Resonantly-Enhanced Photon Regeneration

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Naval Postgraduate School, LLNL

- Shining light through walls
- Resonant enhancement
- Design requirements
- Strawperson design
- Sensitivity

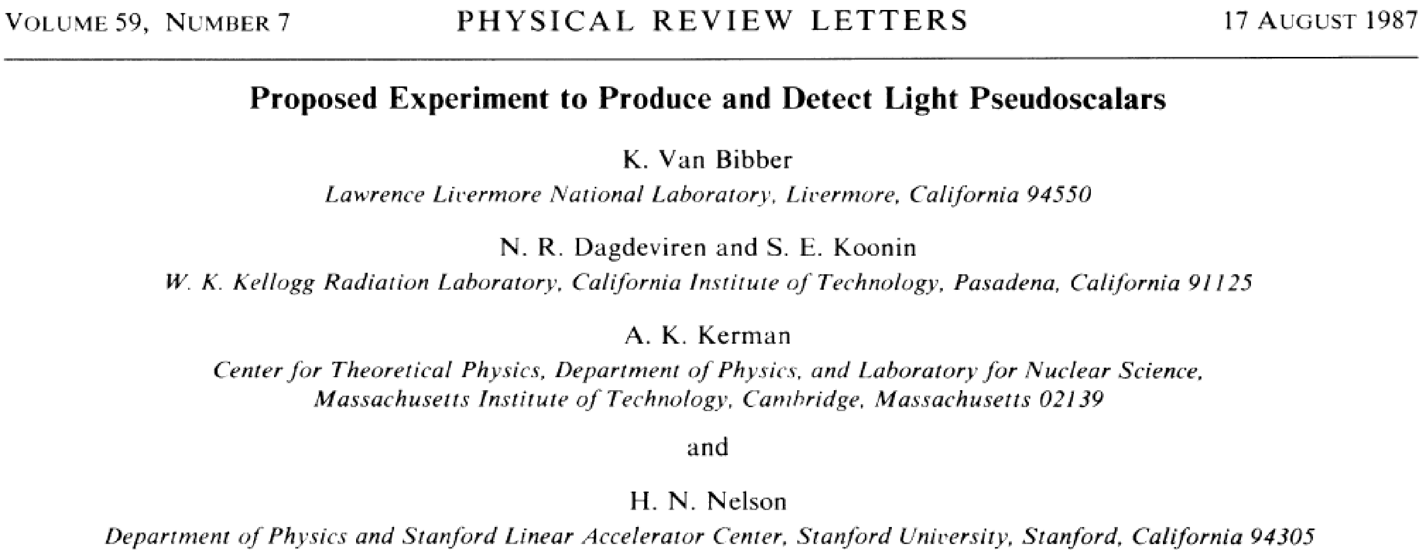
Axion 2010, Gainesville, FL, Jan 15-17

- Goals;
  - highlight recent experimental and theoretical work in all areas of axion physics
  - have a low-key celebration of Pierre Sikivie's sixtieth birthday.
- Friday January 15 and Saturday January 16
  - The main days for presentations,
- Sunday January 17
  - Discussions and perhaps some special activities.

Prof. Pierre Sikivie, University of Florida

Born: 29 October 1949 – Sint-Truiden
Licencie en Sciences Physiques – Liege
Ph.D. 1975 – Yale University

Shining light through the wall



VOLUME 59, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1987

Proposed Experiment to Produce and Detect Light Pseudoscalars

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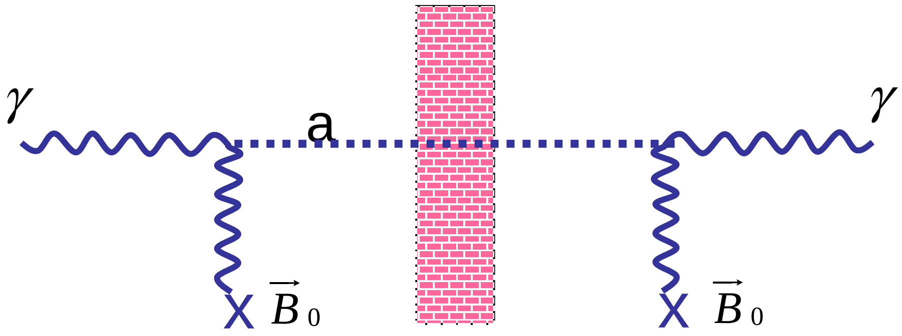
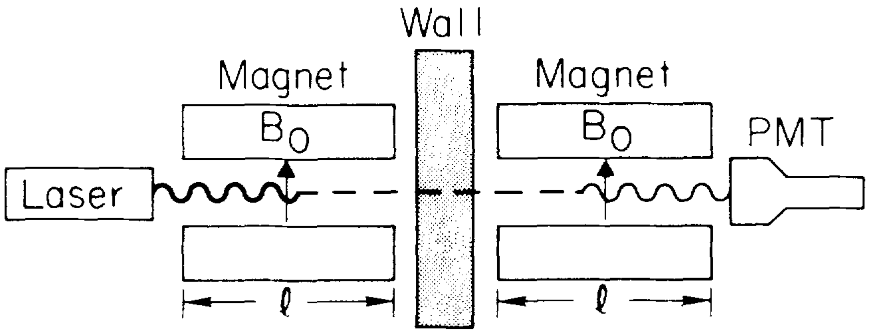
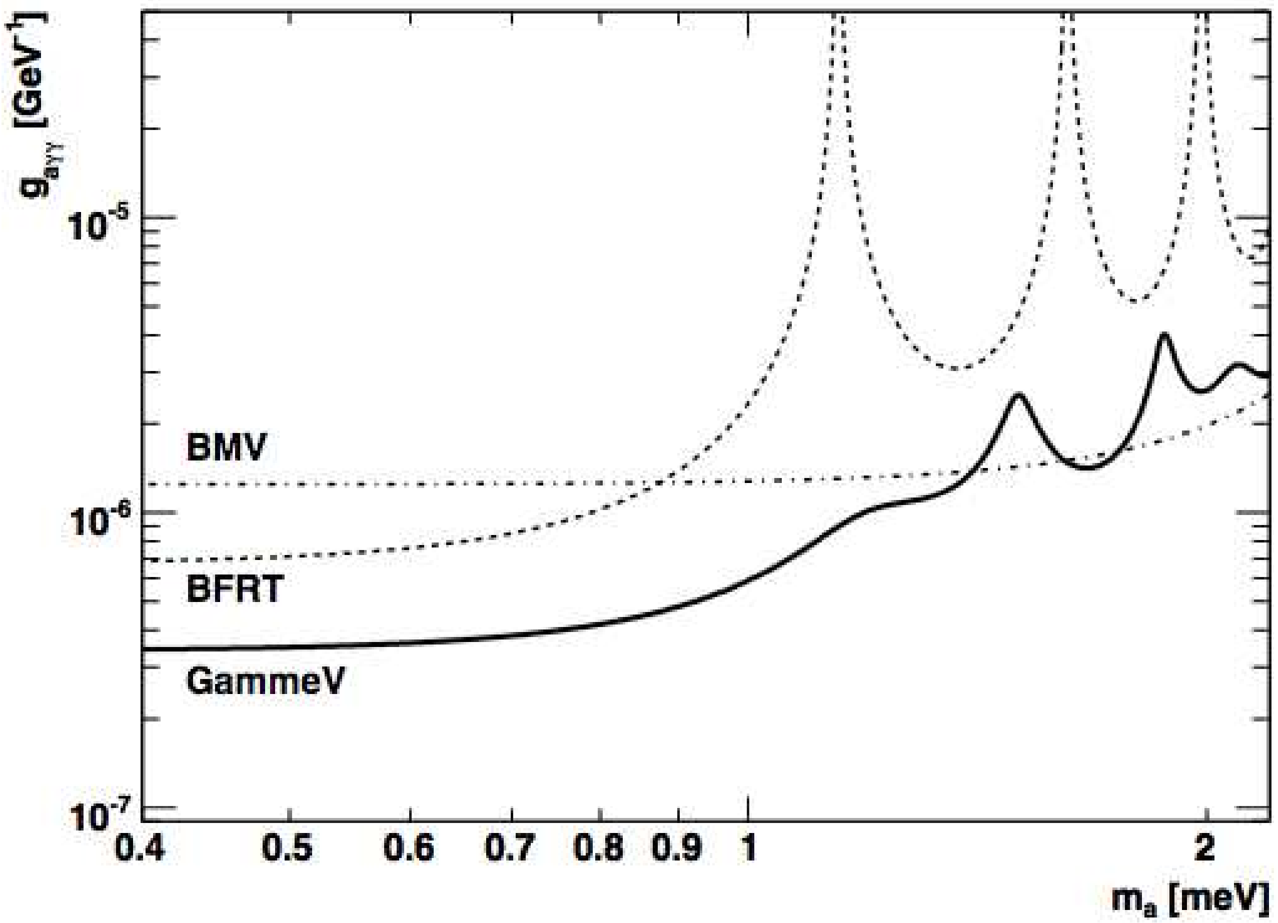
$$\text{rate} \propto \frac{1}{f_a^{\;4}}$$





BFT, BMV, GammeV limits. LIPPS, OSQAR similar



An application of the effect has been proposed

PHYSICAL REVIEW D **76,** 111701(R) (2007)

Long distance signaling using axionlike particles

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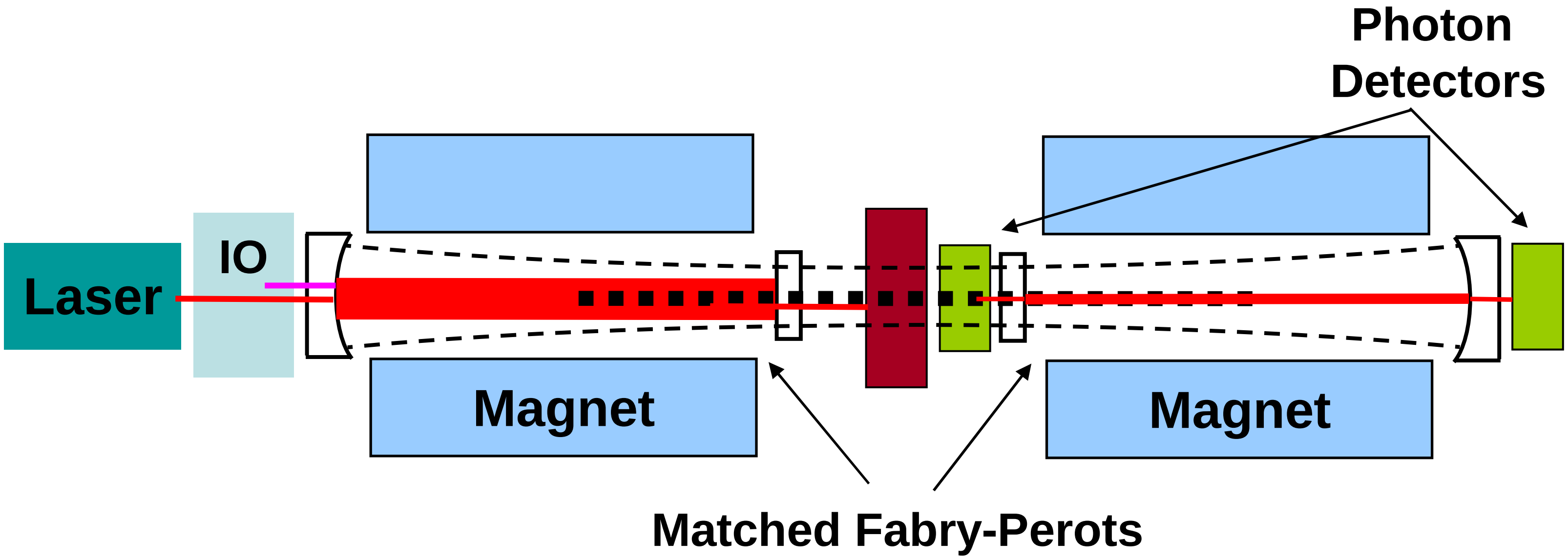
(Received 4 April 2007; published 12 December 2007)

The existing experiments have all reached sensitivities within about a factor of 3-4 of each other, with limits on $g_{a\gamma\gamma}$ in the range of 3×10^{-7} to 1×10^{-6}

Resonantly-Enhanced Photon Regeneration



Basic concept – use Fabry-Perot optical cavities in production and regeneration magnet.

$$P^{\text{Resonant}}(\gamma \to a \to \gamma) = \frac{2}{\pi^2} F F' \cdot P^{\text{Simple}}(\gamma \to a \to \gamma)$$

where F, F' are the finesses of the cavities

Hoogeveen and Ziegenhagen (1991); Sikivie, DT, and van Bibber (2007), Mueller et al (2009)

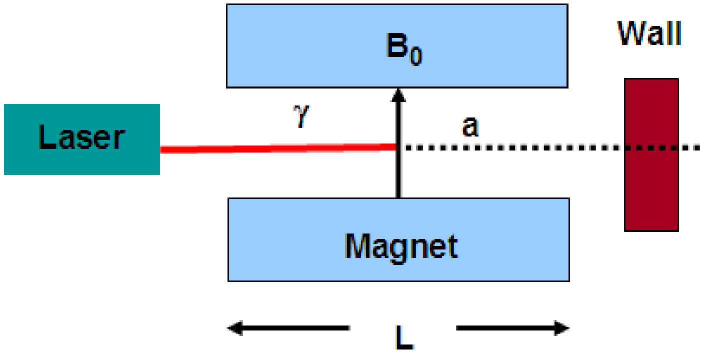
Karl van Bibber's "EE" argument

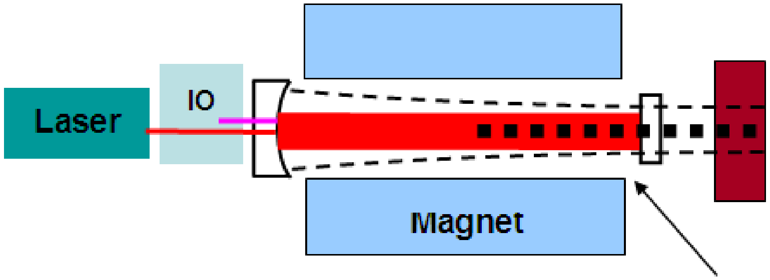
The gain on the production side is simple:

- The number of forward passes the light makes in the magnet is larger by a factor of F/π

- Or, the cavity gain in power is F/π

- The axion flux is larger by a factor of F/π





Karl van Bibber’s “EE” argument

- On the regeneration side, 1 pass through the magnet produces:

  $$P_1 = E_1^{\,2}$$

- In the cavity, the light approaching a mirror is

  $$P_c = E_c^{\,2}$$

- After 1 round trip this partial ray has intensity

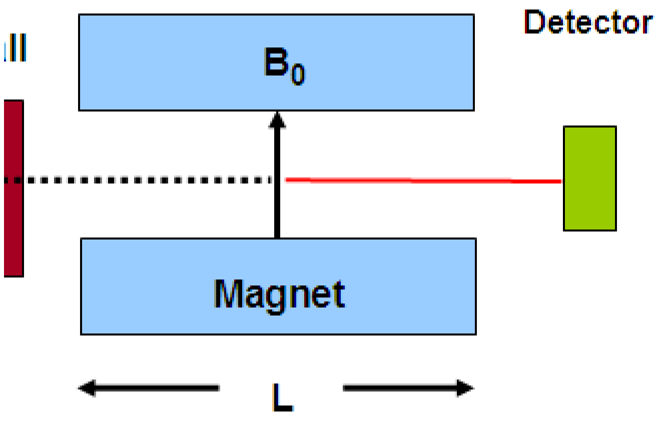
  $$P_{rt} = R^2 * E_c^{\,2}$$

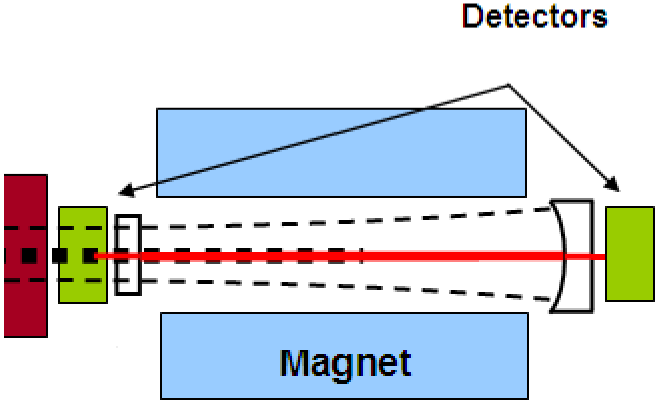
- This adds in phase to the regenerated wave E_1 (add amplitudes!)

  $$E_c = R*E_c + E_1$$
  $$(1-R)*E_c = E_1$$
  $$E_c = E_1/T$$
  $$P_c = P_1/T^2$$

- This light is transmitted through the mirror to the detector

  $$P_{det} = P_1/\mathrm{T} \sim F*P_1/\pi$$

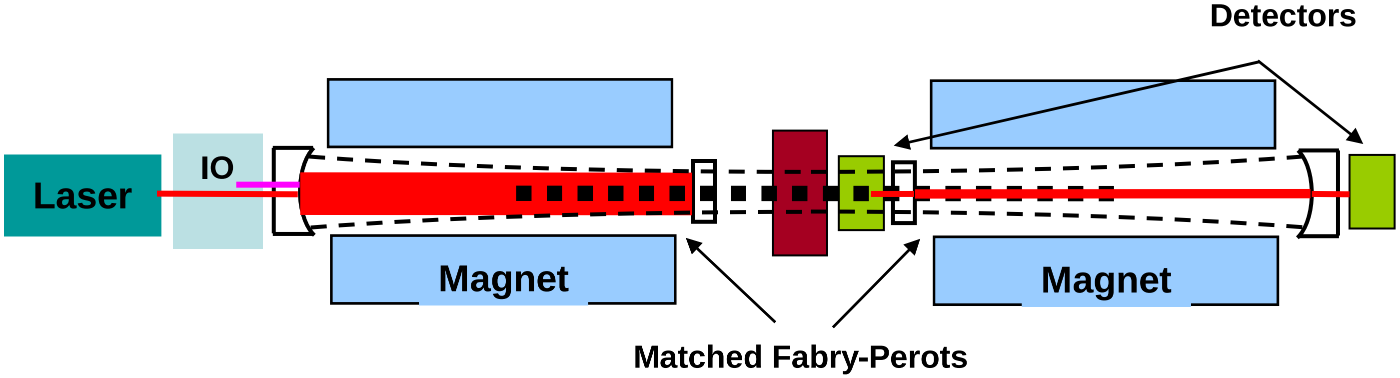




Take $R + T = 1$ for both mirrors

Requirements

- Laser must be “locked” to production cavity.
- Regeneration cavity must be locked to resonance of production cavity *without filling it with light at the laser wavelength.*
- Cavities must be aligned on mirror image modes (as if inner mirrors and wall were not present).
- Need sensitive readout of weak emission from regeneration cavity.



Strawman design

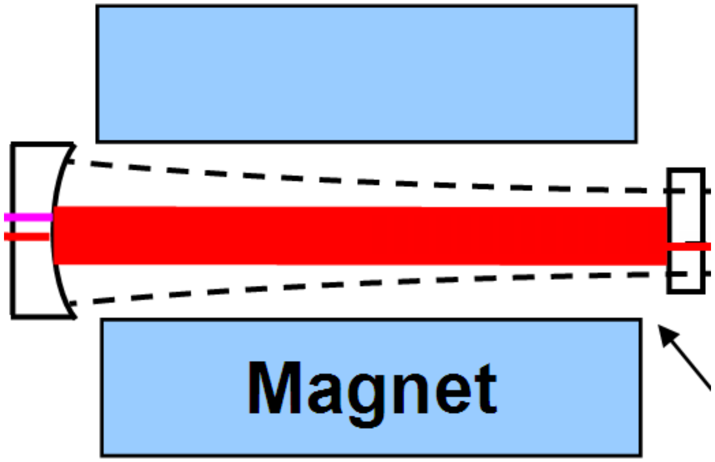
Magnets: 12 Tevatron dipoles

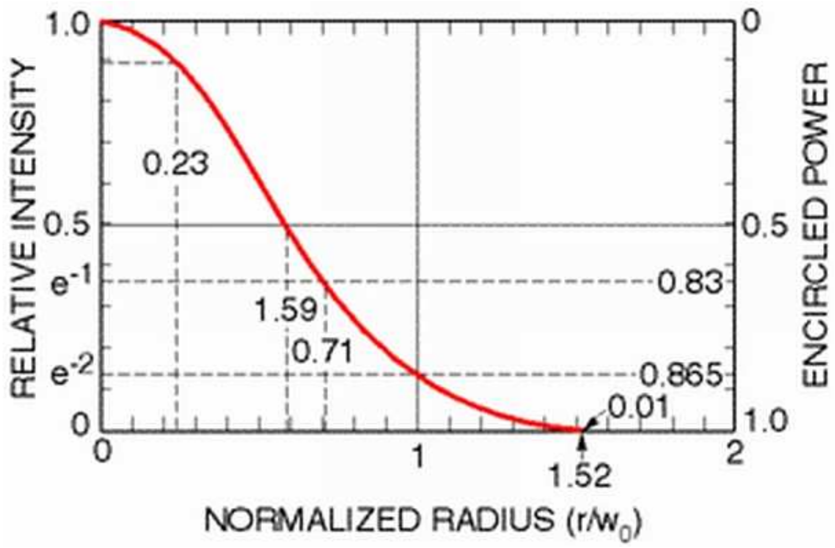
- 6 on each side of the wall
- 5 T field
- 6 m length each
- 48 mm diameter
- $B_0 * L_{mag}$ = 180 T-m

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 clip at 30 mm diameter
- Finesse = 3.1 x 10^5 ; T = 10 ppm;

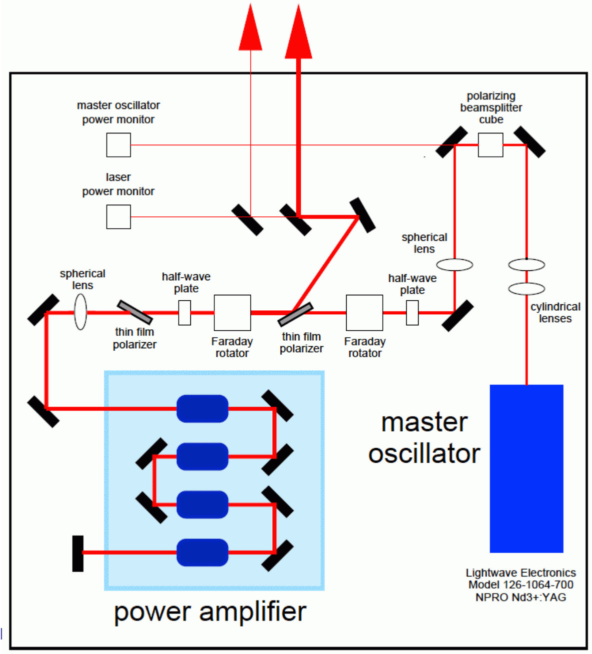
  A = 1 ppm/mirror
- Stored power ~ 1 MW

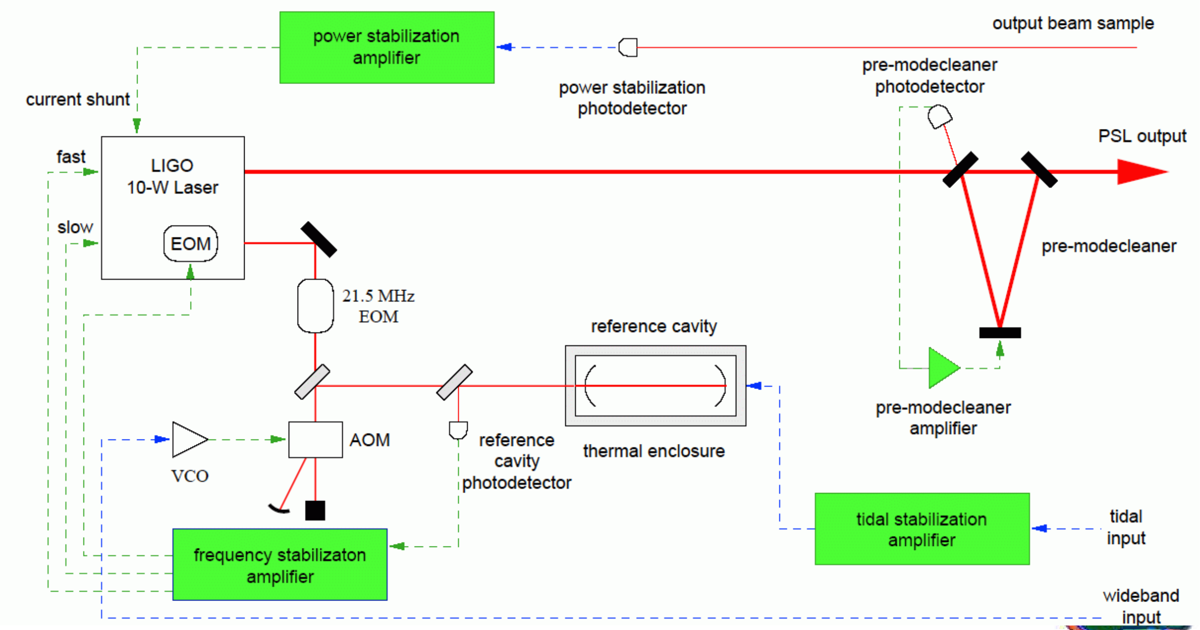




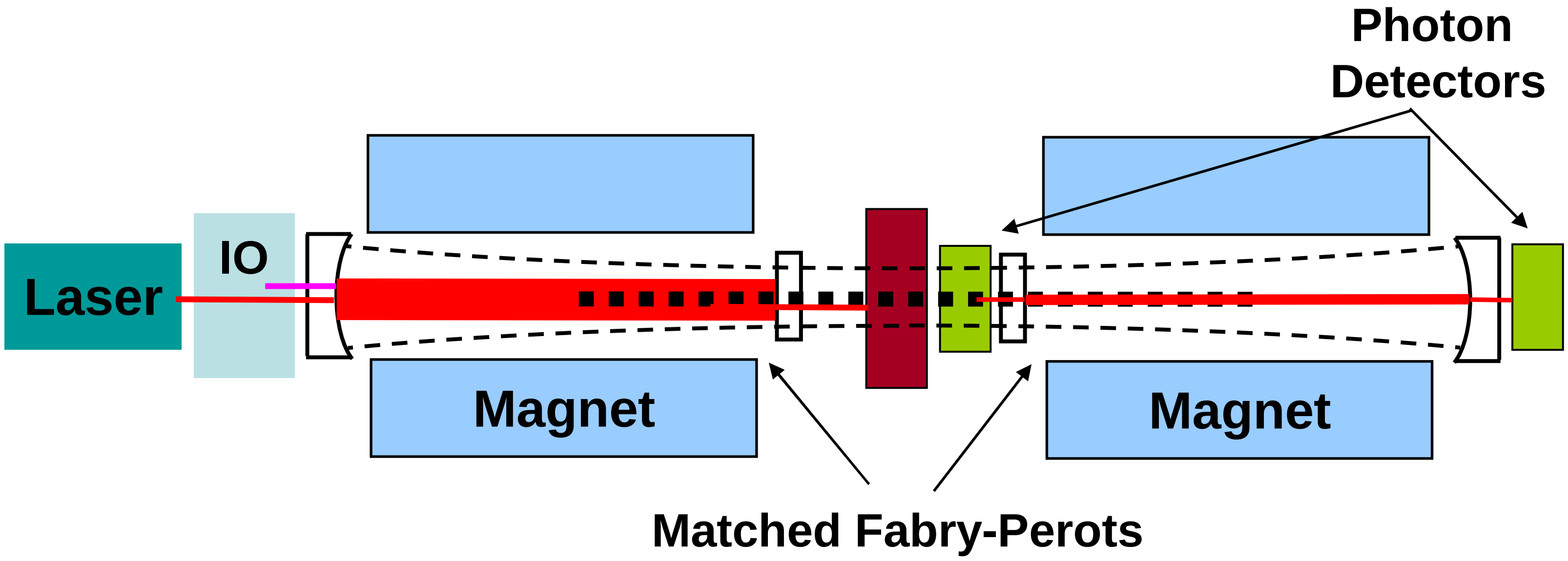
LIGO-style laser

- Diode pumped Nd:YAG MOPA
- 6-8 Watt.
- 1064 nm (282 THz).
- Stabilized by reference cavity.
- Pre-mode cleaner for spatial mode.
- TEM_{00} single-frequency VCO.





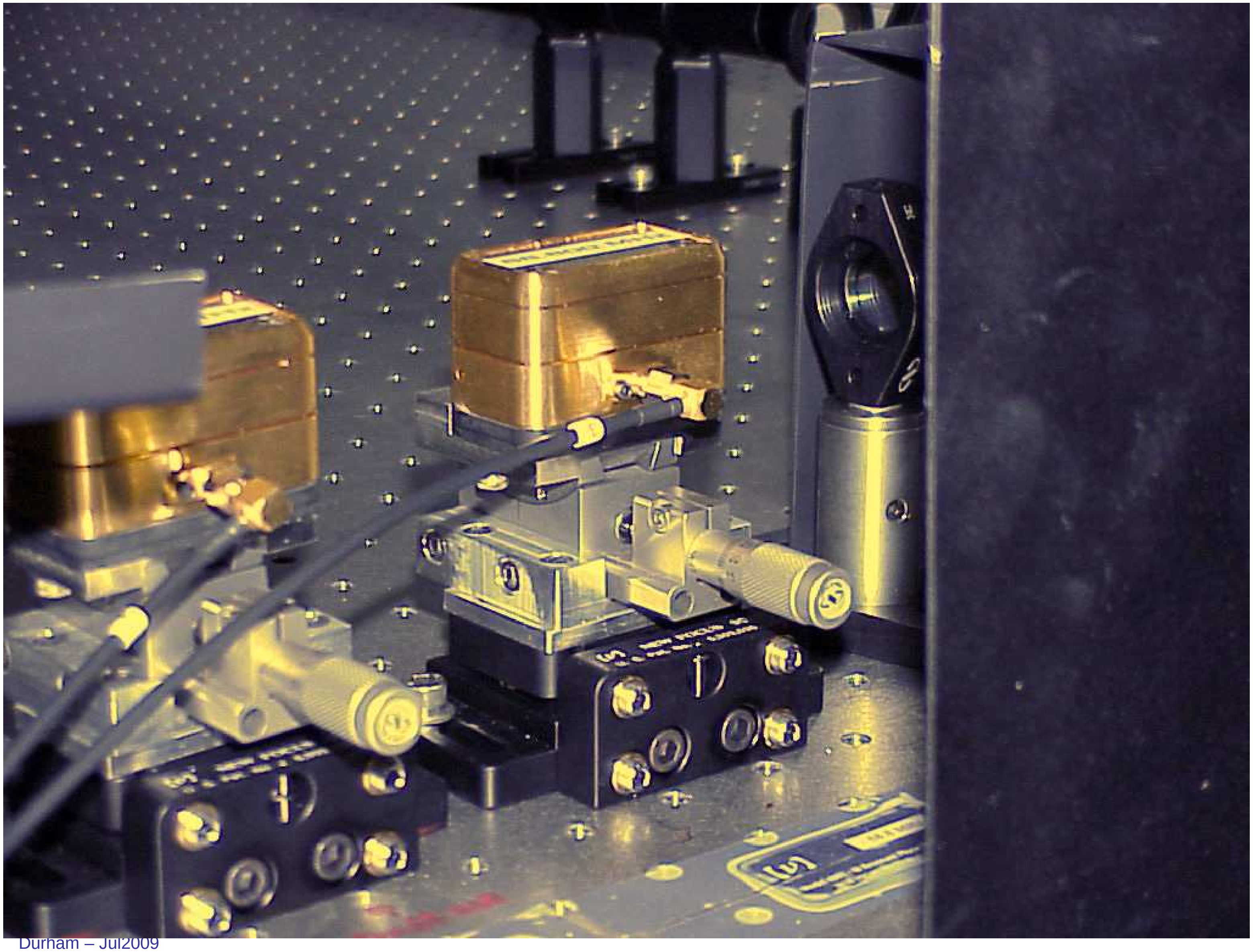
Length control



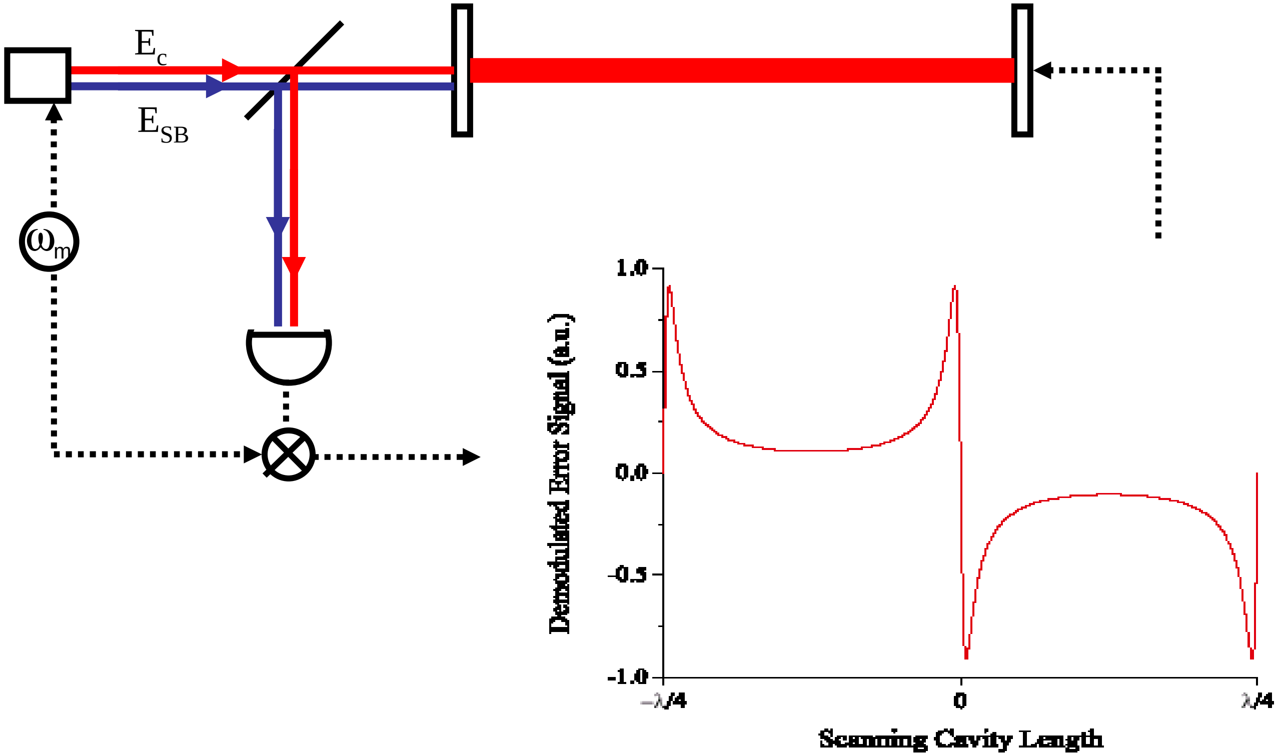
IO provides mode-matching of laser to cavity (telescope)

Modulation for "locking the cavity."

RF Pockels cell modulators



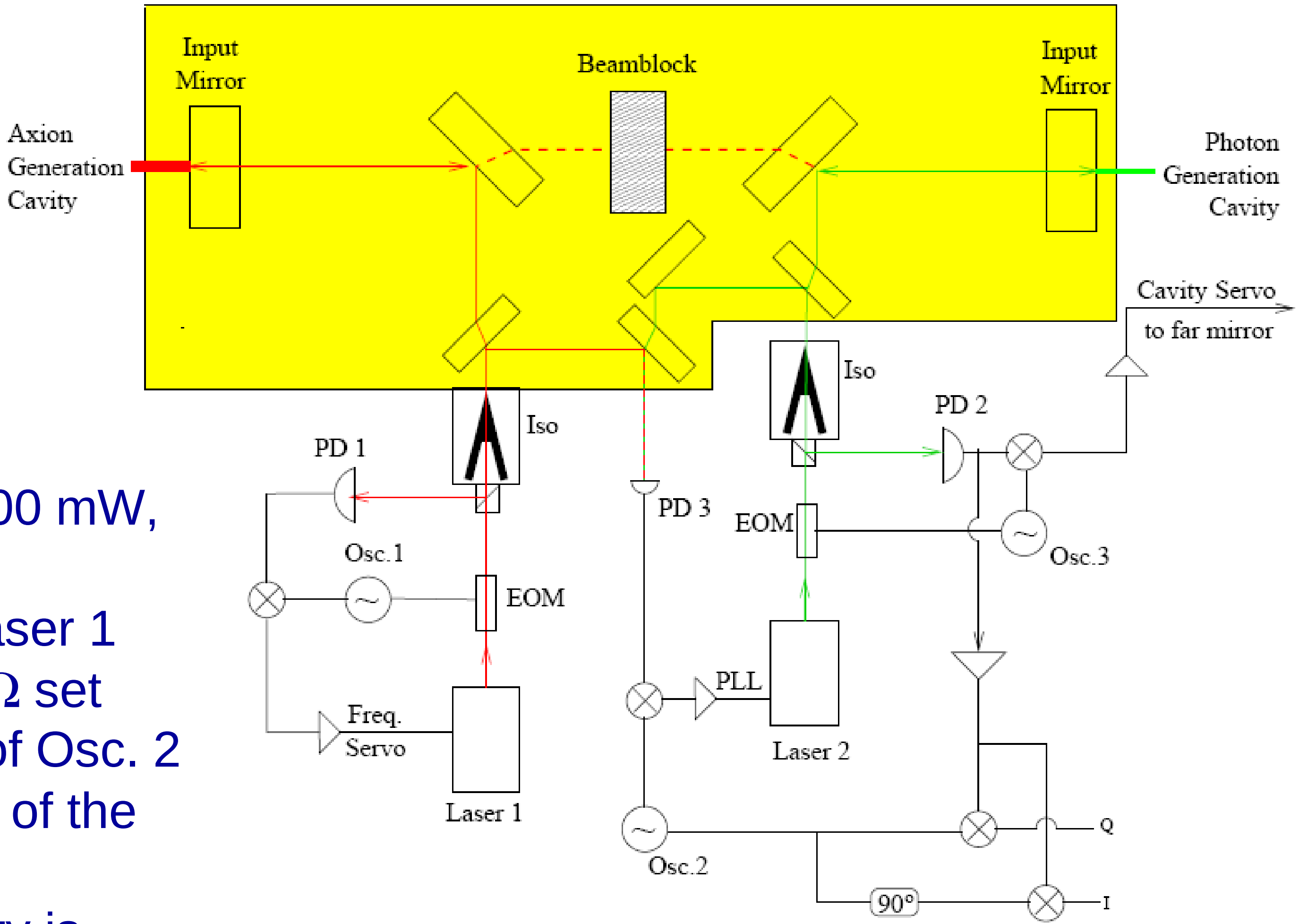
Locking the cavities



- Pound-Drever-Hall locking

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

Offset lock the regeneration cavity



- Use low power, 100 mW, Laser 2
- Offset locked to Laser 1
- Offset frequency Ω set by the frequency of Osc. 2
- Ω = integer * FSR of the cavities
- Regeneration cavity is PDH locked to Laser 2

Readout scheme

- The axion field converts in the regeneration cavity to a signal field E_S at Laser 1 frequency ω_0.

$$E_S = E_{SO} e^{i\omega_0 t} e^{i\phi} \qquad \phi = k_a d$$

- Mix this with laser 2 (the LO) at a photodiode; the signal is proportional to the intensity

$$S = \left|E_S\right|^2 = |E_{LO}|^2 + 2E_{LO}E_{SO}\cos(\Omega t + \phi)$$

- Write this in terms of the number of photons in each field

$$S = N_{LO} + S_I \cos\Omega t + S_Q \sin\Omega t$$

$$S_I = 2\sqrt{N_{LO}N_S}\cos\phi \qquad S_Q = 2\sqrt{N_{LO}N_S}\sin\phi$$

Readout scheme II

- Noise is shot noise:

$$\sigma_I = \sqrt{2\bar{N}} = \sqrt{2N_{LO}} = \sigma_Q$$

- Phase is arbitrary and unknown, so add I and Q in quadrature

$$S_\Sigma = \sqrt{S_I^2 + S_Q^2} = 2\sqrt{N_{LO}N_S}. \quad \sigma_\Sigma = \sqrt{\sigma_I^2 + \sigma_Q^2} = 2\sqrt{N_{LO}}$$

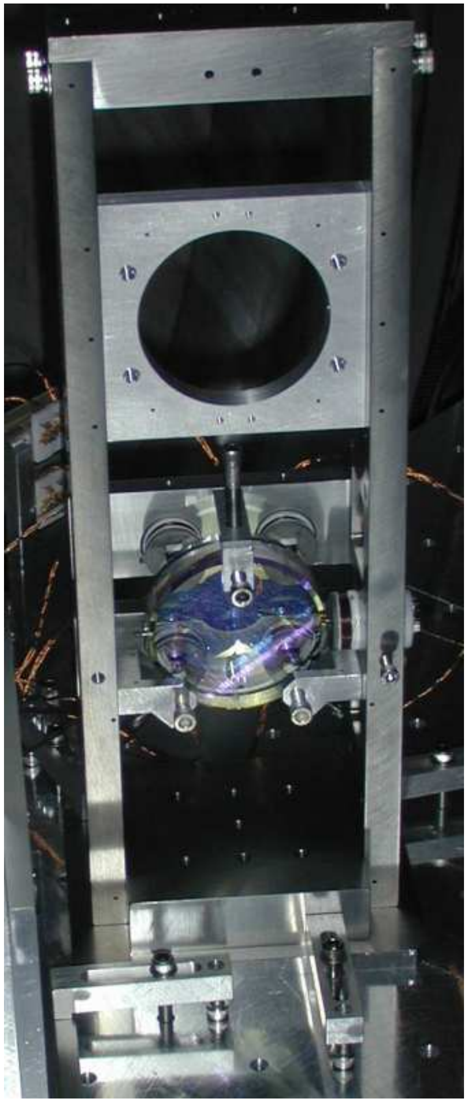
- Shot-noise limited SNR is

$$\frac{S_\Sigma}{\sigma_\Sigma} = \sqrt{N_S}$$

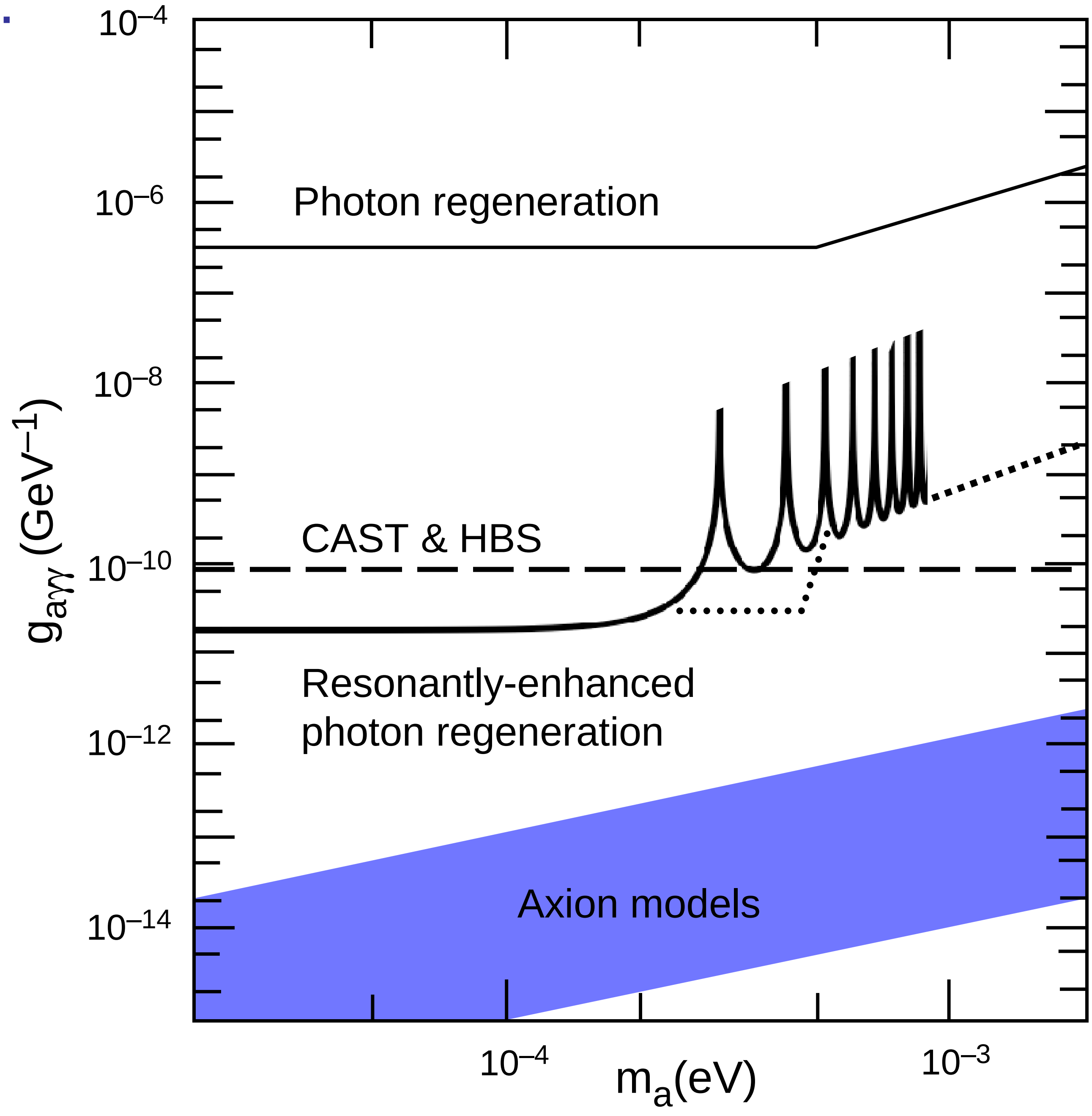
i.e, one photon at an SNR of 1.

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.



Sensitivity:



The Resonant Regeneration Collaboration

FNAL:

Aaron Chou (Wilson Fellow, co-spokesperson GammeV),
William Wester (co-spokesperson GammeV),
Jason Steffen (Brinson Fellow)
Peter Mazur,
Ray Tomlin,
Al Baumbaugh

Naval Postgraduate School and Lawrence Livermore National Lab:

Karl van Bibber (Chief Scientist, co-spokesperson ADMX)

Univ. of Florida:

David Tanner (ADMX, LIGO)
Guido Muller (LIGO, Chair of LISA Interferometer working group)
Pierre Sikivie (ADMX, axion physics)

Univ. of Michigan:

Dick Gustafson (LIGO)

Collaborations need names…

“This time we mow the axion down for good”

Conclusions

- Resonant approach improves sensitivity to $g_{a\gamma\gamma}$ by a factor of 300 or so.
- It can reach 2 x 10^{-11} GeV^{-1} in 90 days of live time.
- All the technology for such an experiment exists.
  - TeV magnets.
  - Laser, cavity, instrument control, and readout adopt technology proven in LIGO and LISA.

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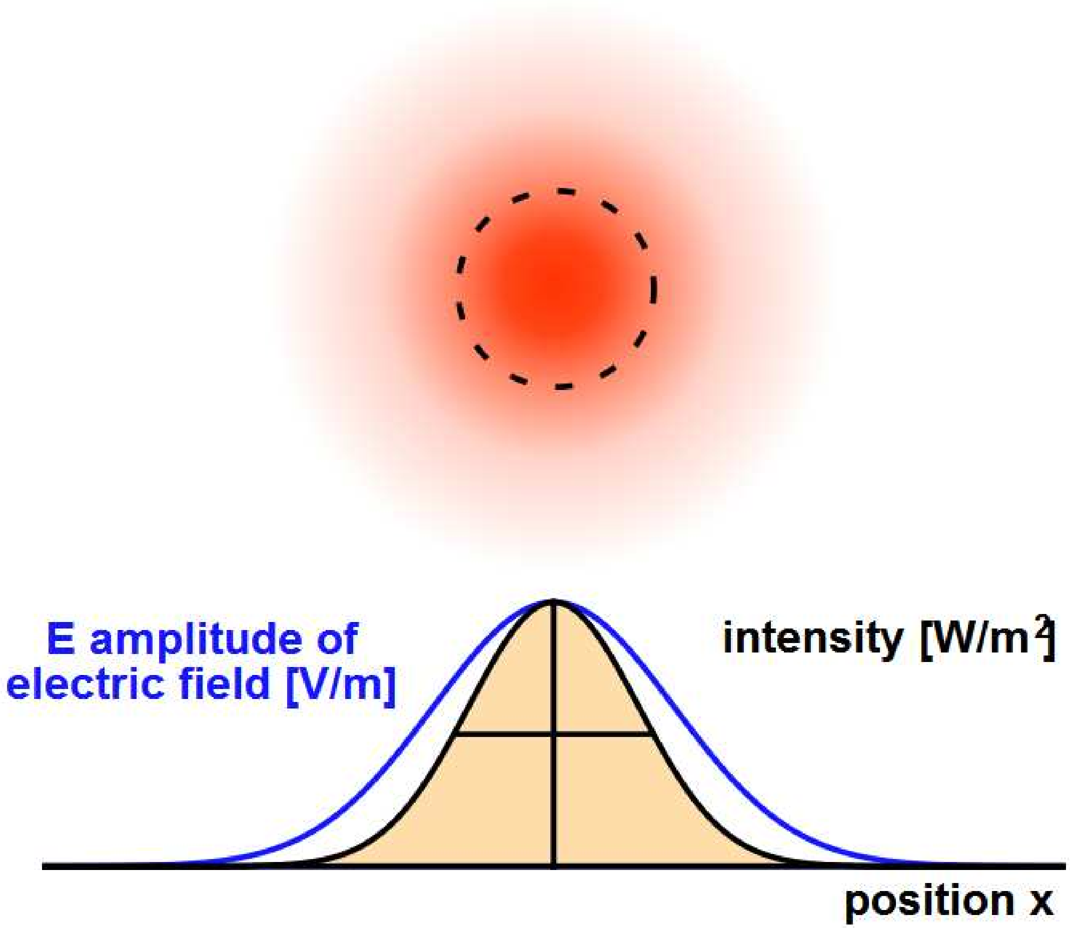
Born: 29 October 1949 – Sint-Truiden
Licencie en Sciences Physiques – Liege
Ph.D. 1975 – Yale University

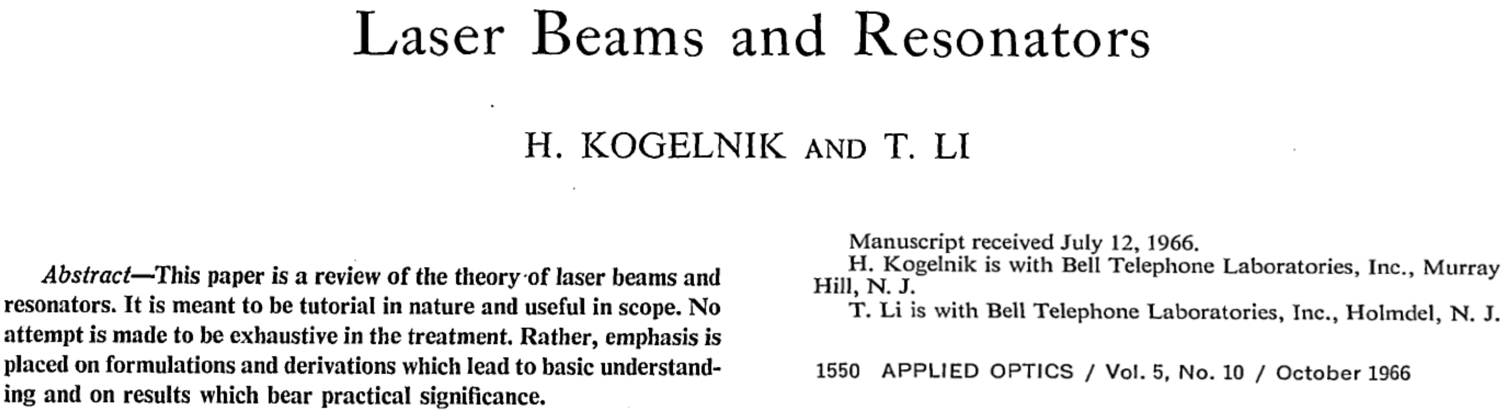
THE END

Cavity parameters

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



References



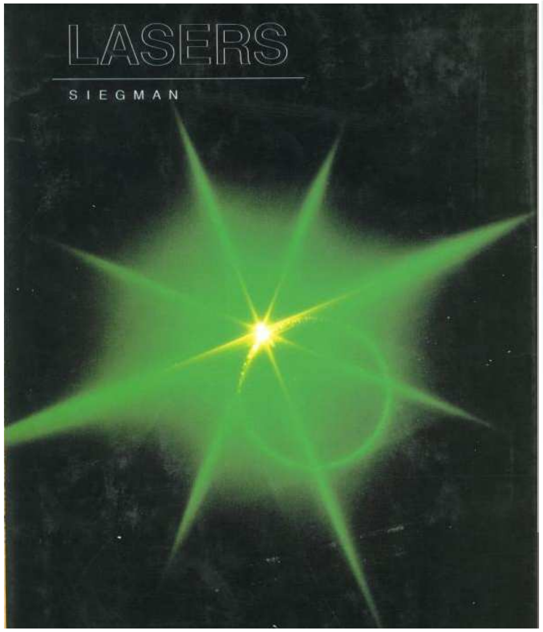
Laser Beams and Resonators

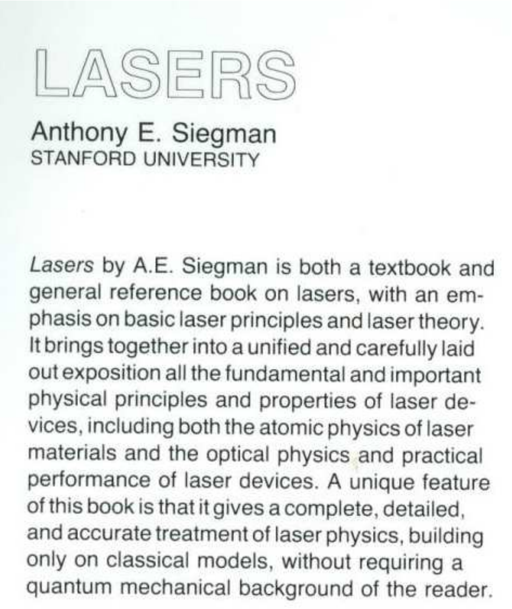
H. KOGELNIK AND T. LI

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

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]

1 Mathematical form
2 Beam parameters
  2.1 Beam width or "spot size"
  2.2 Rayleigh range and confocal parameter
  2.3 Radius of curvature
  2.4 Beam divergence
  2.5 Gouy phase
  2.6 Complex beam parameter
3 Power and intensity
  3.1 Power through an aperture
  3.2 Peak and average intensity
4 Higher-order modes
  4.1 Hermite-Gaussian modes
  4.2 Laguerre-Gaussian modes
  4.3 Ince-Gaussian modes
5 See also
6 Notes
7 References

Cavity mode

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

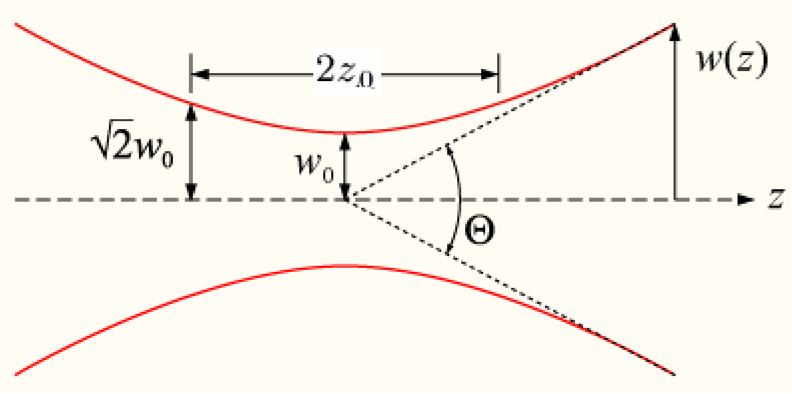
$$z_0 = \frac{\pi w_0^2}{\lambda}$$

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

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

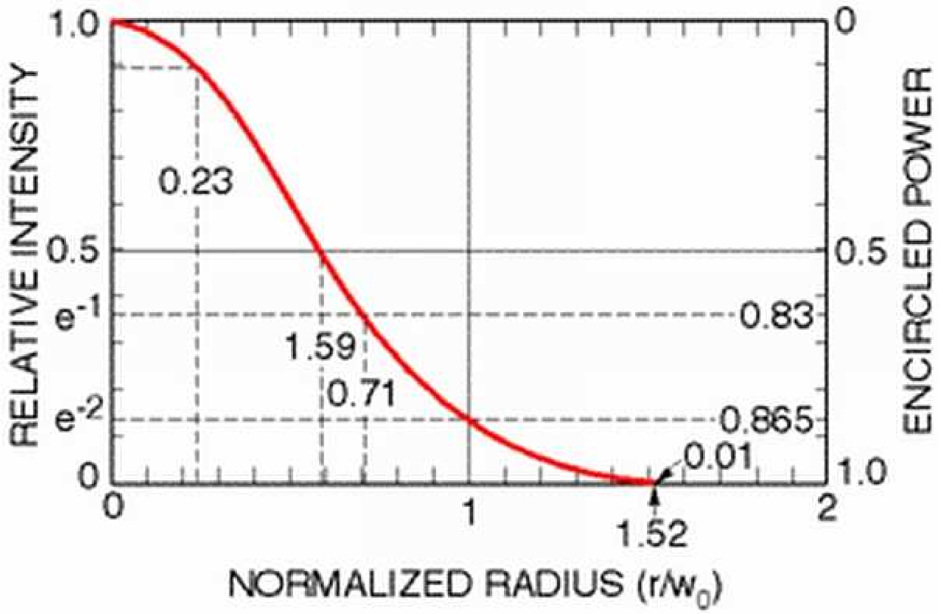
The intensity $\propto E^2$, so

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

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

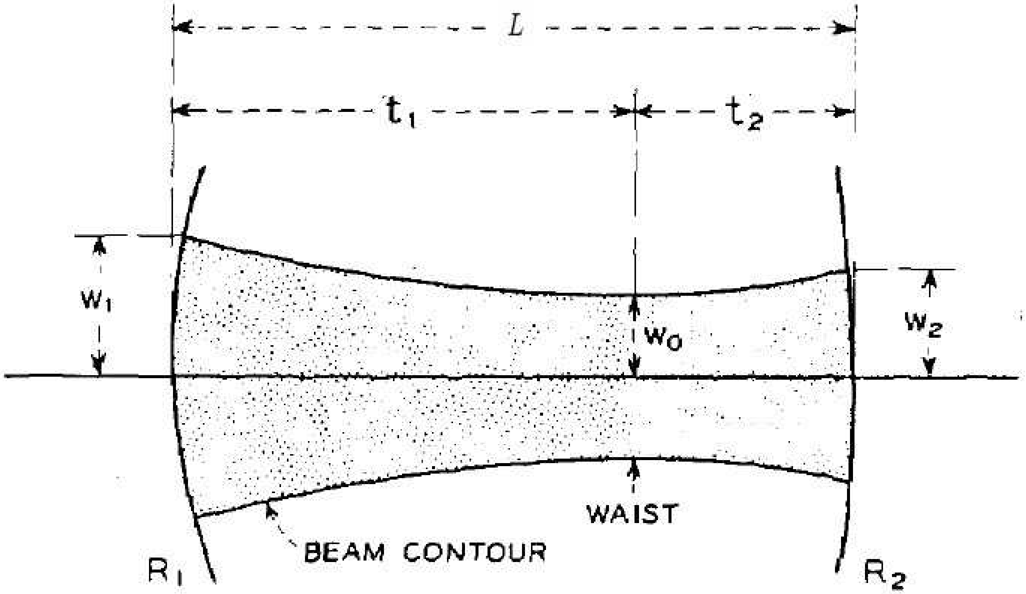
How do we find the waist? Set up a cavity, with curved mirrors of radii R_1 and R_2 and with a distance L between them. The resonant beam will have radii of curvature of R_i at each mirror, and a waist between them. For us, with curve/flat, $R_1 = R$ and $R_2 = \infty$. Then,

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

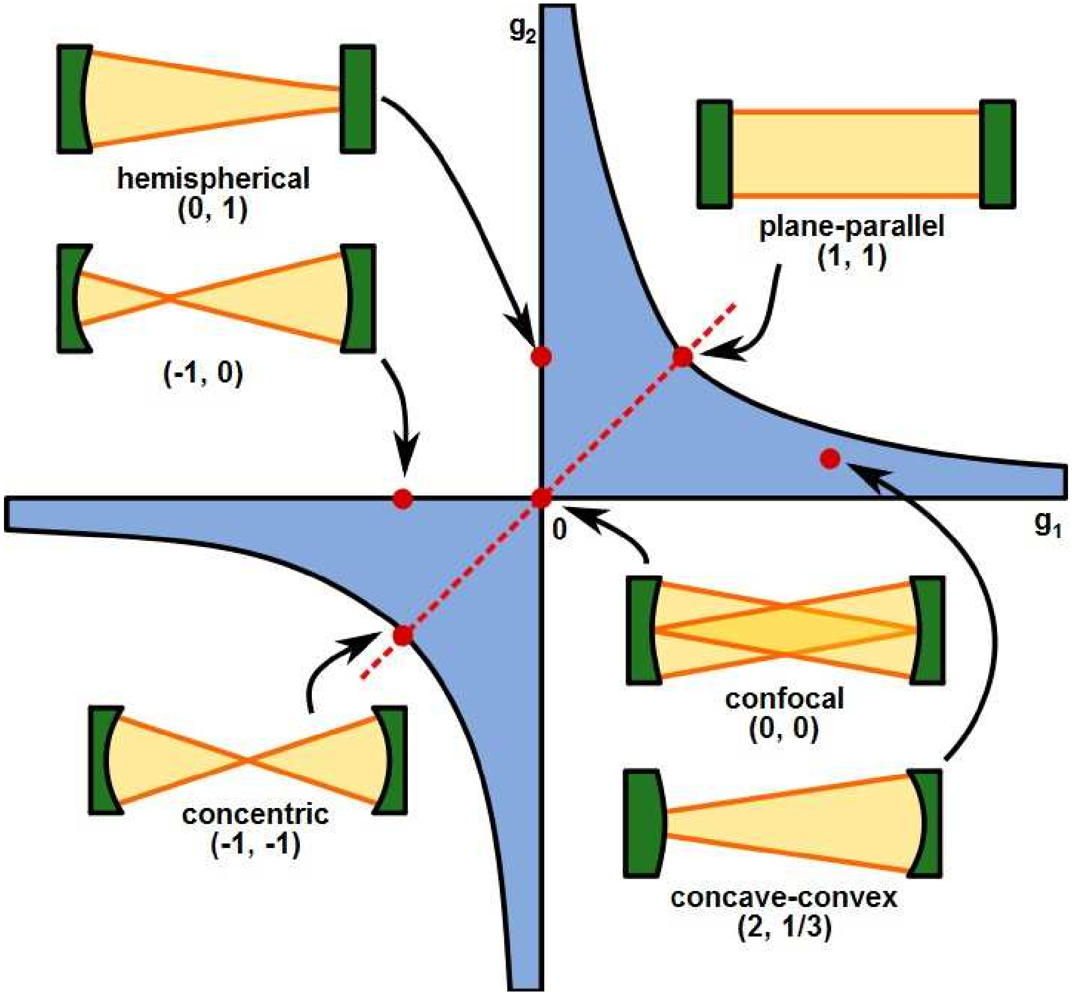
and

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

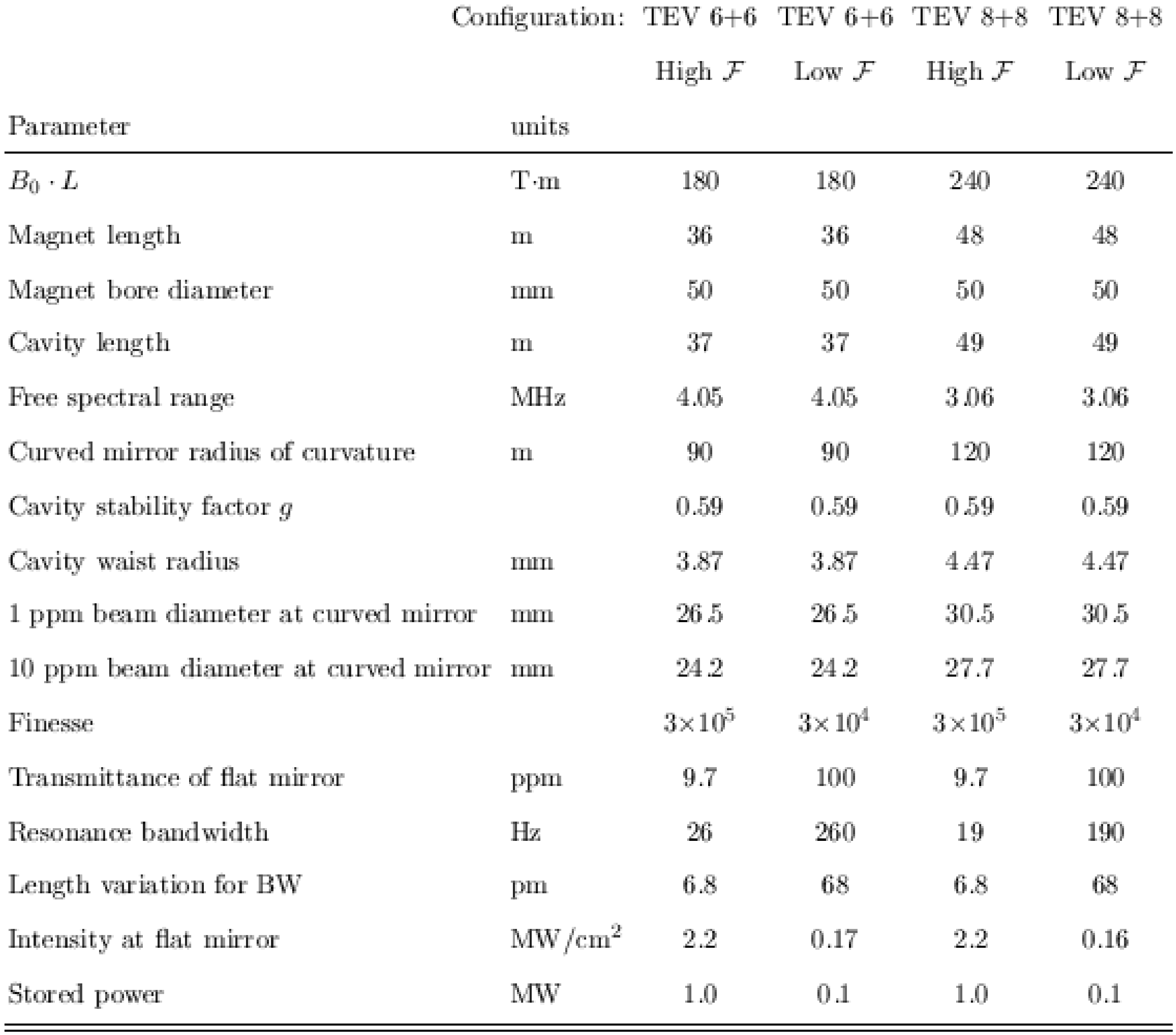
$g (= g_1 g_2)$ is called the stability product. We have $g_2 = 1$. Want $0 < |g| < 1$.



Stability


g2
g1
0
hemispherical
(0, 1)
(-1, 0)
plane-parallel
(1, 1)
confocal
(0, 0)
concentric
(-1, -1)
concave-convex
(2, 1/3)

Cavity parameters (10 W in; 0.8 / 8 ppm loss)



	Configuration:	TEV 6+6	TEV 6+6	TEV 8+8	TEV 8+8
		High $\mathcal{F}$	Low $\mathcal{F}$	High $\mathcal{F}$	Low $\mathcal{F}$
Parameter	units				
$B_0 \cdot L$	T·m	180	180	240	240
Magnet length	m	36	36	48	48
Magnet bore diameter	mm	50	50	50	50
Cavity length	m	37	37	49	49
Free spectral range	MHz	4.05	4.05	3.06	3.06
Curved mirror radius of curvature	m	90	90	120	120
Cavity stability factor g		0.59	0.59	0.59	0.59
Cavity waist radius	mm	3.87	3.87	4.47	4.47
1 ppm beam diameter at curved mirror	mm	26.5	26.5	30.5	30.5
10 ppm beam diameter at curved mirror	mm	24.2	24.2	27.7	27.7
Finesse		3×10^5	3×10^4	3×10^5	3×10^4
Transmittance of flat mirror	ppm	9.7	100	9.7	100
Resonance bandwidth	Hz	26	260	19	190
Length variation for BW	pm	6.8	68	6.8	68
Intensity at flat mirror	MW/cm^2	2.2	0.17	2.2	0.16
Stored power	MW	1.0	0.1	1.0	0.1

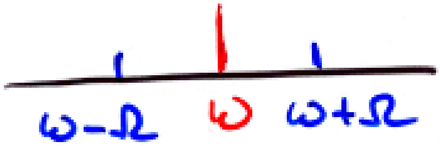
PDH 1

- Phase modulated light

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

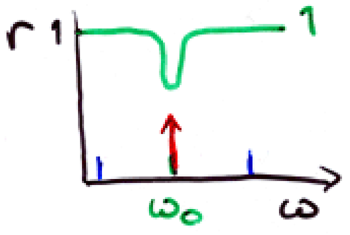
$$= e^{-i\omega t}\left[1 + i\Gamma\cos\Omega t + \ldots\right]$$

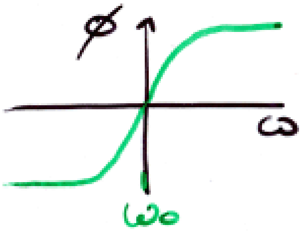
$$= e^{-i\omega t} + \frac{i\Gamma}{2} e^{-i(\omega+\Omega)t} + i\frac{\Gamma}{2} e^{-i(\omega-\Omega)t}$$



PDH 2

- Reflect from cavity





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

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

$$I_r = \underset{r^2}{\mathcal{R}} + \Gamma^2 \cos^2 \Omega t \;-\; 2\Gamma\, r \sin\epsilon \,\cos \Omega t$$

- Demodulate at $\cos \Omega t$

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

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

Cavity with F = 1500

Transmittance (power) of mode cleaner near the resonance. Left panel shows transmittance as a function of frequency; right as a function of length.