Adaptive Thermal Compensation

Advanced Photodetectors

Photon Drive

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LIGO Project, MIT Center for Space Research

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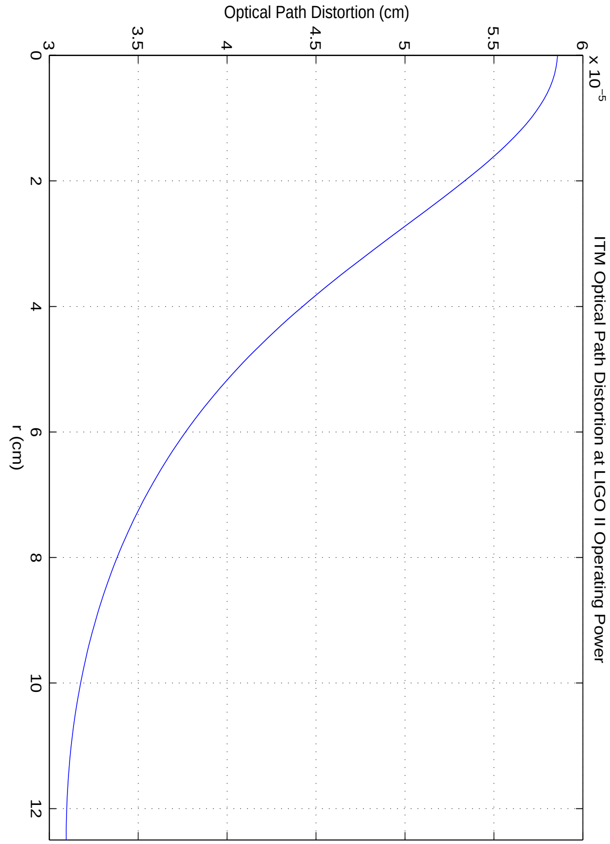
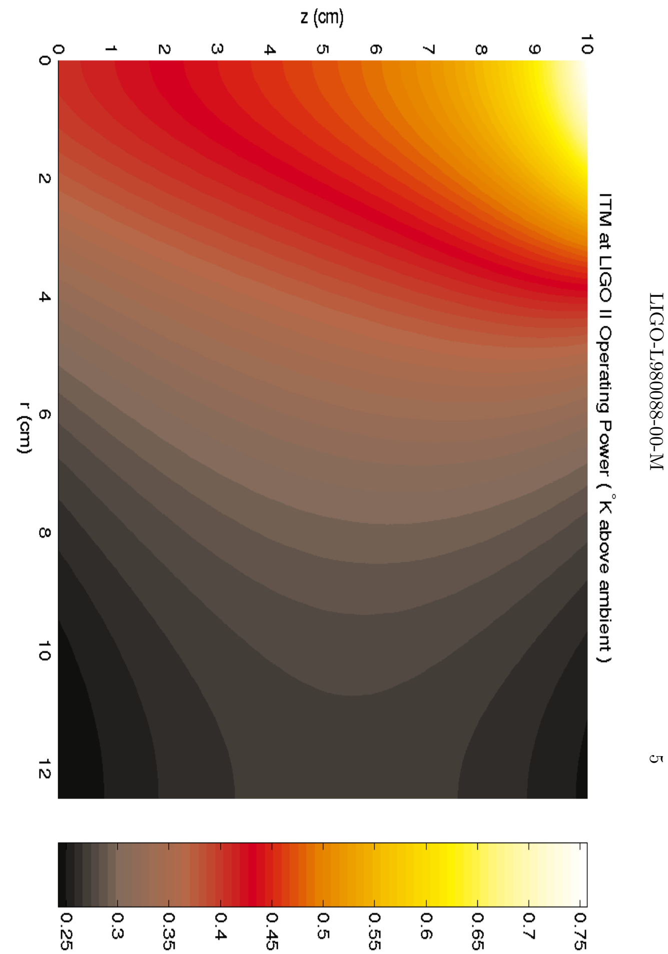
FEA model: uncorrected SiO_2 ITM





Adaptive Compensation of Thermal Lensing in LIGO II Core Optics

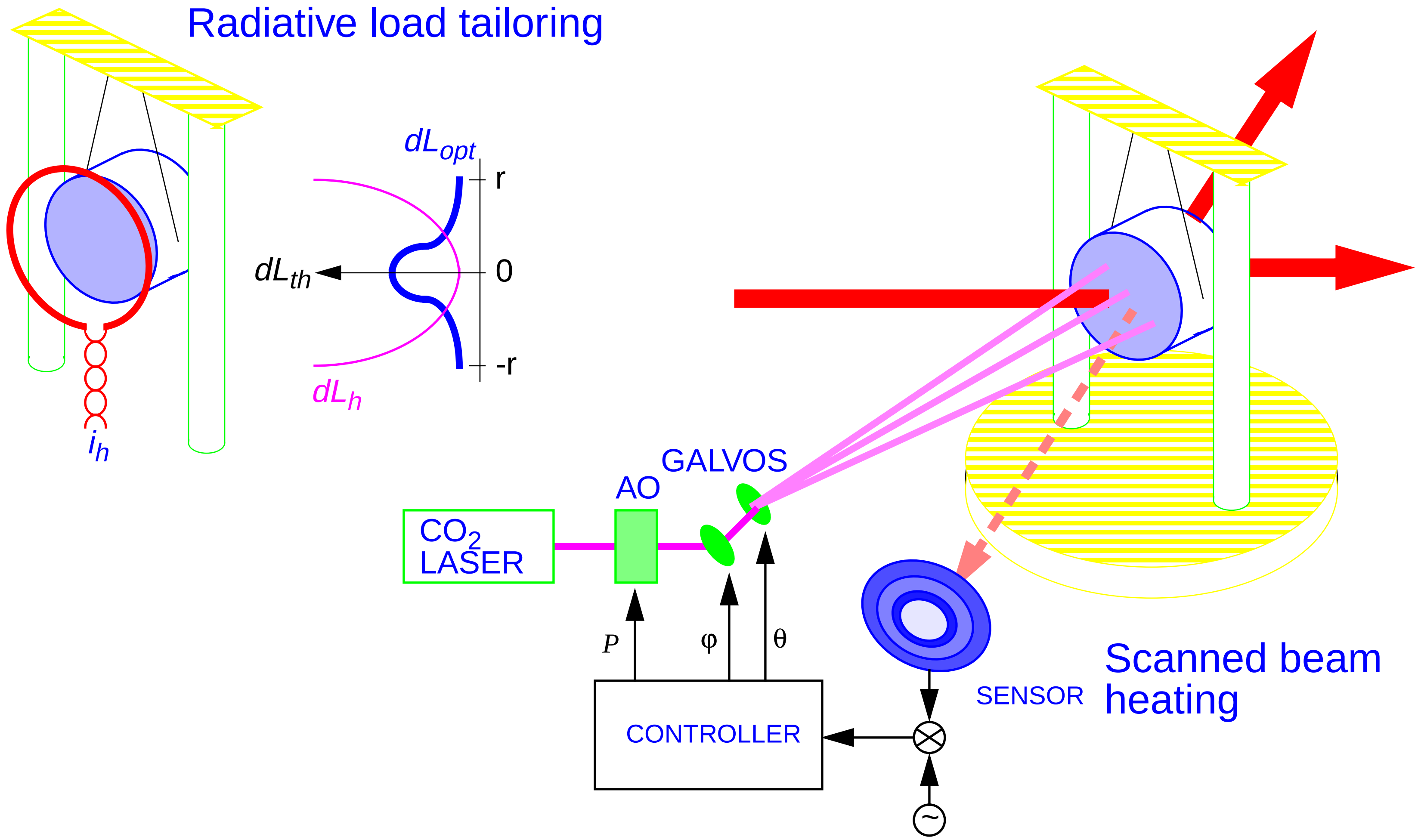
- Thermal lensing forces polished-in curvature bias on LIGO I core optics for cavity stability at operating temperature
- LIGO II will have ~20X greater laser power, ~3X tighter net figure requirements

  - higher order (nonspherical) distortions significant; prepolished bias, dynamic refocusing not adequate to recover performance
  - possible bootstrap problem on cold start
- Test mass & coating material changes may not be adequate
  - SiO_2 has low k_{th}, high dn/dT, but low bulk absorption
  - Al_2O_3 has higher k_{th}, moderate dn/dT, but high bulk absorption (so far...)
  - coating improvements still speculative

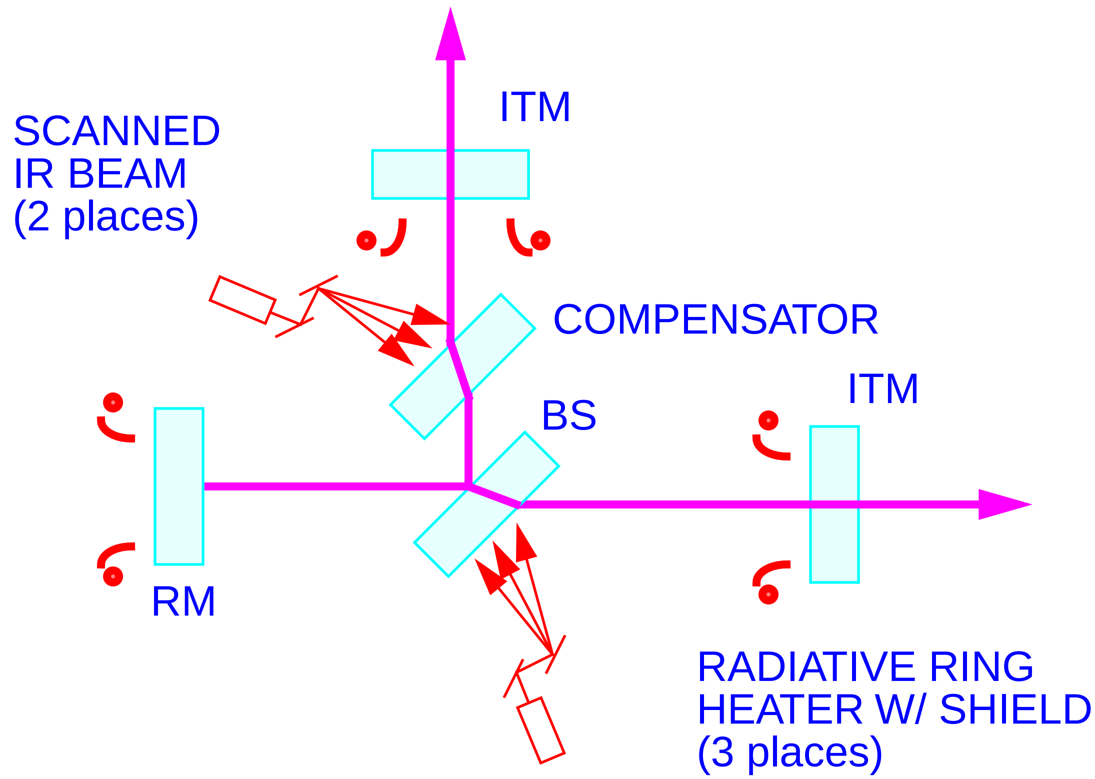
Sensing & Actuation

- Extend LIGO I "WFS" to spatially resolve phase/OPD errors
  - scanning "Phase Camera" (Adhikari, MIT)
  - staring "Bullseye WFS" (Mueller, UF)
- Thermal actuation on core optics
  - Noncontact actuator with minimal spurious phase noise
  - Time constants matched to disturbance timescales
- Two actuators in development
  - Passive radiative ring heater and low-emissivity shields
    - Only copes w/axisymmetric errors, but minimal potential for spurious noise
  - Scanned directed beam
    - Arbitrary spatial correction, but induced thermoelastic noise is a concern

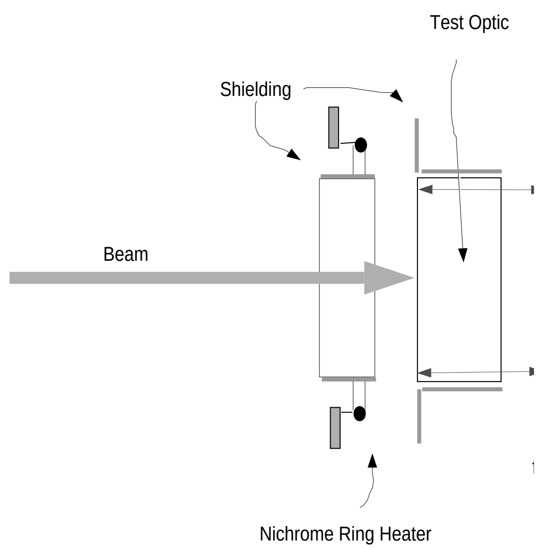
Thermal OPD Actuators

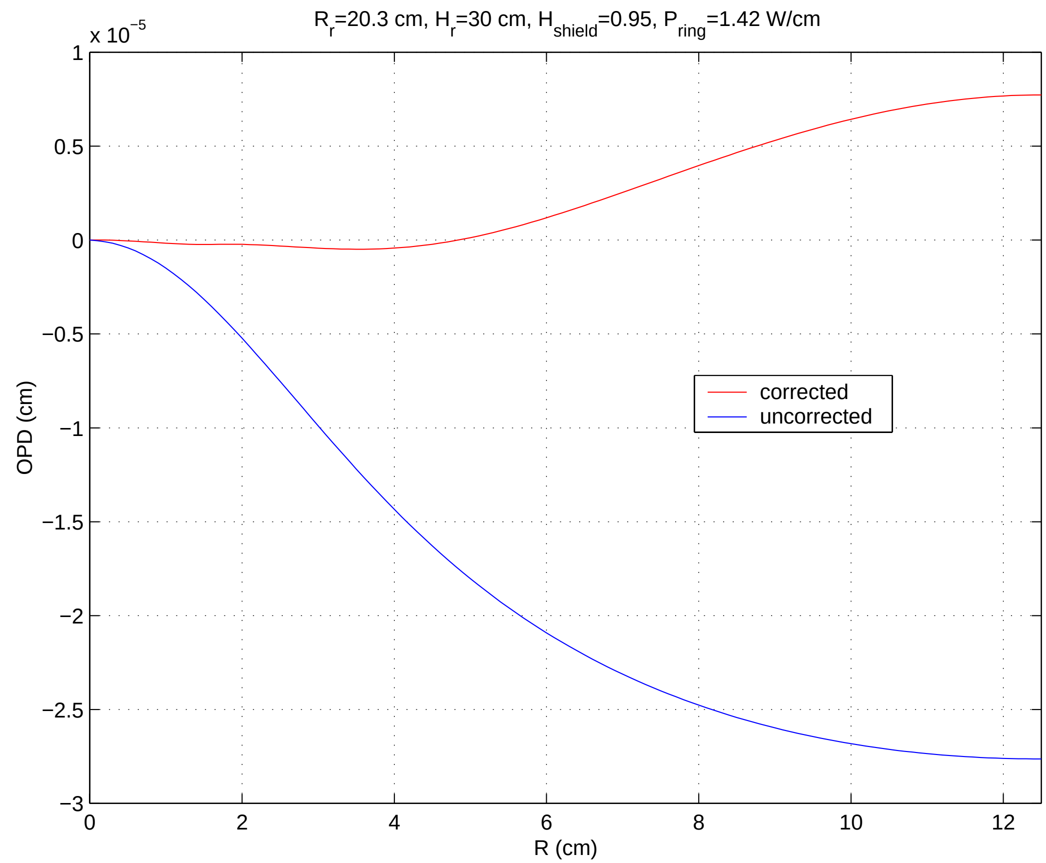


Implementation (SRM and ETM's not shown)

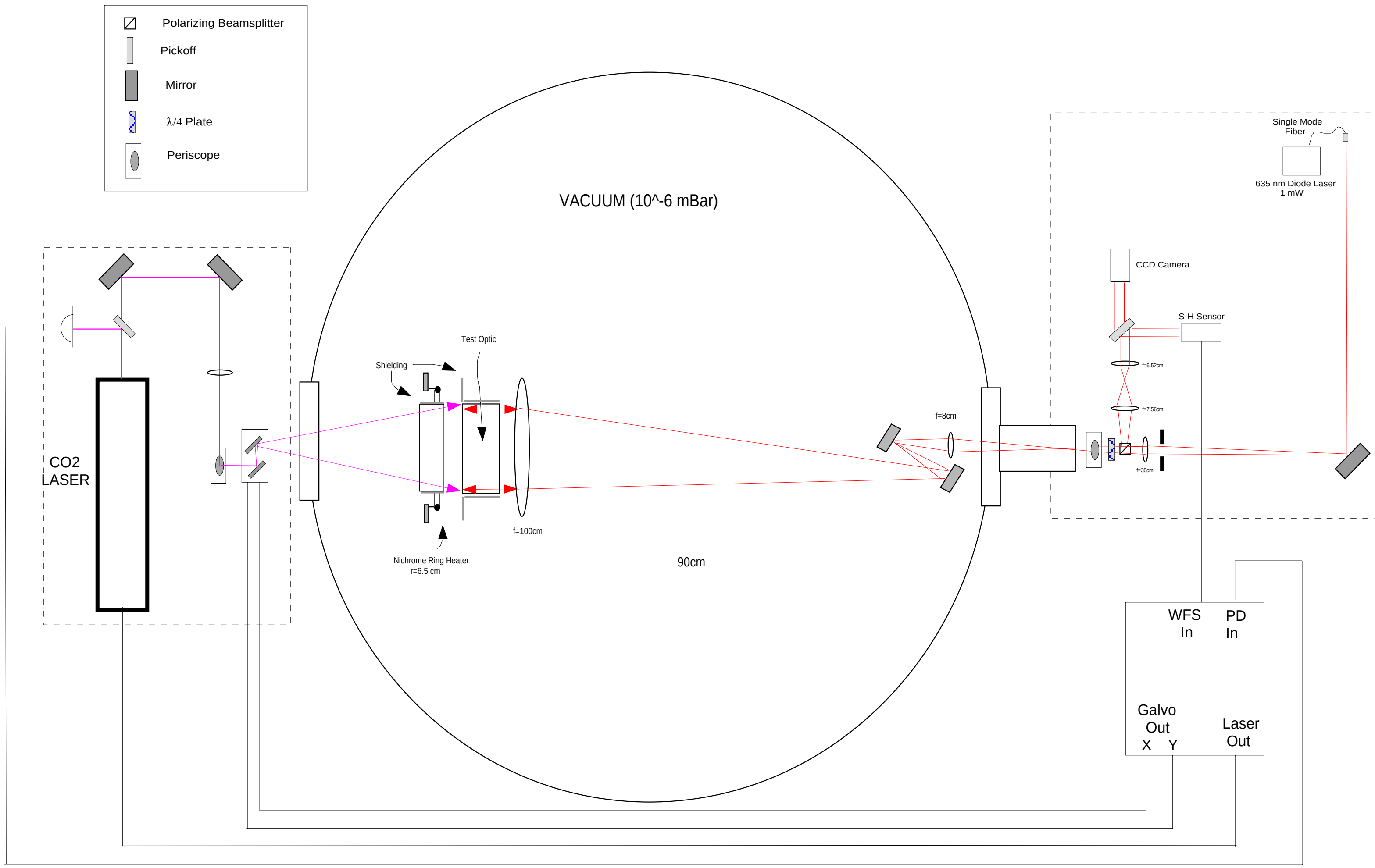


FEA model w/correction: ring heater + cylindrical radiation shield





AOTC Experiment at MIT



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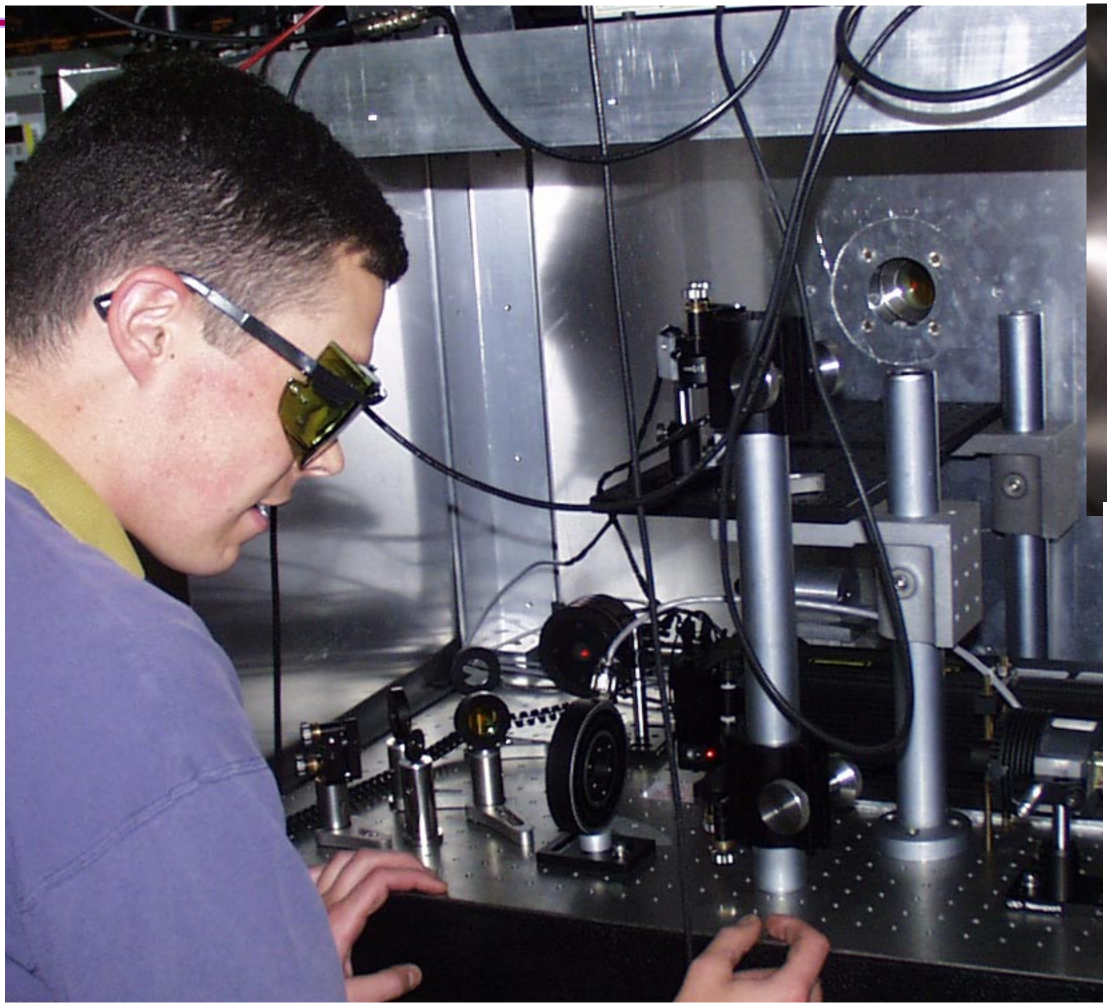
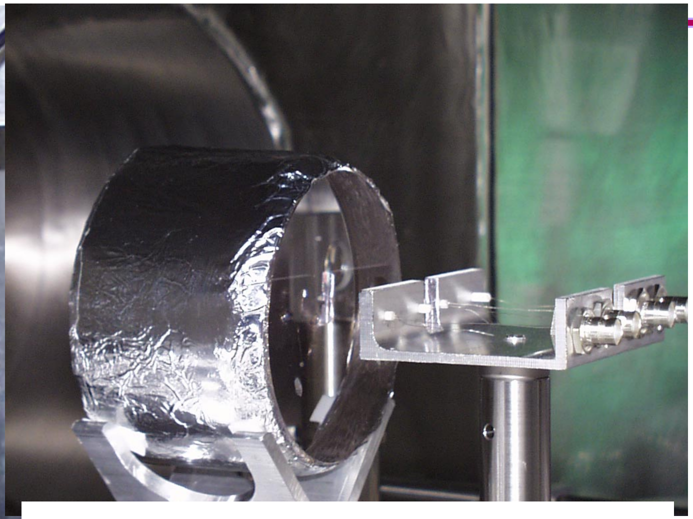
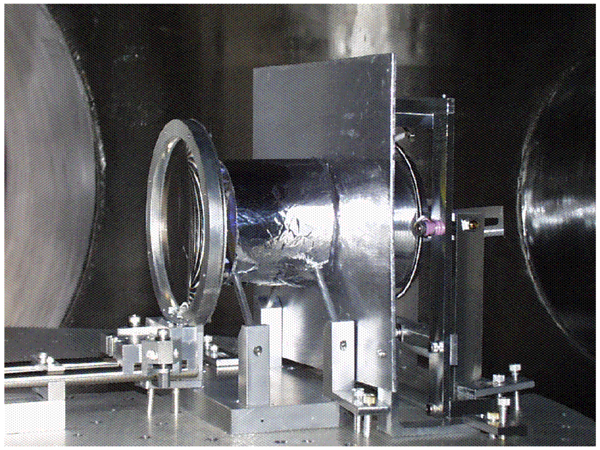
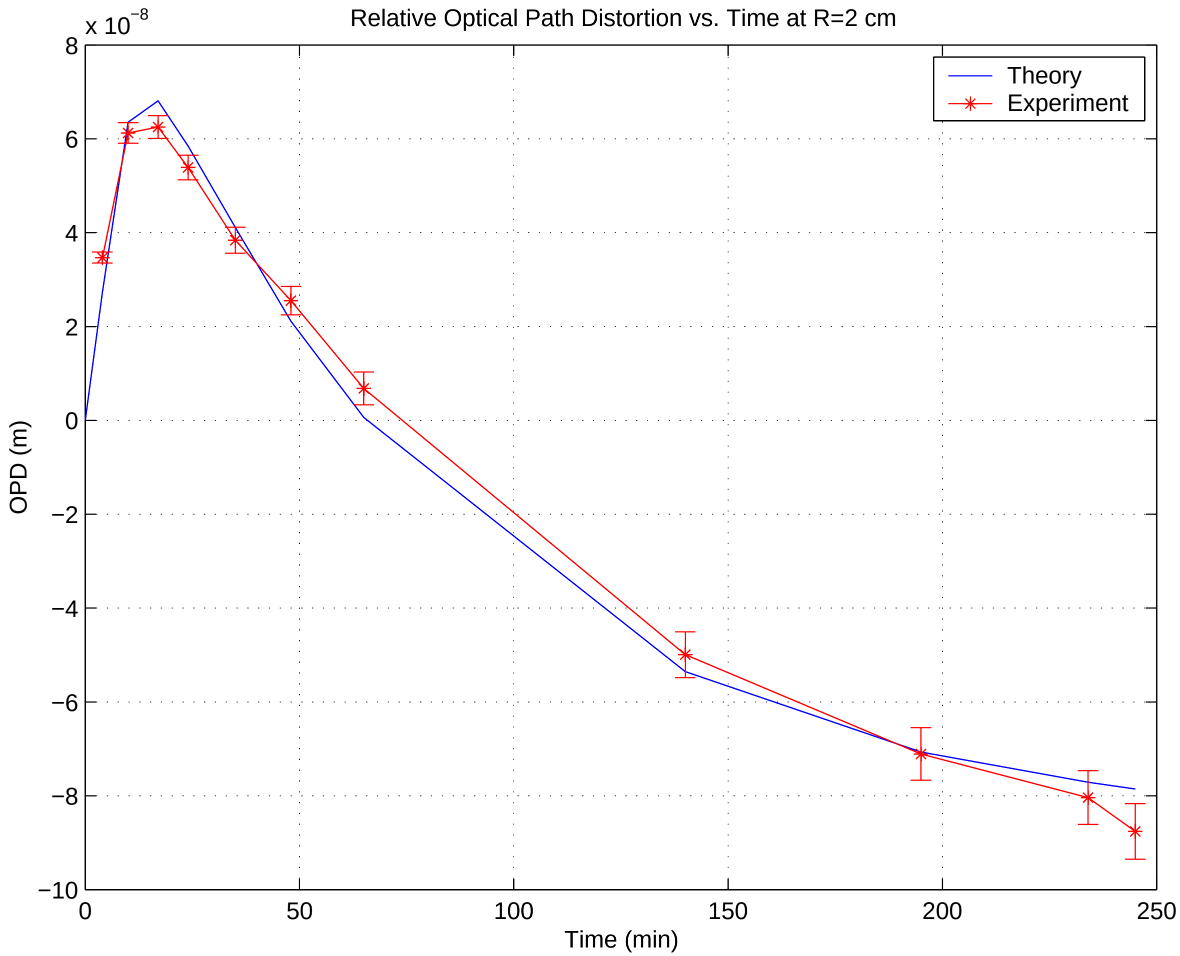


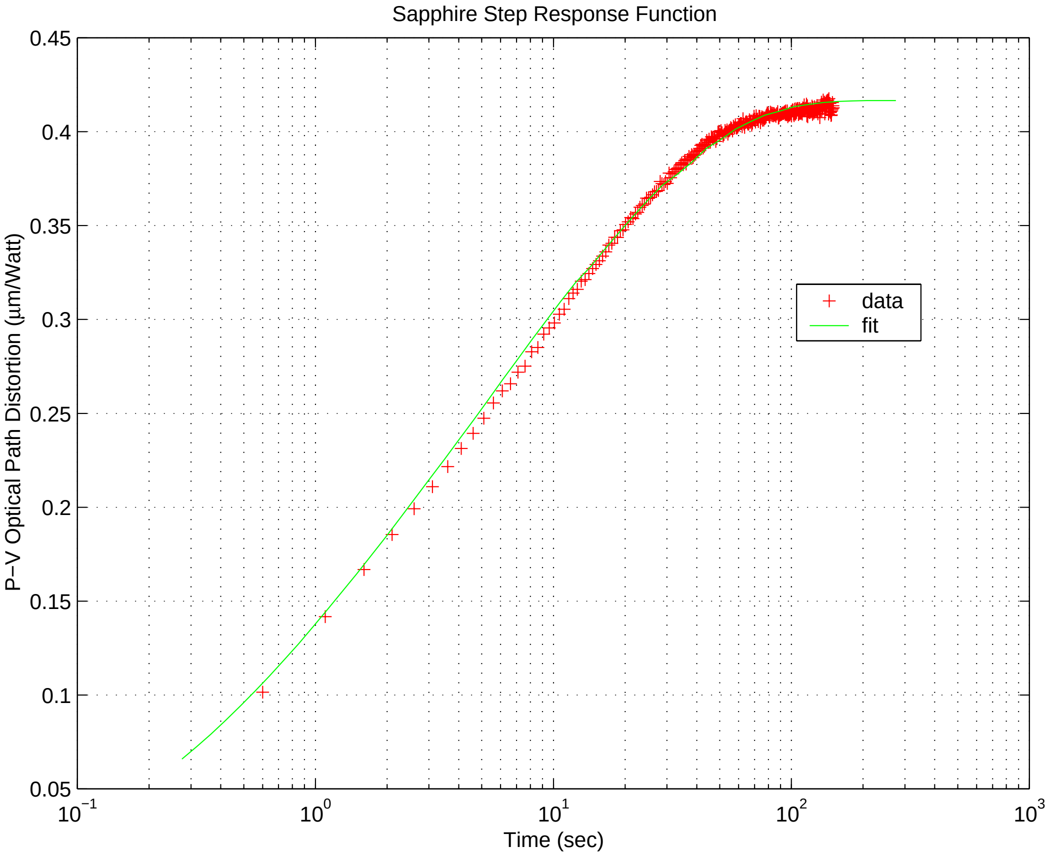




OPD vs. t, ring heater w/SiO2 test optic



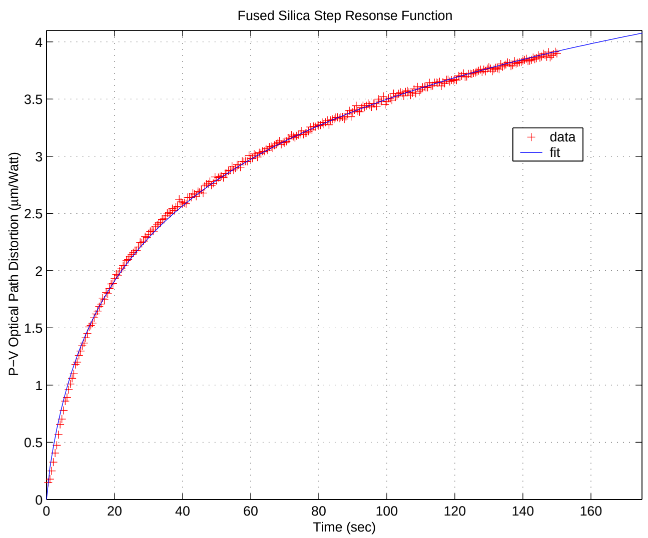
Directed Beam Compensation Tests



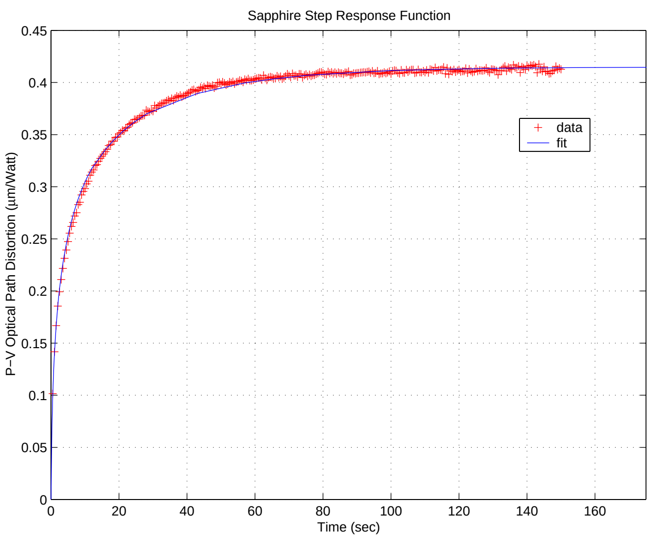
(neat sideshow: accurate constraint of sapphire material properties)

Measure waist, power; fit thermal OPD vs. time by adjusting α/k_{th}, $(dn/dT)/k_{th}$, k_{th}/C_v

SiO_2:
$(dn/dT)/k_{th}$ ~ 7.61 μm/W,
k_{th}/C_v ~ 8.7e-3 g/cm/s



Al_2O_3(c-axis):
$(dn/dT)/k_{th}$ ~ 0.252 μm/W,
k_{th}/C_v ~ 0.353 g/cm/s,
α/k_{th} ~ 0.119 μm/W



Thermal Compensation: Issues

- Total heat deposited & net temperature rise
  - ◊ "Efficient" compensation will ~ double net ΔT w.r.t. ambient
  - ◊ 30K total rise plausible, would increase kT noise 5%
- Noise
  - ◊ Thermoelastic response to varying beam intensity/position (for sapphire)
  - ◊ Developing time-dependent thermal FEA to model better
- Absorption spatial inhomogeneity
  - ◊ Determines pixellation, complexity/depth of compensation required
- Net efficacy & trade with optics/material improvements
  - ◊ Depends on sensitivity of IFO sensing to figure errors & their spatial scales

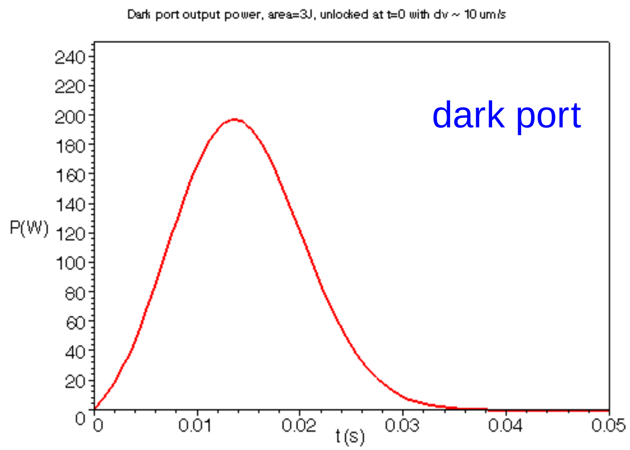
Thermal compensation: Status & plan

- 1Q'01: Proof-of-concept experiment initial results
  - ◊ Model validation for FE code & parametrizations for efficient incorporation in Melody
  - ◊ Verification of time dependence to feed E2E simulation
  - ◊ Improved requirements definition
- 3Q'02: Full scale radiative compensator demonstration
  - ◊ Engineering prototype at full mechanical scale (time constants, etc.)
  - ◊ Also demo main parts of wavefront error sensing technology
- 4Q'04: Full scale directed beam actuation demonstration
  - ◊ Exercise actuation basis transform, optimum pixelization

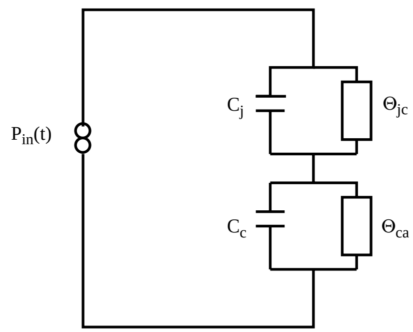
Photodetectors: optical & thermal requirements

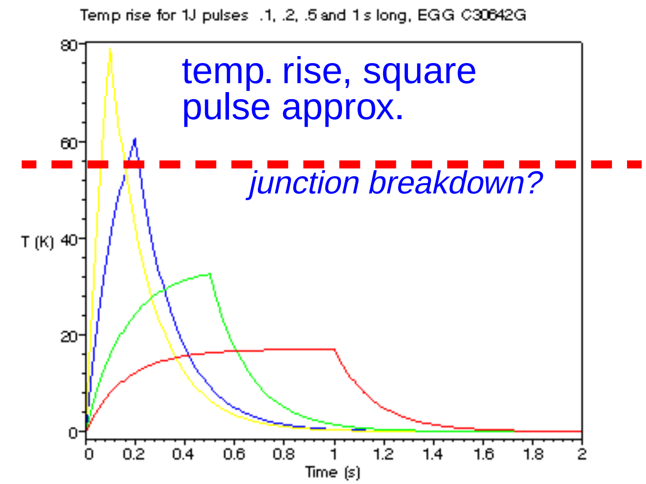
- CW power handling
  - "Dark" port with/without active thermal compensation: 1W? 10W?
- Transient power handling
  - reflection from PRC, MC ; full incident power, spike to 4x incident on unlock
- quantum efficiency
  - shoot for 90% (trades w/laser power, but poorly)
- backscatter
  - need 10-100 X improvement over LIGO I diodes (assuming Faraday isolator)

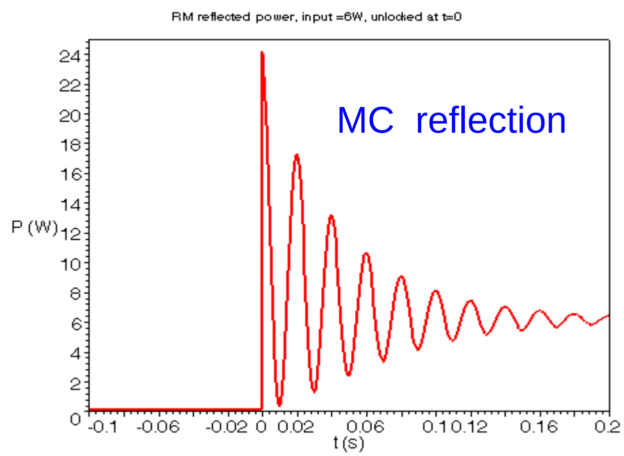
PD power transients (conceptual)

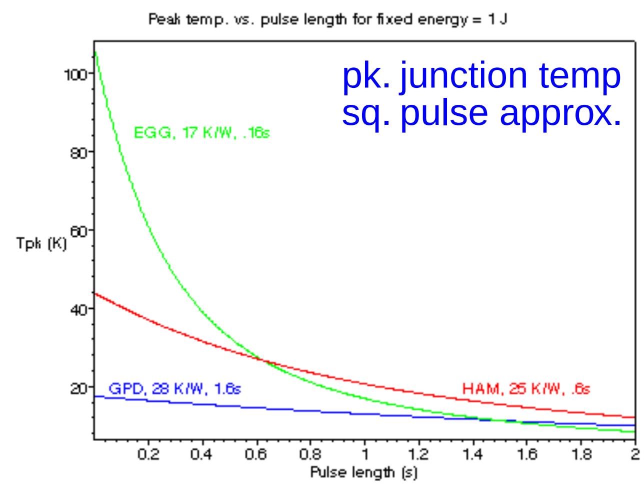


thermal device model





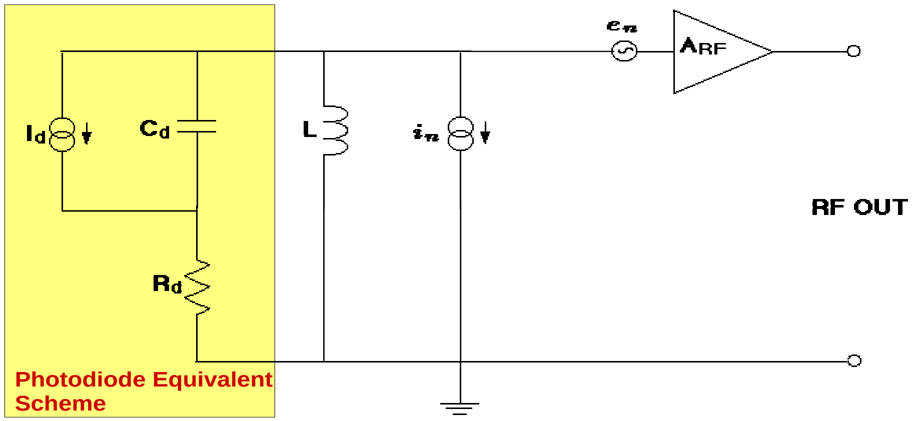




Electrical & signal requirements (RF)

- RF frequency $f_{RF} \approx$ 100 MHz (for likely schemes)
- SNR (i.e., 'shot:electronic noise ratio')
  - $\frac{e_{elec}^2}{e_{shot}^2} = \frac{1}{2eI_{DC}K_{mod}}\left(\frac{4k_BT}{Z_D} + \frac{e_n^2}{Z_D^2} + i_n^2\right)$

    $Z_D(\omega_0) = \frac{1}{R_D\omega_0^2C_D^2}$
  - damage -> lower I_{DC}
  - SNR -> raise I_{DC}
  - e.g., 1.2 W, 1 nV/√Hz, *N*=10 diodes => $|Z_D(\omega_0)| > 150\Omega$
  - EGG G30642G, 100 MHz: $|Z_D(100\text{MHz})| \approx 54\Omega$ (OK @29 MHZ, NG@ 100 MHz)



Electrical & signal (DC readout)

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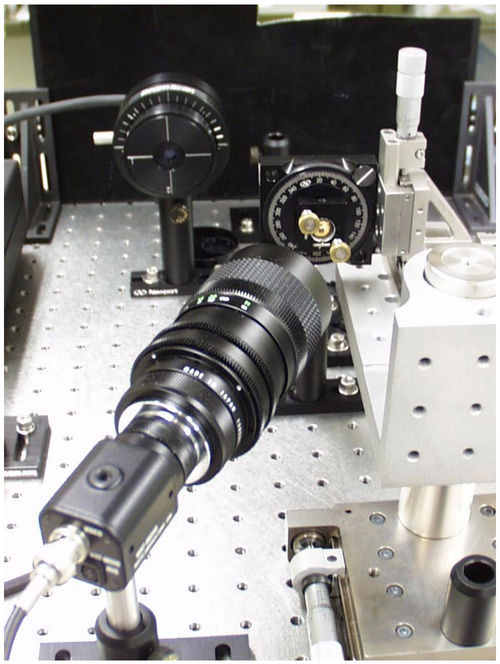
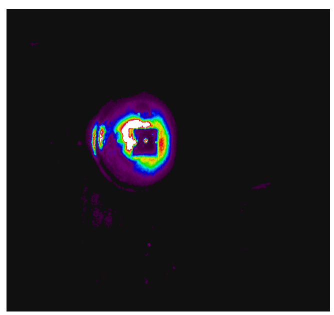
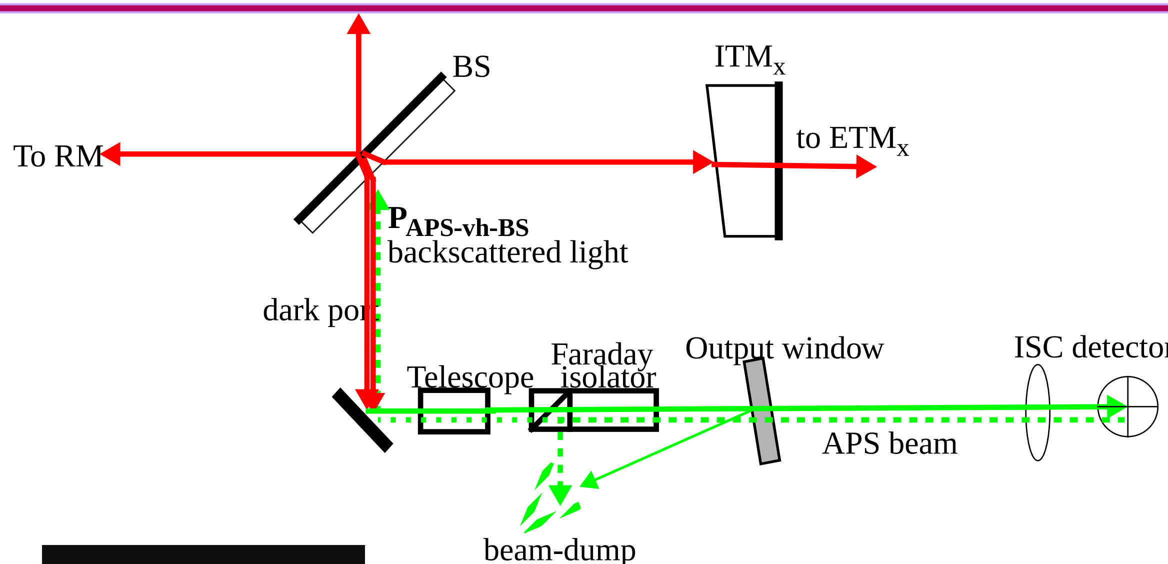
Photodetector backscattering







LIGO II Photodetectors: Status & Plan

- Requirements definition & simulation
  - First-cut Requirements draft circulated for discussion at LSC 3/00
  - additional Melody & FFT simulations required to bound steady-state power
  - additional E2E simulations required to bound transient power
  - selection of modulation/readout configuration will determine frequencies
- Device fabrication
  - High power custom RF devices now being fabricated by D. Jackrel at Stanford
- Testing
  - MIT PD test rigs upgraded to *f* > 125 MHz, P > 0.5 W /diode, B < 10^{-6} sr^{-}

Likely PD Specs for LIGO II Power and Sensitivity

Parameter	*LIGO I*	*LIGO II guess*
Steady-state power	0.6 W	3 W[a] ?
Transient damage	3 J / 10 ms	100 J / 10 ms ?
Signal/Noise	1.4×10^{10} $Hz^{1/2}$	3.1×10^{10} $Hz^{1/2}$
Quantum efficiency	80%	90%
Spatial uniformity	1% RMS	0.1% RMS ?
Surface backscatter	10^{-4} /sr	10^{-6} /sr[b]

a. Assumes significant improvement in contrast defect & cancellation of thermal lensing

b. Assumes Faraday isolator and seismic isolation of detector

Photon Recoil Drive for Test Masses

- Problem: eliminating attachments to test masses (magnets etc.) in LIGO II may leave insufficient actuation bandwidth for angle/length control actuation
- Pure actuation from upper stages (a la “marionette”) may not offer sufficient bandwidth (TBD)
- Electrostatic actuators promising, but noise susceptibilities are hard to exclude conclusively (patch effect, nonlinear upconversion,...)
- Photon recoil drive offers relatively simple non-contact drive alternative with well-defined limits

Photon recoil drive dynamic range

- Dynamic range follows from power available:

$$\ddot{x}(t) = \frac{2P(t)}{Mc} \longrightarrow x_{RMS} = \frac{2P_{RMS}}{4\pi^2 f^2 Mc} \approx 5.6\times10^{-13}\,\mathrm{m}_{RMS}\cdot\left(\frac{10\ \mathrm{Hz}}{f}\right)^2\cdot\left(\frac{P_{RMS}}{10\ \mathrm{W}}\right)\cdot\left(\frac{30\ \mathrm{kg}}{M}\right).$$

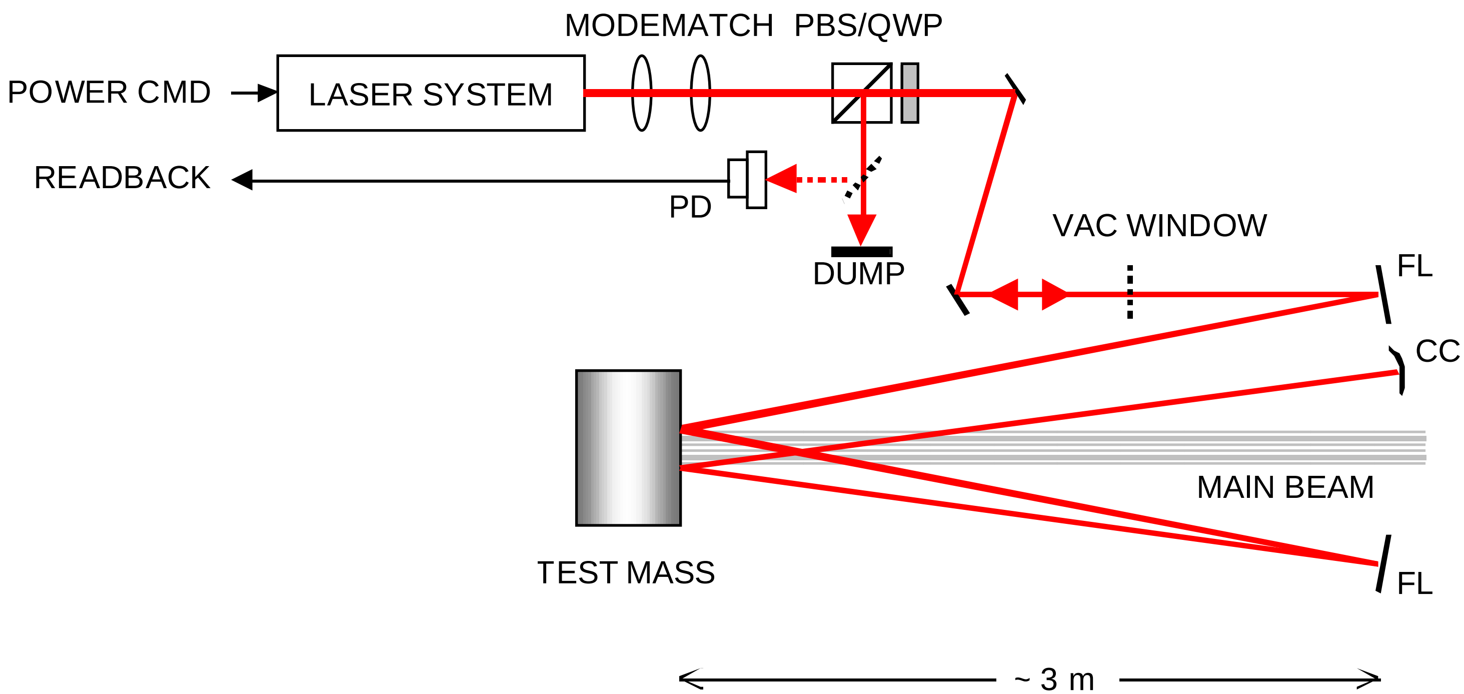
- Noise due to intensity fluctuations constrained by sensitivity goal, e.g.

$$\tilde{P}(10\ \mathrm{Hz}) \le 4.0\times10^{-7}\,\frac{\mathrm{W}}{\sqrt{\mathrm{Hz}}}\cdot\left(\frac{30\ \mathrm{kg}}{M}\right),$$

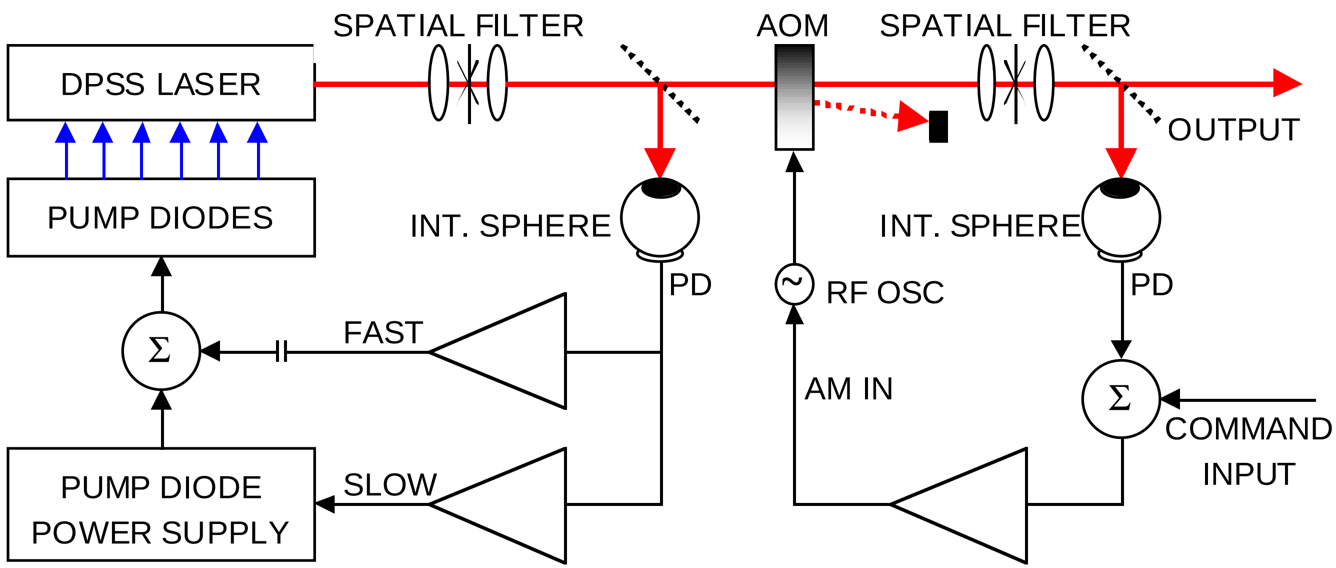
- Taking "reasonable" RIN (e.g., shot noise in 100 mW sample $\tilde{P}(f)/\overline{P} = \sqrt{2h\nu/\overline{P}_{sample}} \approx 1.4\times10^{-9}/\sqrt{\mathrm{Hz}}$) gives maximum power and thus dynamic range, e.g., $F_{p-p} \le 2\overline{P}_{max}/c \approx 2\times10^{-6}\ \mathrm{N}$ for ~ 290 W reflected power.

Multibounce beam delivery

(N=4 bounces depicted for clarity)



Low-RIN photon drive laser system



- Cascaded intensity stabilization stages
- Spatial filters, int. spheres to insure “true” RIN cancellation

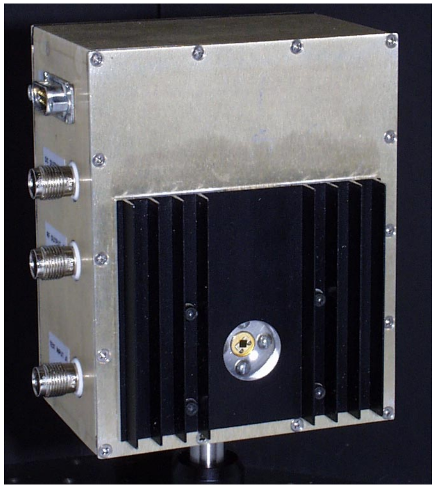
Photon drive issues & concerns

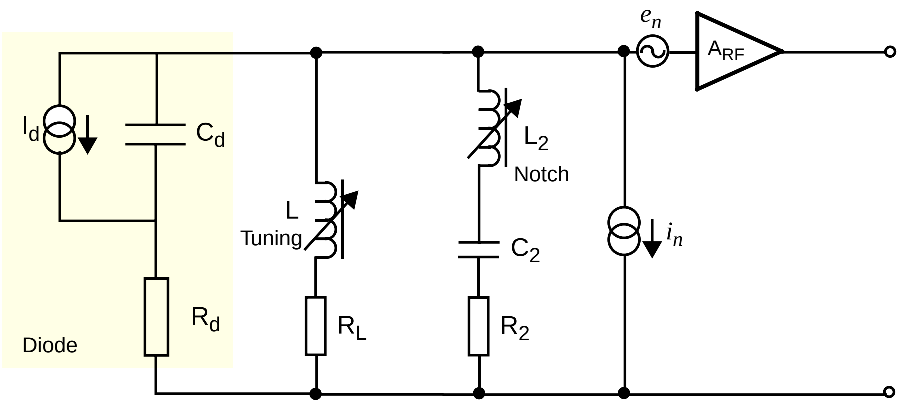
- How much peak force is actually required?
  - ◊ Depends on detailed apportionment of corrective signals between upper and intermediate stages
  - ◊ Depends on detailed "crossover" behavior and stability criteria
  - ◊ Also depends on narrowband features with high RMS (stack/suspension eigenmodes, internal mirror & suspension wire modes, etc.)
- Can low enough intensity noise be achieved?
  - ◊ Probably, main IFO laser is more demanding
  - ◊ Question of technical trades, cost & complexity

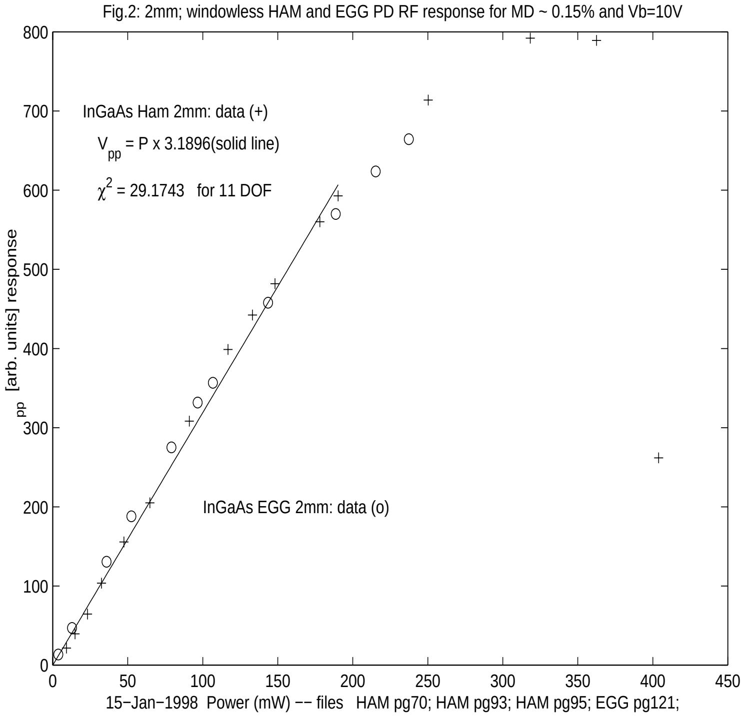
Photon Actuator Milestones

- 2Q'02: Initial demonstrator system commissioned
  - ◊ Single stage AM stabilization
  - ◊ Steerable White cell geometry & dynamics (small-scale)
  - ◊ Modeling completed for primary design requirements
- 2Q'03: Preliminary test results
  - ◊ Design iteration: dynamic range, power, bounce number, agility
  - ◊ Control specification
- 2Q'04: Final test results on iterated design
  - ◊ Sufficient to complete final design

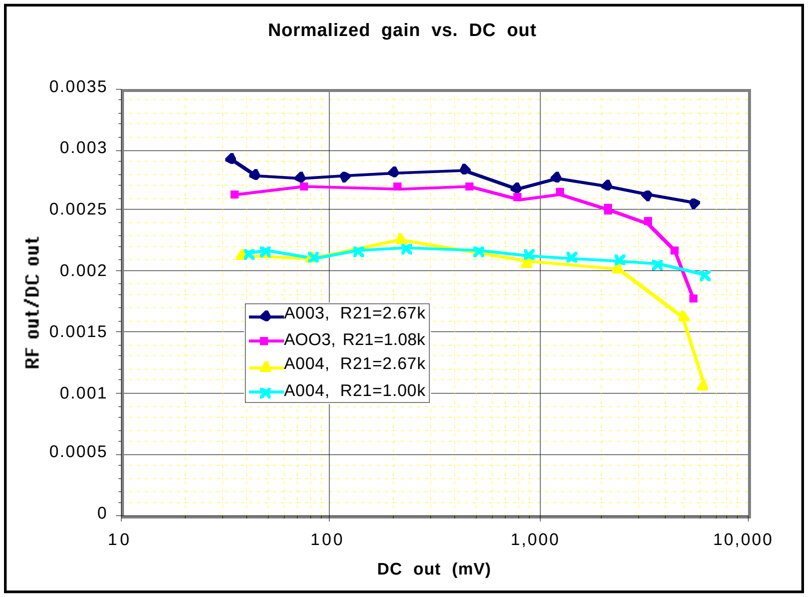
LIGO I RF Photodetectors

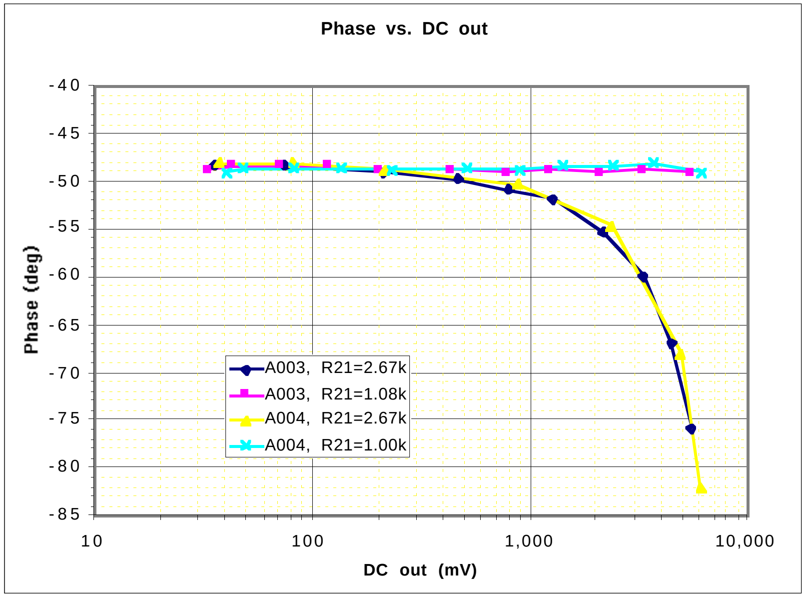






Linearizing RF response through feedforward I_{DC} bias compensation





ISC digital signal processing