Progress of Cavity Mirrors: 1975 - 2005

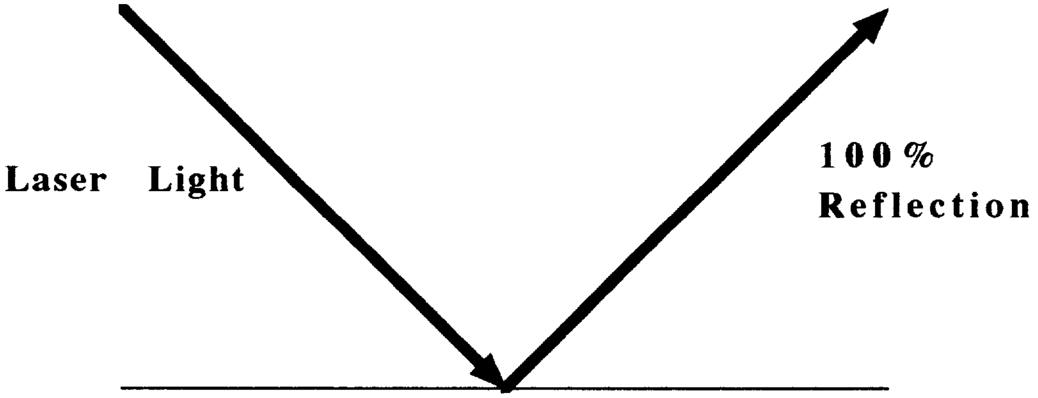
by

David T. Wei, Ph.D.

Wei & Assoc.
Malibu, CA 90265
e-mail: dwei@eudoramail.com
Phone/Fax: (310)454-3501

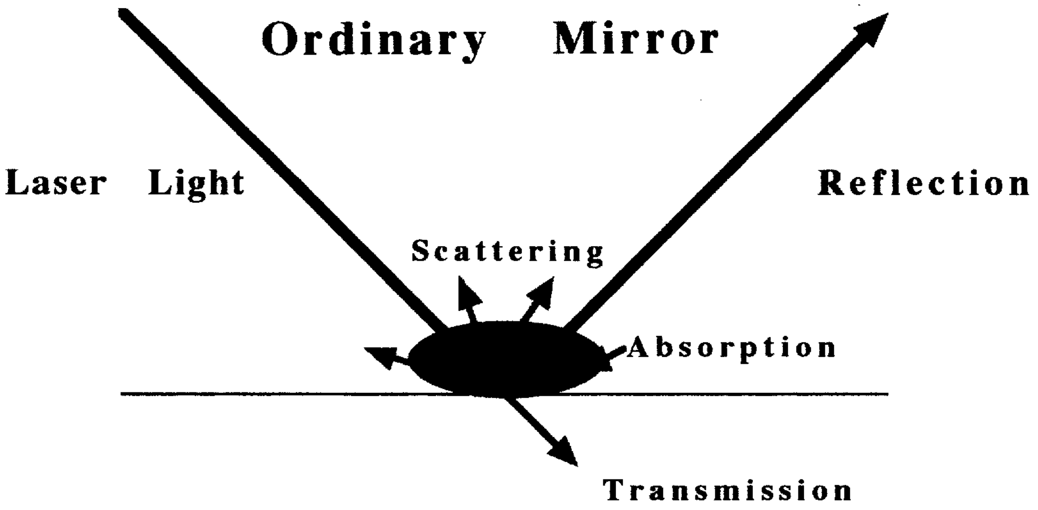
LIGO-G990125-00-D

Super Mirror

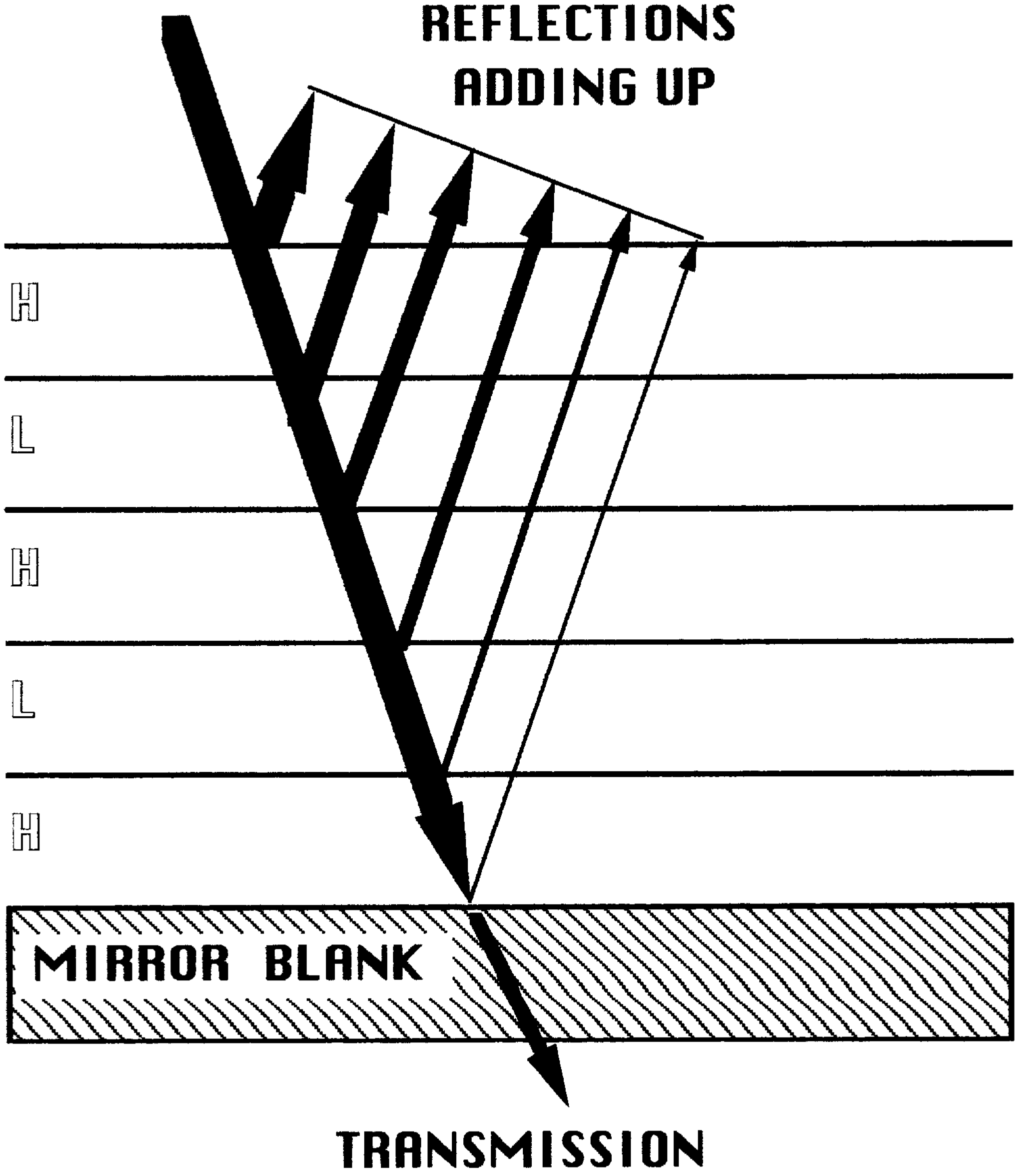


INTRODUCTION
Principles of Mirror Making
Early History
Dreams about Future
Reality Checks: OIC vs. SC
Conclusions.

Ordinary Mirror



INTERFERENCE COATING



H: TiO_2 (Titania)
L: SiO_2 (Silica)

THE FIRST TIME (CIRCA 1975)

A. Indications:

1. Prior to 1975 @ Litton, from vendors and contracted research samples:
   - o Scattering: Discrete (Mie) & Continuous (Rayleigh) clarified
   - o Scattering causes determined.
2. Year 1972 @ GTE Lab data, ion implanted waveguides:
   - o Core clarity estimated: T = 0.01%
   - o Surface damaged, scattering strong. (Slide)

B. Planning Stages (with Dates):

1. A New Year Resolution (1/1/75):
   - o Drop Plasma Sputtering development
   - o Initiate Ion Beam Sputtering development
   - o Rationale:
     - a. Eliminate "back-scattering"
     - b. No runaway heat:--eliminate crystallites
     - c. No charging effect:--eliminate pitting.
2. Deadline Set: -- Samples to be delivered 3 months after equipment installation.

3. Milestones: --

- o Funding Granted (7/75)
- o Ion Beam Equipment Identified (8/75)
- o Coating Chamber Designed (10/75)
- o Assembly & Test Begun (12/75)
- o First Samples Delivered (7/3/76)
- o Celebrating a 200 Anniversary (7/4/76)
- o And a New Beginning!

  (Photo, Drawing & Patent Disclosure)

FIRST RESULTS SUMMARIZED:

SAMPLE SIZE: 2 PIECES, BETTER DATA AS FOLLOWS:

MIRROR SIZE: 0.8” DIA. x 0.375”

SUBSTRATE: SUPERSIL, REJECTS (SiO_2 WITH FLAWS)

NUMBER OF QUARTER-WAVE LAYERS: 15

HIGH INDEX LAYERS: TaOx, ($n_H = 2.2$, ESTIMATE)

LOW INDEX LAYERS: 7059 GLASS, ($n_L = 1.46$, ASSUMED)

THEORETICAL REFLECTANCE: $R = 99.72\%$

MEASURED TRANSMITTANCE: $T = 0.25\%$

MEASURABLE LOSSES: $S+A = 0.12\%$

DEDUCED REFLECTANCE: $R = 99.63\%$ (BALANCE)

NON-LOSS INTENSITY: $R + T = 99.88\%$.

COMMENTS.

- o OVERALL RESULTS COMMENSURATE WITH THE BEST COMMERCIAL MIRRORS @ 1976.

- o SUBSTRATES NOT PRECLEANED, BUT IN SITU CLEANED BY ION BEAM ONLY.

- o SUBSEQUENT RUNS WITH MORE LAYERS OF COATING, BETTER SUBSTRATE AND CLEANING: $R = 99.99\%$ (AS APPEARED ON PATENT).

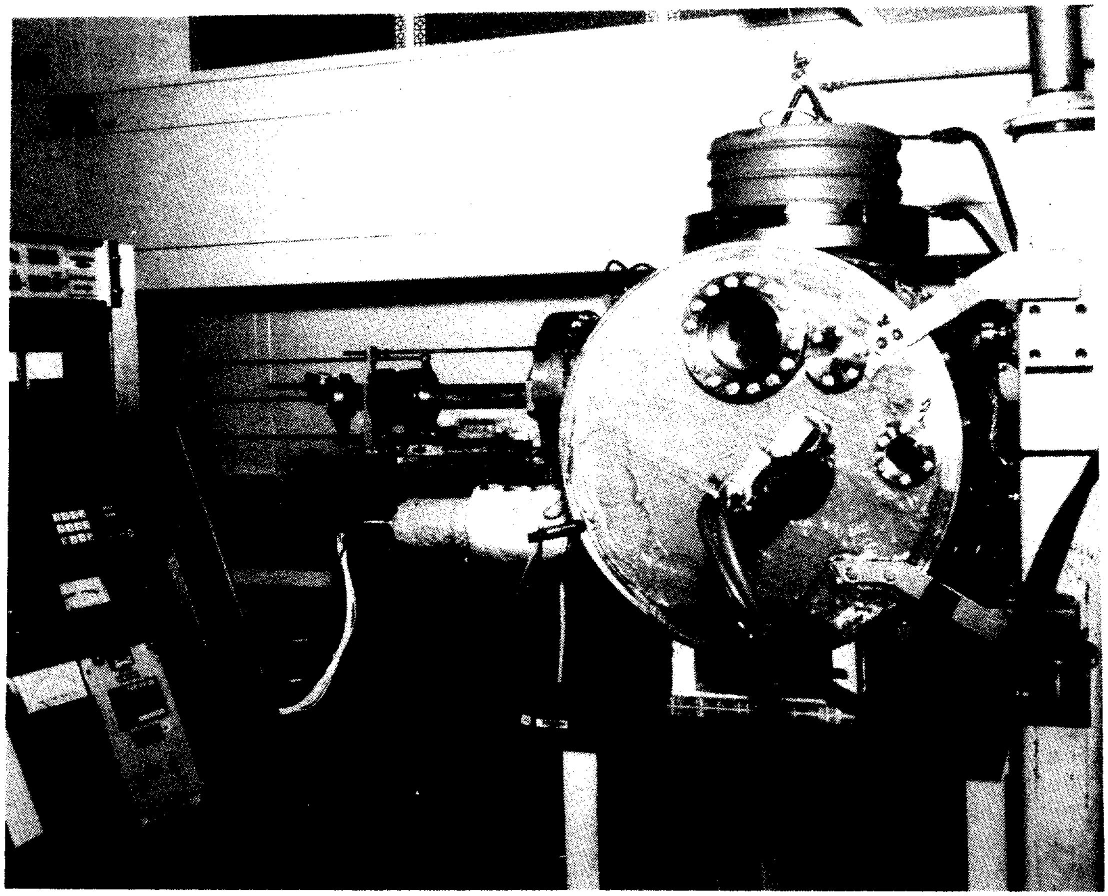


Fig 1. The original IBS coating chamber at Litton Guidance and Control Division. The substrate holder is mounted on the long insertion mount on the left side of the picture.

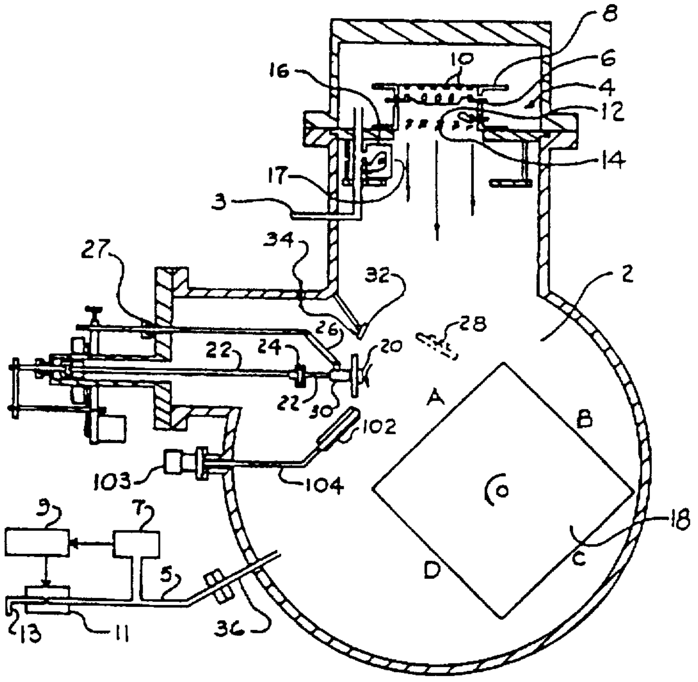
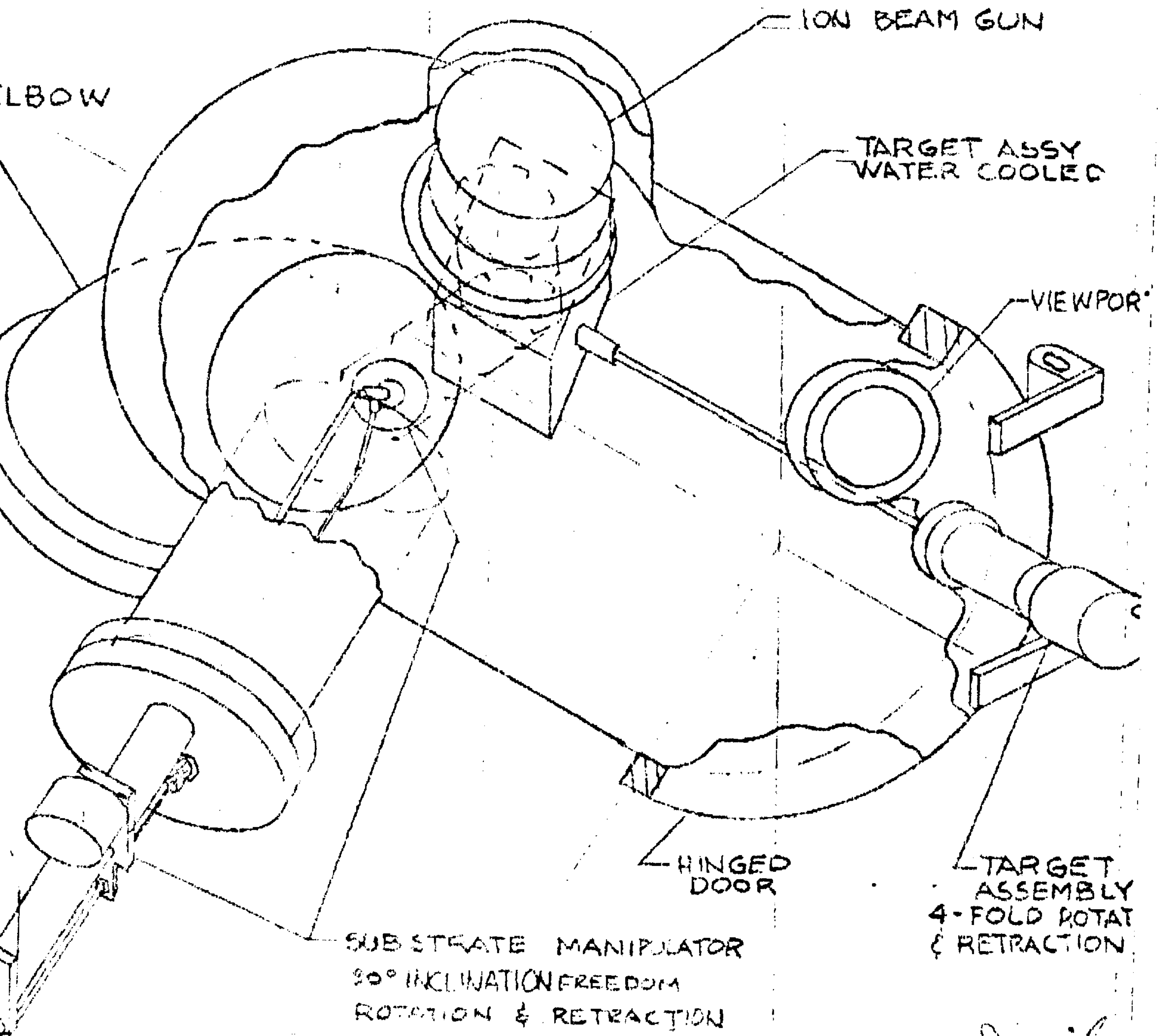


Fig 2. A block diagram of the internal functioning elements of the original IBS coating system in Fig. 1



4/29/76

4/12/1976

COATING CHAMBER
CUT AWAY VIEW

FIG 2

Guidelines for Dreaming .

Braginsky & Khalili, 'Quantum Measurement,' p. 105: "…. the weakness of the interaction guarantees there is almost no back action of the probe on the gravitational field. As a result, gravitational wave acts on the probe ...as precisely classical force."

J. Wheeler: 'Geons, Blackholes & Quantum Foam,' p.290: (On correspondence principle): "...a barrel of sugar, for all its 'continuous behavior,' is ultimately granular."

In their spirits, we shall deal with mirrors & cavities as classical objects, except when a quantum explanation is evident.

SOME OPTIMISTS' DREAMS

o ***Dream A***. 1988--

G. A. Thomas et al: High T_c superconductor Ba-Y-Cu-O, in single crystal form showed reflectance R > 99%.

D. T. Wei: superconductor film can attain R = 100% ***theoretically***.

o ***Dream B***. 1994-- H. Bilger et al: TiO2/SiO2 mirror reflectance can attain 12-9's (R= 0.999,999,999,999), ***theoretically***.

o ***Dream C***. 1999--

Tama and Virgo Groups seriously consider using cryogenic cooled mirrors to reduce thermal noise.

****

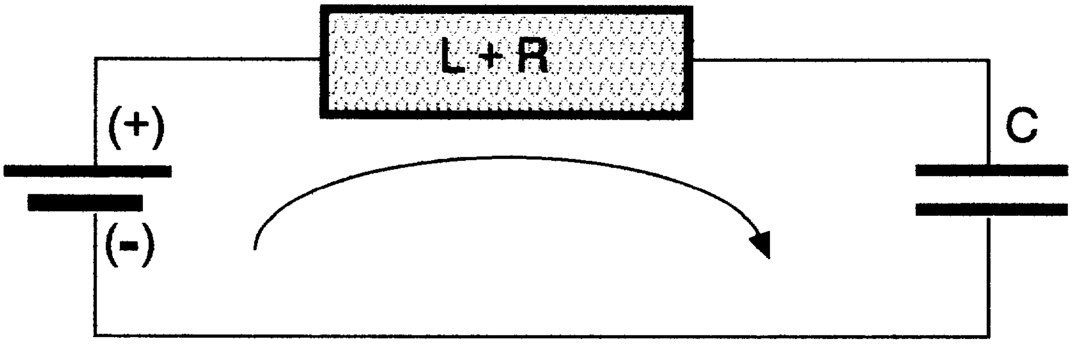
At year 2000, SHALL WE review some difficulties involved? Admitting dreams A&B were either unrealistic or impractical, We ask the following questions:

Q 1. Is a cavity of no-loss a stable cavity?

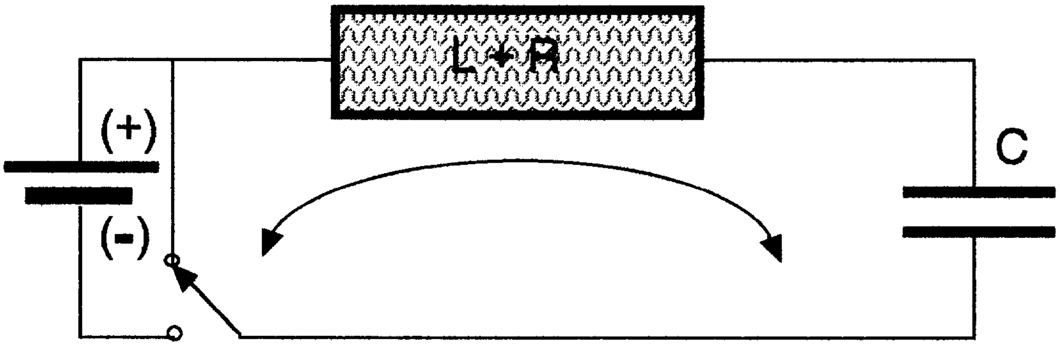
Q 2. Can no-loss create any false sideband?

Q 3. How much is the usable bandwidth for a superconductor mirrored cavity? At what frequency?

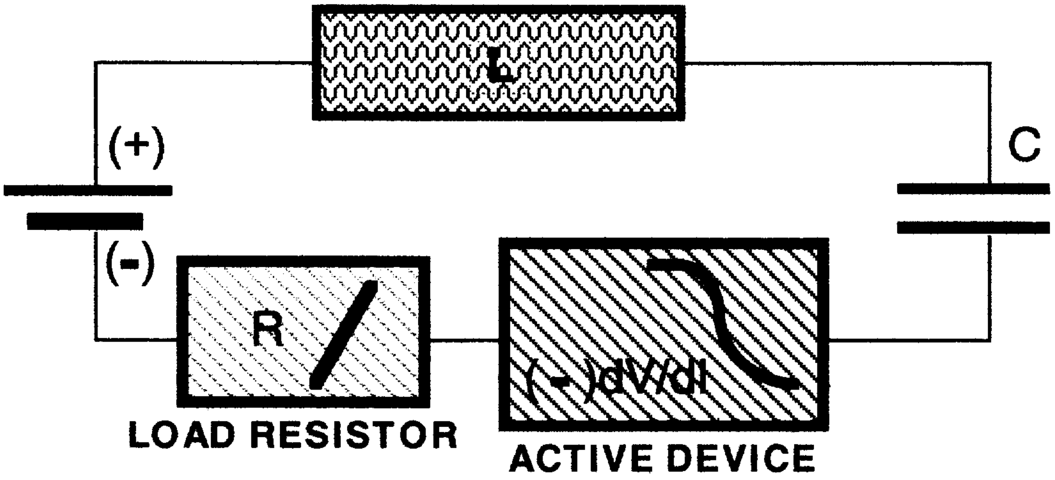
Q 4. How do stresses affect an optical interference coated (OIC) mirrors and cavity?



WHEN $R >> 0$, CIRCUIT IS STABLE



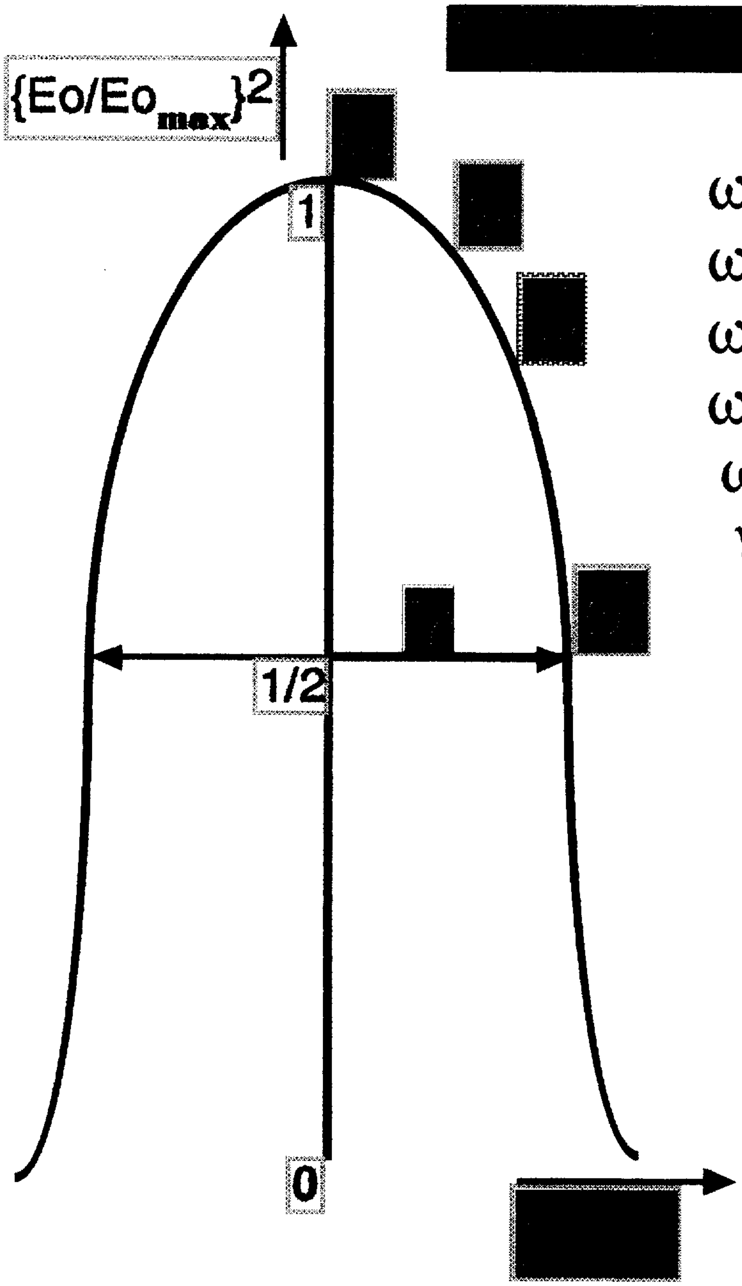
IF COIL IS SUPERCONDUCTING, ($R=0$)
CIRCUIT OSCILLATES BY ITSELF ($\omega^2 = 1/LC$)



REAL CIRCUIT ($\omega^2 = 1/LC$)
WHEN $dV/dt < R$, CIRCUIT STABLE
WHEN $dV/dt > R$, CIRCUIT OSCILLATING

NEGATIVE RESISTANCE OSCILLATIONS
WANTED: SWITCHING TRANSISORS-- OPTICAL COMM.
UNWANTED: CMOS -- IN MEMORY DEVICES, VLSI

[redacted]



ω_0 : NATURAL FREQ.

ω_1 : DECAY FREQ.

ω_2 : RESONANCE FREQ.

ω_γ : HALF INTENSITY FREQ.

ω : DRIVER FREQ.

γ : HALF INTENSITY WIDTH.

ω_0 : NATURAL FREQ.

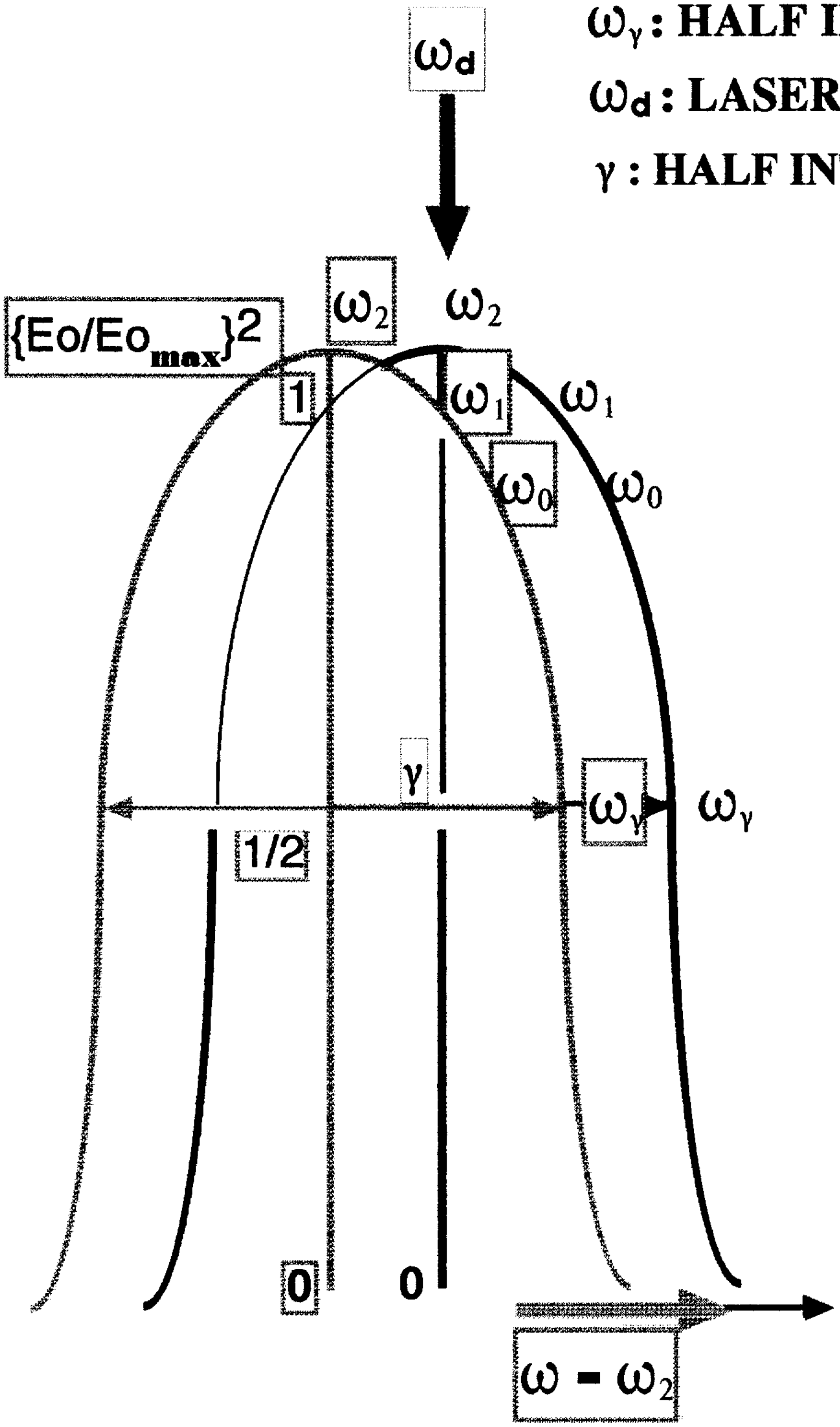
ω_1 : DECAY FREQ.

ω_2 : RESONANCE FREQ.

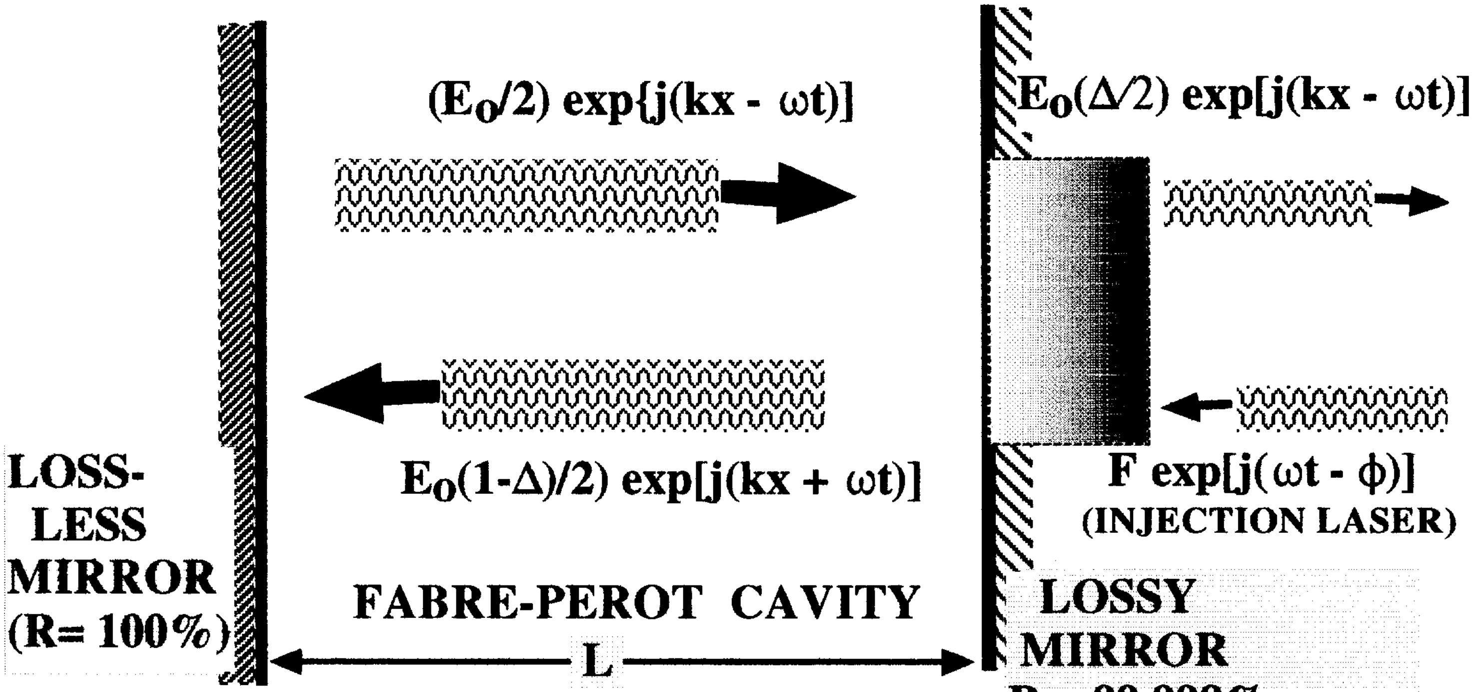
ω_γ : HALF INTENSITY FREQ.

ω_d : LASER DRIVER FREQ.

γ : HALF INTENSITY WIDTH.



CONSIDERING A CAVITY WITH PENETRABLE MIRROR COATING



R = 99.999%

$(\Delta/4)^2 = T = 0.001\%$

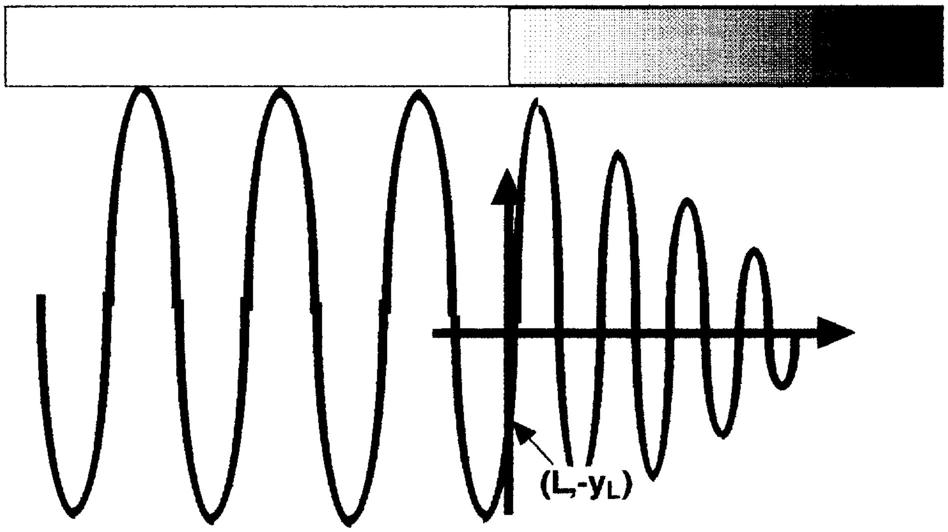
STANDING WAVE (99.999%)

Wave Func. = Sin(kx)Cos(ωt)

If W. F.= 0 at x = L, then $kL=N\pi$

(# NODES: $N = 2L/\lambda$).

HOWEVER, WHEN T > 0, THE Nth. NODE IS NOT AT x = L. A RUNNING WAVE TUNNELS THROUGH THE MIRROR WHOSE COATING IS A MULTIPLE OF 'PENETRATION DEPTH, Λ.' UP TO 12Λ IS NEEDED TO ACCOMPLISH THE R > 5-9's REFLECTANCE.



Relations on Resonance Curve (Fig. 1):

Exact or first order approximation:

$$\omega_0^2 - \omega_1^2 = \omega_1^2 - \omega_2^2 = \gamma^2/4$$

$\gamma \approx 2(\omega_\gamma - \omega_2)$	**half intensity width**
$N = 2L/\lambda$	**Number of nodes**
$Q \approx \omega_2/\gamma$	**Q-value**
$\mathcal{F} \approx \pi/(1-R)$	**Finesse**
$\mathcal{F} \approx Q/N$	**Finesse**

THIS SUPER-CAVITY DEMONSTRATES (Fig. 2):

o If Cavity Length L changes, $\omega_0 \dashrightarrow \omega_0'$ correspondingly.

o Some Standing Wave <--> Running Wave $\exp[j(kx - \omega_0' t)]$ which may penetrate the mirror and change cavity loss, $\gamma \dashrightarrow \gamma'$.

o New Peak Frequency $\omega_2 \dashrightarrow \omega_2'$ forms, (as $F[\omega_0', \gamma']$).

o Therefore, the Cavity will be detuned from the driver frequency ω_d. (It was at ω_2, now near ω_1').

Even without [growth], the driving frequency ω **can be so close to** ω_1 that for a slow decay rate (loss Δ small), they create a beat frequency which can persist over a long period in a decay.

$$\nu = (\omega - \omega_1)/2\pi \,. \tag{5}$$

Consequences:

o Beats modulate laser's carrier wave and create sidebands.
o A sideband in audio range disturbs detector with false signals.

B. Phase Factors.

Phase Factor Φ and Transmittance, T.

In Eq. (1-5), Δ **and** γ are both loss factors, linear to each other and a function of,

$$1 - R = T + A + S \qquad (6).$$

(i) A traditional but simplified formula for Fabry-Perot filter cavity is,

$$T = T_a T_b \,[\, 1 + \mathrm{Sin}^2\, (\Phi_1 + \Phi_2)\,] \qquad (7),$$ **where**

T: Transmission loss of F-P cavity,
T_a, T_b : standing wave tarnsmittance by end mirror set (a,b),
Φ_1:due to running wave leaked through the mirror set,
Φ_2:due to absorption/scattering of the mirror set.

In particular,
o Add AC/Random signals to the loss factors [Δ and γ]
o Affect the resonance amplitudes through [Δ and γ]

(ii) As another check, time average of the random phase ϕ_α of a given transmission amplitude Δ_α should obey,

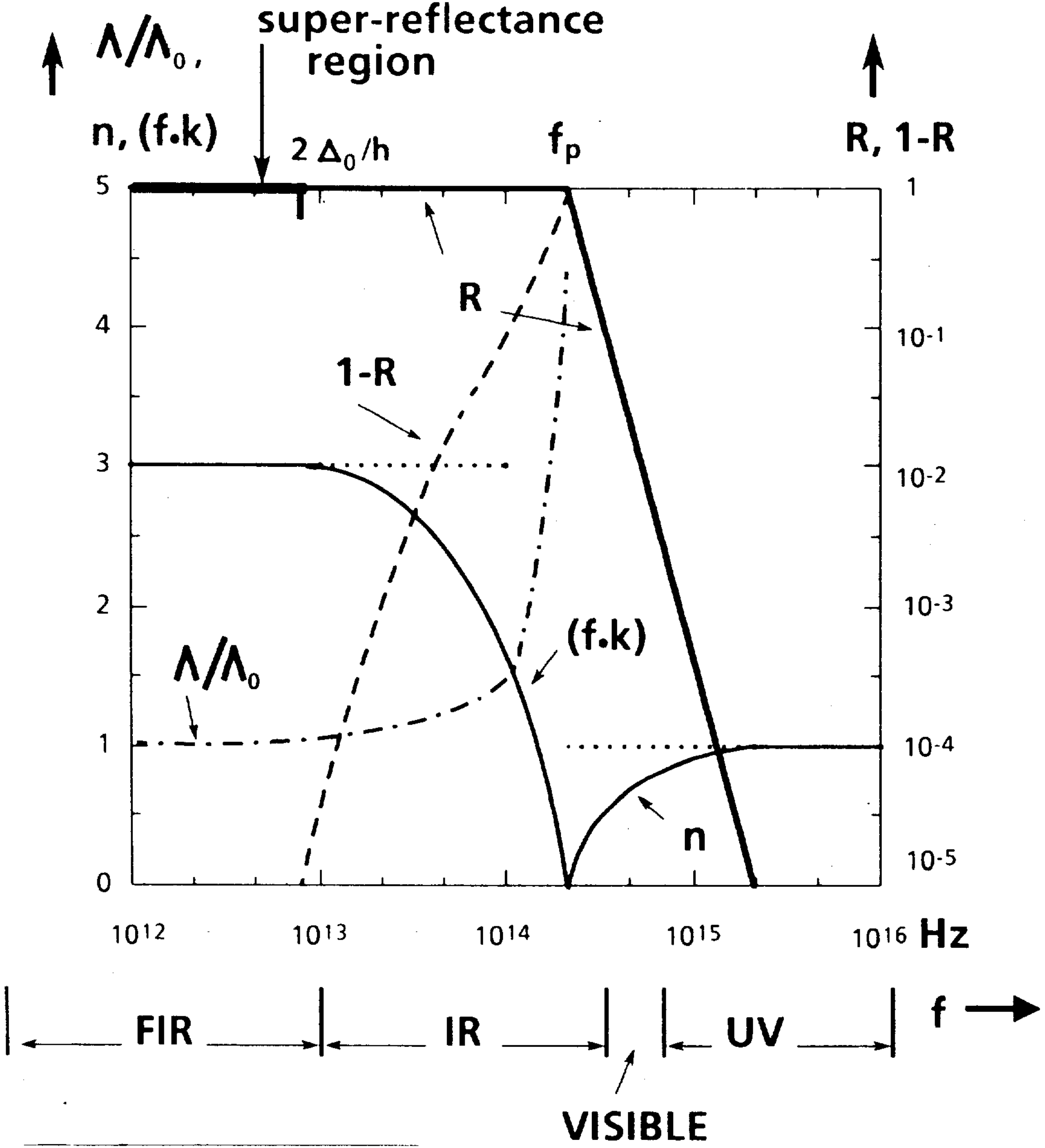
$$\begin{aligned} \Delta_{total}^2 &= \Sigma_n(\Delta_\alpha)^2 \\ &= \Delta_\alpha^2\, \{\Sigma_n[\mathrm{Cos}^2\phi_\alpha + 2\mathrm{Cos}\phi_\alpha \mathrm{Sin}\phi_\alpha + \mathrm{Sin}^2\phi_\alpha]\}_{time\text{-}ave} \\ &= n\, \Delta_\alpha^2 \qquad (6). \end{aligned}$$

This is similar to the experience that the sound volume of a string section in an orchestra is proportional to number of violins.

(iii) The non-zero phase factors modify cavity loss and create sidebands through AM, FM and ΦM.

WHY SUPERCONDUCTOR COATING?

- o Advocates to use cryogenic cooling for mirrors
- o Preliminary study/data (1988) showed promises[1,2,3]
- o Single layer coating: cost effective and easy to maintain
- o Requirements, development timing conformed to LISA.



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[1] G. A. Thomas et al., "Ba$_2$YCu$_3$O$_{7-\delta}$: Electrodymics of Crystals with High Reflectivity," Phys. Rev. Lett. 61, 1313-1317 (1988)

[2] D. T. Wei, "High Tc Superconductor Coating: Superreflectance and Surface Waves," Applied Optics, 28, 2728-2722 (1989), and those quoted therein:

[3] D. T. Wei, "Searching for Superreflectance in a Superconductive Mirror Coating," paper PDL-5, 4th. topic. mtg. in OIC (1988); ibid, Symposium Optics and High-Tc superconductors, paper TuJ7 (1988).

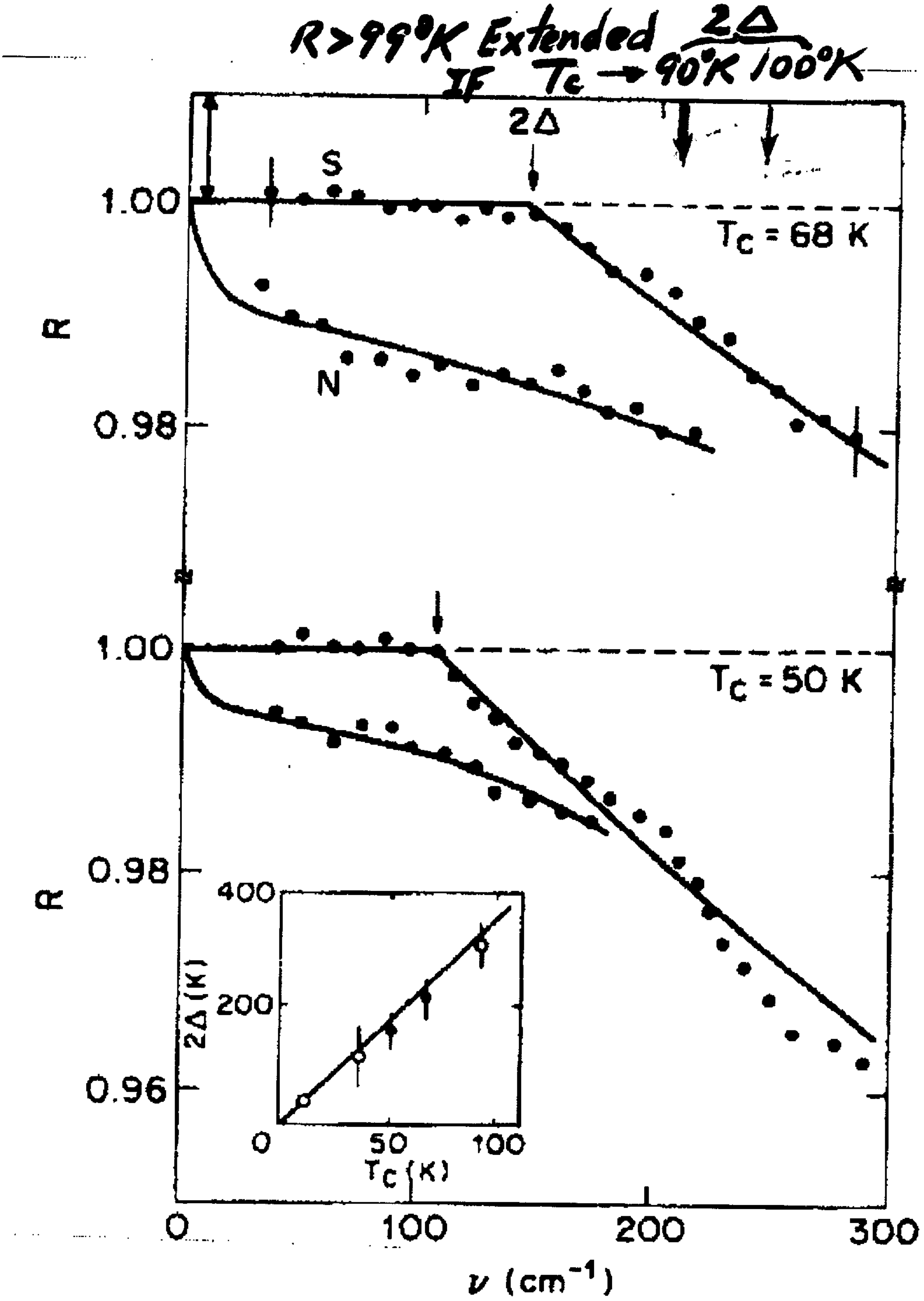

Fig. 5. “Reflectance on an expanded scale for two samples of $Ba_2YCu_3O_{7-\delta}$ with Tc values as labeled.” From G. Thomas et al. (Ref. 1).

The two samples shown in Fig. 6 have reduced oxygen content δ. Wave number (ν) is used in horizontal scale ($\nu = 1/\lambda$ or $\omega/2\pi c$). The figure inset is a plot of energy gap 2Δ vs. T_c for a group of ceramic material, from which BCS's prediction is verified:

$$2\Delta = C\, k_b T_c, \quad C = 3.5 \; ; \tag{7}$$

Handwritten remarks on top right corner indicate that if superreflectance could be secured at 90°K to 100°K, then the energy gap could be at λ = **46 μm, to 41 μm.**

Wei's reasoning was from Meissner effect: that a coomplete exclusion of magnetic field at very high frequency should be a total reflectance of radiation. Also, from another version of prediction, if C = 7.7 is allowed for some superconductor, 2Δ could correspond 20.8 μm at 90°K to 18.7 μm at 100°K.

Apart from the high reflectance in the FIR region, there are some very attractive features about considering superconductor mirror as a future candidate for LISA, or even for LIGO.

o According to J. Bennett et al., scattering magnitude reduces quickly with λ as:

$$S = (4\pi\sigma/\lambda)^2 \tag{8}$$

where σ is rms. surface roughness. This means 3 to 4 orders of reduction in scattering.

o At temperature <100°K, acoustic phonons are quenched, thus thermal noise are greatly reduced.

o Superconductor mirrors need a single layer coating only. There is a big saving in cost and convenience en mass.

o Superreflectance detectors will go hand in hand with superconducting electronics. This will further reduce the noise and cost of LISA and LIGO experiments.

o As part of a quantum detector, the lower the ratio ω/E the better the accuracy $\Delta x/x$, -- non-demolition uncertainty theory.

-- A REALITY CHECK --
LOSS: SCATTERING & ABSORPTION

A. Scattering

1. Individual Scatterers
   - o Debris, Oil Drops, Aerosols
   - o Charge Damage:
     - -- By neutralizing the beam ions and by good grounding of target, pittings in dielectric layers were eliminated.
     - -- Note: other types of sputtering still have pittings.
   - o Continuum back-scattering:
     - -- Microstructure which form a continuous scattering background are eliminated.
     - -- As a result Rayleigh (back) scattering is solved.

2. History:
   - o Aronowitz's foresight (circa 1970): ring-laser-gyro's lock-in is due to the back-scattering of laser light by mirrors. Reducing backscatter to 10 ppm loss of forward laser light will make laser-gyro take off.
   - o Observations (Wei @ Litton, circa 1975): a background of blue haze is due to the same origin as why the sky is blue (Rayleigh). Thus, to achieve amorphism became our first priority.

3. Interface & rms. roughness.
   - o Substrate (J. Bennett, China Lake, circa 1988). 'When substrates are not smooth enough, all the other roughness will add on to it.' Super-polishing technique follows (Livermore).
   - o Study of high index layer (NCU, Taiwan, to be shown next). The morphology of a hard metal oxide layer is the

cause of interface scattering. Post-baking and neutralized ion beam bombardment are the best cure.

B. Absorption.

1. Absorption sources are listed in the order of significance below:
   - Deficiency in oxide or nitride (off-stoichiometry)
   - Impurity centers and micro-voids
   - Organic contamination, on the surface or entrapped
   - Point defects and Interstitial flaws.
2. Measurement.
   - Photothermal Deflection Method. LIGO has used it so far.

C. Inelastic (Raman) Scattering.

- Defects above, etc., will scatter light which shifts in optical frequency, either down or up. Stimulated emissions possible.
- The missing energy may not be detectable thermally
- Raman spectroscopy is one of the best method for detection, in coating as well as in substrate
- Roman scattering in optical fibers have been studied.

Stress and Strain in Mirror Coatings

A. Stress.

o A mirror is not a surface. It has a coating on a substrate.

o A cavity mirror has a curved surface to contain EM radiation.

o The coating has a finite thickness ranging from 1 to 100 μm.

o A stress radially traversing a coating bends the mirror surface.

o A change in mirror CURVATURE causes extra loss in cavity. (see Illustration.2a).

o Nature of Stresses shows 2 origins.
Either it is built inside coating as deposited. (see Illustration 2b).

o Or, it is external from environmental change (see Table 1).

TABLE 1
TYPES OF EXTERNAL STRESSES ON MIRROR COATINGS
(assuming α,γ are linear coefficients.;)

Type of Stress, S	From	to	$\Delta\ell$ @ℓ=1 μm	Remark
Thermal Stress	Rm. temp.	Cryogenic	$\alpha.10^{-10}$m.	@ $\Delta T=100^{O}$K
Vacuum Pressure	Atm.	$\gamma.1.33$ μtorr	10^{-20} m.	@$Y=\gamma.10^{-11}$nwt/m^2
Radiation Pressure	None	$\gamma.10^{-6}$ newt/m^2	10^{-20} m.	@Y; $u=10^{-6}$joul/m^3

Symbols: **S** stress; **Y**: Young's modulus; α: material parameter in thermal coefficient;
γ: material parameter in Young's modulus (e.g., for (100) silicon crystal γ = 1.30);
ℓ: thickness of coating; **$\Delta\ell$**: deformation in thickness of coating; **u**: radiation energy.

o Internal stress measurement formula (for a single film on a thin substrate, see Illustration 2c).[1]

$$S = YD^2/[6(1 - \eta)R\ell] \qquad (9)$$

Symbols: **S**: stress in newt/m^2; **Y**: Young's modulus of substrate; **D**: thickness of substrate;
η: Poisson ratio; **R**: radius of curvature induced by stress; **ℓ**: coated film thickness.

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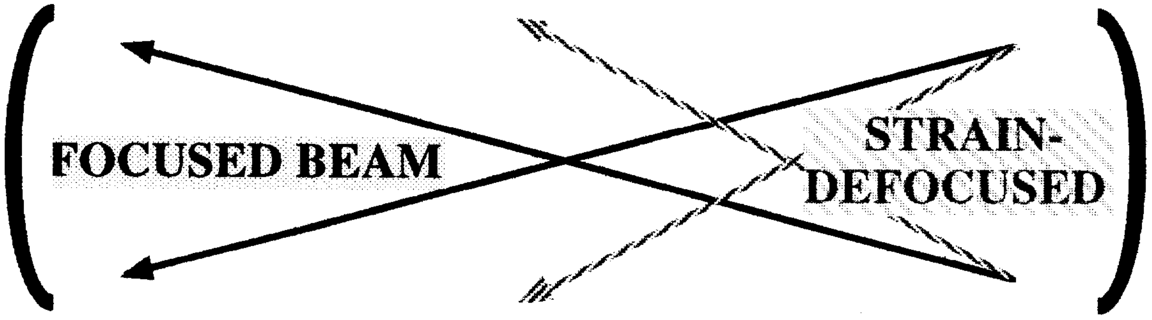
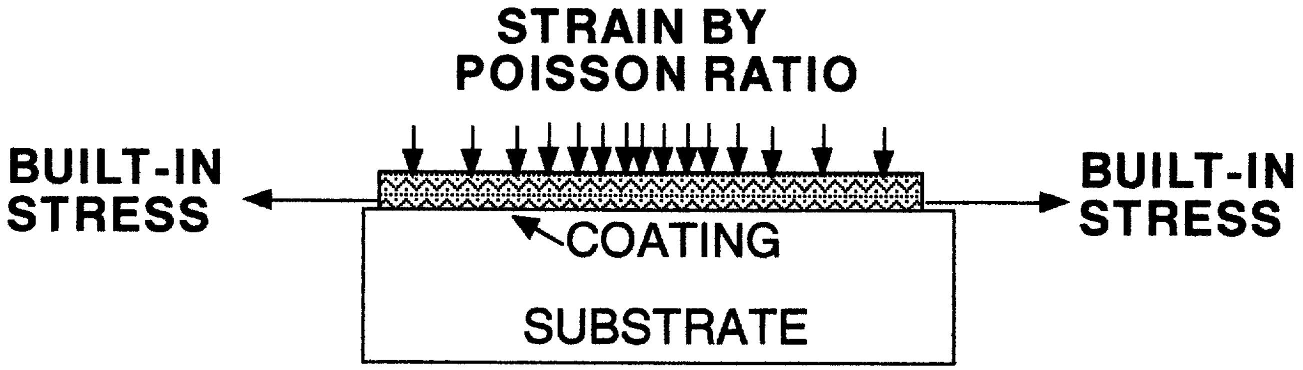
[1] R. Castellanmo et al., 'Composition and stress state of thin films by IBS.' Vacuum, 27, p.109 (1976)

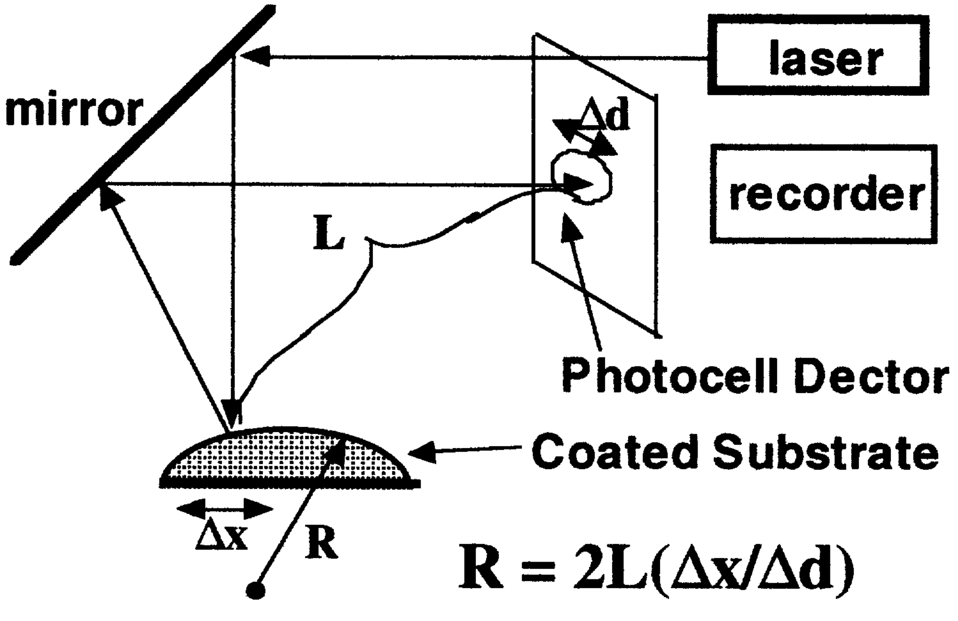
ILLUSTRATION 2



(a) CURVATURE DETUNING



(b) BUILT-IN STRESS INDUCED STRAIN



(c) SCHEMATICS: CURVATURE MEASUREMENT

TYPES OF PENETRATION DEPTHS.

1. FOR PERFECT STANDING WAVES (& MOST PAPERS FROM 3rd. AMALDI CONFERENCE)

$\Lambda = 0$ **IS ASSUMED.**

2. FOR TOTAL INTERNAL REFLECTION (e. g., FIBER OPTICS)

$\Lambda = (\lambda/2\pi)/\sqrt{[(\mathrm{Sin}\theta/\mathrm{Sin}\theta_C)^2 - 1]}$,

$\theta > \theta_C$, θ_C: **CRITICAL ANGLE.**

3. FOR SUPERCONDUCTOR (TYPE II) ,

$\Lambda = \mathbf{c}/\sqrt{[\omega_{\mathbf{p}}{}^2 - \omega^2]}$,

$\omega_{\mathbf{p}} = \sqrt{[\mathbf{e^2 n_e/m_e}]}$, $\omega_{\mathbf{p}}$ **: PLASMA FREQUENCY**

4. FOR CONDUCTOR (METAL) ,

$\Lambda = \sqrt{[2/\mu\omega\sigma]}$, σ: **CONDUCTIVITY.**

5. For OPTICAL INTERFERENCE COATING (OIC)

$\Lambda \approx \mathbf{P}(\lambda/4)$, **P: # PAIRS OF H/L REFRACTIVE INDEX.**

Structure of a High Reflectance Optical Interference Coating (Such as a Super Mirror)

Reflectance Calculation Program Made Easy:

Step 1: $M = [n_H / n_L]^{2(p+1)}$

Step 2: $R = [(M - 1) / (M + 1)]^2$

Step 3: $T = 1 - R$

Exercise:

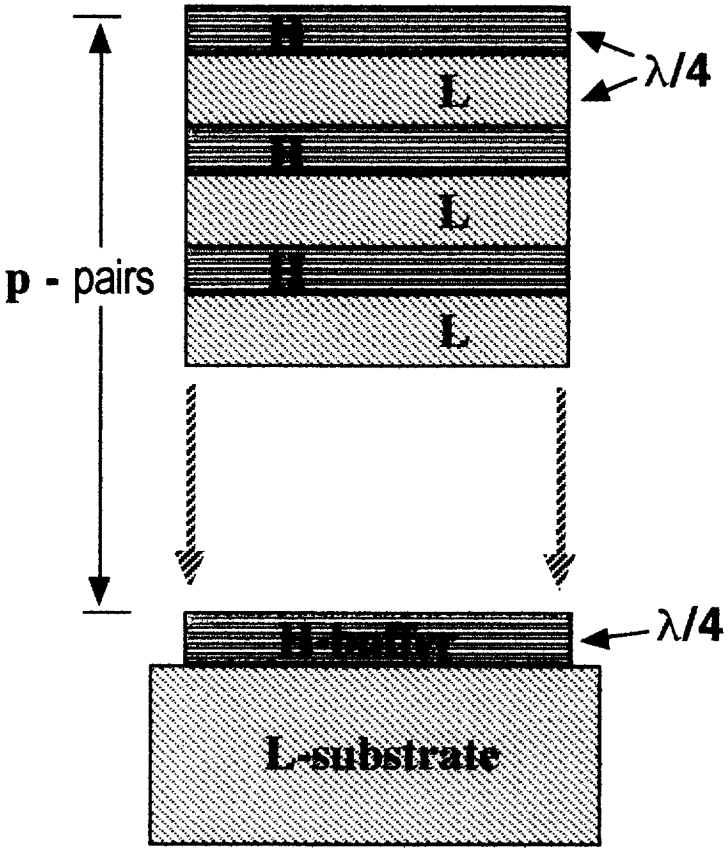
$n_H = 2.2$

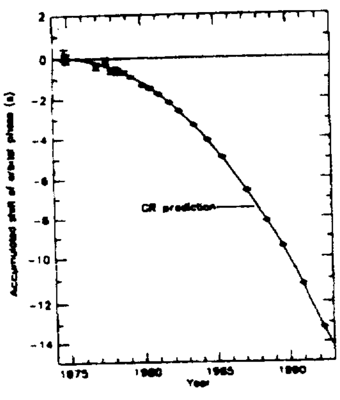
$n_L = 1.46$

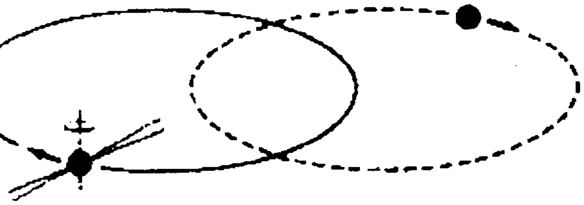
$p = 30$

To Find: **R, T**

Always a good approximation







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is forties, b
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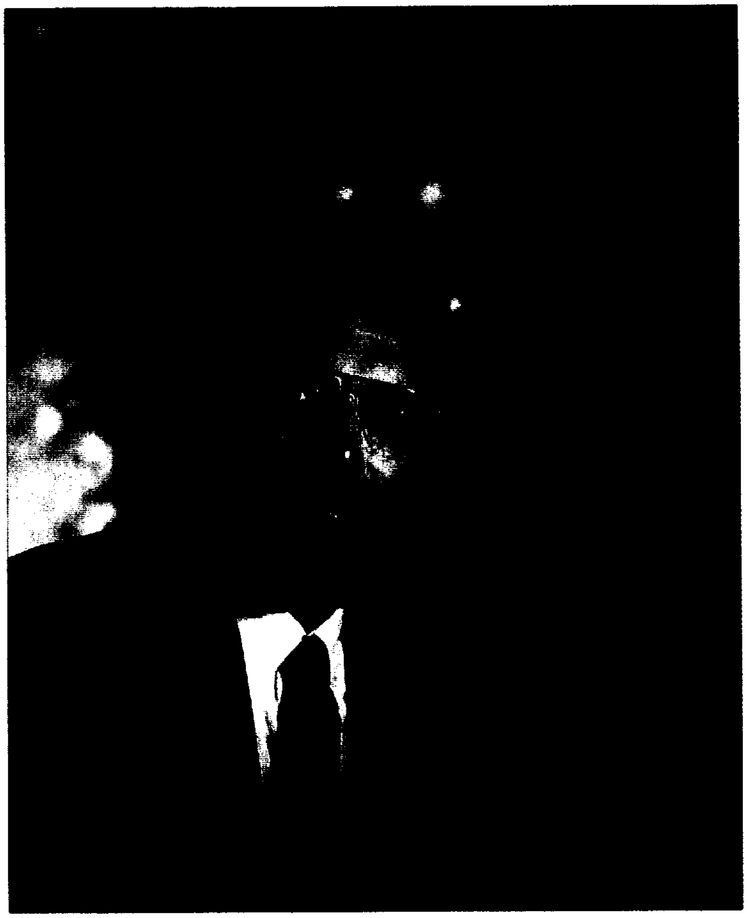
ngs about wi
v many people it's made
ppy," he says.
His family's support was a
ch appreciated lifeline
en Hulse entered el-
entary school and met
chers who did not smile
his love of science. "I had
d of a rough time," he
, "or my parents had a
gher time when I was in
mentary school, because
re were some teachers
re who just didn't under-
nd this perhaps compul-
fascination with science
l were not supportive of
There were some teach-
who far from encourag-
me in my passion, tried
discourage me. In fact, I
forbidden to read sci-
ce books for a couple of
nths. It wasn't consid-
d healthy in some sense.
as just weird.
'There were some teach-
who were very supportive and I
ued them a lot, but there were
er ones who just thought it was
rd. I was too narrow. I would end
socially warped somehow if I be-
ne too focused on science. I think
a very big problem how science is
t of excluded and viewed as some
ange thing that is somehow not
te normal.
'Back when I was growing up, that
s the post-Sputnik era and science
minally had a very positive place
American society. There were
ows on TV like 'Our Friend the
om' and 'Mr. Wizard' and there



JOSEPH TAYLOR *(left), co-recipient of the*

find all the
igement he
geoning interest
ed to a desire to
elescope, he
e project as a
ar activity. Mom
here for him
g a location for
e of upstate New
now the site of
their retirement home.

"The clearest personal expressions of my interest in science were through the things I did myself outside of school," Hulse says. "Going to school was important and sometimes interesting, but it was sort of a separate activity, sort of a *job.* And that was in some ways true until I did my thesis at UMass, because that was the first time when doing science, what I wanted to do, was actually now my job. They finally came together."

THE FIRST PULSARS were discovered in 1967, just a few years before Hulse arrived at UMass to commence his graduate studies. Astronomers had identified about 100 pulsars by the time Hulse decided to make these intriguing objects the topic of his Ph.D. dissertation. The thesis project Hulse and Taylor designed involved a new computerized technique for searching out pulsars and separating their rhythmic signals from all the rest of the energy emissions that crowd the sky.

Early in his graduate student career, Hulse helped to build an array of radio telescopes at the Quabbin Reservoir site where the dome of the Five College Radio Astronomy Observatory now stands. He used that local equipment for some preliminary work on his pulsar search, but

Note 1, Linda Turner, 11/30/99 10:04:06 AM

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