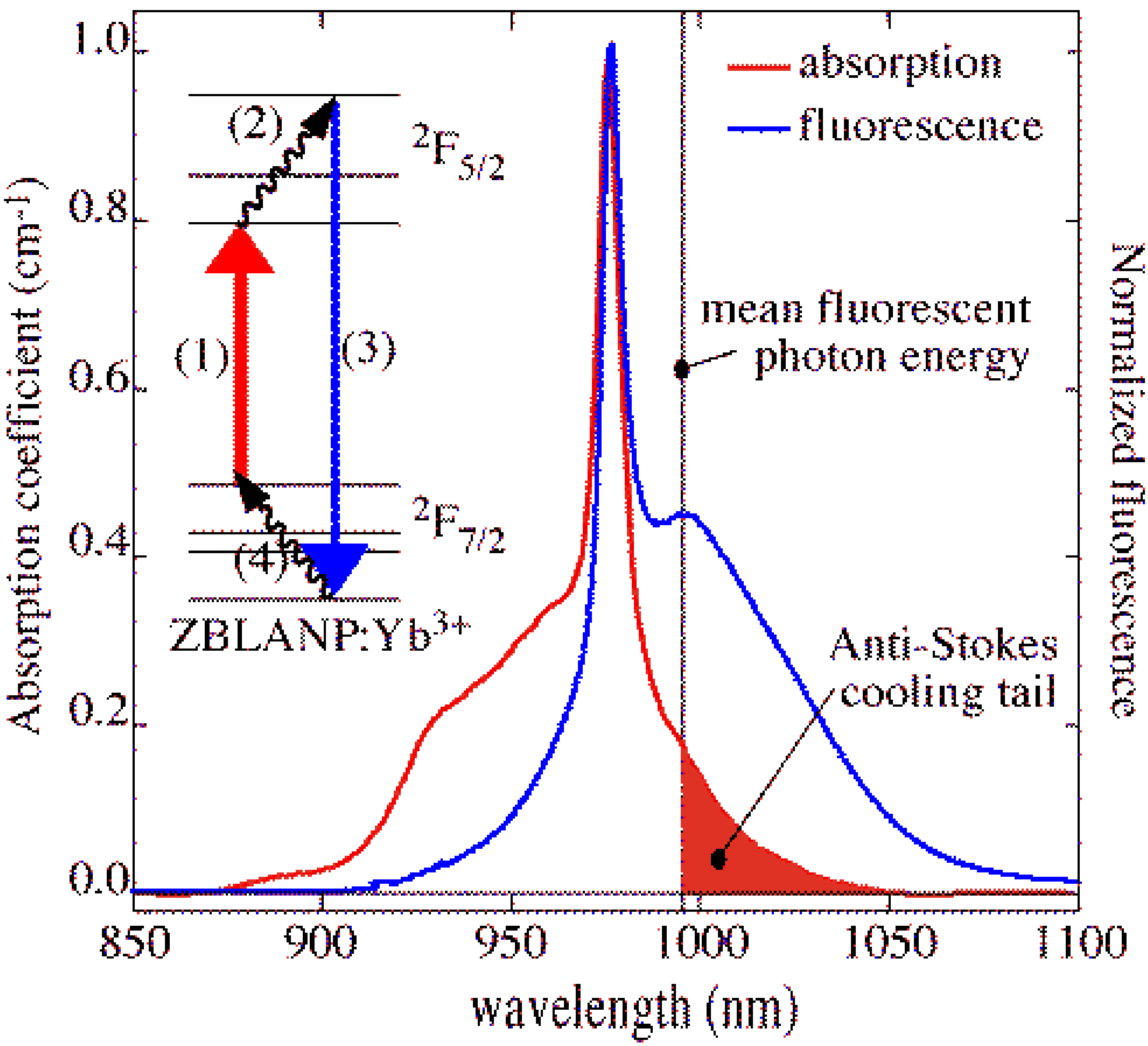
Semiconductor-based Optical Refrigeration



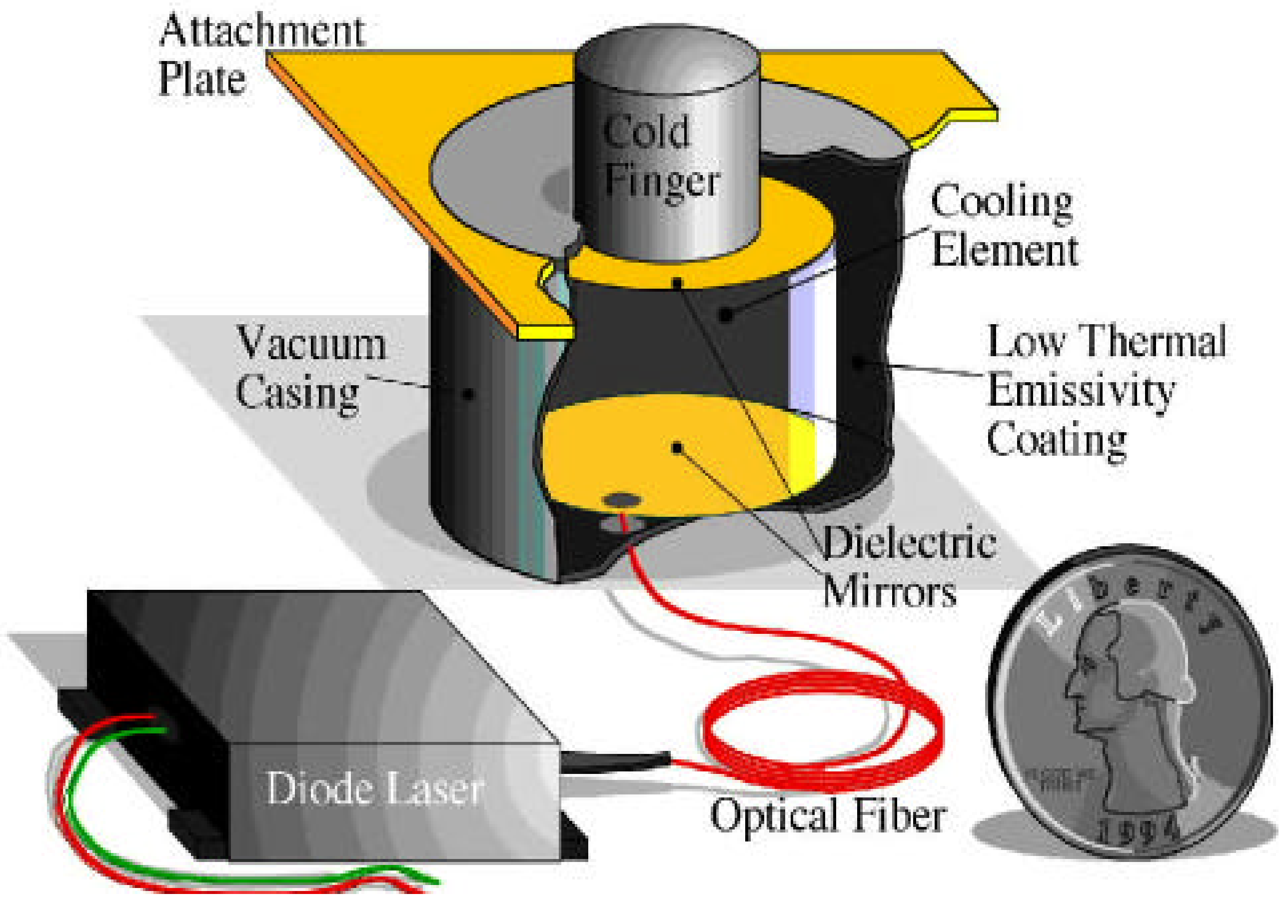
Direct-band-gap Semiconductors; e.g., InGaAs

Yb-doped ZBLANP Fluoride Glass:

The first solid cooler

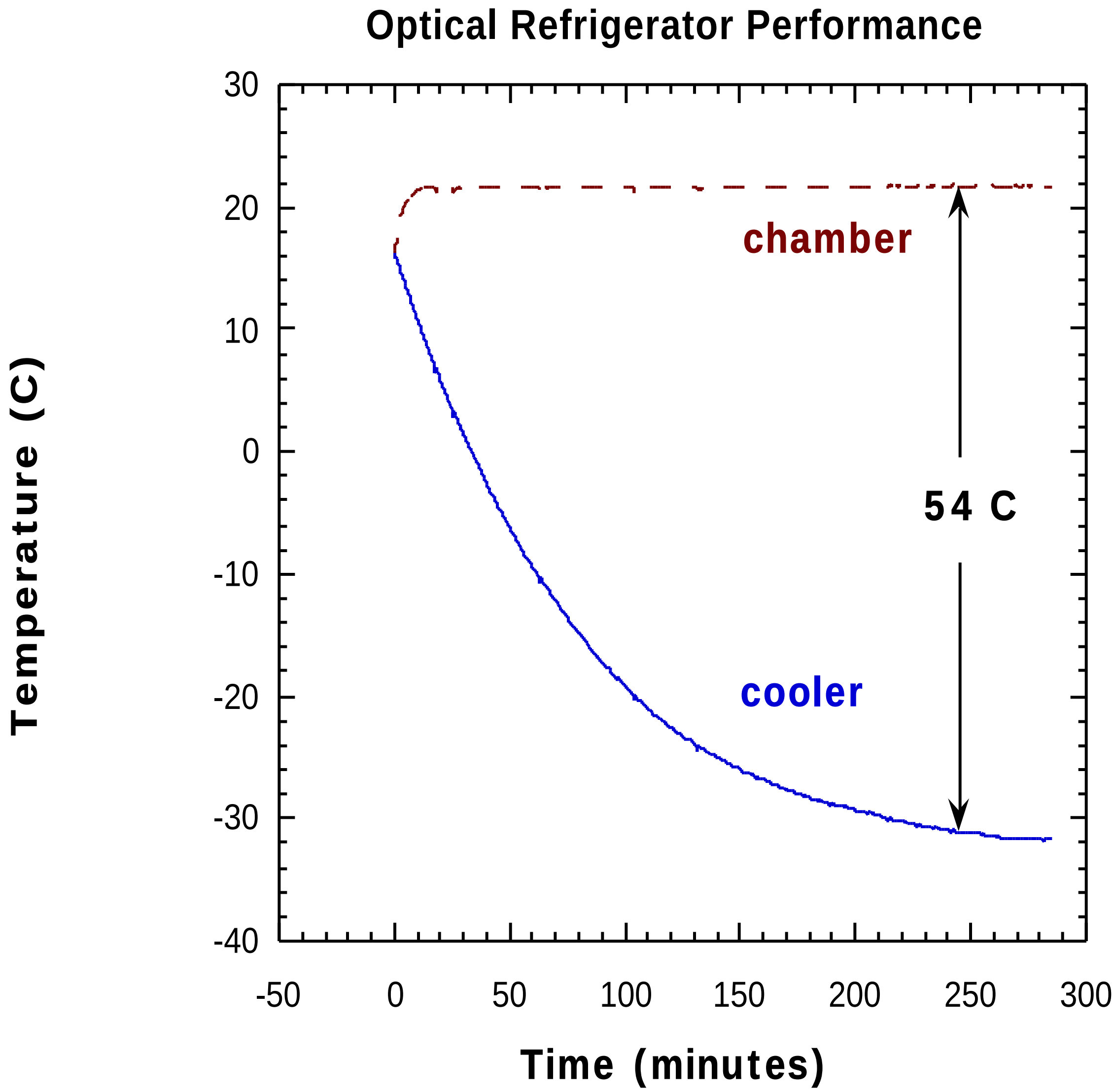


Schematic Optical Refrigerator

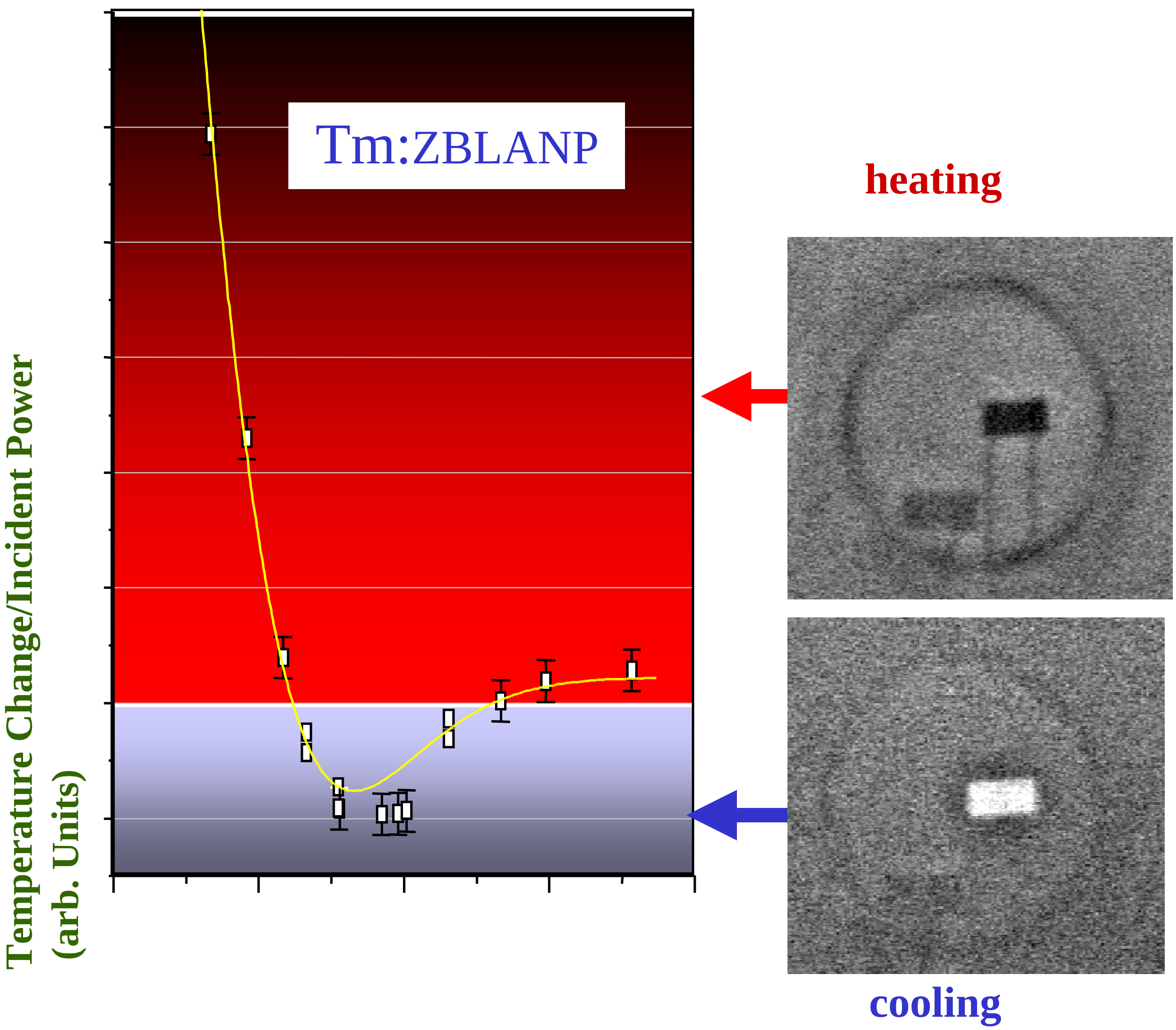


- Laser diode produces light
- Optical fiber carries it to cooling element
- Light enters through pin hole in one mirror
- Light is trapped, absorbed and re-emitted
- Fluorescence is absorbed on chamber walls
- “Load” is connected in shadow region

Results with Yb-ZBLAN

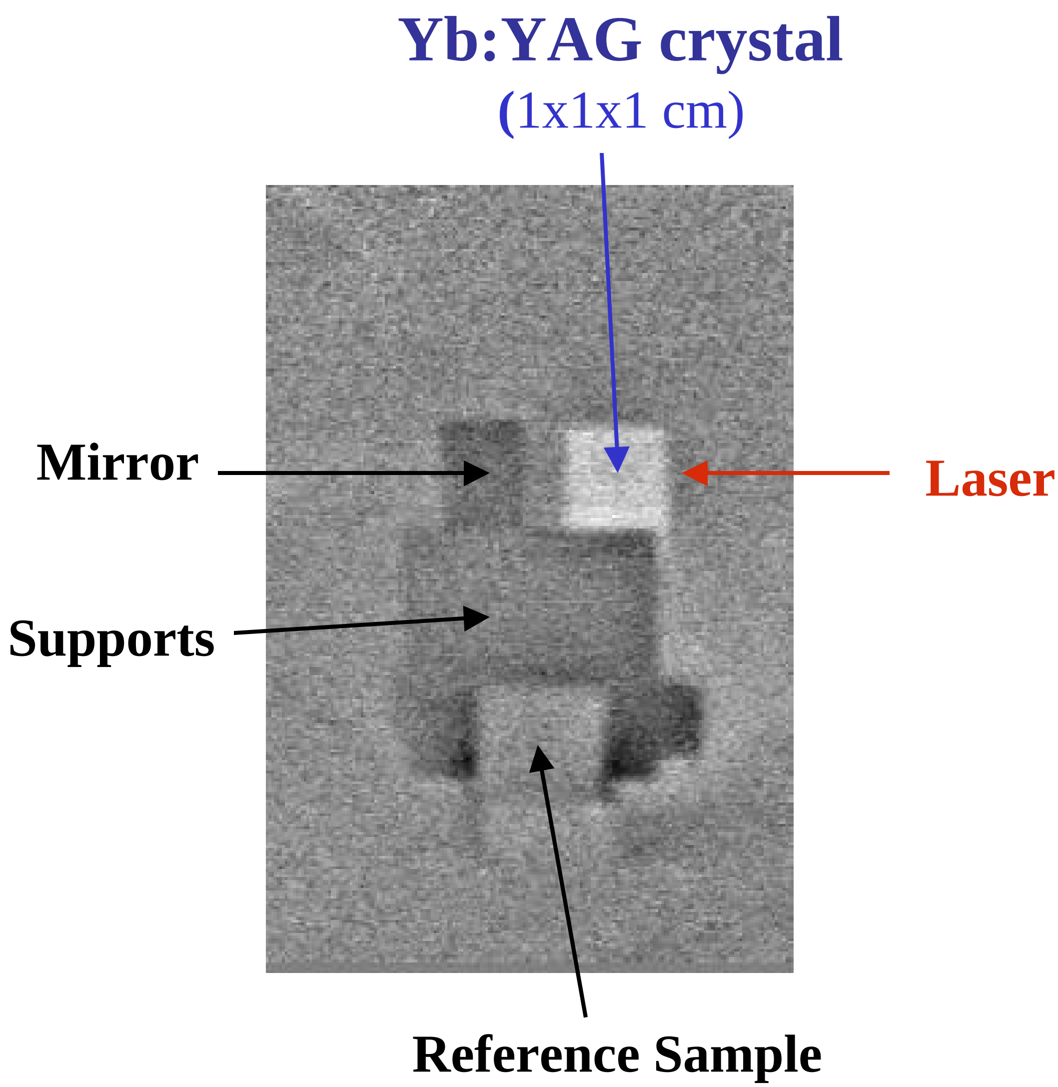


Laser REFRIGERATION IN A TM-DOPED SOLID (UNM, FEB. 2000)



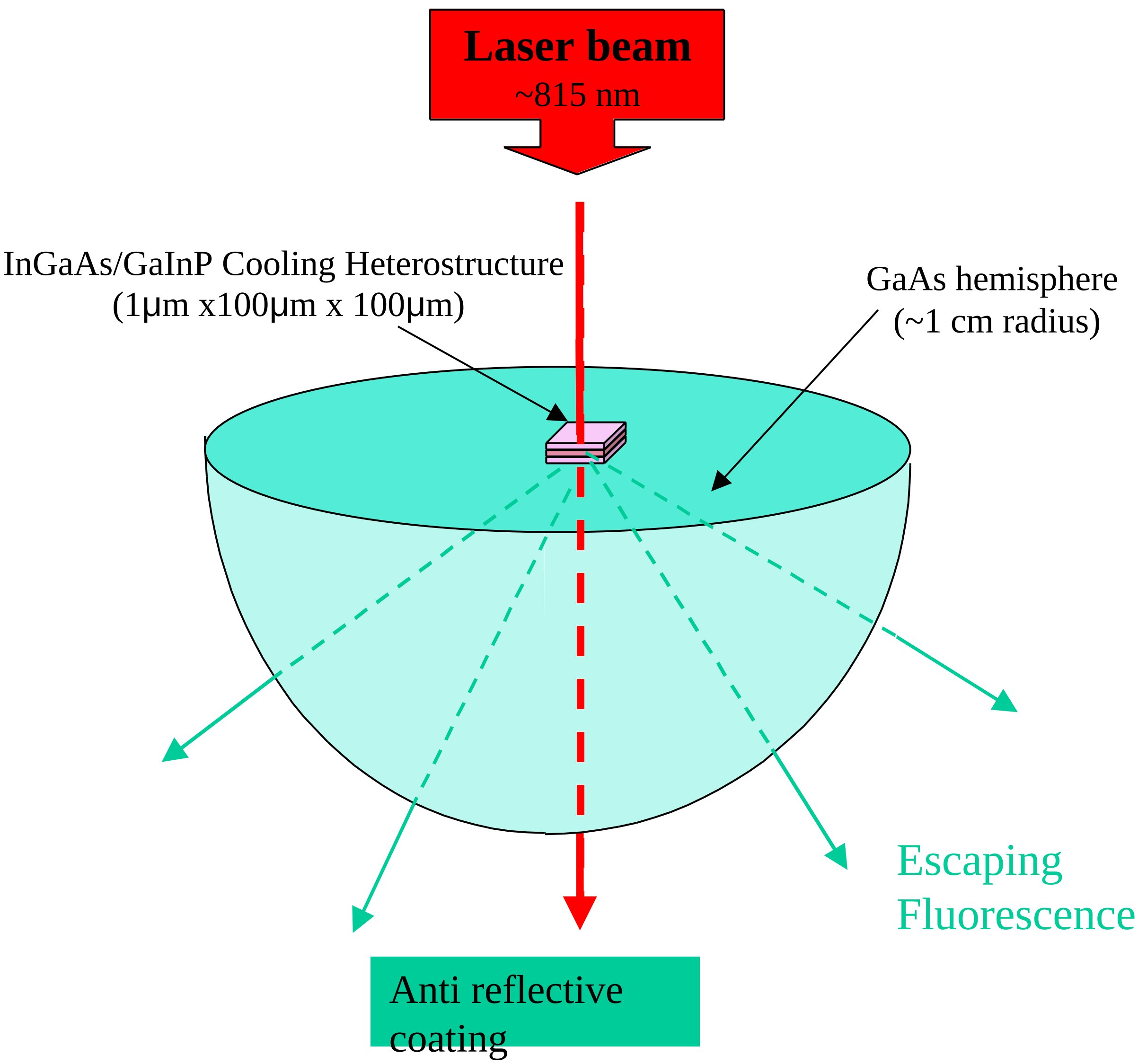
Normalized temperature measured as a function of the incident laser wavelength. The line is the theoretical fit assuming a background absorption of 0.0002 cm^{-1}.

First Laser Cooling of Yb:YAG Crystal (April 10, 2000)



ΔT ~ 0.3 C with 1.2W at 1030 nm

Semiconductor test Cooling Element For LIGO



Problems with optical chiller

- Need large optical power
- Efficiency ~ kT/1eV ~10^{-4} @3^{o}K
- Must evacuate to better than ~10^{-4}
- Must extract from high refractive index medium
  - Will need extensive A.R coatings

Problems with superfluid helium

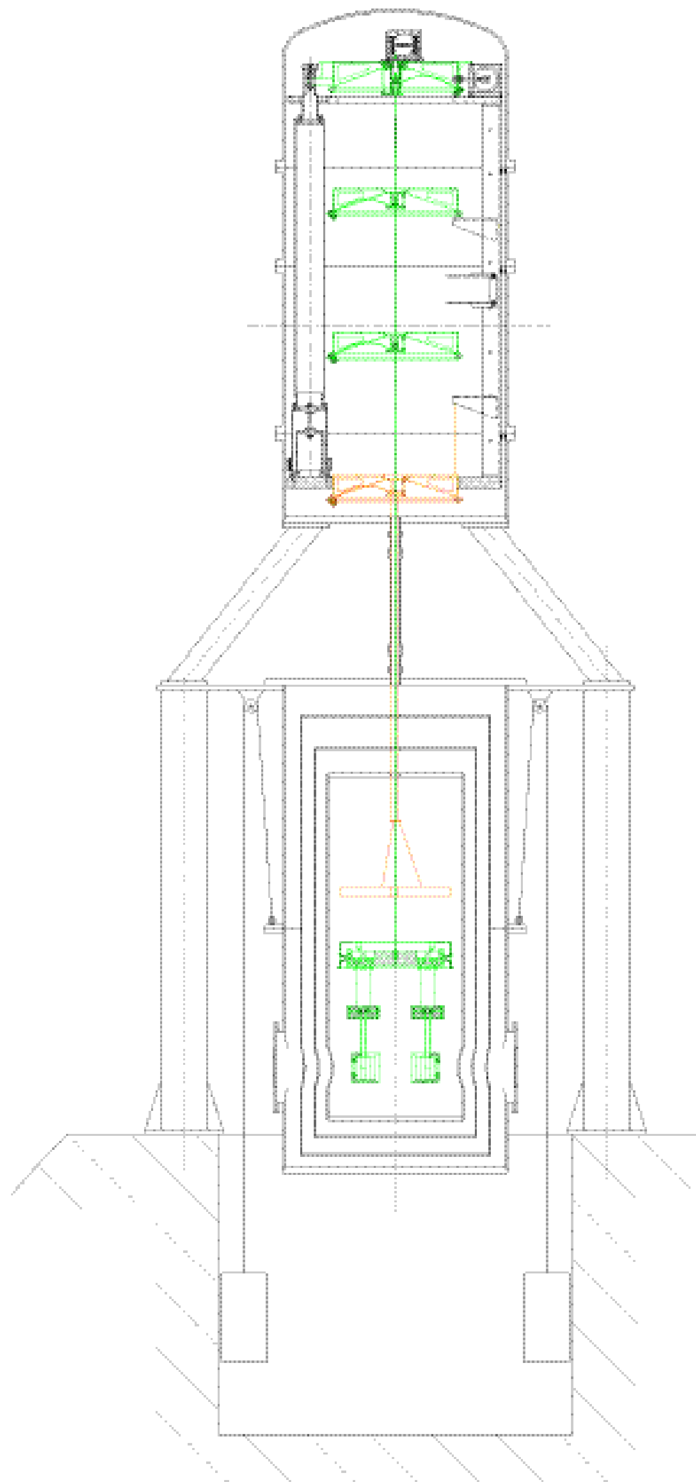
- Above ~ 0.1 W/cm^2 goes normal
  - (boils off)
  - Requires ~ 10 cm^2 /W
- Conducts phonons coherently, so short circuits thermal,
- But also acoustic conductor to all outer surfaces
  - (Pumping noise, ambient noise)
- Must be recessed from test mass at least two sapphire isolation stages

- # Other needs
- To match the low displacement noise possibly achievable.

- Need matching seismic attenuation system that also allows suspension of “uncontrolled” mirrors (OK with SAS)
- Need to develop wireless, low power electrostatic actuators for lock acquisition and for actuation of masses above mirror

The battle plan

- UT Cryogenic thermal noise test
- Not the final solution
- Learning curve
- Test bed for different solutions



The battle plan

- Coating developments
  - Parassite Advanced LIGO (Tests in UT)
- Sapphire substrate developments
  - Parassite Advanced LIGO (Tests in UT)
- Flex struts
  - Engineering studies (INSA)
  - Machining tests (CIT)
  - Q testing (SU), ...
- Optical chiller
  - Development tests (LANL)
- Superfluid Helium (LNF?….)
- Electrostatic drive (UP)

Conclusions

- Cryogenic interferometers have great promises (see Fidecaro's evaluation)
- They are not proven unfeasible
- Will need massive amount of basic R&D

- Need more collaborators
  – Cannot burden Advanced LIGO