High finesse optical cavities

R. Martin, G. Mueller, and D.B. Tanner
University of Florida

Margot Phelps, Liyuan Zhang, G. Billingsley and D. Reitze
Caltech

References

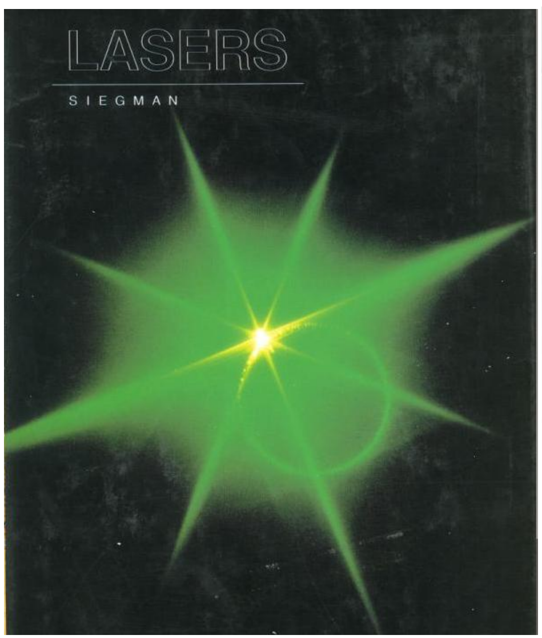
Laser Beams and Resonators

H. KOGELNIK AND T. LI

Abstract—This paper is a review of the theory of laser beams and resonators. It is meant to be tutorial in nature and useful in scope. No attempt is made to be exhaustive in the treatment. Rather, emphasis is placed on formulations and derivations which lead to basic understanding and on results which bear practical significance.

Manuscript received July 12, 1966.
H. Kogelnik is with Bell Telephone Laboratories, Inc., Murray Hill, N. J.
T. Li is with Bell Telephone Laboratories, Inc., Holmdel, N. J.

1550 APPLIED OPTICS / Vol. 5, No. 10 / October 1966



LASERS

Anthony E. Siegman
STANFORD UNIVERSITY

Lasers by A.E. Siegman is both a textbook and general reference book on lasers, with an emphasis on basic laser principles and laser theory. It brings together into a unified and carefully laid out exposition all the fundamental and important physical principles and properties of laser devices, including both the atomic physics of laser materials and the optical physics and practical performance of laser devices. A unique feature of this book is that it gives a complete, detailed, and accurate treatment of laser physics, building only on classical models, without requiring a quantum mechanical background of the reader.

http://en.wikipedia.org/wiki/Gaussian_beam


WIKIPEDIA
The Free Encyclopedia

navigation
- Main page
- Contents
- Featured content
- Current events
- Random article

search

Go Search

interaction
- About Wikipedia
- Community portal
- Recent changes
- Contact Wikipedia
- Donate to Wikipedia
- Help

toolbox
- What links here
- Related changes
- Upload file
- Special pages
- Printable version
- Permanent link
- Cite this page

languages
- Български
- Deutsch
- Français
- Italiano
- Lietuvių

article

Gaussian beam

From Wikipedia, the free encyclopedia

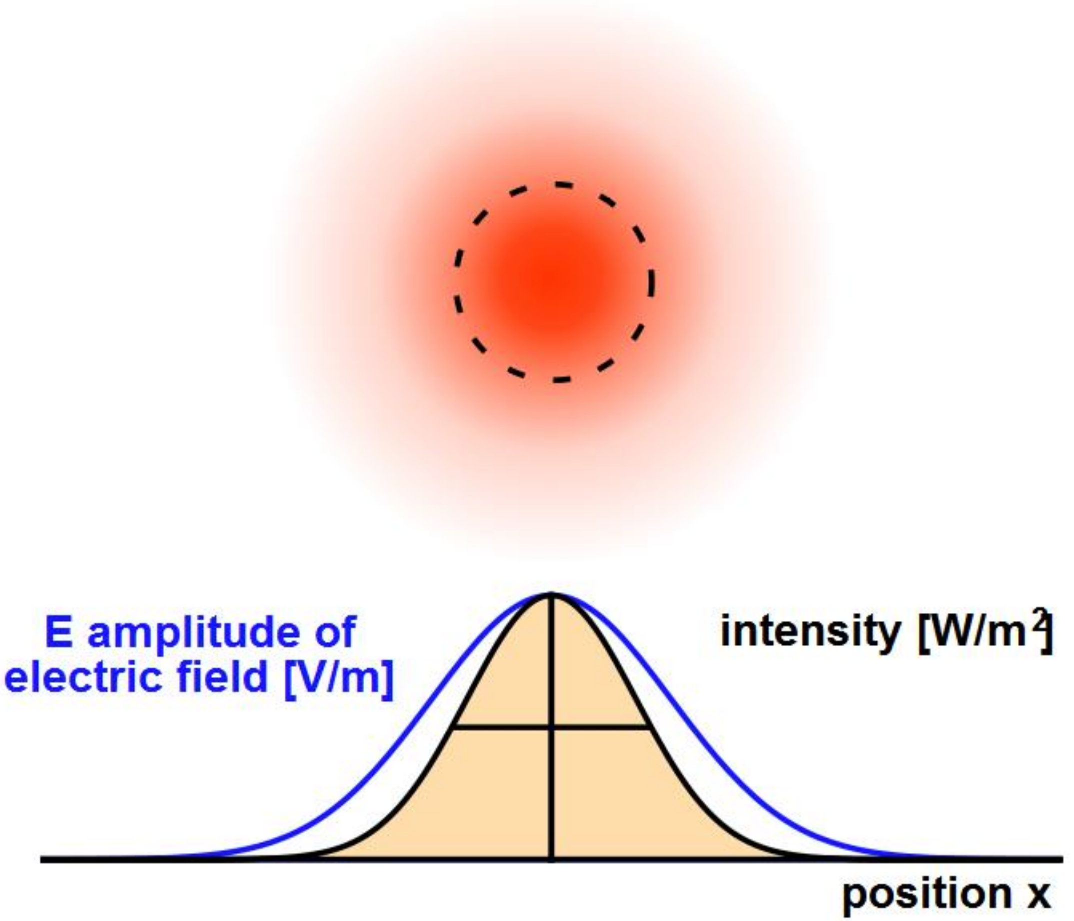
In optics, a **Gaussian beam** is a beam of electromagnetic radiation whos
which case the laser is said to be operating on the *fundamental transvers*
(characterized by a different set of parameters), which explains why it is

The mathematical function that describes the Gaussian beam is a solutic
represents the complex amplitude of the electric field, which propagates

Contents [hide]

Cavity parameters

- Gaussian beams
- Strawman parameters
- Items governing finesse
- Items governing length



Paraxial approximation

A gaussian beam is described in the *paraxial* approximation ($\sin\theta = \theta$) by

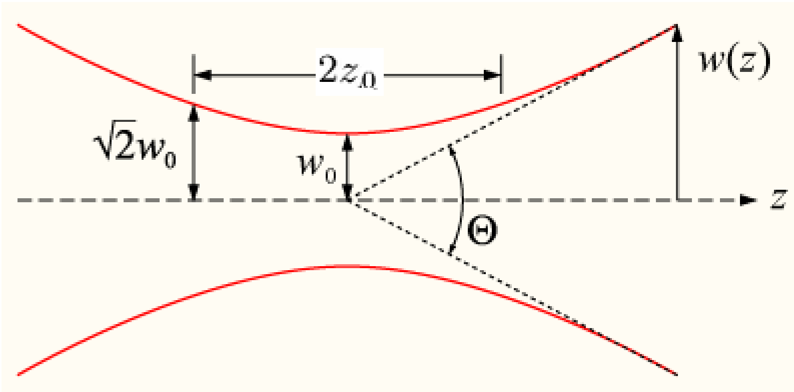
$$E(\rho, z) = A\frac{w_0}{w(z)}\, e^{ikz}\, e^{-\tan^{-1}(z/z_0)}\, e^{ik\rho^2/2R(z)}\, e^{-\rho^2/w^2(z)}$$

where w_0 is the beam waist dimension (a *radius*) and

$$z_0 = \frac{\pi w_0^2}{\lambda}$$

is the Rayleigh range. The beam is $\sqrt{2}$ bigger at $z = z_0$ from the waist. The beam has a "diameter" of $2w(z)$, with

$$w^2(z) = w_0^2\left[1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2\right] = w_0^2\left[1 + \left(\frac{z}{z_0}\right)^2\right]$$



the beam "size," and a curvature

$$R(z) = z\left[1 + \left(\frac{\pi w_0^2}{\lambda z}\right)^2\right] = z + \frac{z_0^2}{z}.$$

Finally,

$$\theta = \frac{\lambda}{\pi w_0}$$

is the beam divergance angle.

Intensities

At the waist, $z = 0$, $w = w_0$, $R = \infty$, and

$$E = Ae^{-\rho^2/w_0^2}$$

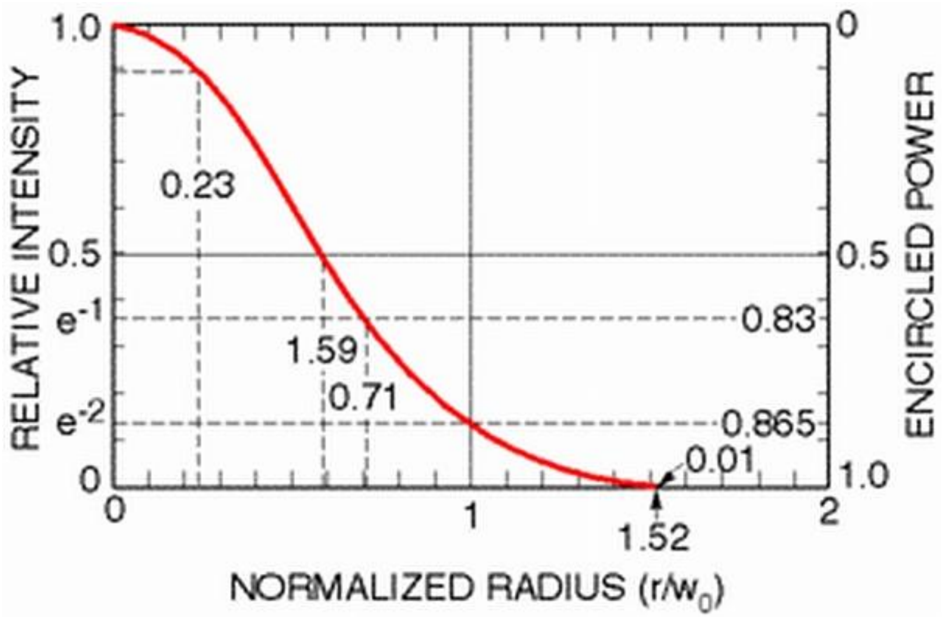
The intensity $\propto E^2$, so

$$I = I_0 e^{-2\rho^2/w_0^2}$$

and the power enclosed by a circle of diameter D is

$$P(D) = P_0 \left[1 - e^{-D^2/2w_0^2}\right]$$

with P_0 the total power of the beam.



Cavities

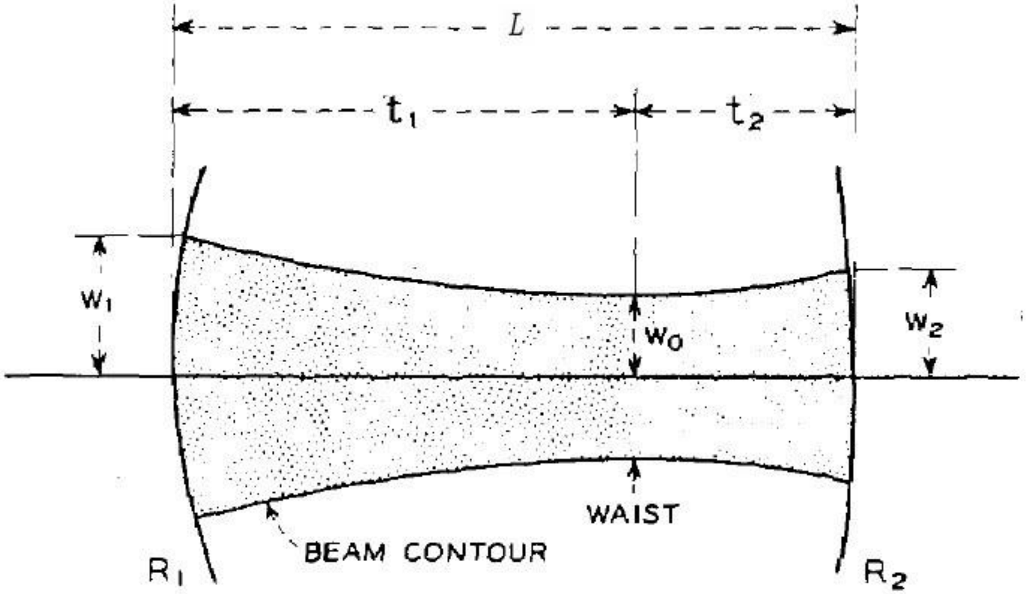
How do we find the waist? Set up a cavity, with curved mirrors of radii R_1 and R_2 and with a distance L between them. The resonant beam will have radii of curvature of R_i at each mirror, and a waist between them. For us, with curve/flat, $R_1 = R$ and $R_2 = \infty$. Then,

$$g = 1 - \frac{L}{R}$$

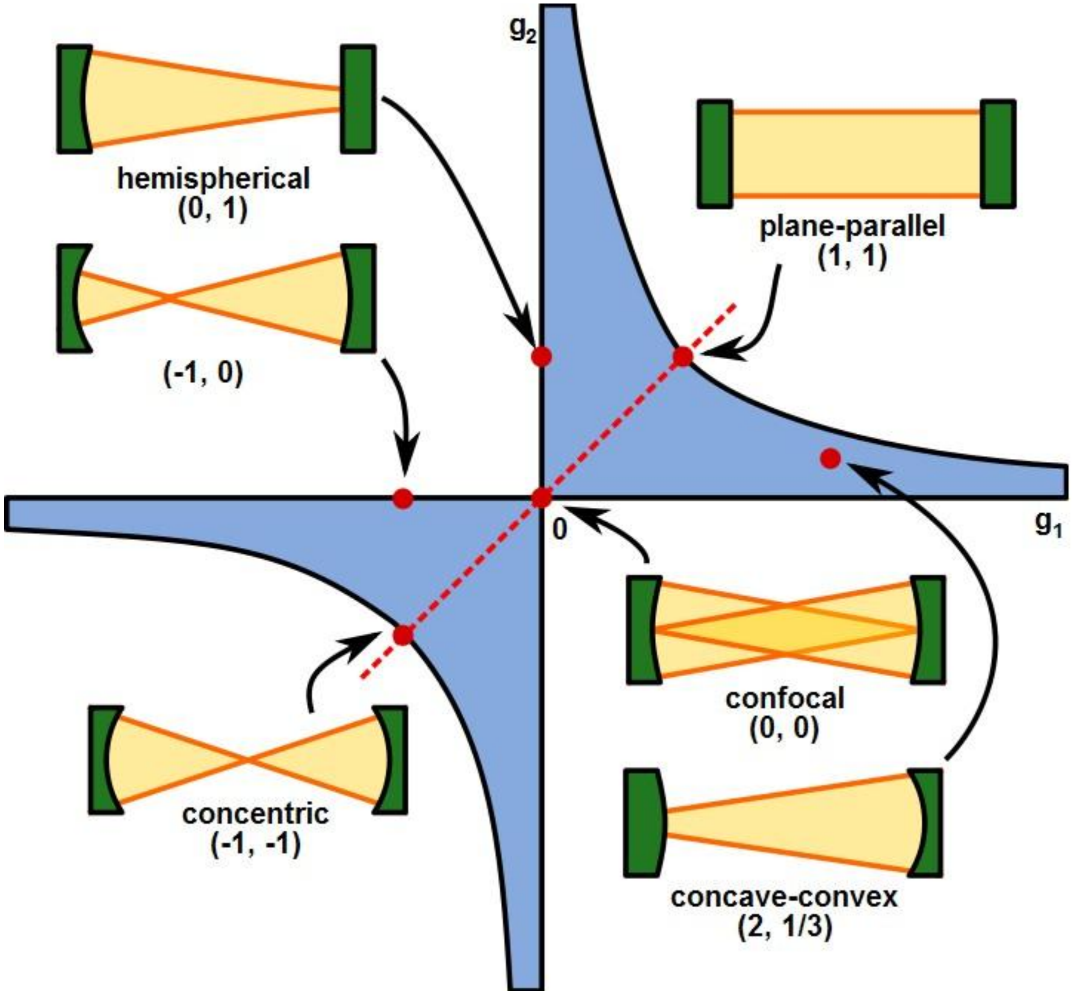
and

$$w_o^2 = \frac{\lambda L}{\pi}\sqrt{\frac{g}{1-g}}$$

$g(= g_1 g_2)$ is called the stability product. We have $g_2 = 1$. Want $0 < |g| < 1$.



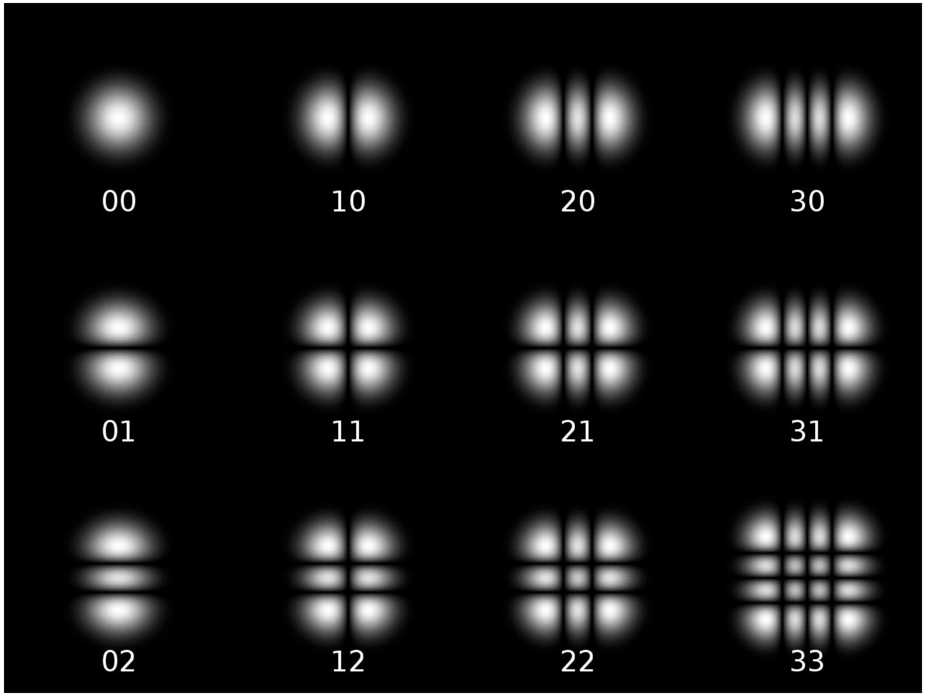
Stability

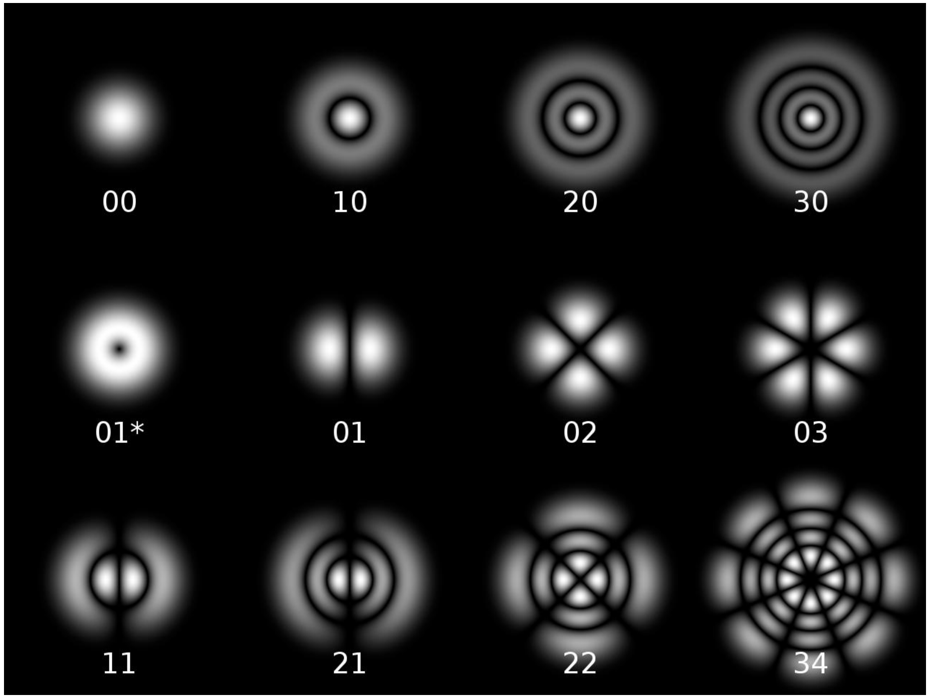


g_2
hemispherical
(0, 1)
(-1, 0)
plane-parallel
(1, 1)
0
g_1
confocal
(0, 0)
concentric
(-1, -1)
concave-convex
(2, 1/3)

Cavities have an infinite set of modes

- Hermite Gauss (r) or Laguerre Gauss (l)





Finesse and free spectral range

- Finesse is like *Q* of a metal cavity
- Effectively, it is the number of bounces a beam makes before leaking out or being absorbed.

$$\mathcal{F} = \frac{4\pi T_1}{(T_1 + V)^2}$$

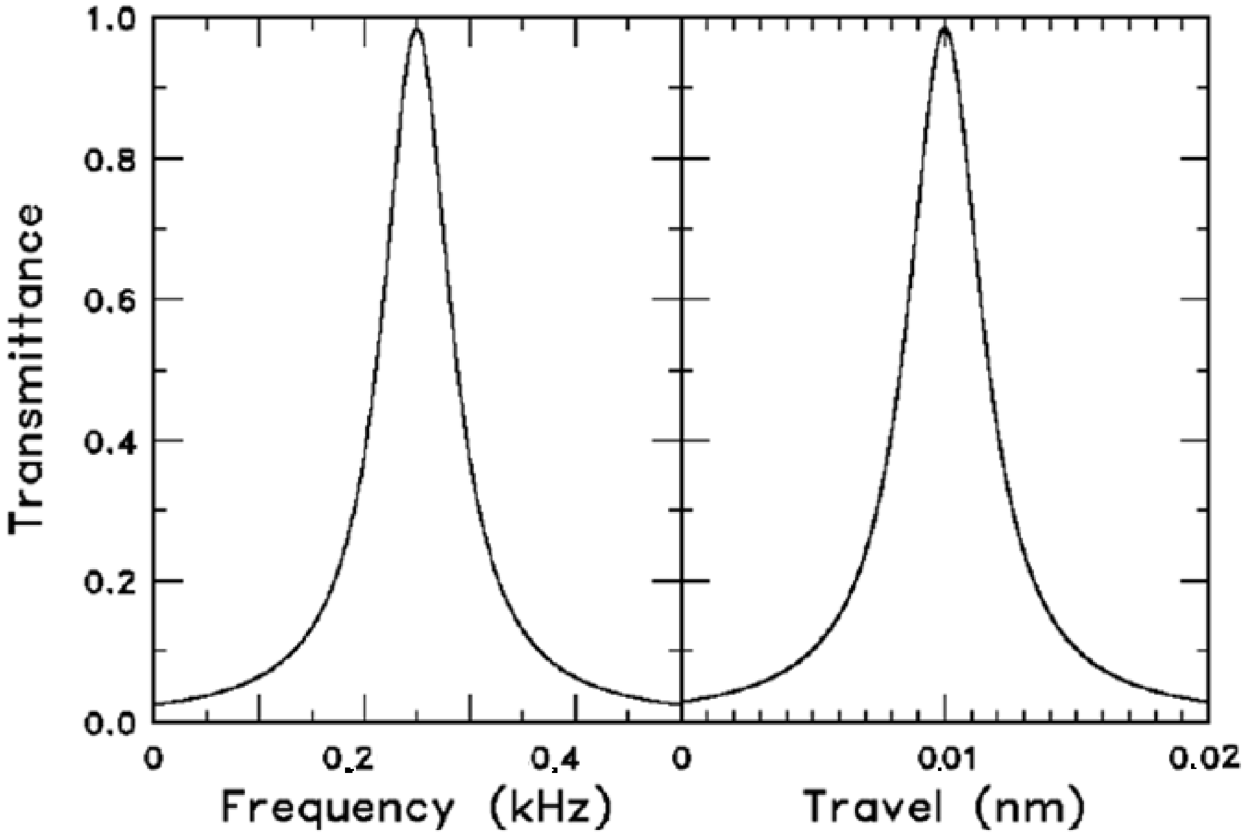
- with T_1 the transmission of the input mirror (assumed to be larger than that of the end mirror) and *V* the round-trip fractional power loss from power absorption in both mirrors, scattering due to mirror defects, diffraction from the finite mirror size, etc.
- FSR:

$$FSR = \frac{c}{2L}$$

- Finesse is equal to FSR divided by the FWHM of the resonance.

Cavity with Finesse = 100,000

- Cavity transmission as function of frequency (left) or motion of one mirror (right)
- Cavity is 12 m in length, with modes at 12 MHz (=FSR)

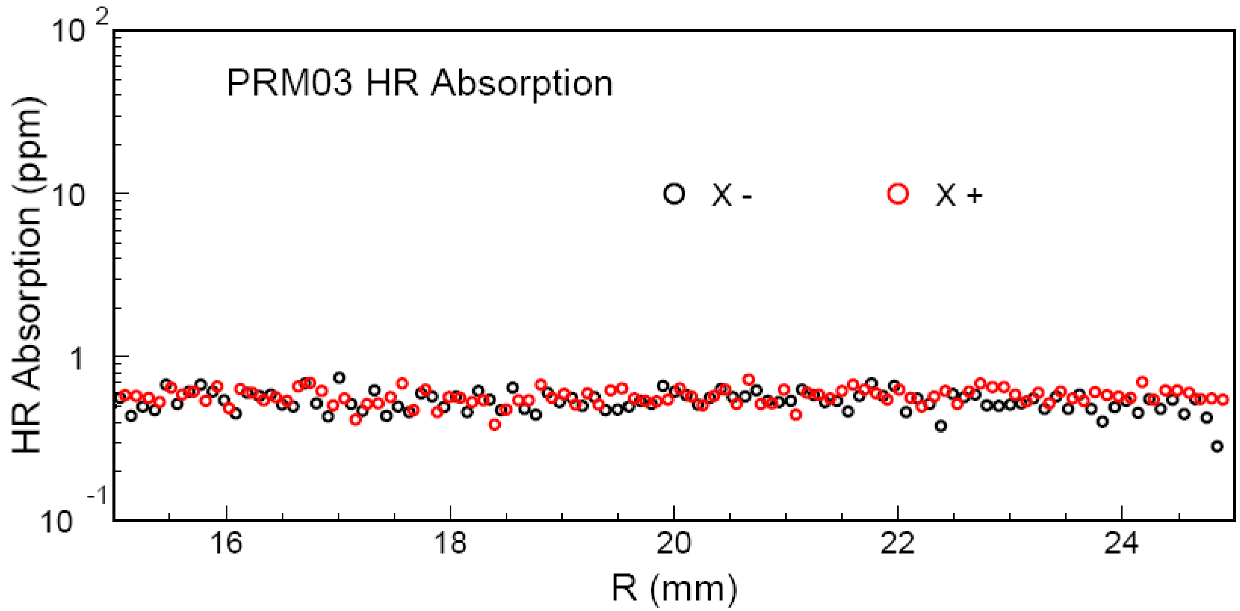


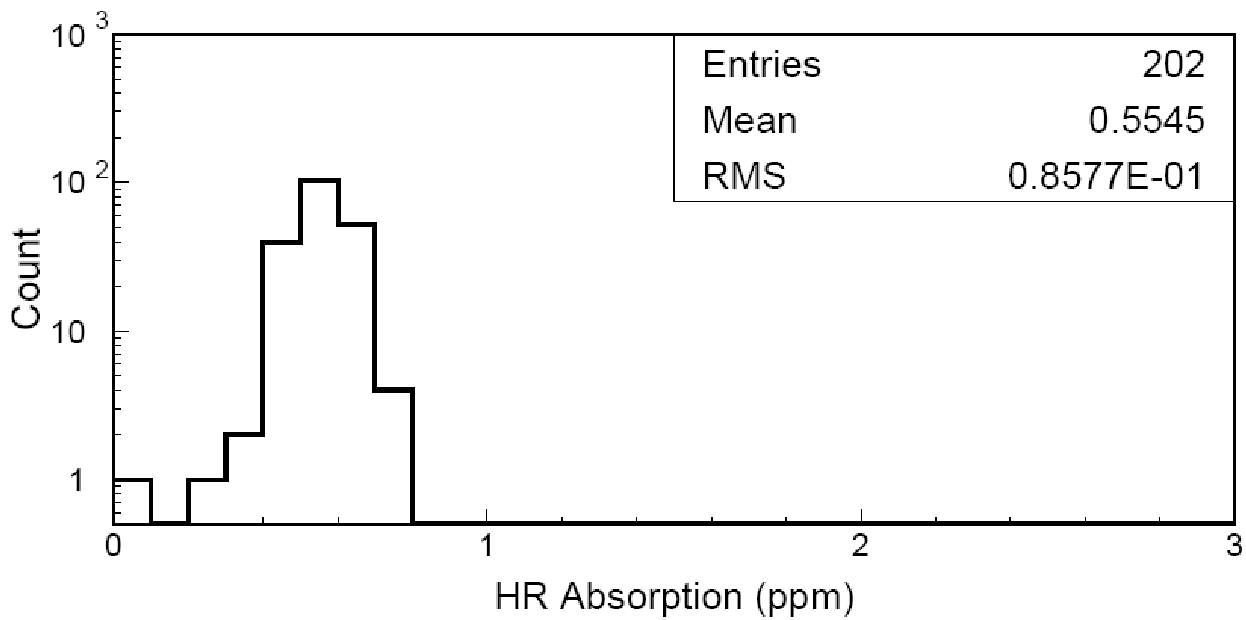
Factors controlling finesse

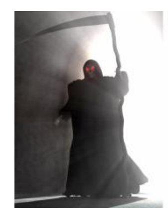
- Loss
- Scatter
- Microroughness
- Coating nonuniformity

- Ultimately, transmission of input mirrors

Loss


PRM03 HR Absorption
X -
X +
HR Absorption (ppm)
R (mm)
10^2
10
1
10^{-1}
16
18
20
22
24


Entries 202
Mean 0.5545
RMS 0.8577E-01
Count
HR Absorption (ppm)
10^3
10^2
10
1
0
1
2
3

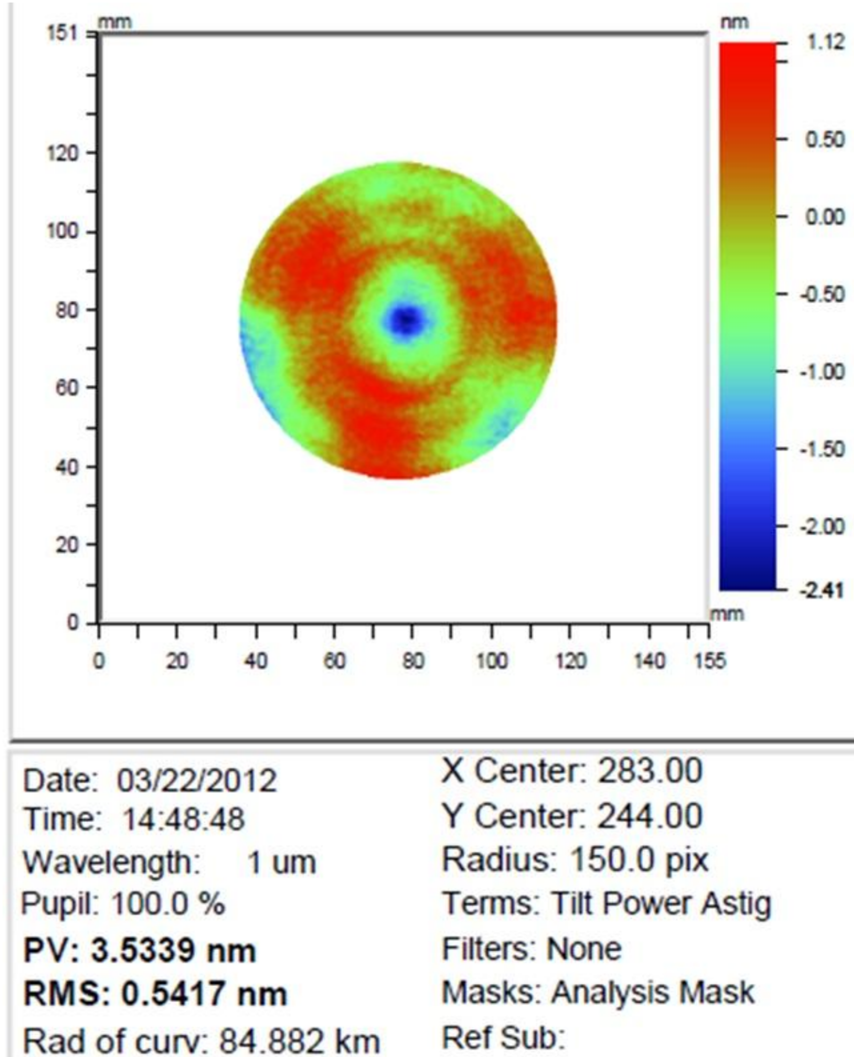


Scatter

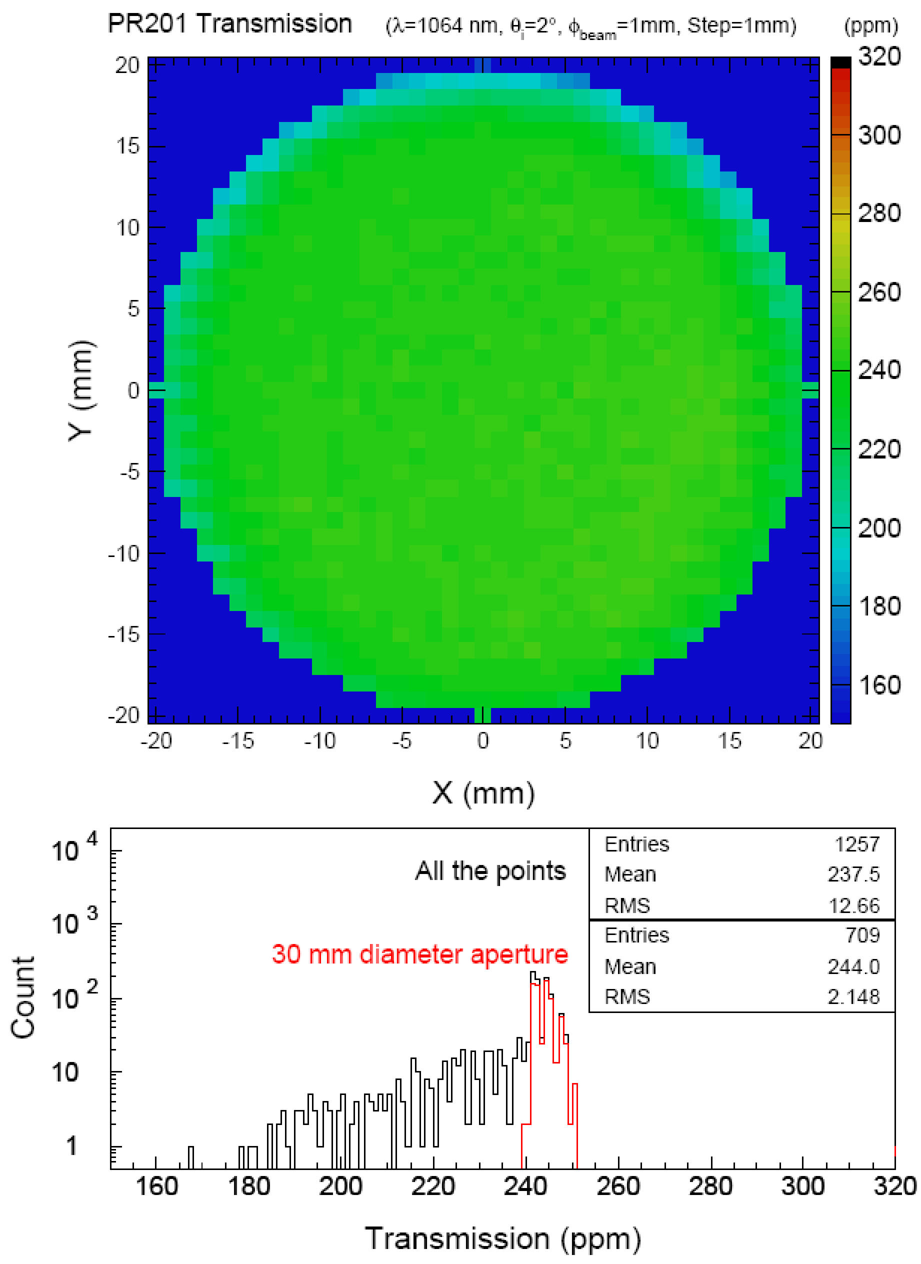
- Determined by dust particulates on surface, as well as by defects from polishing
- Scatter from 100 particles of 10 μ diameter already dominates the loss budget
- Cleanliness!

Microroughness

- Low-angle scatter
- Rms ~ 0.5 nm
- “superpolish”

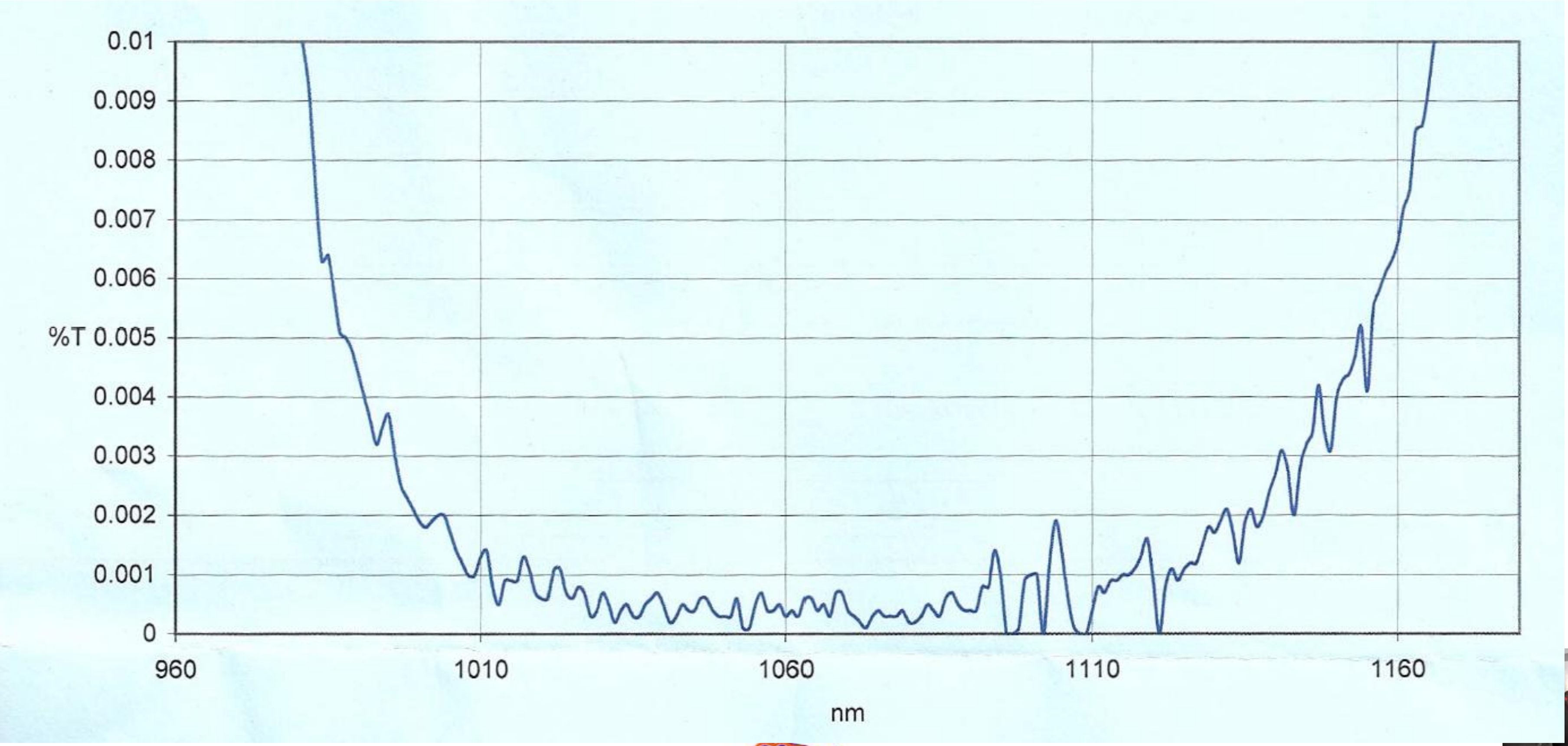


Coating nonuniformity



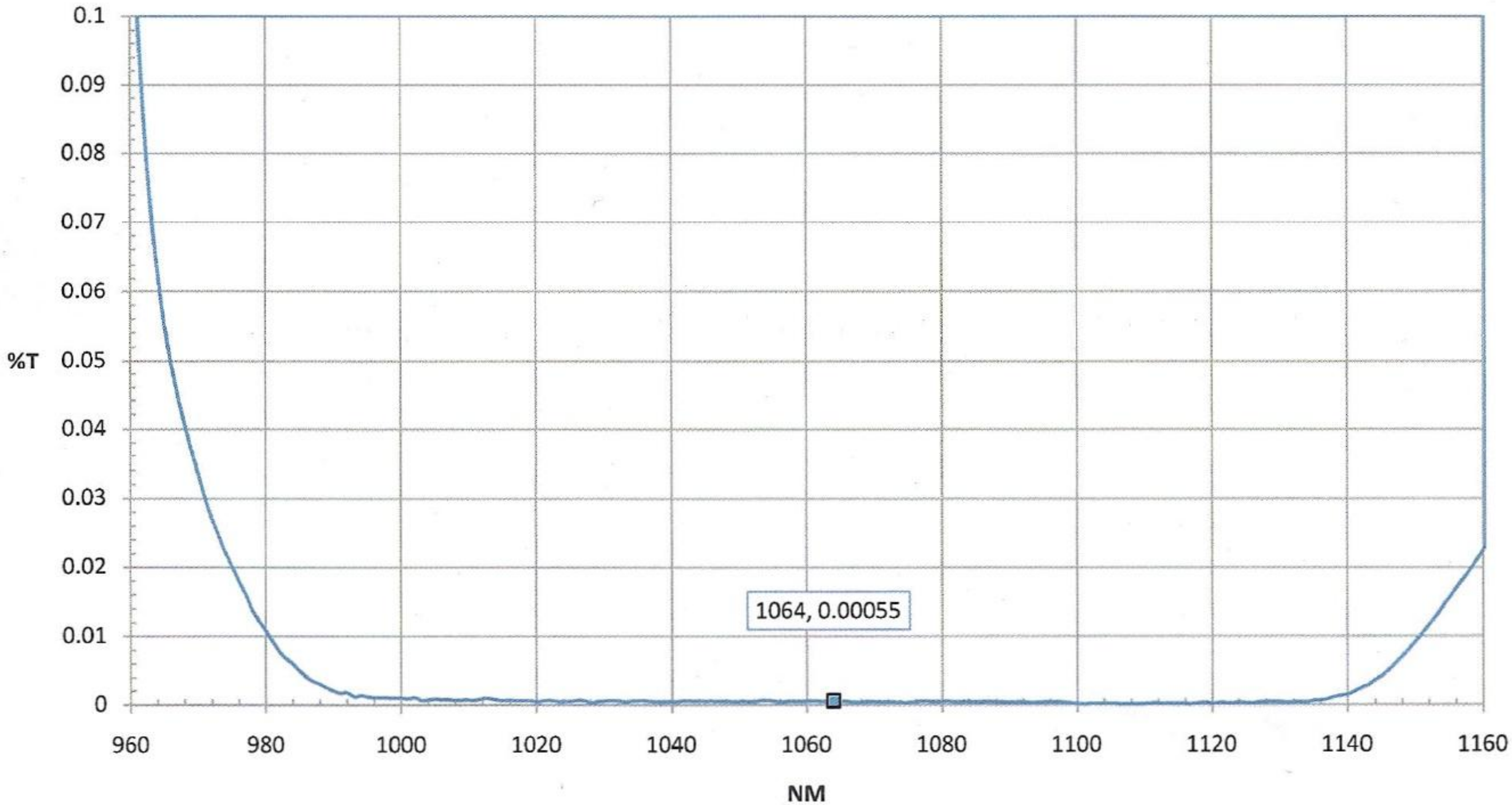
Transmission

- At 1064 nm, T ~ 3 ppm
- Finesse ~ 2 million (ignoring scattering, which you cannot do)



Transmission 2

- At 1064 nm, T ~ 5.5 ppm
- Finesse ~ 1 million (ignoring scattering, which you cannot do)



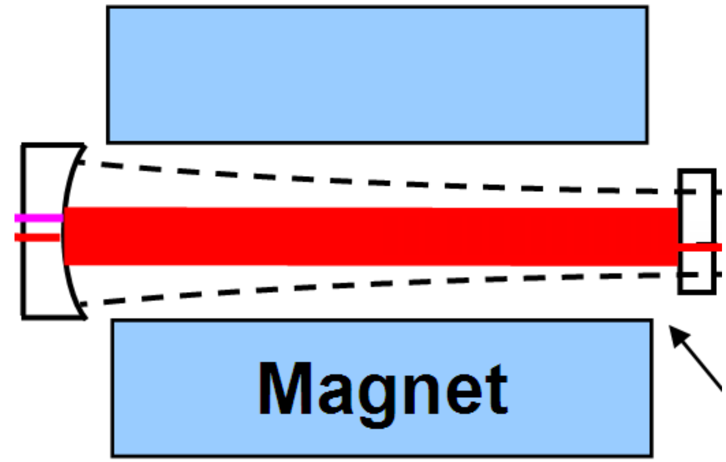
Strawman cavity design

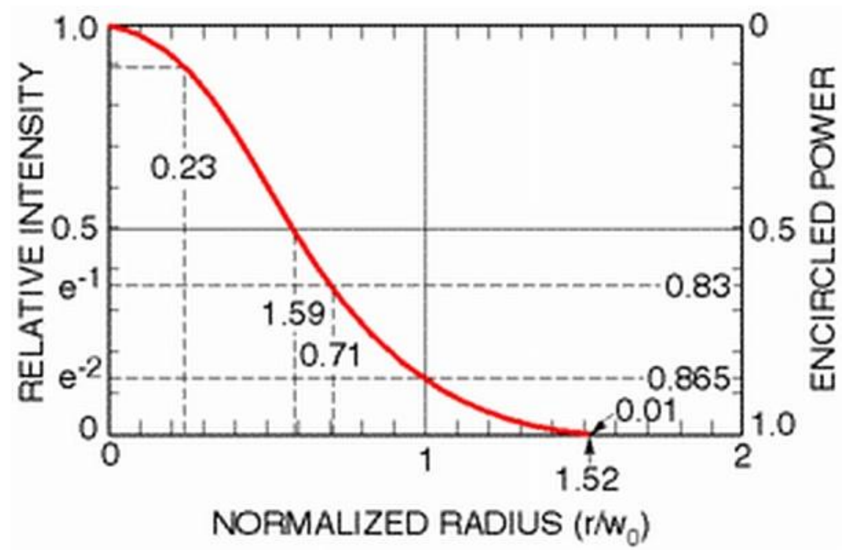
Magnets: 6+6 Tevatron dipoles

- 5 T field
- 6 m length each
- 48 mm diameter
- B_0*L_{mag} = 180 T-m

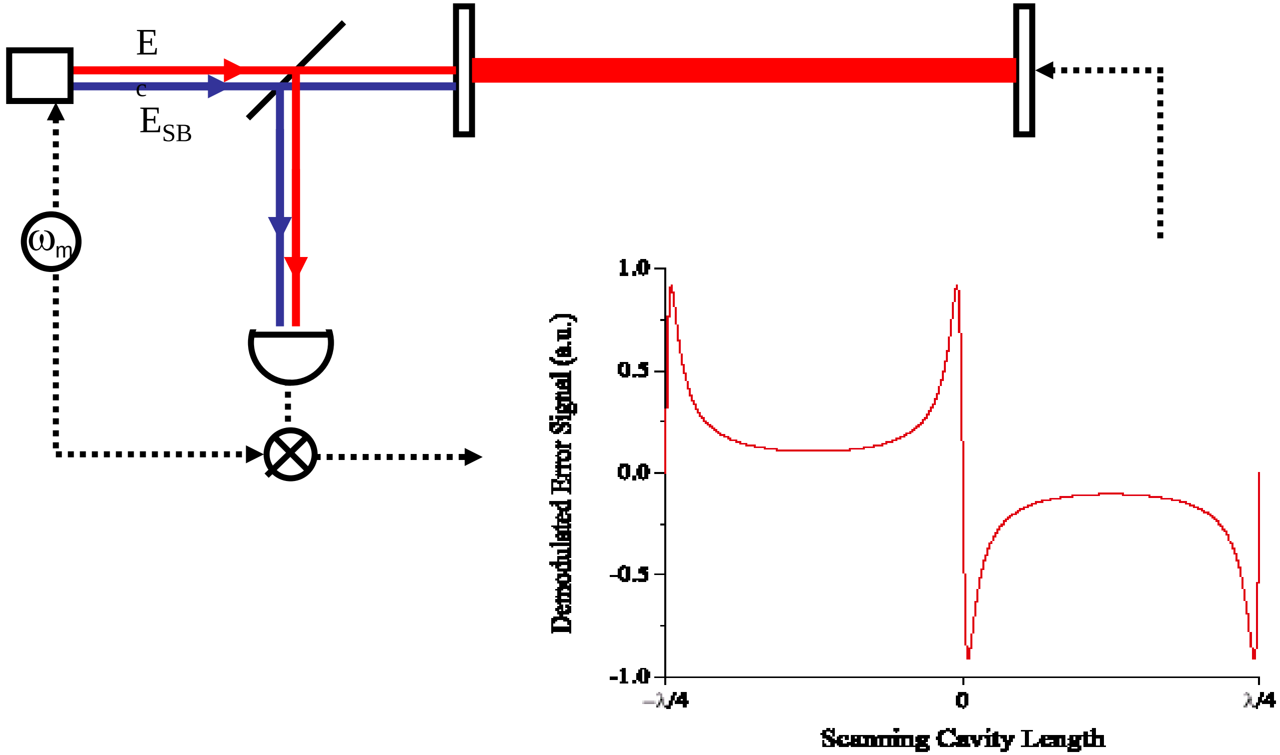
Cavity: curved-flat FP

- 45 m length; FSR = $c/2L_{cav}$ ~ 3.3 MHz
- Mirror radii: 114 m (outer) and -4500 m (inner); g = 0.59
- Gaussian beam radii (field): 5.5 mm (outer); 4.3 mm (inner)
- 1 ppm diameter = 30 mm
- Finesse = 3.1 x 10^5 ; T = 10 ppm;
  A < 1 ppm/mirror
- Stored power ~ 1 MW
- Intensity 2.2 MW/cm^2





Locking the cavities

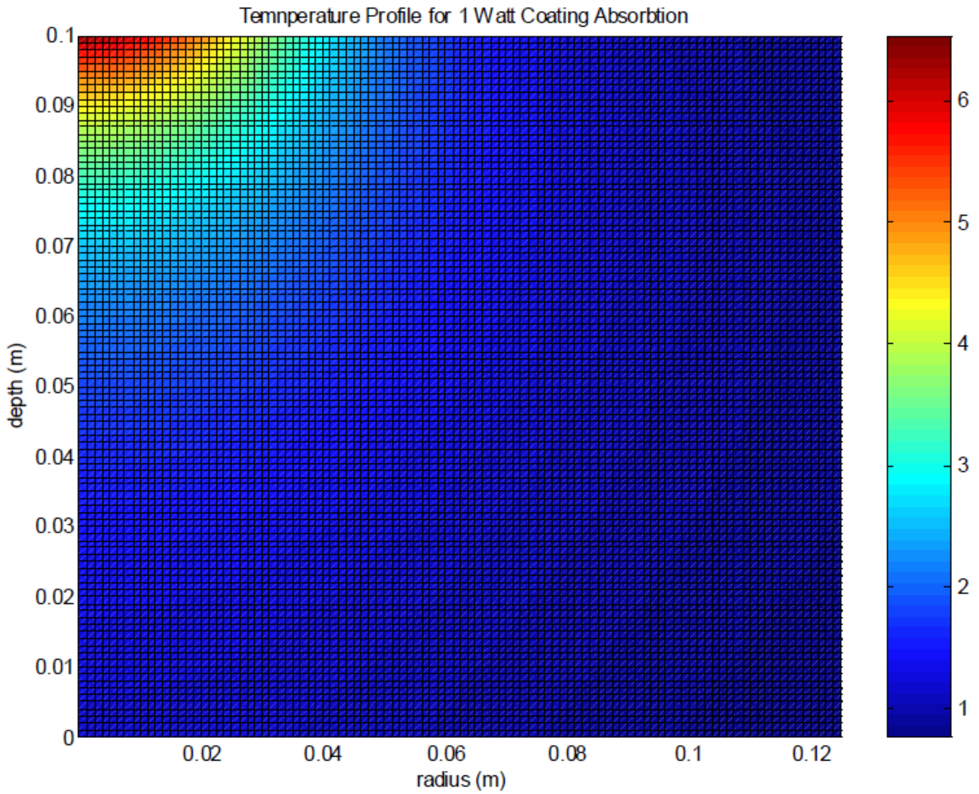


- Pound-Drever-Hall locking

- Resonant regeneration experiment is complex:
  - 2 length degrees of freedom + alignment
  - Absolute position must be held to ~10^{-13} m

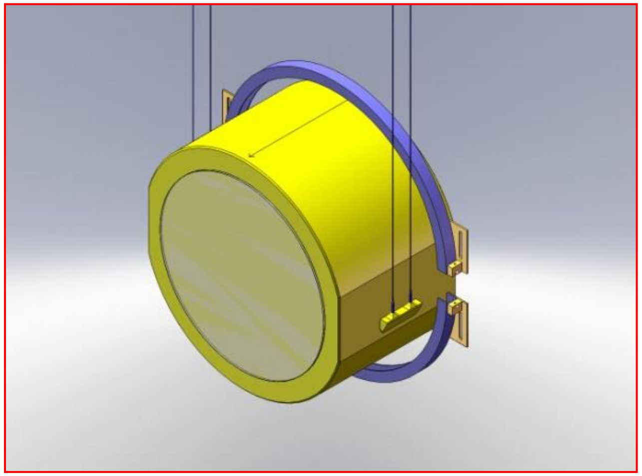
Heating

- With 1 MW incident, 1 ppm loss, absorbed power would be 1 W
- Heating, deformation of mirror surface, loss of mode



Thermal Compensation

- Add heaters to perimeter of mirror
- Heat reduces thermal gradients
- Used successfully in eLIGO



DAMAGE

- An unknown unknown
- Damage thresholds said to be 1 GW/cm^2
  - vs 0.002 GW/cm2 in strawman

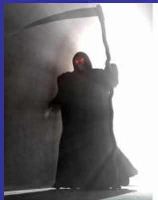
- Dust, sleeks, point defects seed damage

Summary

- With care, optical cavities with lengths of ~50 m and finesses of ~ 100,000 are well within the state of the art.

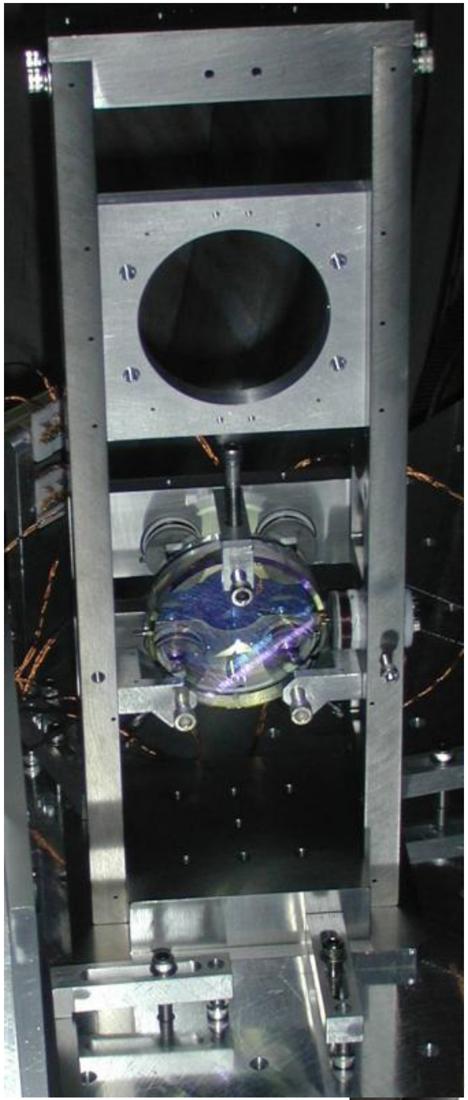
- Peter's 105-110 m is OK. (1 ppm spot on curved mirror is 46.5 mm diameter. [Spot on flat is 34 mm.], g ~ 0.64)

THE END



Other issues

- Can avoid zeros of sinc function in conversion rate by alternating field directions.
- To go beyond *L* ~ 90 m would require first removing sagitta and then using larger diameter magnets. Km scales => 200 mm diameters.
- For high power in production cavity, thermal management/thermal lenses become important.
- Avoid stray light.
- Must run in UHV.
- Dust elimination is critical; scatter from 100 particles of 10 μ diameter already dominates the loss budget.
- Need vibration-free mirror suspensions. Possibly suspended.
- Include quantum efficiency, photodetector dark current.



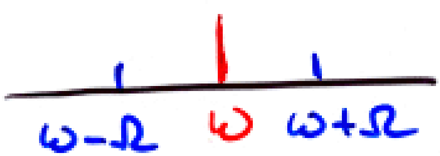
PDH 1

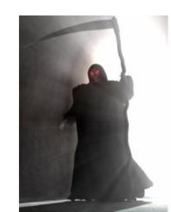
- Phase modulated light

$$E = e^{-i\omega t + i\Gamma\cos\Omega t}$$

$$= e^{-i\omega t}\left[1 + i\Gamma\cos\Omega t + \cdots\right]$$

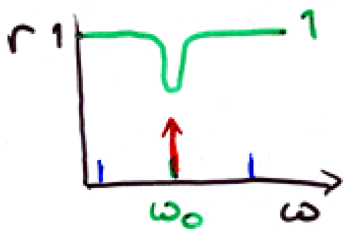
$$= e^{-i\omega t} + \frac{i\Gamma}{2} e^{-i(\omega+\Omega)t} + i\frac{\Gamma}{2} e^{-i(\omega-\Omega)t}$$

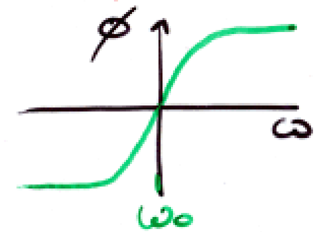




PDH 2

- Reflect from cavity





$$\phi = \begin{cases} \frac{\omega - \omega_0}{\Delta\omega} \equiv \epsilon & \omega \sim \omega_0 \\ \pm\pi & \omega \gg \omega_0, \ \ll \omega_0 \end{cases}$$

$$E_r = \left(r e^{i\epsilon} - i\Gamma \cos \Omega t\right) e^{-i\omega t}$$

$$I_r = \underbrace{R}_{r^2} + \Gamma^2 \cos^2 \Omega t - 2\Gamma r \sin\epsilon \cos \Omega t$$

- Demodulate at $\cos \Omega t$

$$\langle \cos^2 \rangle = 1/2$$

$$\langle I_\Omega \rangle = -\Gamma r \sin \epsilon$$