Cryogenic interferometer R&D ideas

Cryo-LIGO

Riccardo DeSalvo

LSC Meeting

March 14th, 2001

LIGO-G010110-00-D

- 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

  - Low frequency (5Hz < f ≤ 100 Hz) low power interferometer
    – ~10° Kelvins
  - High frequency (50 Hz ≤ f < 3kHz) high power interferometer
    – ~30° Kelvins

- Cryo-LIGO will be heat evacuation limited

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

- Heat conduction or heat extraction?

- May need both sequentially ! ! !

Needs outline

- Energy conservation:
  - Substrate loss improvement R&D [1]
  - Coatings absorption reduction R&D [1]
- Thermal noise reduction aim:
  - Coatings (substrate mechanical loss R&D [1]
- Heat conduction from mirrors
  - Flex rod development [2]
- Heat extraction techniques
  - Metal, Super-fluid He, Optical [3,4]
- Test facilities
  - KEK suspended cryogenic F.P. [2]
  - Kashiwa rapid cycle test facility [3]
  - Other test facilities
- Development prospects color code
  - parallel with Advanced LIGO [1]
  - LIGO direct contribution [2]
  - LSU, KEK, ICRR, Roma 1 University/LNF [3]
  - DOE support [4]

- 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.

- 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 $\leq 4^o$ K
  - No boiling Helium allowed,
    No thick heat conductors allowed

- 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)
  - Third power of temperature in crystals
  - Increasing with decreasing defect density
- Heat extraction technique
  - Metal conduction ?
  - Heat piping (Superfluid Helium) ?
  - Active extraction ?

First developments needed
Conservation !!

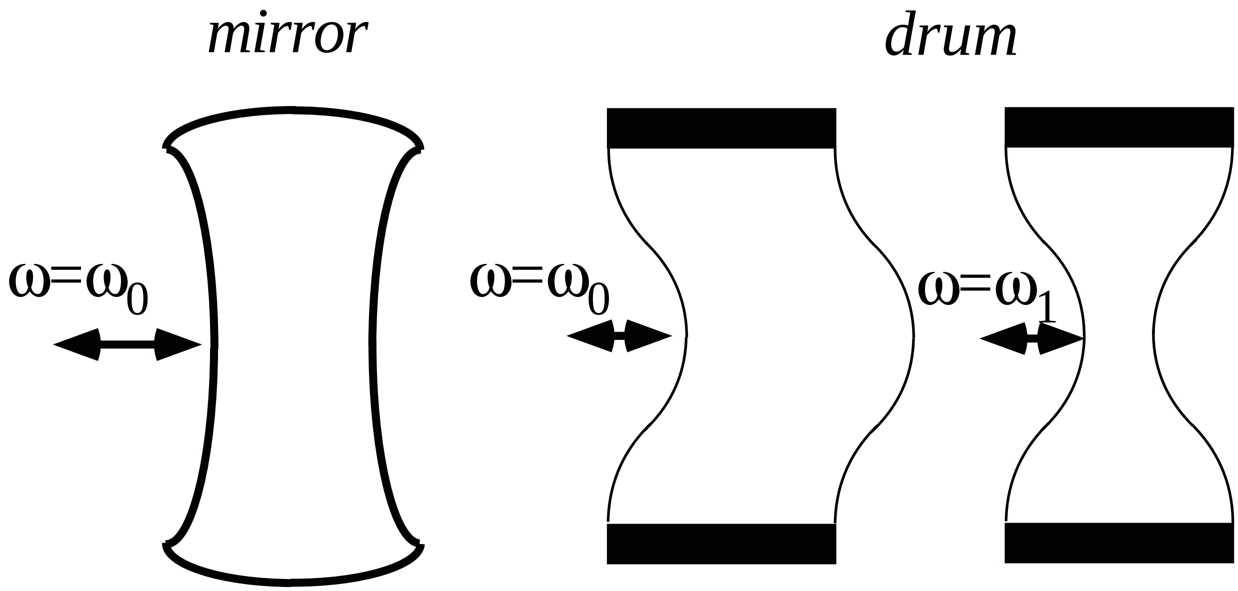
- Need a long term
  mirror coating R&D
  to reduce coating absorption
  much below 1 ppm (1 ppm?)
- Need a long term
  crystal growth R&D
  to reduce Sapphire bulk
  absorption below 20 ppm/cm

Other developments needed
Mechanical losses !!

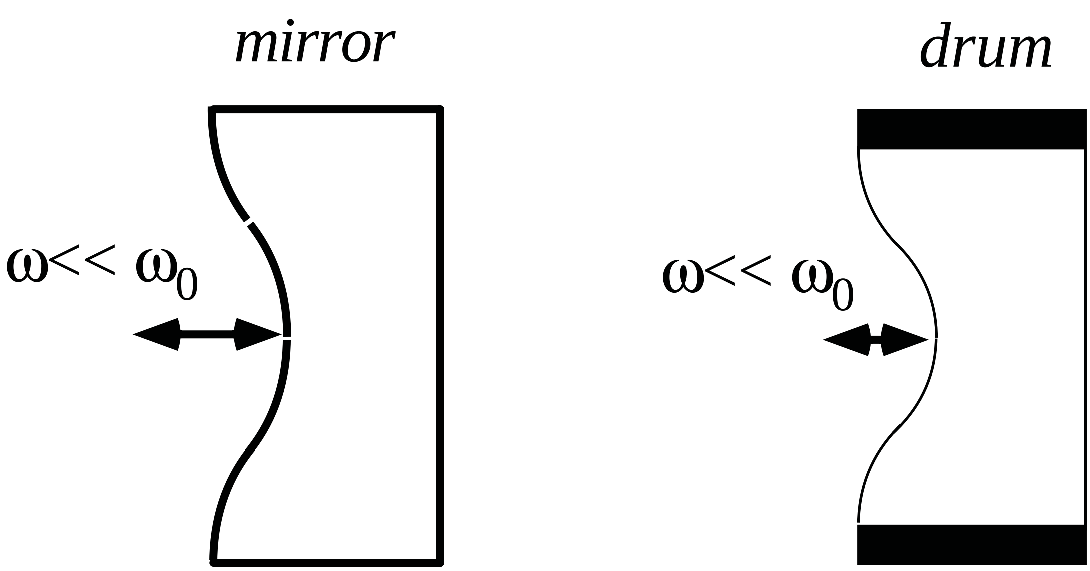
- Need a long term
  mirror coating R&D
  to develop lower mirror
  mechanical losses

- Problem probably underestimated

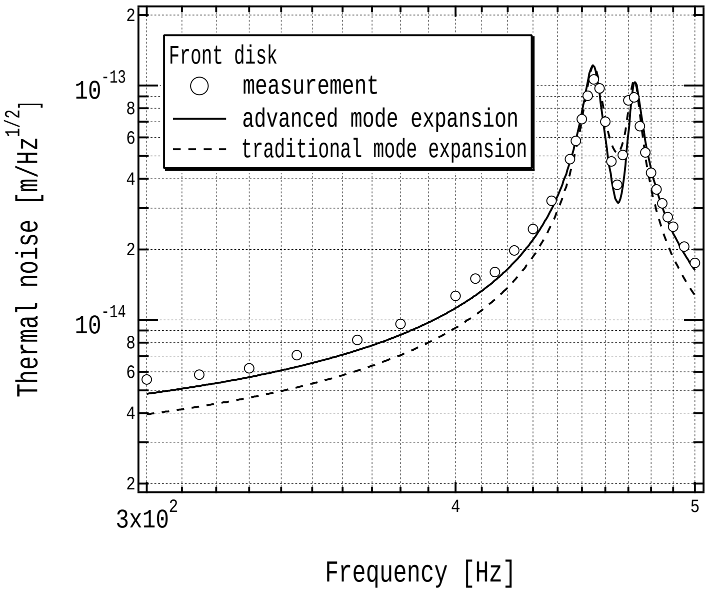
(1) At resonant frequency

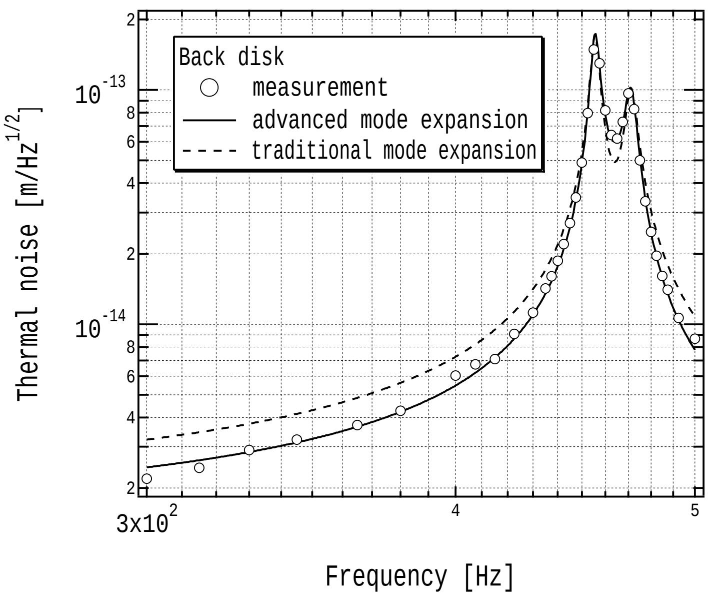


(2) In observation band (<< resonant frequency)



by Kazuhiro Yamamoto





by Kazuhiro Yamamoto

- 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 practically 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

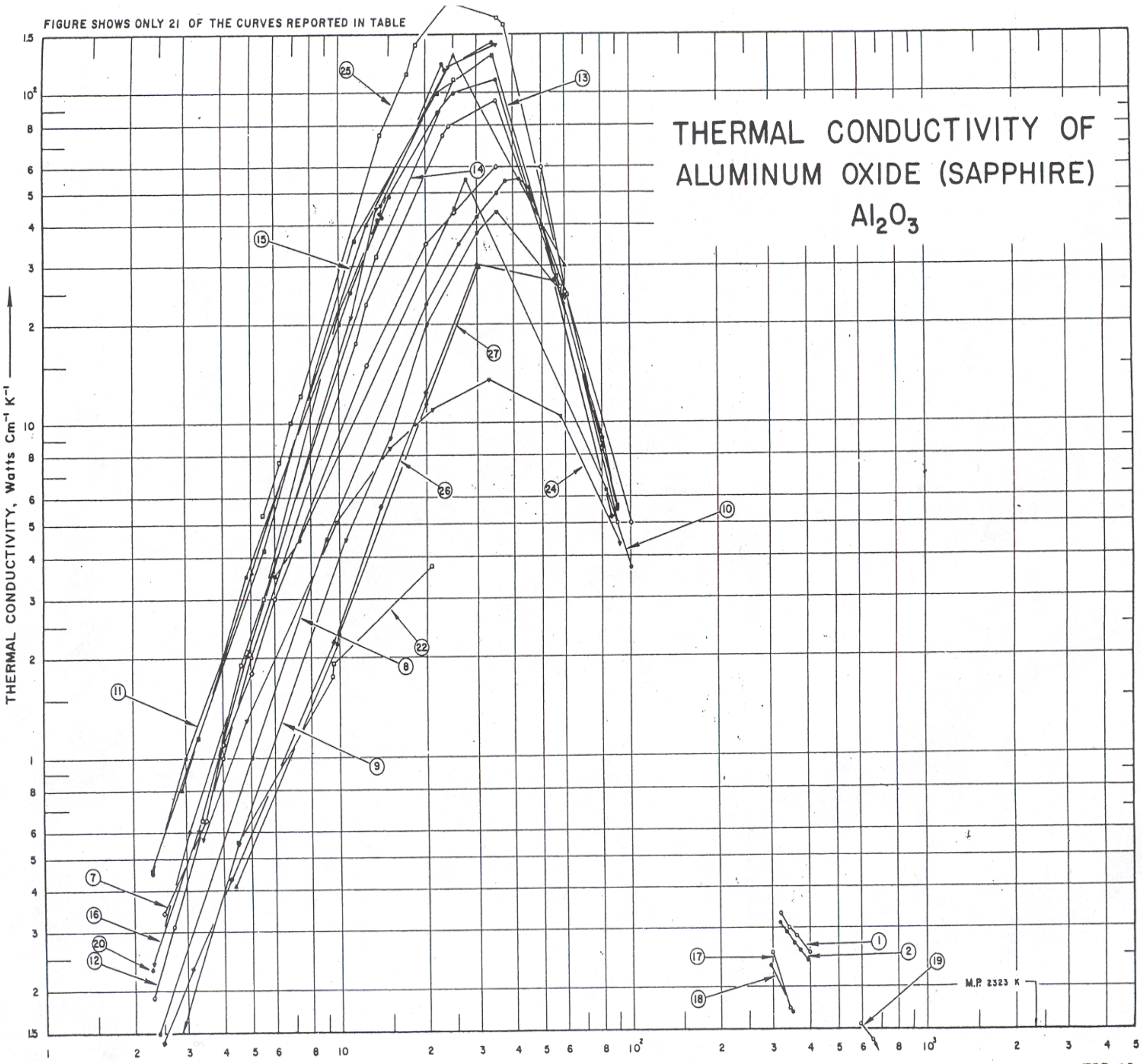
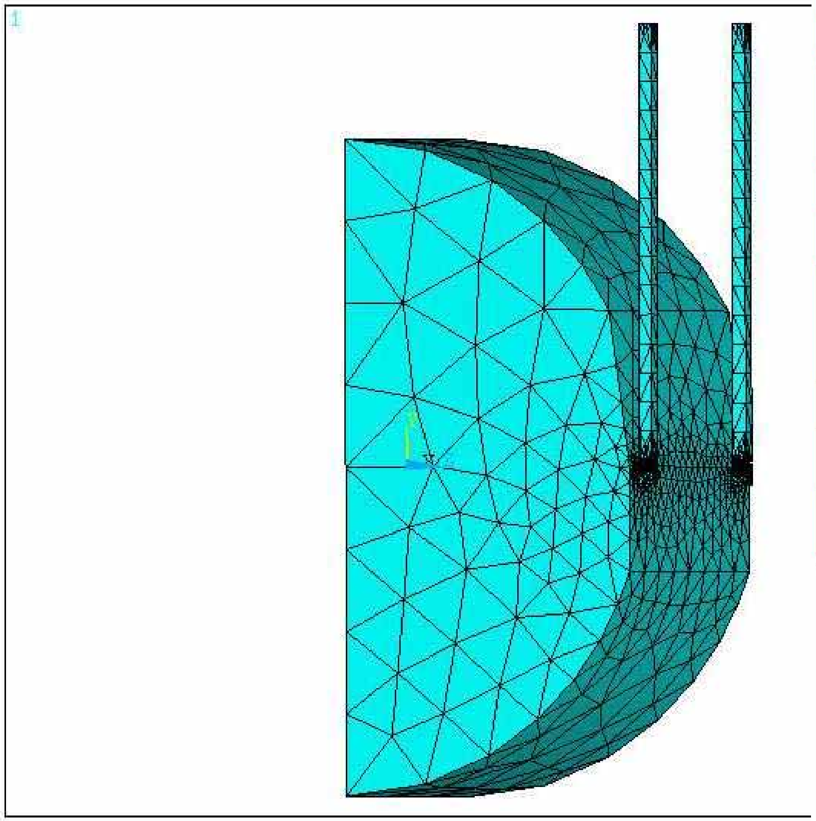
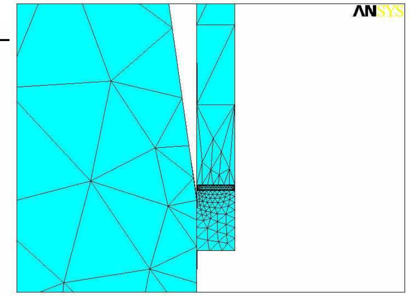
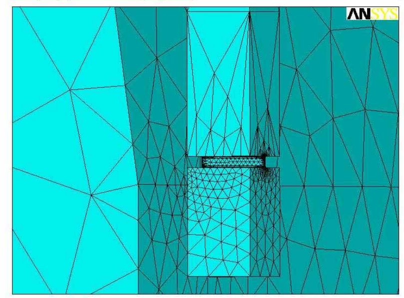


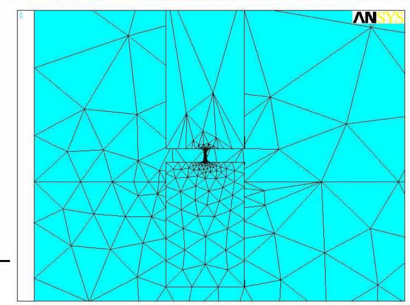
FIGURE SHOWS ONLY 21 OF THE CURVES REPORTED IN TABLE
THERMAL CONDUCTIVITY OF
ALUMINUM OXIDE (SAPPHIRE)
Al_2O_3
THERMAL CONDUCTIVITY, Watts Cm⁻¹ K⁻¹
M.P. 2323 K
TEMPERATURE, K
FIG. 15

Thermal Flow in sapphire Flex-joint

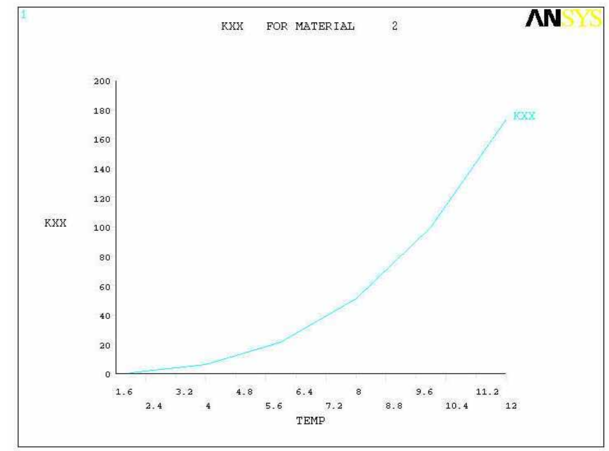








- ***Half system*** modeled:
  Mirror / rigid wire with Flex joint
- ***Non linear conductivity of Sapphire***



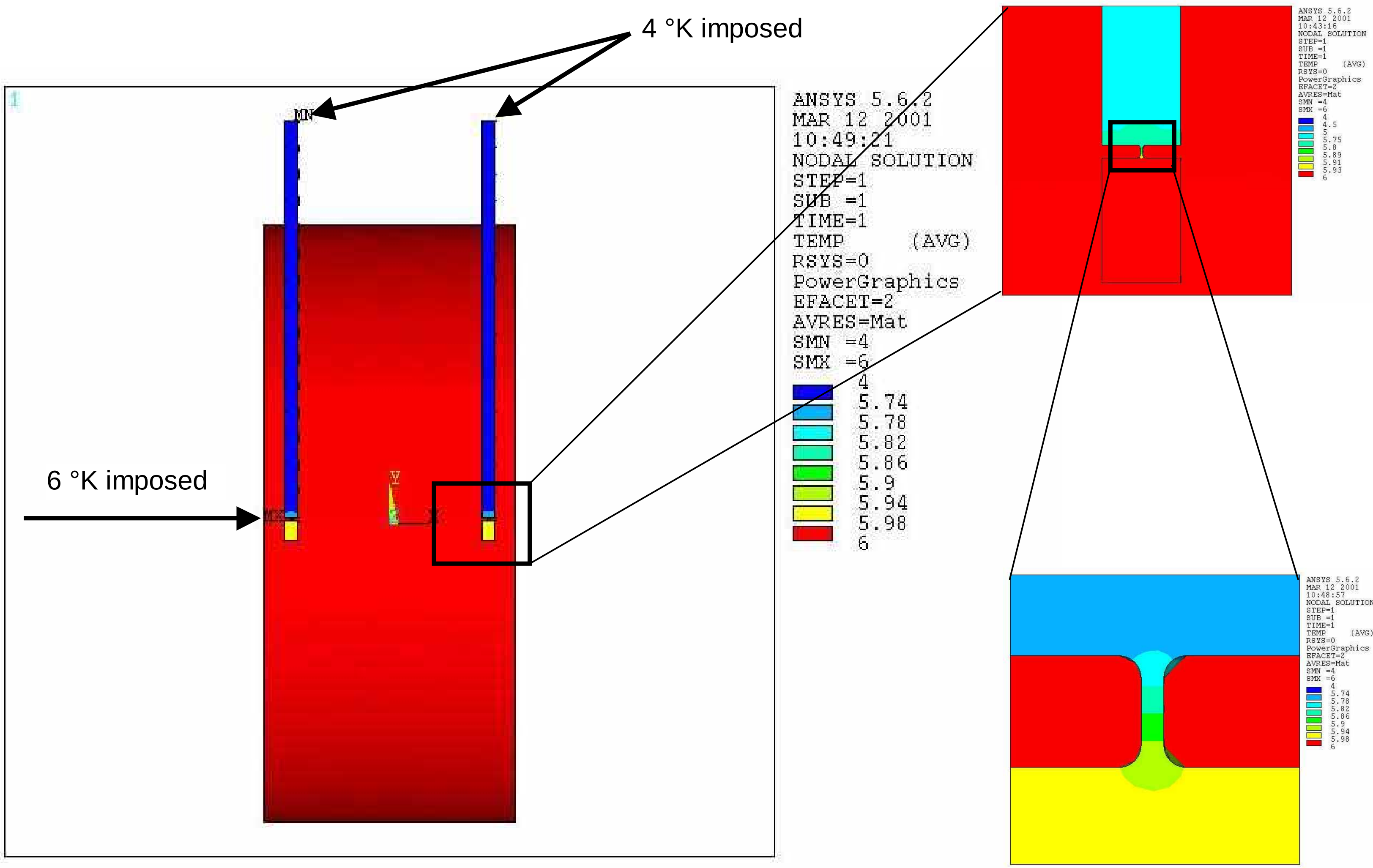
Problem: conductivity from 0 to 30°K ?

- ***Loads applied:***
  - Space temperature: 4°K
  - Laser source: 10 mW at the center of the mirror
  - Symmetrical condition: Heat flux=0 at the interface

- ***Need to be studied:***
  Material properties (non-linear conductivity, etc.), Operating conditions for loads

Frédéric Sève
March 2000

Sample results for a simpler simulation (imposed temperature)

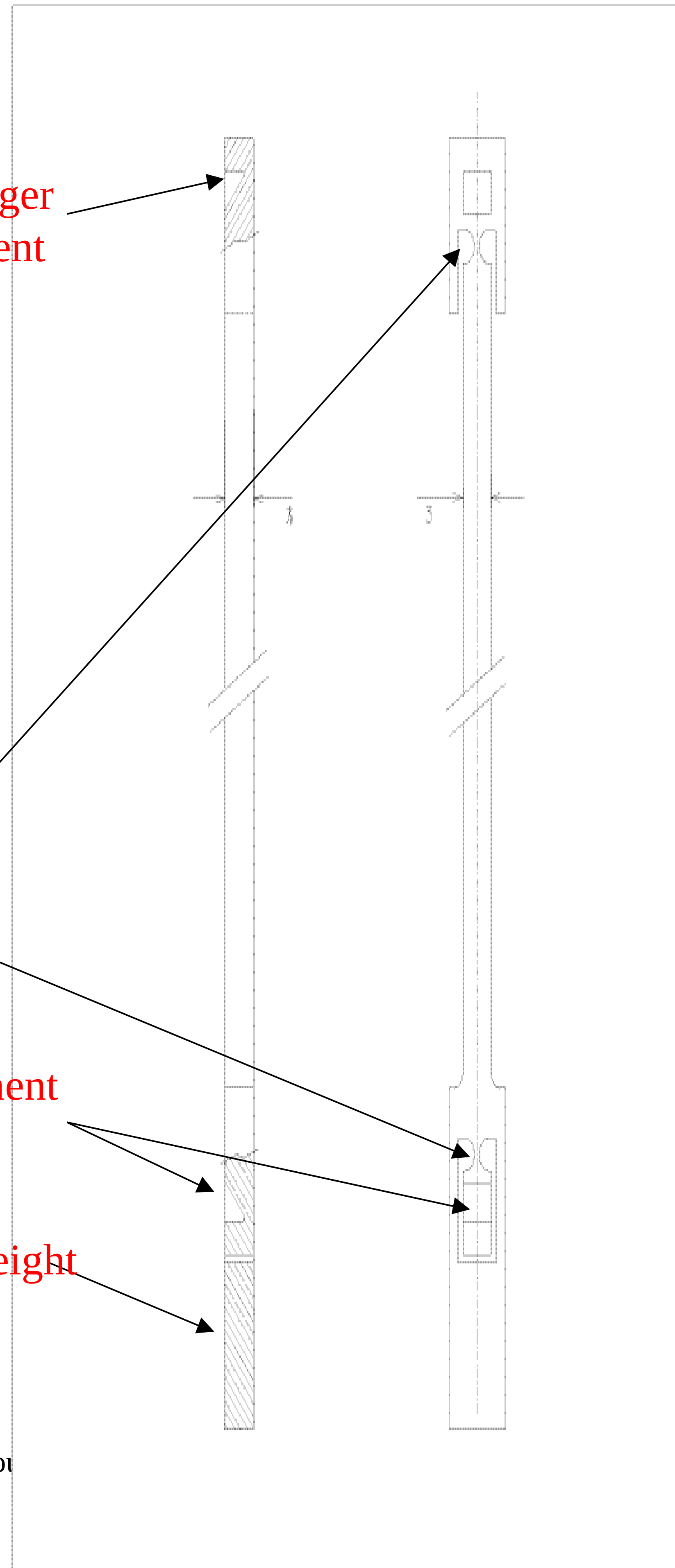


Frédéric Sève
March 2000

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

- Use UltraSound machining
- Surface treatments
  - (equivalent of flame polishing)
  - Ar-cluster polishing
  - Laser heating
  - Electron beam healing
  - Simple baking

Shaping the flex joint links

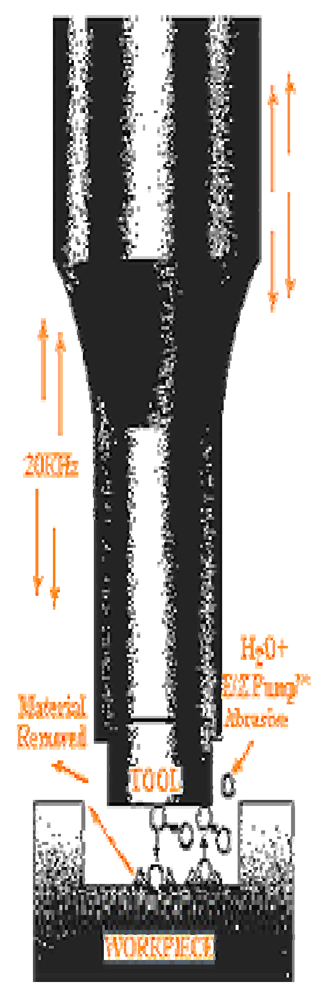


Advantages of flex joint links

- 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

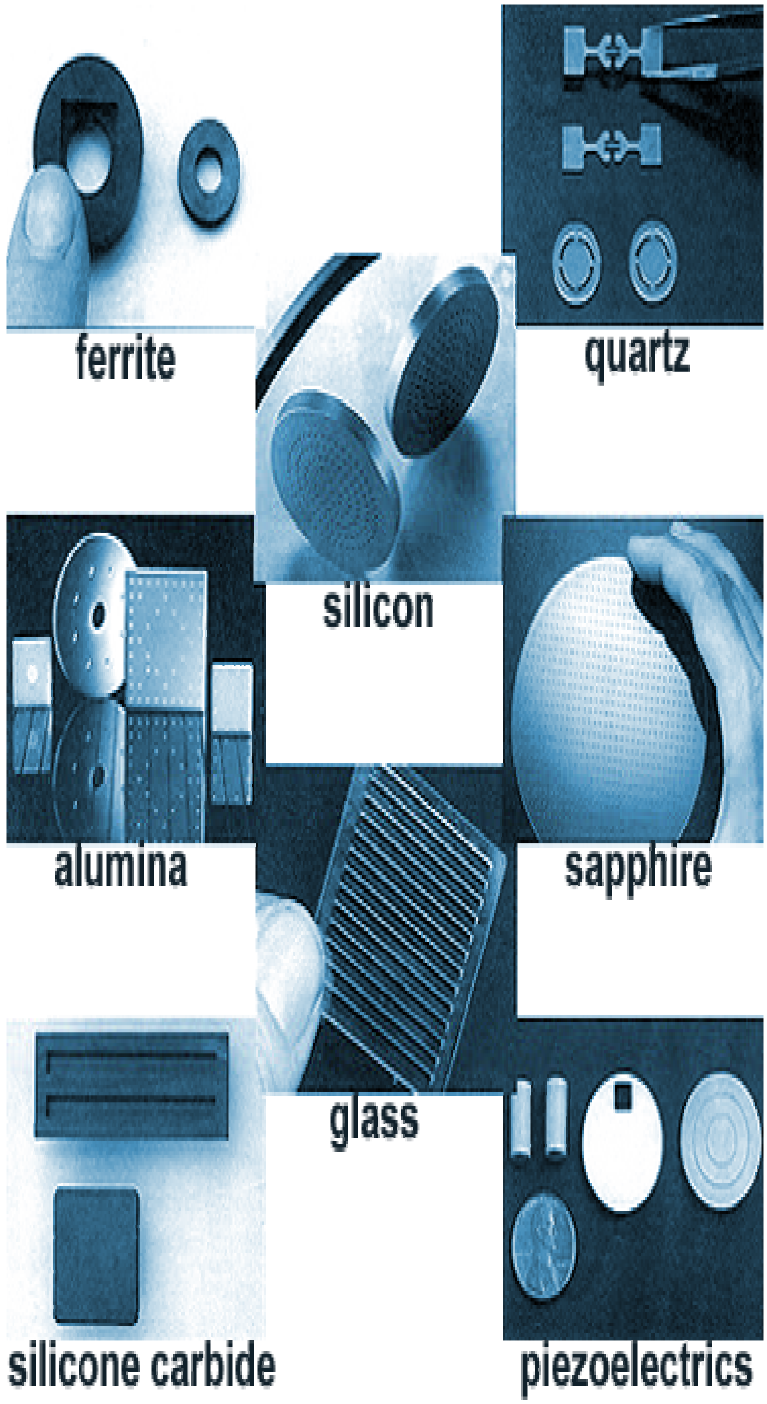
UltraSound machining of crystals

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



Ultrasound machining of crystals

- More examples;

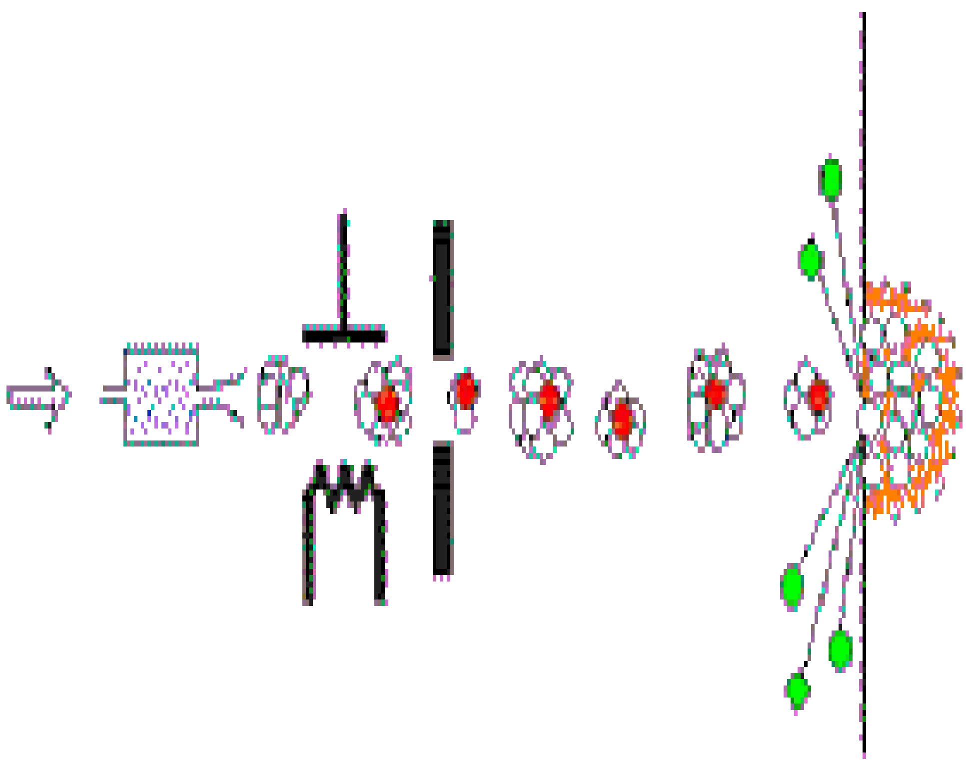


The Flex struts plan

– Engineering studies (INSA)
– Machining tests (CIT)
– Q testing (INSA, SU), ...

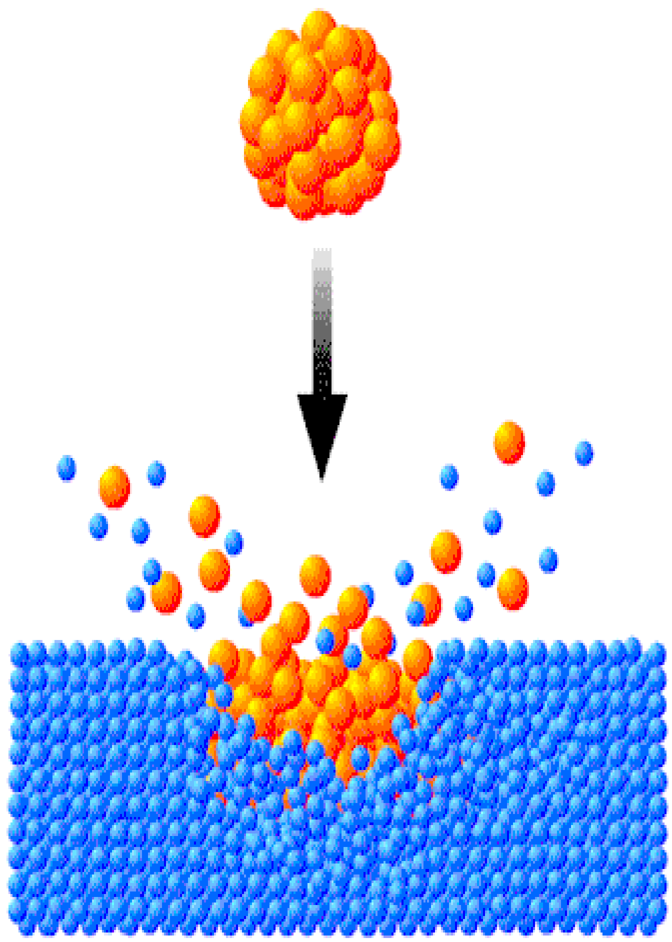
Ar- cluster polishing

- A jet of Argon droplets electrostatically accelerated abrades the surface

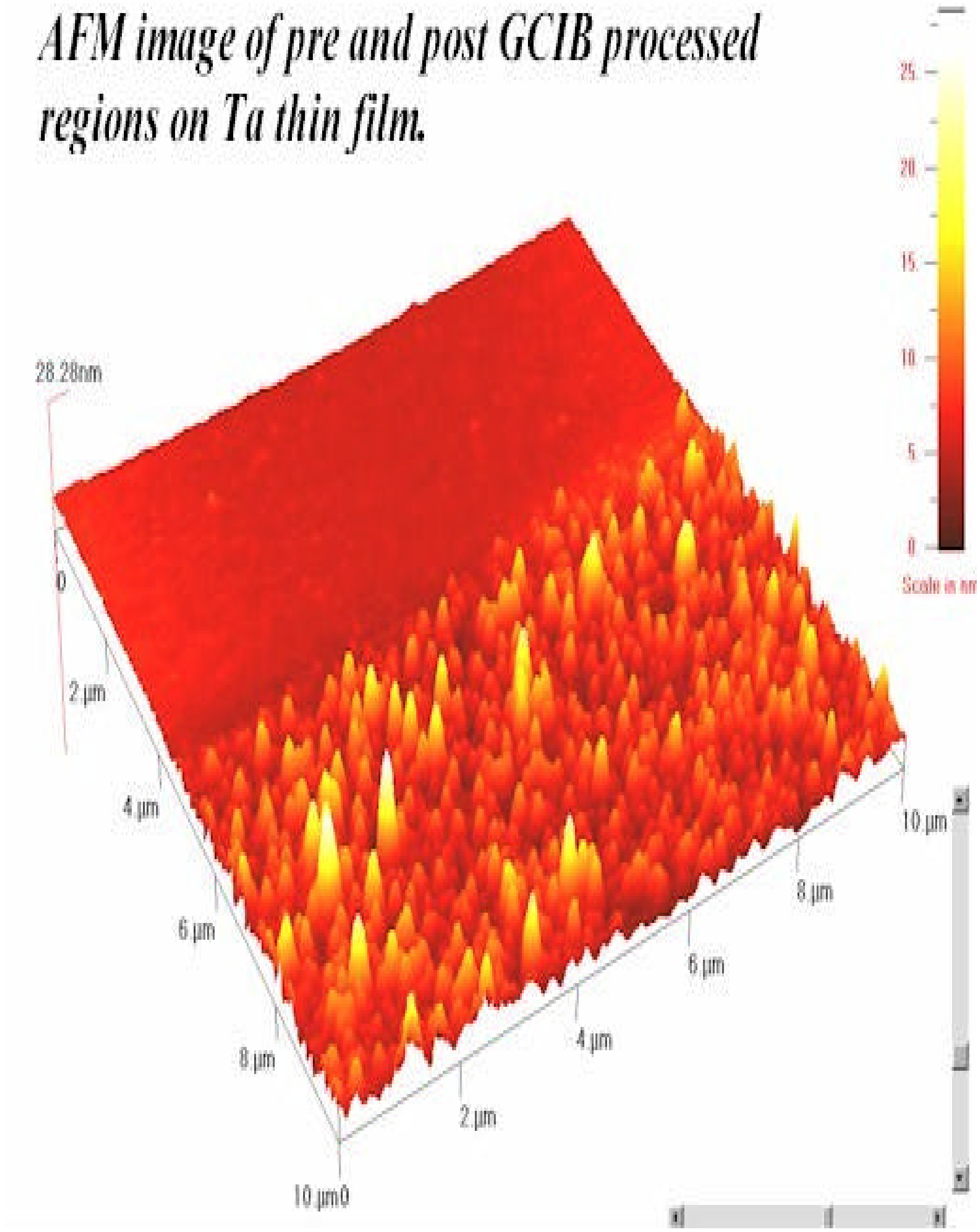


Ar- cluster polishing

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

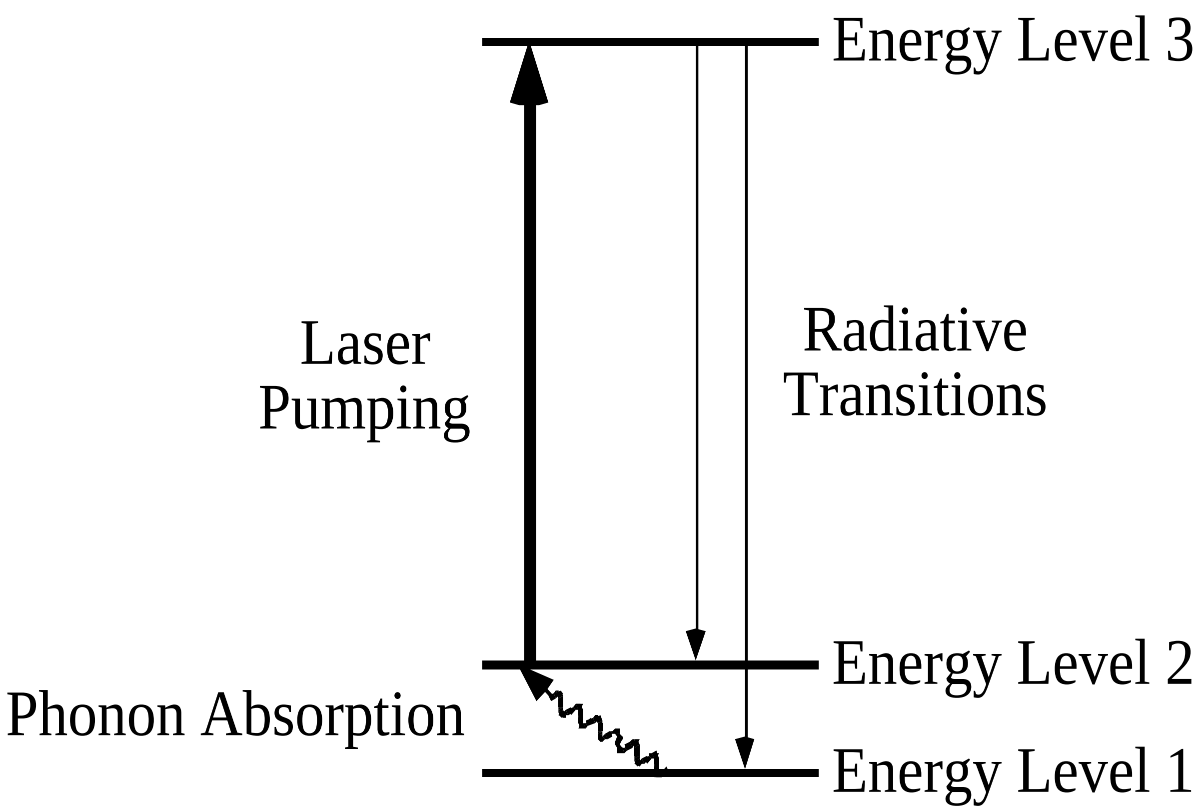


Effects of Ar-cluster polish



Basics of Optical Refrigeration

Three-level "atom" in a transparent solid

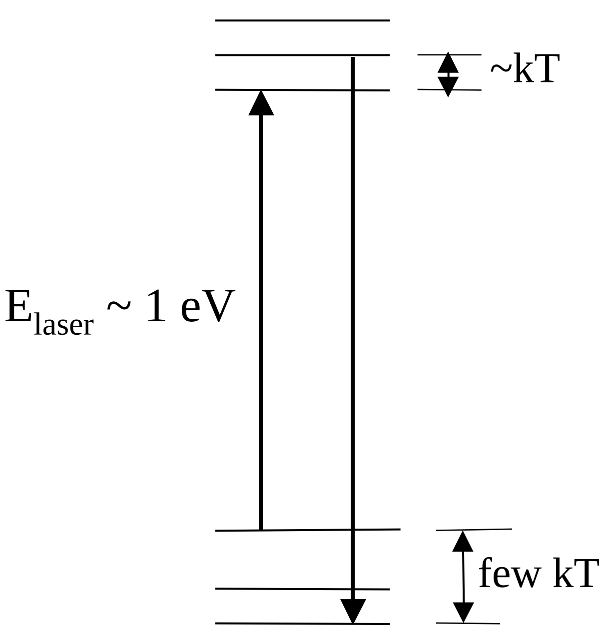


Radiative decay 3→1 followed by phonon absorption cools material

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

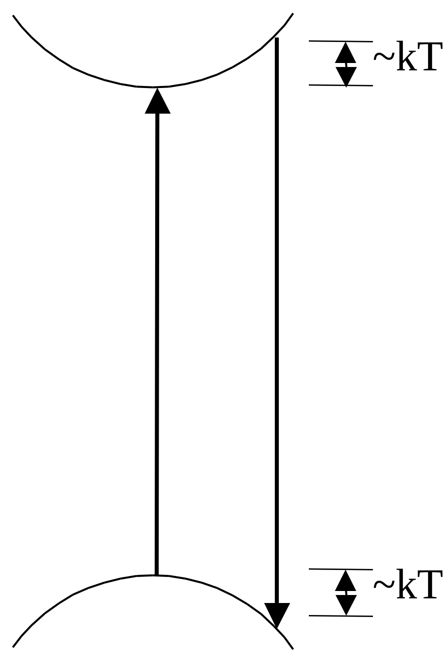
Practical Optical Refrigeration

Rare-earth-based Optical Refrigeration



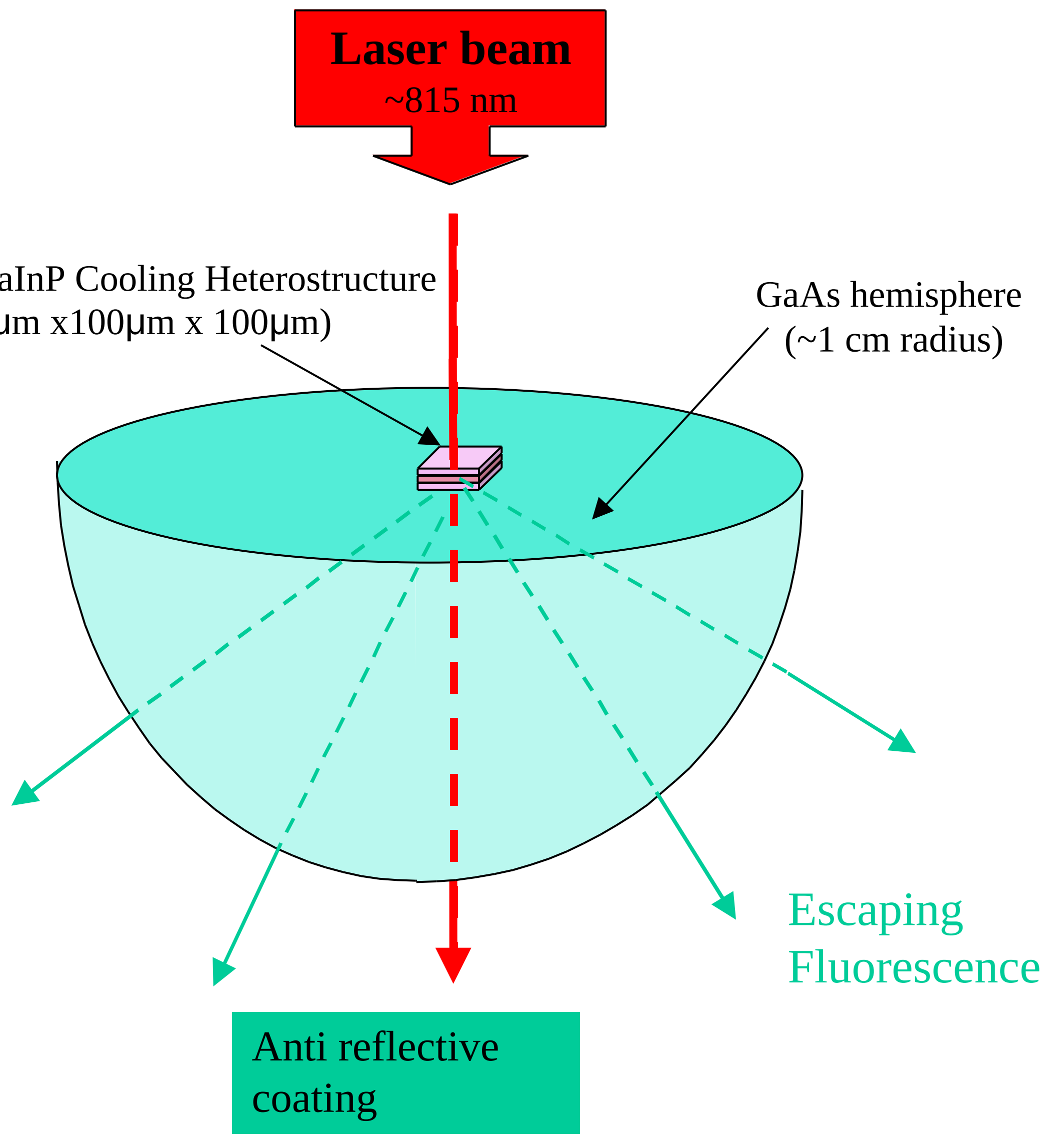
Yb-, Tm- or Ho-doped glasses and crystals

Semiconductor-based Optical Refrigeration



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

Semiconductor test Cooling Element For LIGO



Problems with optical chiller

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

Optical chiller development

- Applying for DOE development grant at Los Alamos

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 cold masses above mirror

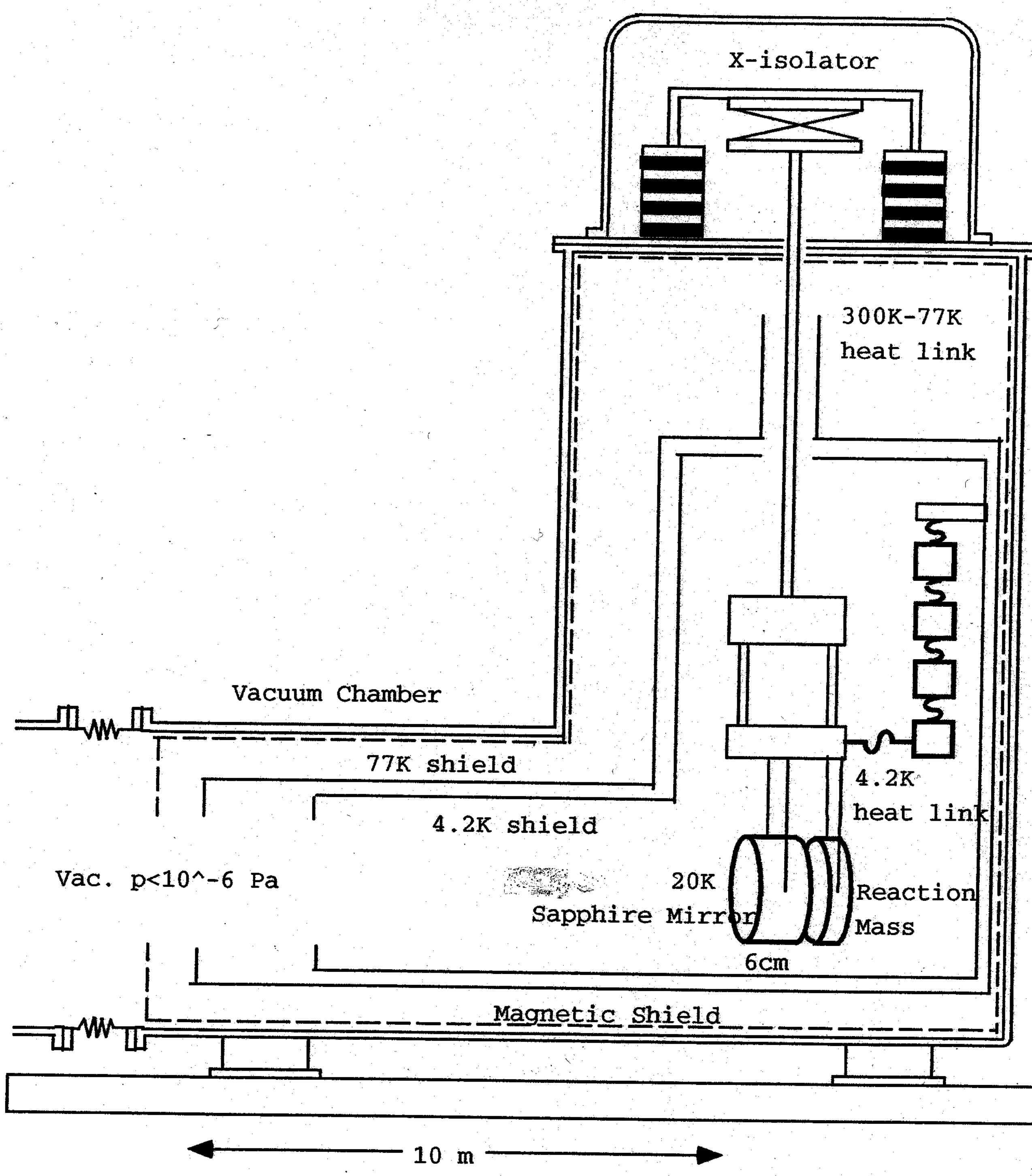
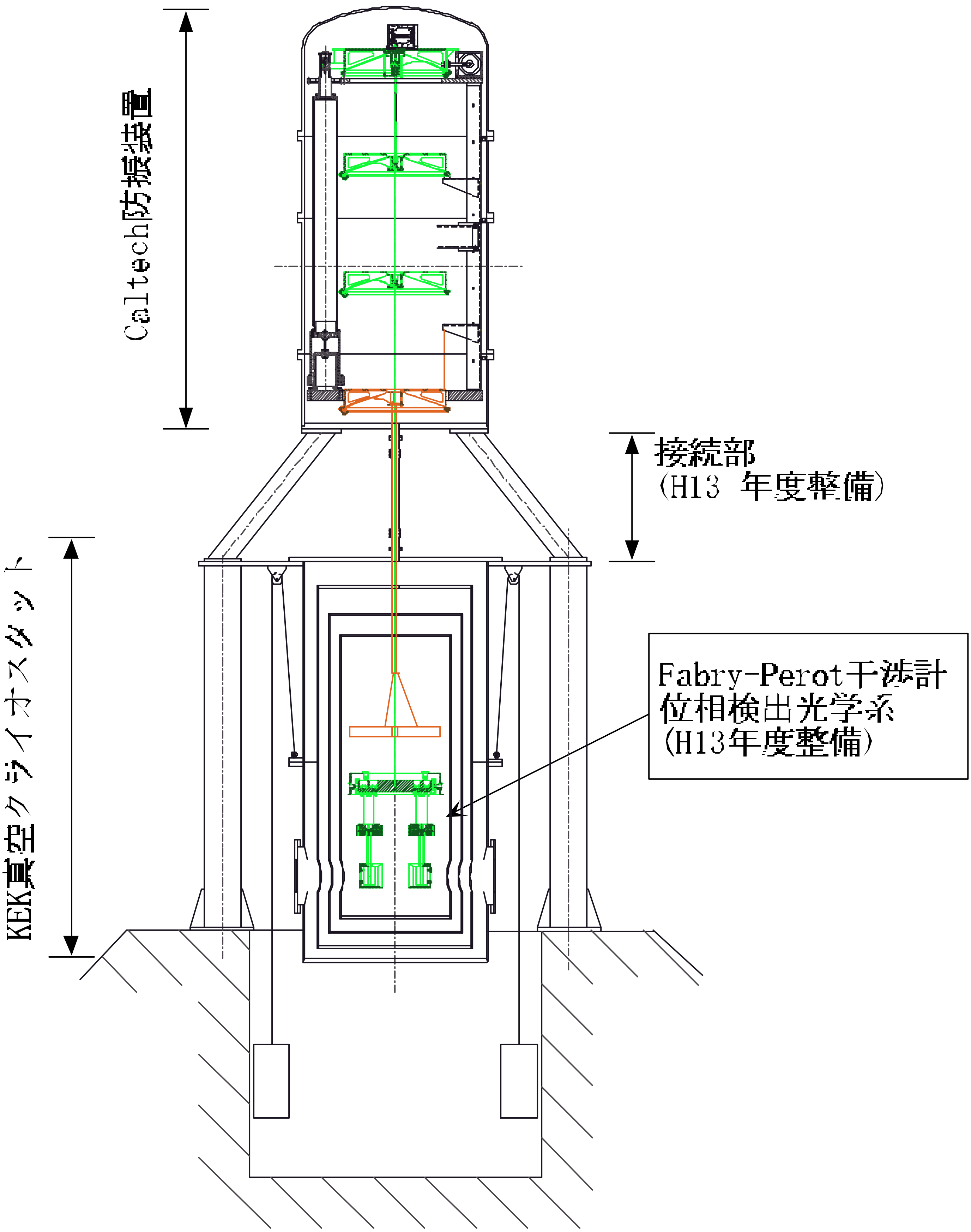


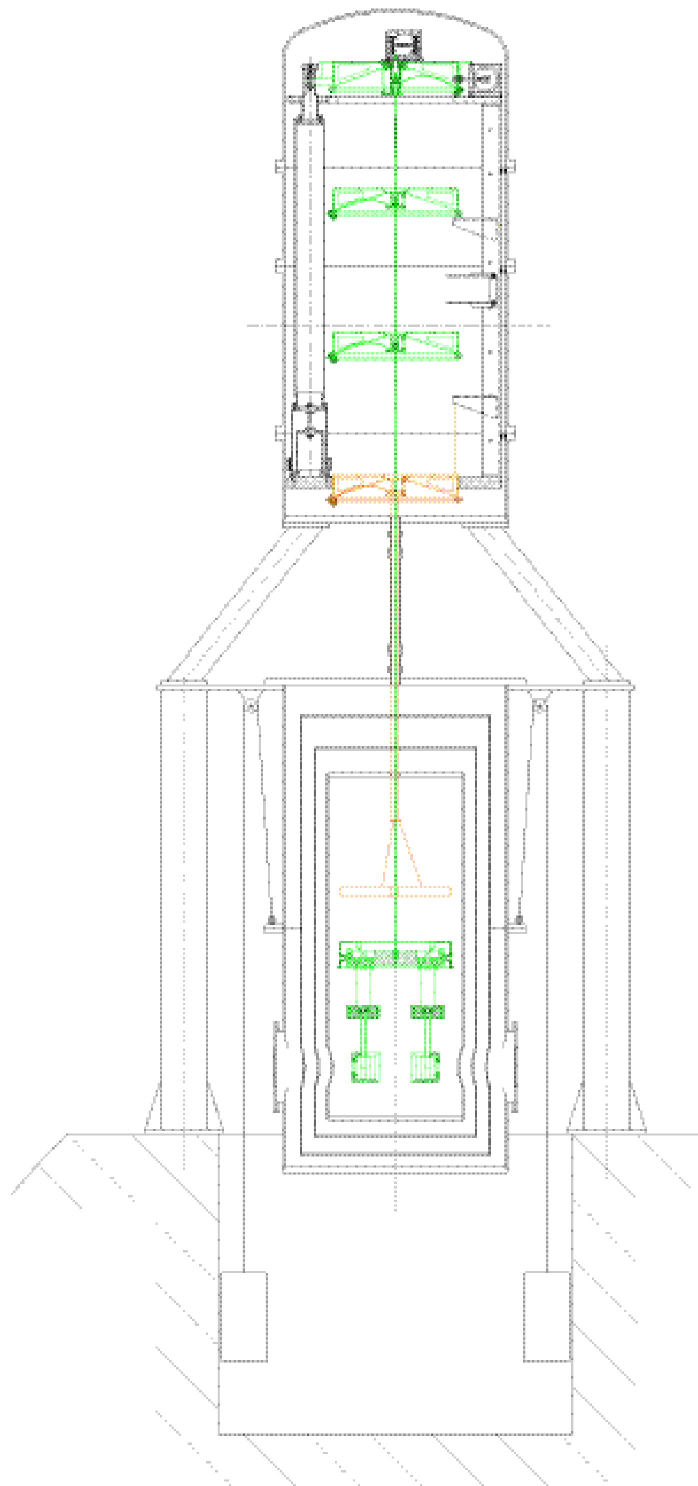
図7　低温鏡 インストールプラン



H13 KEK共同開発研究 低温鏡熱雑音の測定

The KEK cryogenic test facility

- Test present and advanced heat extraction techniques
- Test bed for different geometrical solutions
- Eventually mirror thermal noise test facility

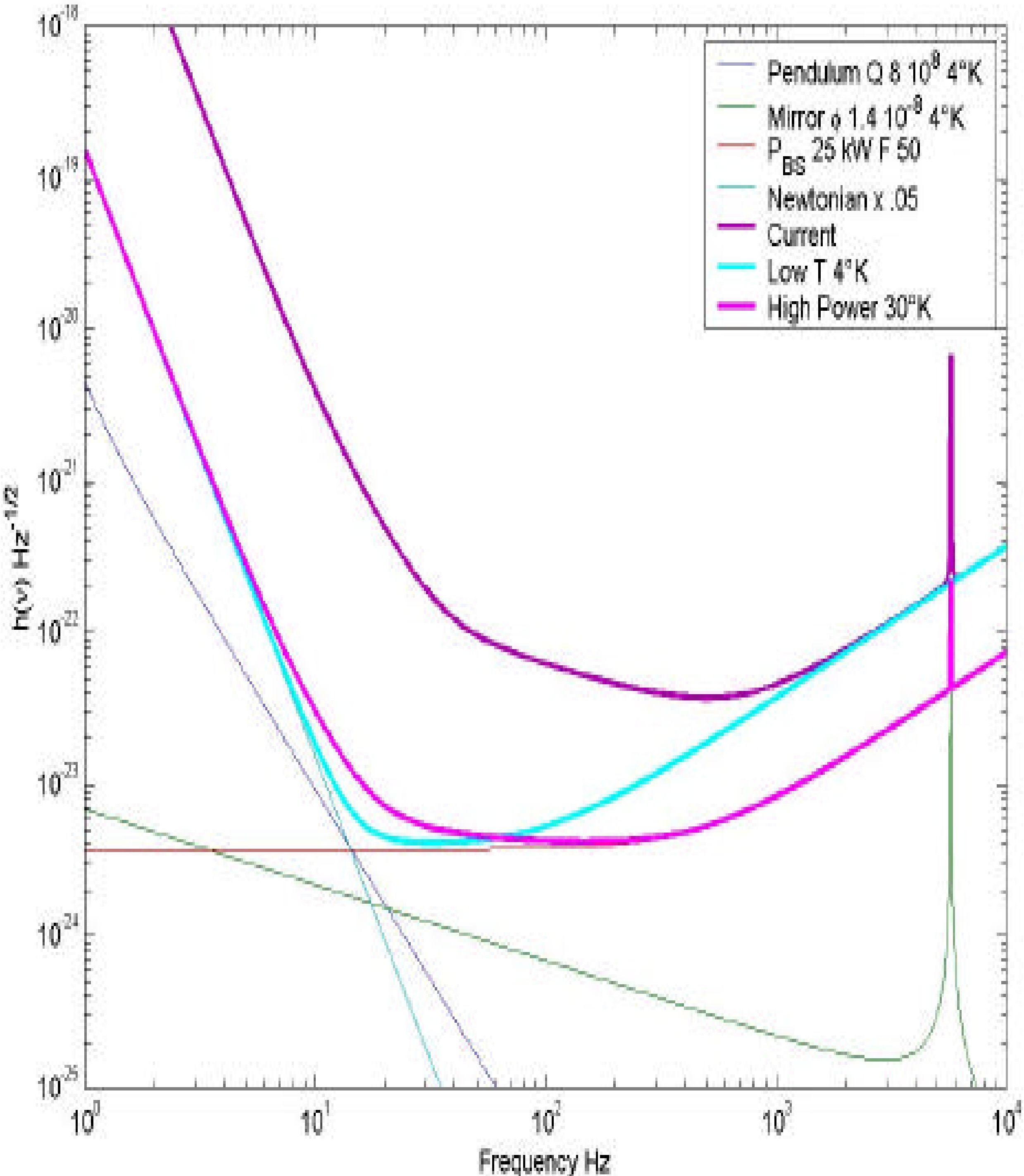


- Dual Frequency ranges
- Dual Cooling techniques

  - 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

Conclusions

- Cryogenic interferometers have great promises
- Will need massive amount of basic R&D
- Need more collaborators
  - Cannot burden Advanced LIGO but will have plenty of synergy

Conclusions

- Studies on mirror and substrates together with Advanced LIGO
- Study mechanics of thick suspensions (INSA)
- Develop sapphire joint machining techniques (CIT)
- Study metallic conduction avenue and geometries (LSU)
- Participate in construction of cryogenic testing facility (KEK)