Recycling Cavities Degeneracy Problems and Solution

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March 23, 2005

Outline of the talk

Problems associated with degenerated recycling cavities

- Power Recycling Cavity & RF Sidebands
- Signal Recycling Cavity & Signal Sidebands

Numerical simulation of a simplified dual-recycle IFO

- Tools (Modal expansion) & Simplified IFO model
- Quantitative description of the problem & Hints on solutions

A possible solution (change geometry of SR cavity)

- Add a lens: practical problems
- Move MMT in: preliminary design

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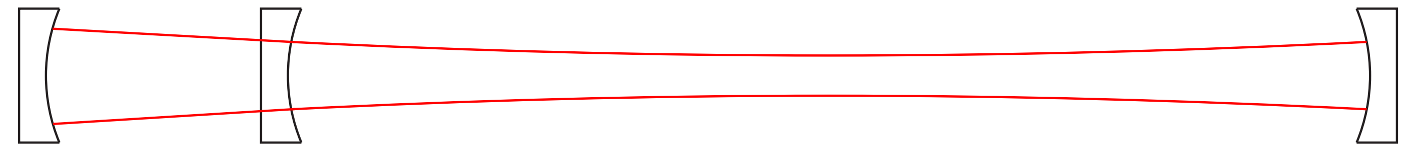
Fundamental Problem with Degenerated Cavities



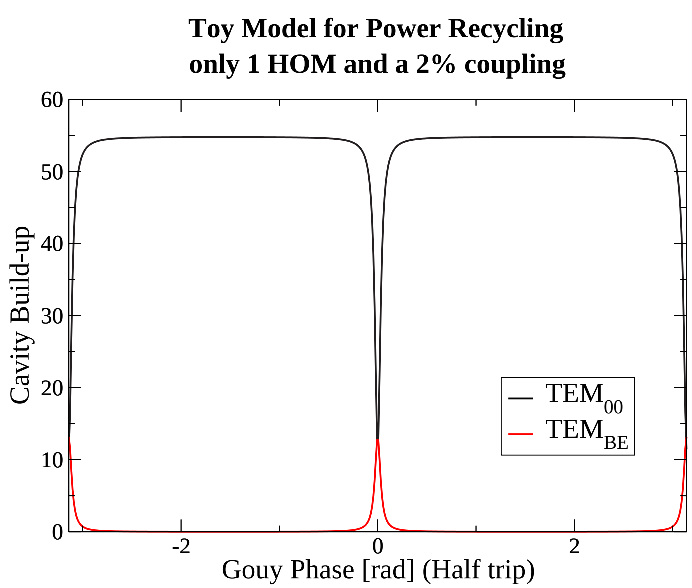
$g_{PRC} = 0.993$ $\quad \Delta\nu_{TEM} = 4.4$ **kHz** $\ll FWHM \approx 300$ **kHz**

$\longrightarrow$ all higher order modes resonant

Imperfections will scatter light into HOM

HOM's will build up and steal energy from the fundamental mode

Include thermal distortions and we are asking for a disaster



Problems with RF-sidebands in degenerated recycling cavity

- Reduces build up of RF-sideband easily by a factor 2!
- Apparent impedance mismatch will increase intensity in reflected field
- HOM-content will cause severe spatial mode mismatch between RF-sidebands and carrier
- Degeneracy distores alignment and Bullseye signals
- Puts additional requirements on thermal compensation

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Problems with Signal sidebands: Detailed model

SRC in AdvLIGO is degenerate

- **Fresnel Length** $r_F = \sqrt{\lambda N l} \simeq 3.3mm \ll w_m \simeq 6cm$
- **Guoy phase (Gaussian beam)** $\eta_{rc} = \arctan \dfrac{L_{rc}}{\pi {w_0}^2/\lambda} = 4.7 \times 10^{-4}$

  SR cavity HM Phase Width $\Delta\phi = 4.4 \times 10^{-2} \Longrightarrow \eta_{rc} \ll \Delta\phi$

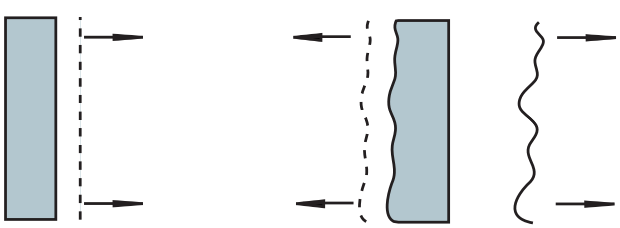
Problem: sensitive to mirror figure error & thermal aberration

- **Weak diffraction coupling $\Longrightarrow$ Geometric optics regime**

  Figure error sampled coherently, large phase front distortion
- **Close eigenvalues of optical modes (Hermite-Gaussian)**

  Strong mode mixing under perturbation
- **Geometric optics estimation** [E. Ambrosio et al]

  1% SNR loss requires $<$1nm r.m.s. figure error
- **Mode structure analysis carried out by simulation**



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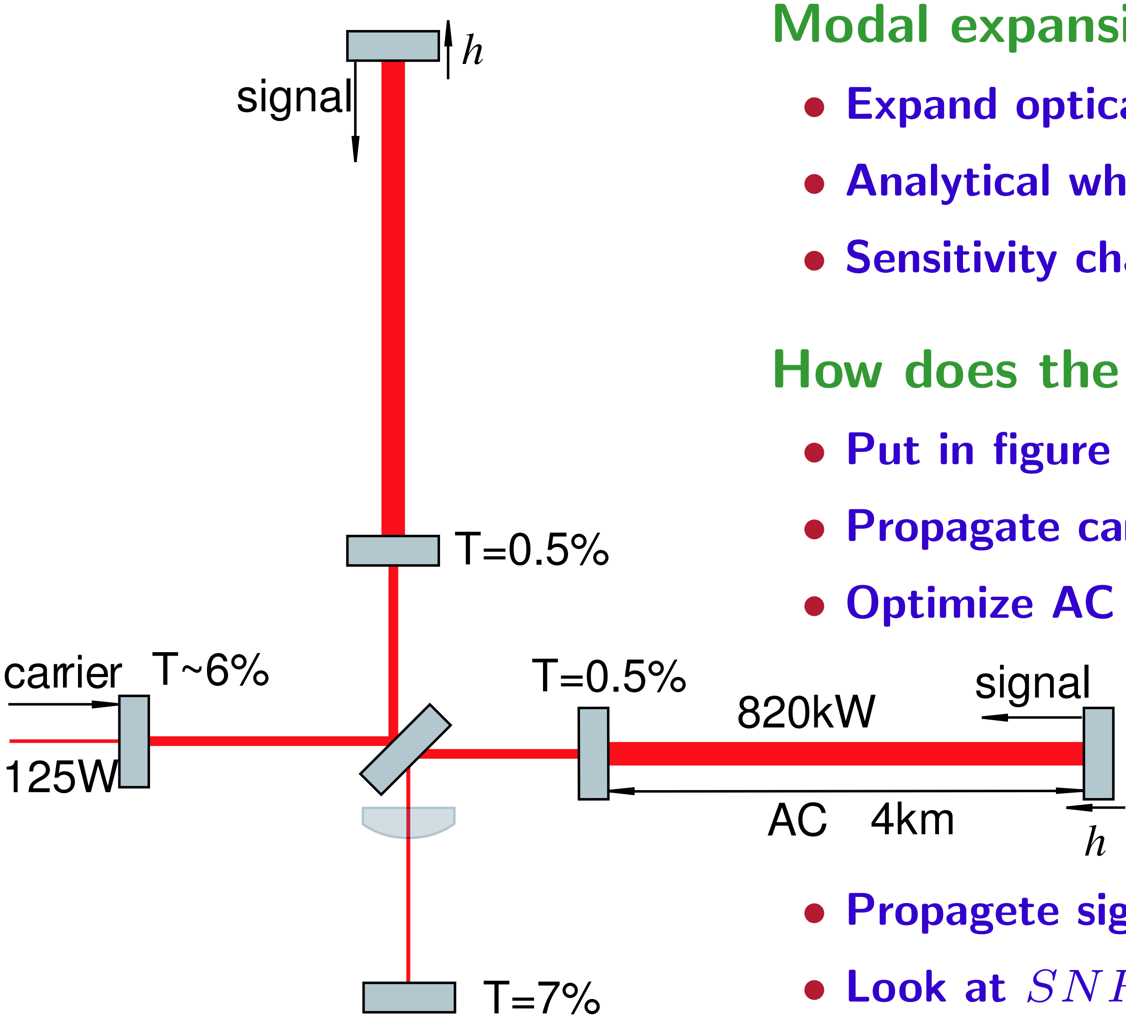
Interferometer simulation



Modal expansion

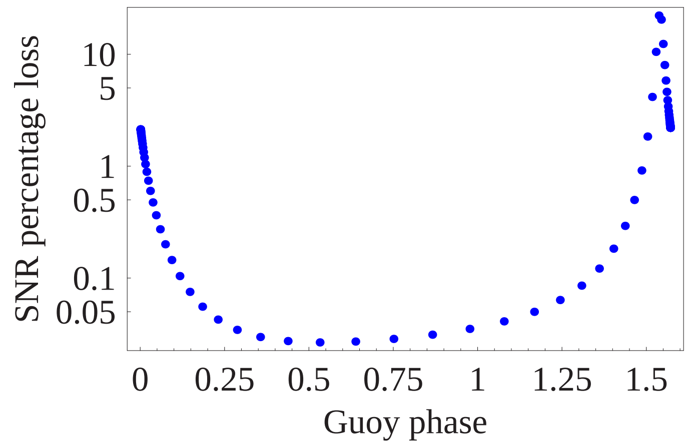
- Expand optical fields with Hermite-Gaussian modes
- Analytical when no diffraction loss
- Sensitivity changes quadratically at leading order

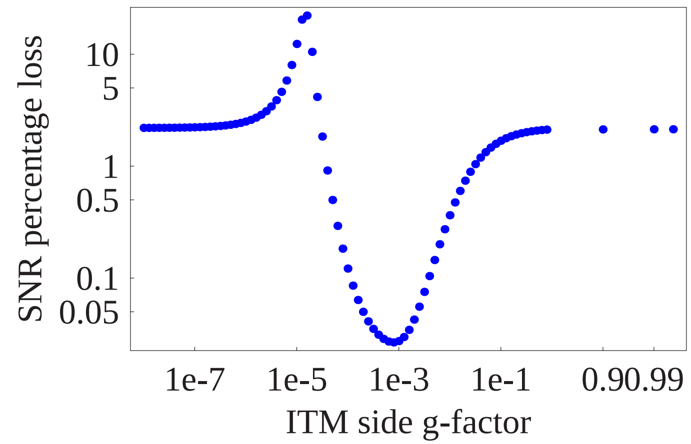
How does the simlation work

- Put in figure error by hand
- Propagate carrier through IFO
- Optimize AC carrier power by tuning PR cavity
- Generate signal sidebands at ETMs
- Propagete signal sideband through IFO
- Look at $SNR \propto \sqrt{P^{(0,0)}_{\text{sig out}}}$

Simulation results

Deferential curvature error in ITMs (3nm r.m.s. figure error)



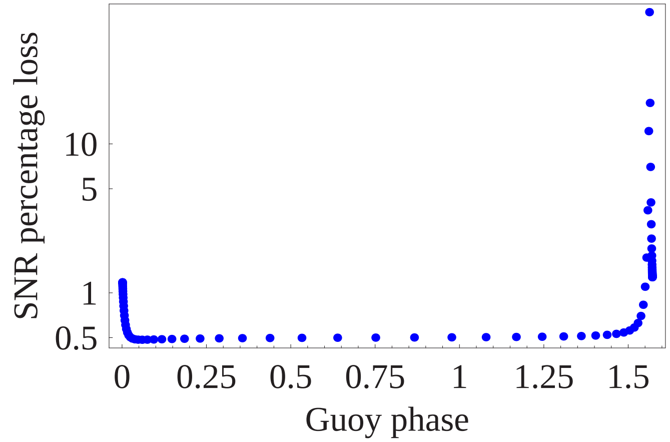


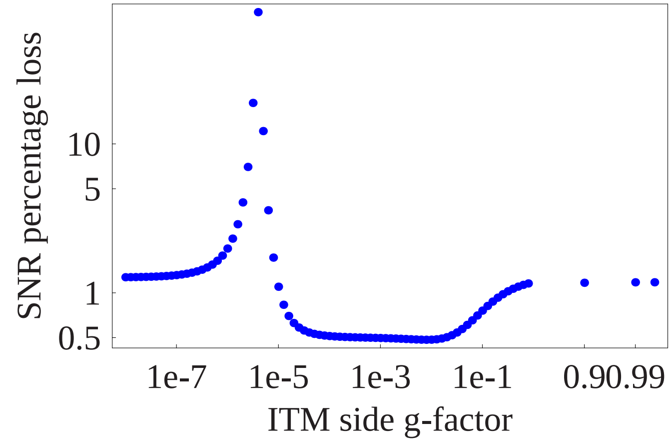
- Significant gain with non-degenerate SRC (Guoy phase ∼0.6)
- Not practical: g-factor ∼0.001

  Beam size: 28μm at waist; 47μm at SRM. Rayleigh length: 2mm
- First exited mode resonant when Guoy phase cancels SRC detuning

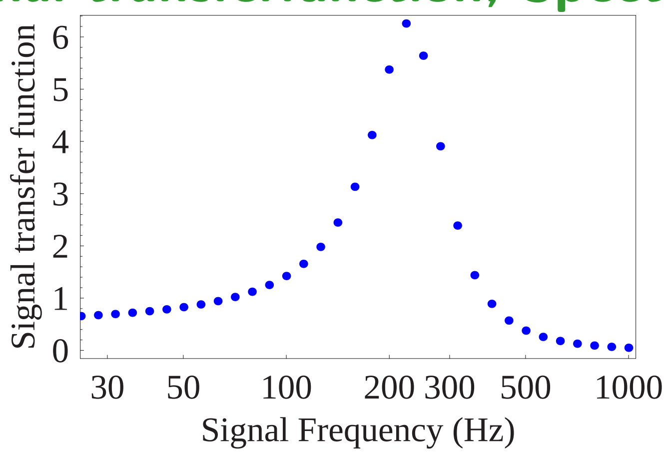
More results

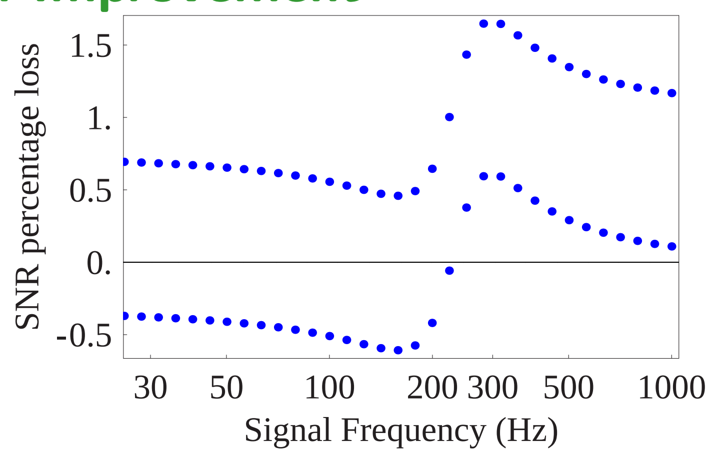
Deferential curvature error in ITMs; Narrow band





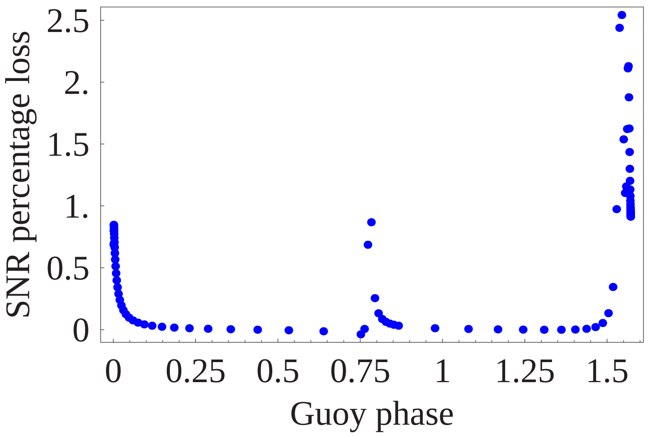
Signal transferfunction; Spectrum Improvement

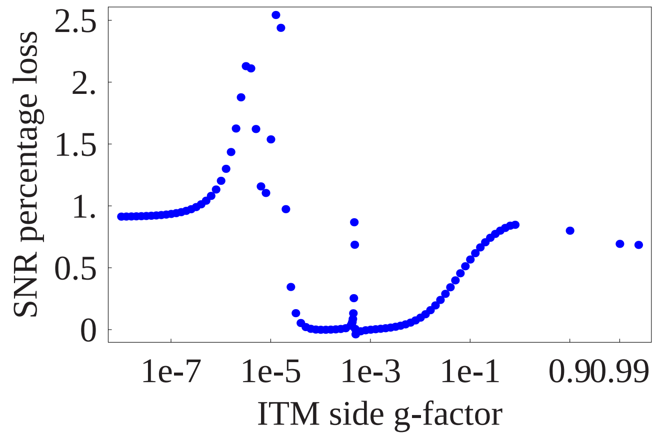




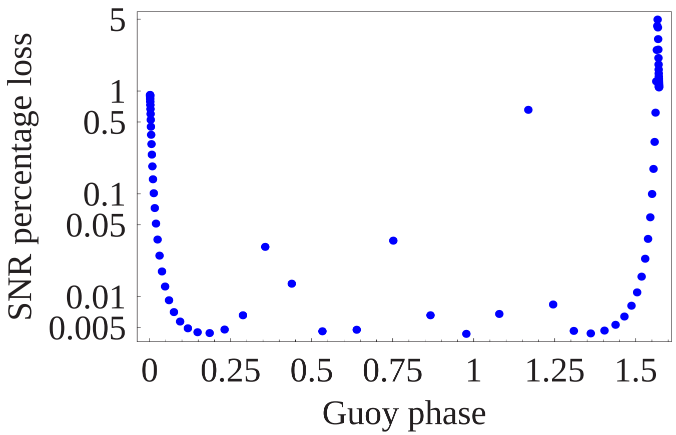
More results

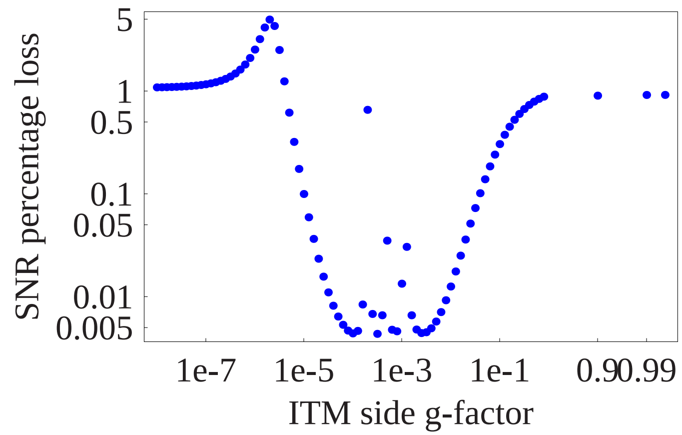
ITM curvature error (1.5nm) & SRM mode (4,0) error (1.5nm)



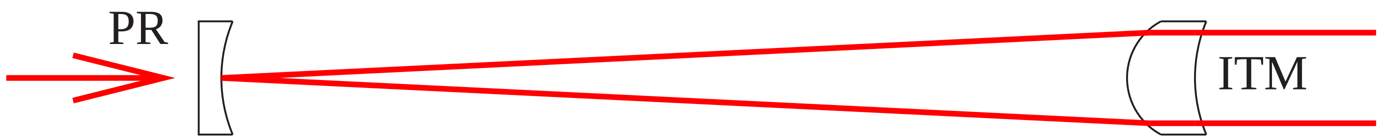


ITM mode (4,0) (0.05nm) & (8,0) error (0.05nm)

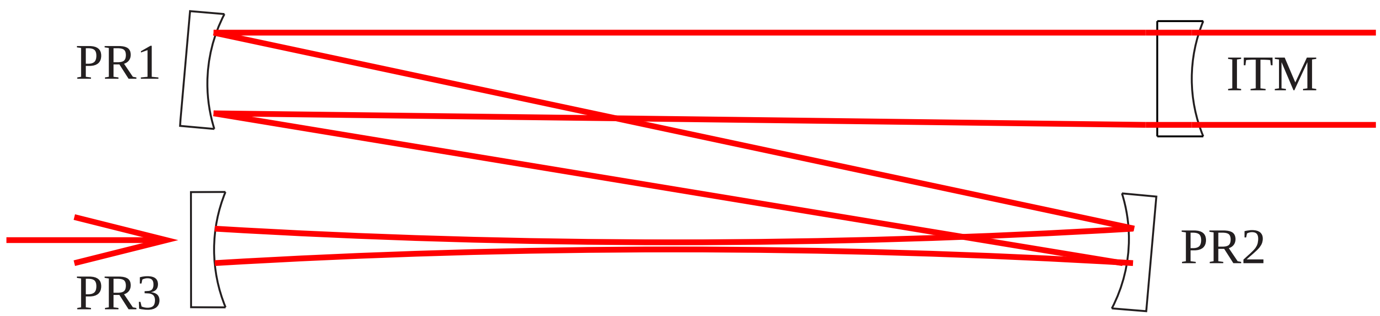




Possible Solutions



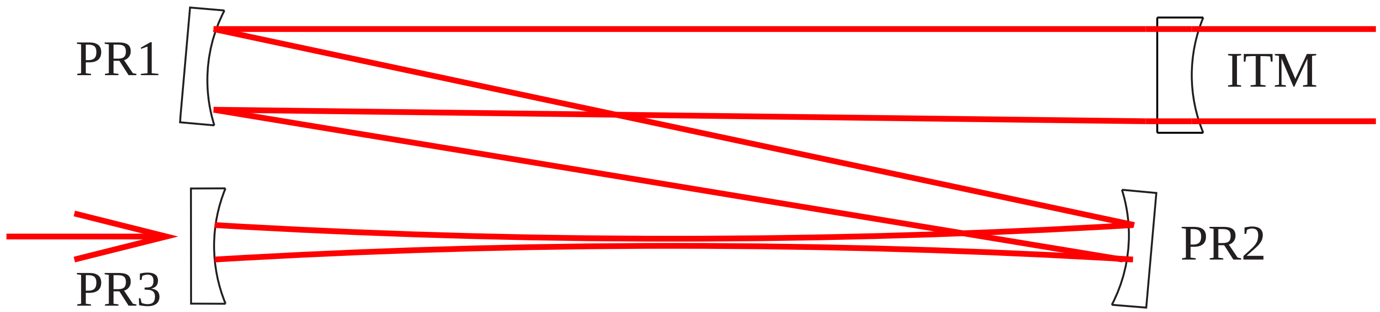
- Will create $\approx 100\mu$m beamsize on Recycling cavity
- Power density: ≈ 10 GW/m^2 **NOT A GOOD IDEA!**



- Beam sizes everywhere above 1.5 mm
- Any g-factor possible $\Longrightarrow$ Stable Recycling Cavity

$\Longrightarrow$ All HOM's non-resonant! **GOOD IDEA**

Additional benefits



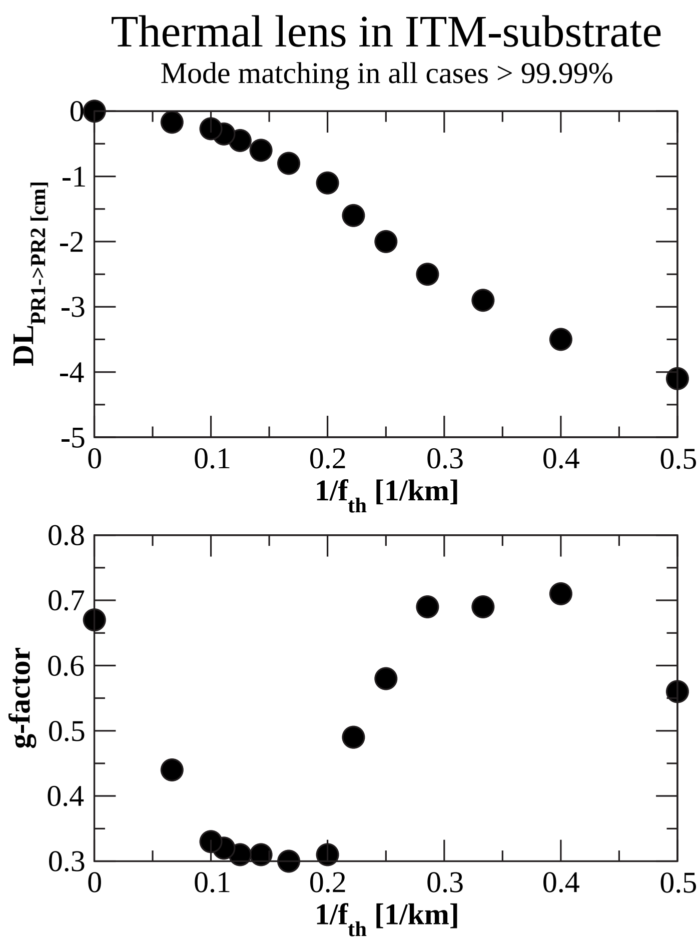
Mode matching between recycling cavities and arm cavities changes with thermal lens in ITM and BS substrates

Difficult to predict and priorities of TCS should be

- optimize beam size with ITM TCS
- optimize contrast with BS TCS
- Not optimize mode matching of PRC or SRC

New design can optimize mode matching w/o changing RF-frequencies (Move PR2 and PR3).

Example: Thermal lens in ITM



Compensate thermal lens in ITM substrates:

Assume thermal lens of up to 2 km:

- **Move PR2 and PR3 by only 4 cm!**
- **Beam size on mirrors at least 1.5 mm**
- **g-factor between 0.3 .. 0.7**

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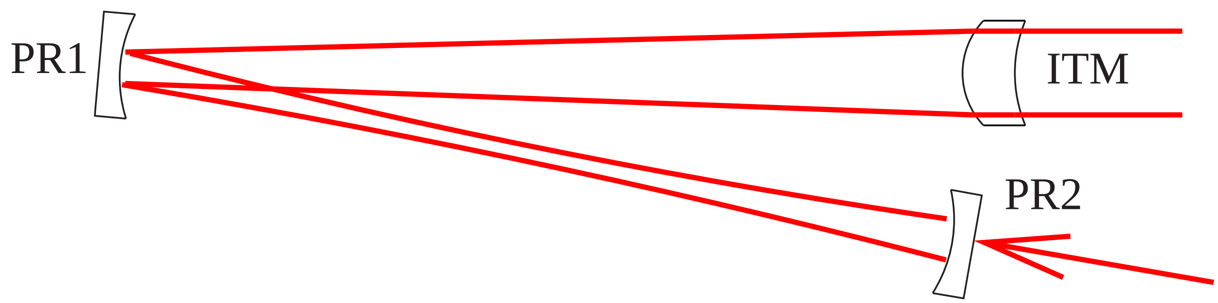
Future work

Fit in LIGO Vacuum envelope
Other Possible Design:



- Model Thermal lensing in new design (Melody)
- Calculate Alignment and Bullseye-Signals
- Pushing and lobbying ...

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Summary

Discussed Disadvantages of unstable recycling cavities

→ **Reduces RF-sidebands inside IFO**

→ **Increases reflected intensity**

→ **Jeopardizes alignment signals**

→ **Reduces Signal!**

Discussed design of stable recycling cavities

→ **Optimizes mode matching between RC's and arms**

→ **Maximizes Signal**

→ **Well defined alignment and Bullseye signals**

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