# Optical Design of the Advanced LIGO Detectors with Stable Recycling Cavities

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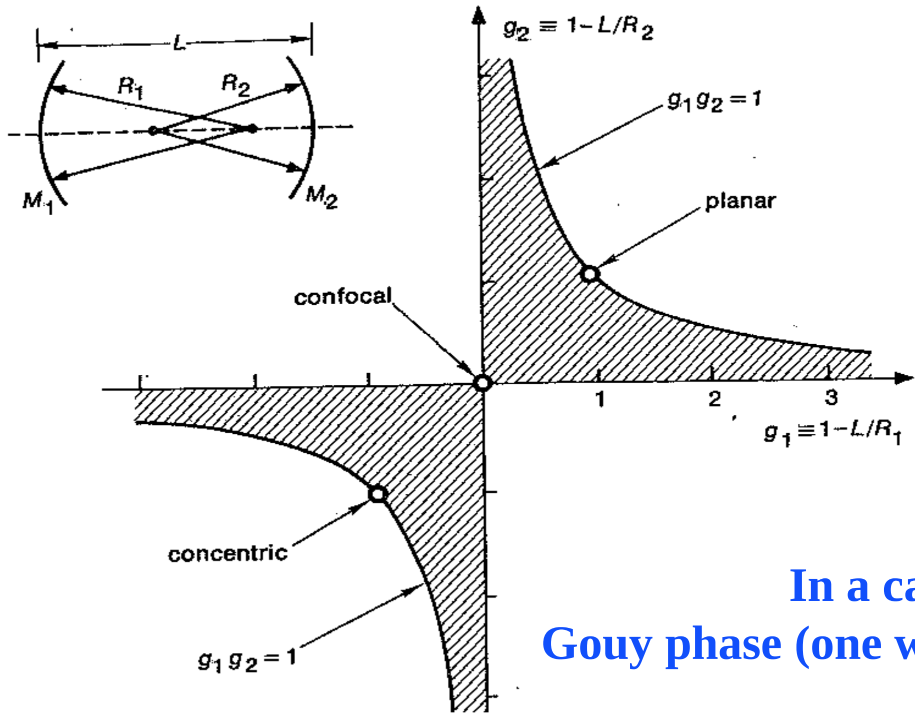
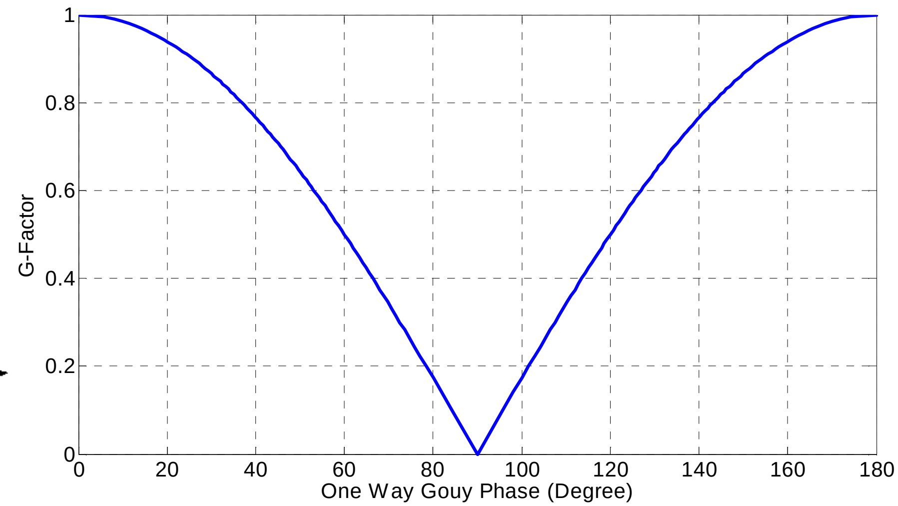
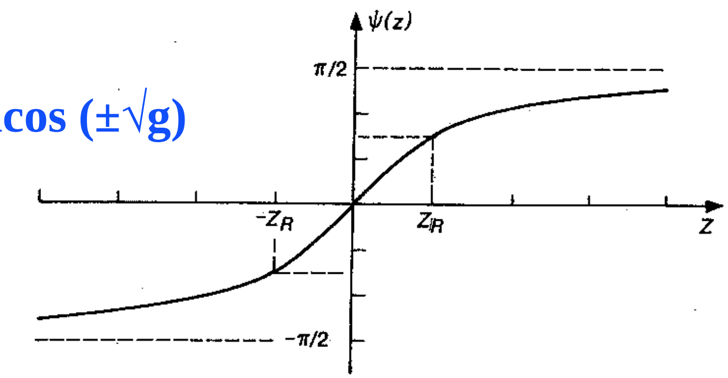
# Cavity Stability 101 (Lasers, Siegman)



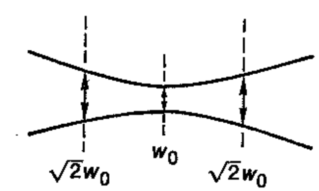

**In a cavity**

**Gouy phase (one way) = acos (±√g)**




$$\text{Gouy Pahse of Higher Order Modes} = (2p + m + 1) \times \psi(z)$$

$$z_R = \frac{\pi w_0^2}{\lambda} = \text{Rayleigh Range, and } \psi(z) = a\tan(z / z_R)$$




**where p is the radial index and m is the azimuthal mode index**
**Whenever Gouy phase becomes 180 degree (one way), we get high order resonances.**

# Marginally Stable Cavity
## Dual Recycled Cavity Enhanced Michelson Interferometer

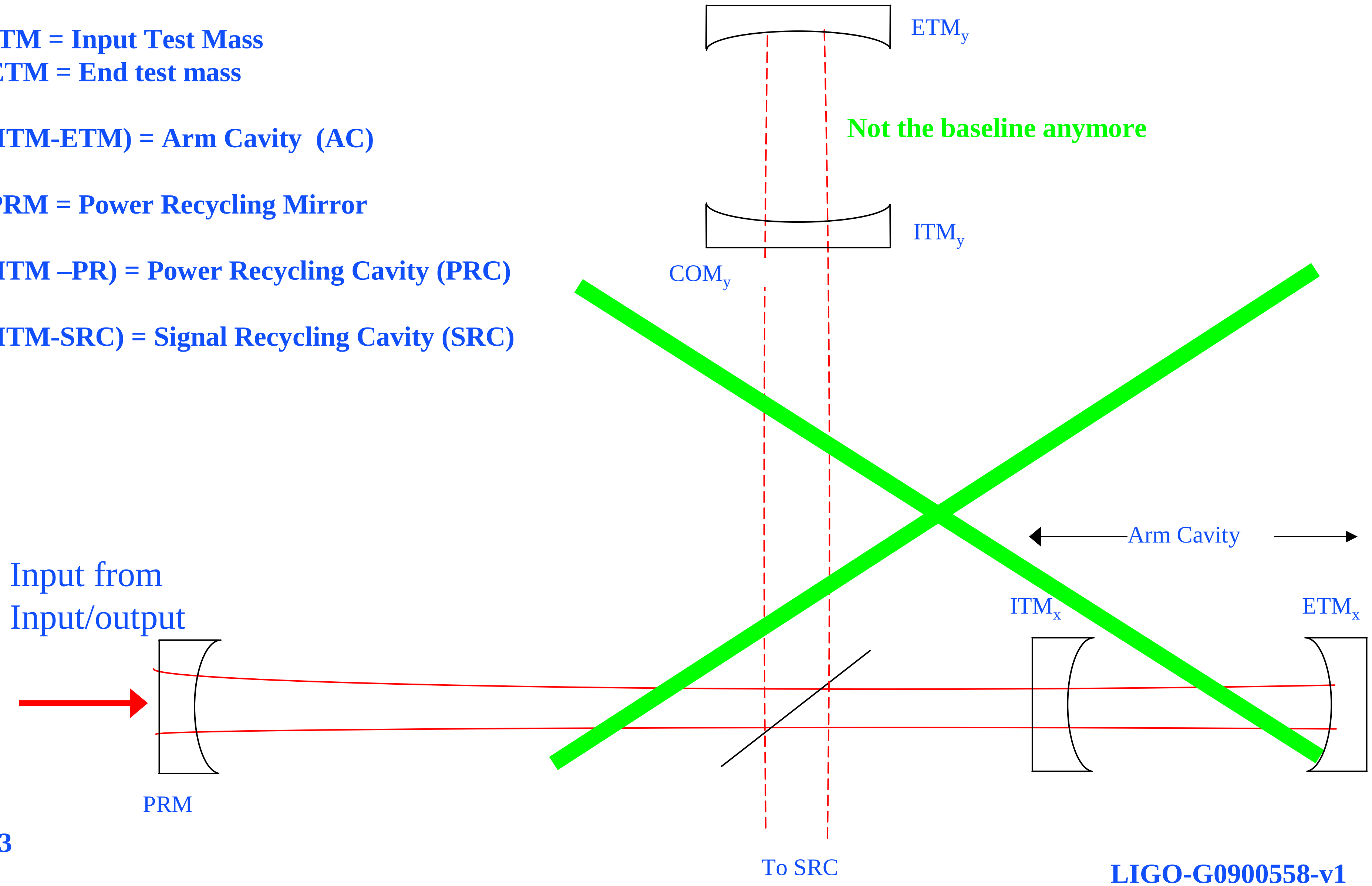
**ITM = Input Test Mass**
**ETM = End test mass**

**(ITM-ETM) = Arm Cavity (AC)**

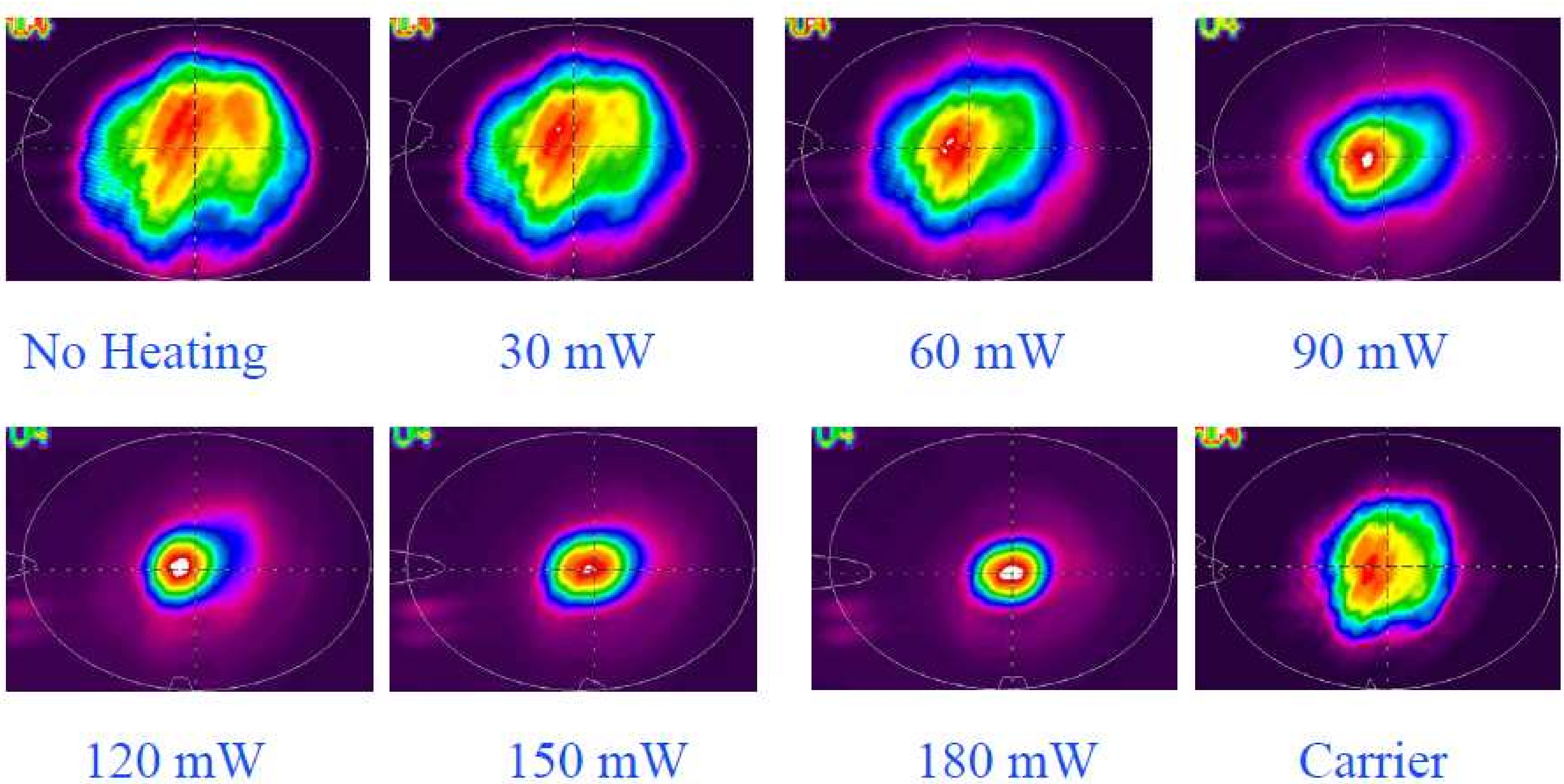
**PRM = Power Recycling Mirror**

**(ITM –PR) = Power Recycling Cavity (PRC)**

**(ITM-SRC) = Signal Recycling Cavity (SRC)**



# Initial LIGO Recycling Cavity Modes RF and Carrier




Phil Willems, “Thermal Compensation in LIGO,” LIGO-G070146-00-Z

# Motivation of Stable Cavities

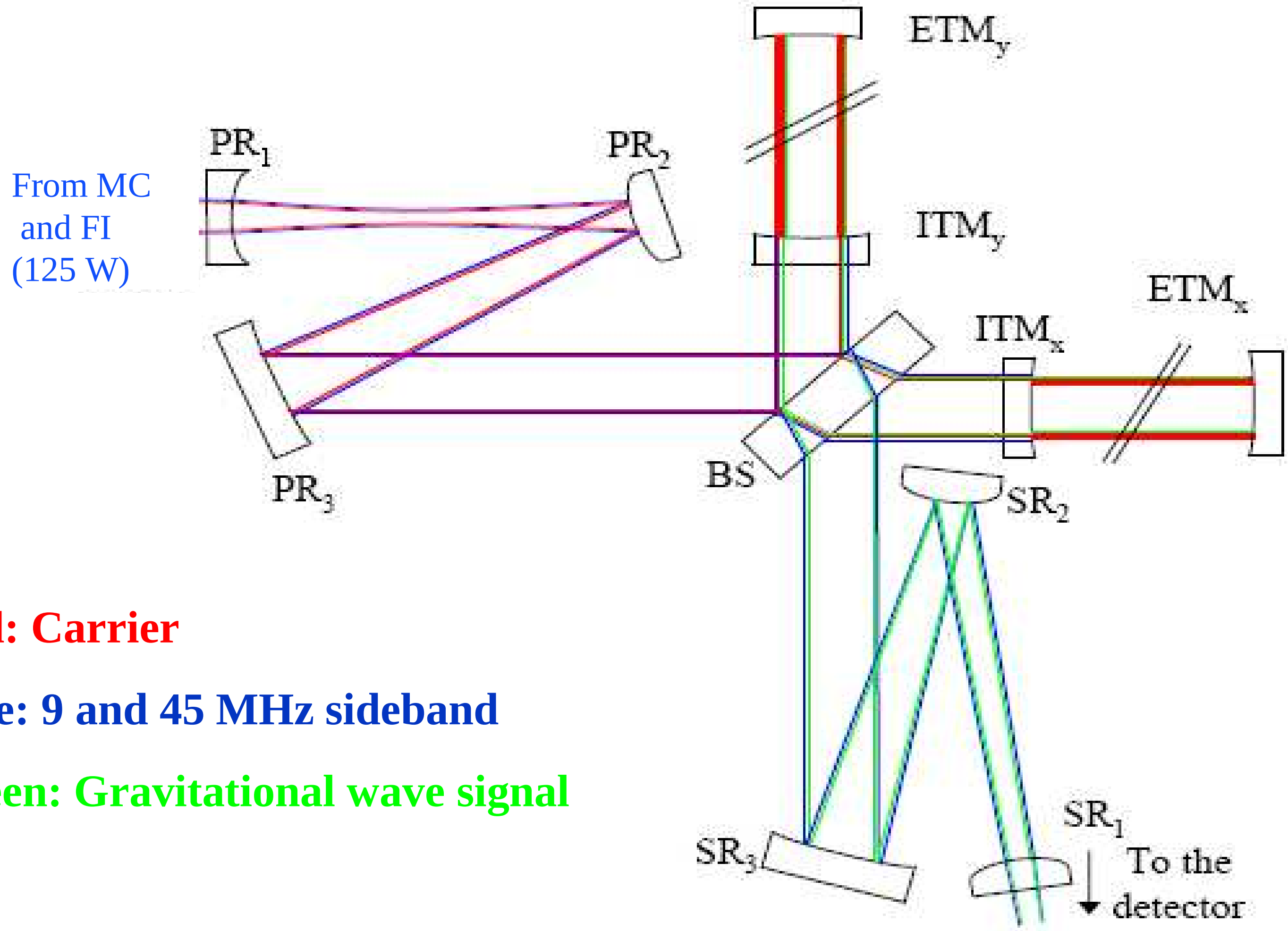
Advantages

- Well defined spatial modes in the Recycling Cavities
  - » Better coupling between RF sidebands and carrier
  - » Symmetrical RF sidebands
- Tolerance to thermal effects
  - » Higher order (spatially 02 and 20 HG) modes non-resonant
    - – Less mode mismatch as we increase power
    - – Less stringent requirements on TCS
- Cleaner and better gravitational signals
  - » Nice overlap between SRC mode and AC
    - – No scatter to higher order modes at the dark port

The cost

- Stringent requirements on:
  - » ROC tolerances/Quality of mirrors
  - » Quality of the RC mirrors
  - » Vacuum constraints
- Last but not the least, slightly difficult alignment sensing scheme
  - » $TEM_{10,01}$ not resonant
  - » Details in the next talk by Lisa Barsotti

# A three Mirror Cavity
# Advanced LIGO Configuration

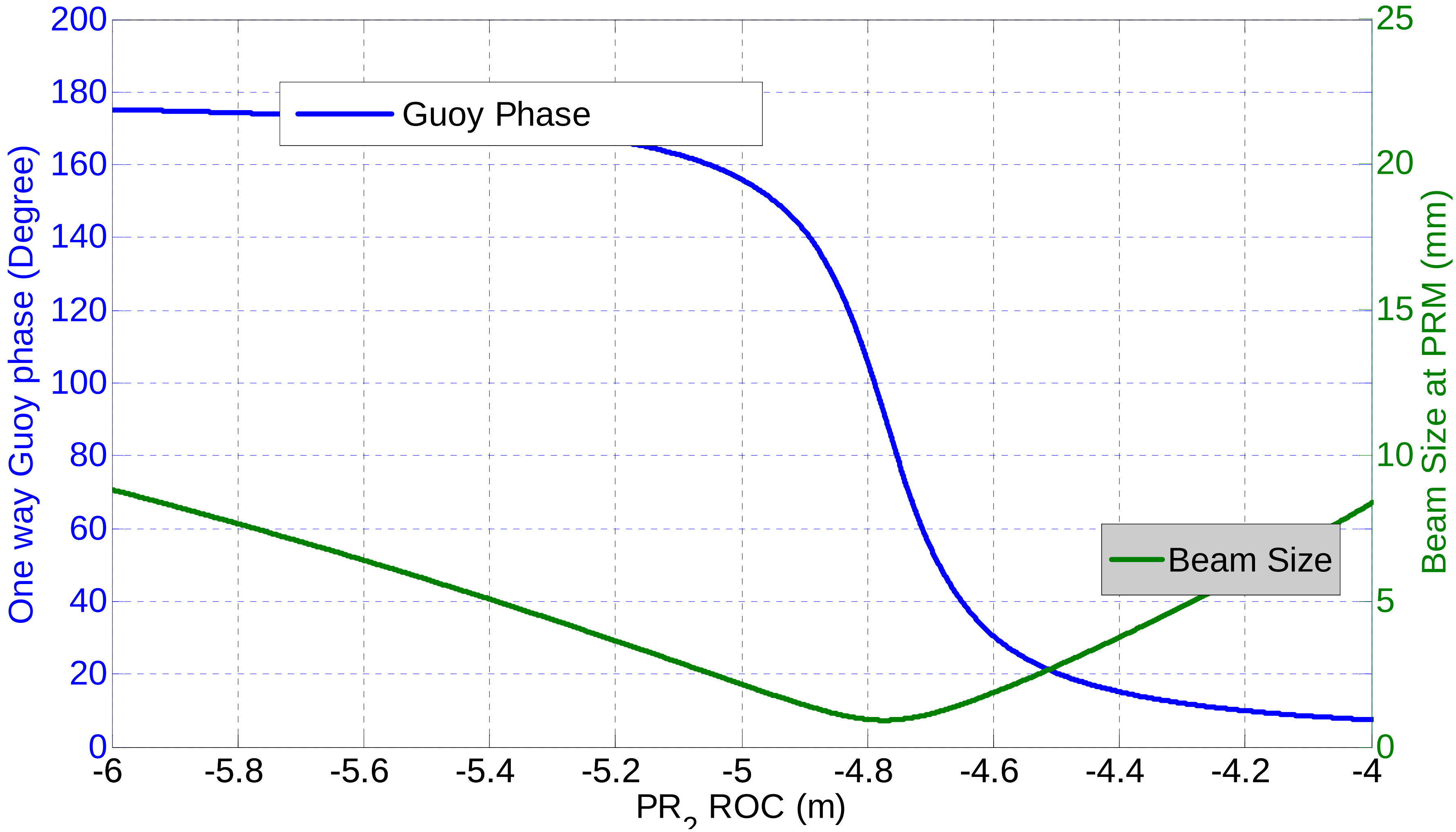



**Red: Carrier**

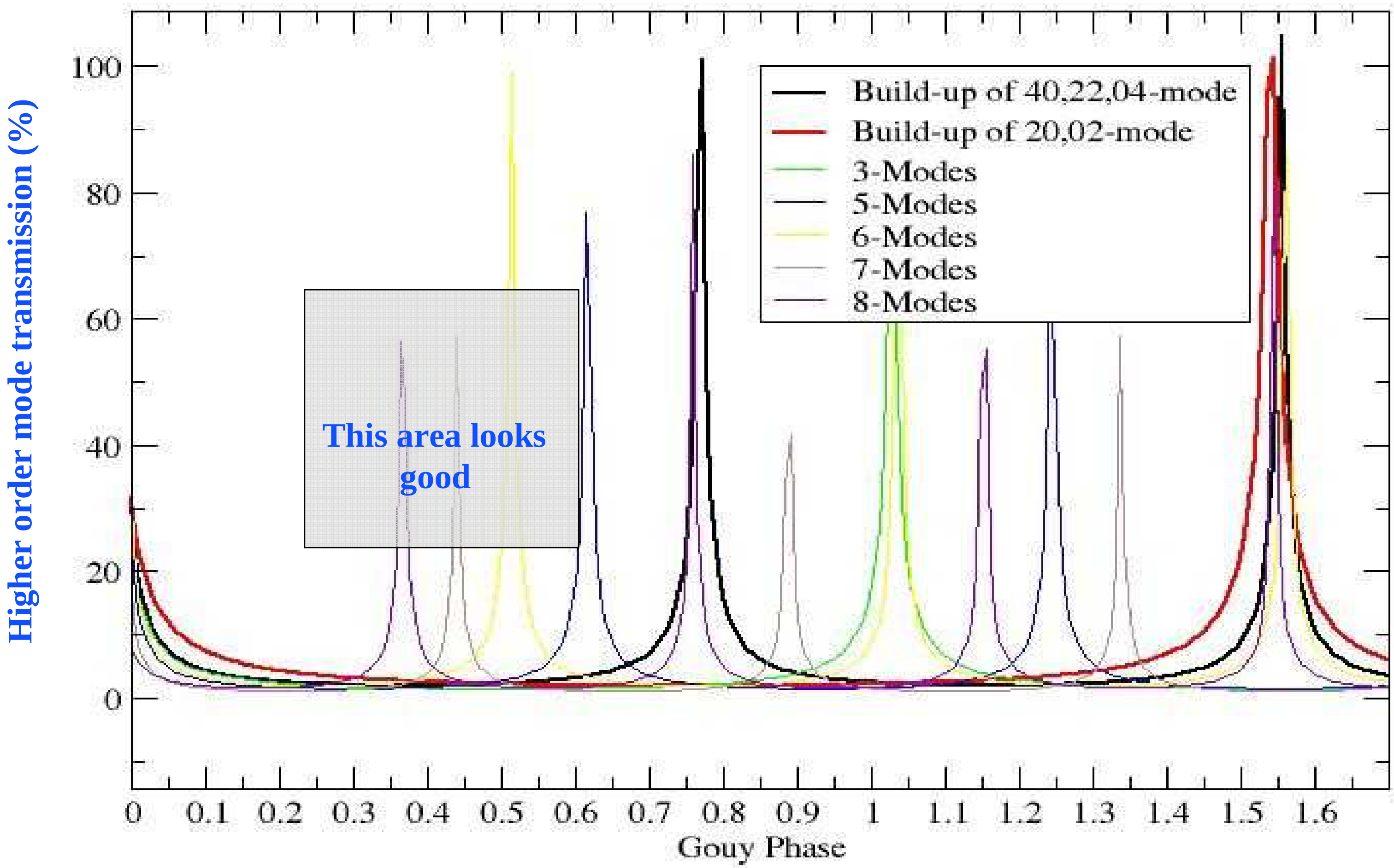
**Blue: 9 and 45 MHz sideband**

**Green: Gravitational wave signal**

# Gouy Phase Tunability and Beam Size at PRM

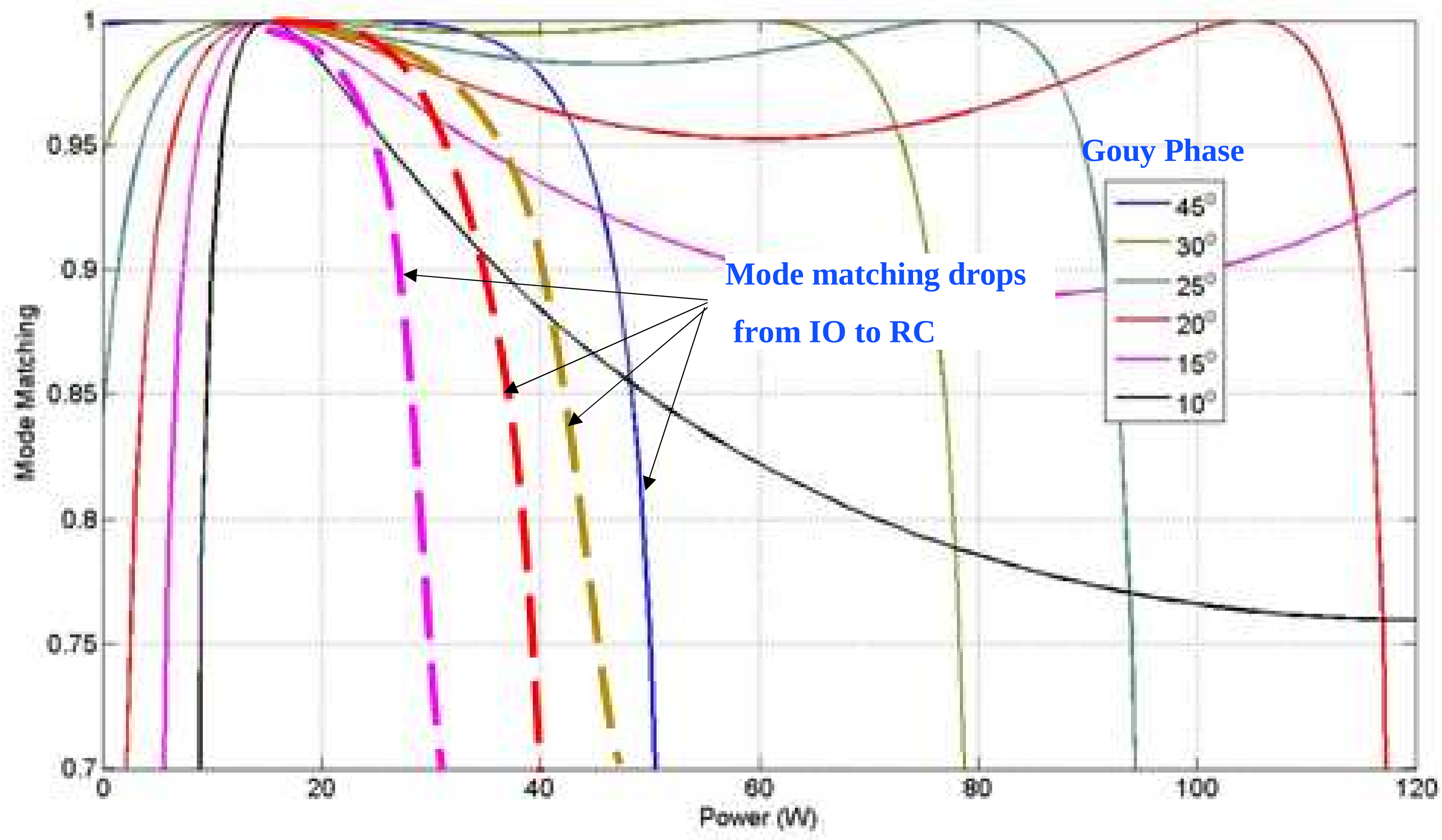


# Which Gouy Phase?



# Mode Matching performance to Thermal Effects

Mode matching is between RC mode and AC mode




Assumed 5 km thermal lens in the ITM at 125 W

# Optical Parameters for Advanced LIGO

**Recycling Cavity Parameters 25º PRC and 19º SRC Gouy Phase**
**A compromise between Tolerance to Thermal variations v/s Alignment**

## Optical Parameters for various IFO Configuration

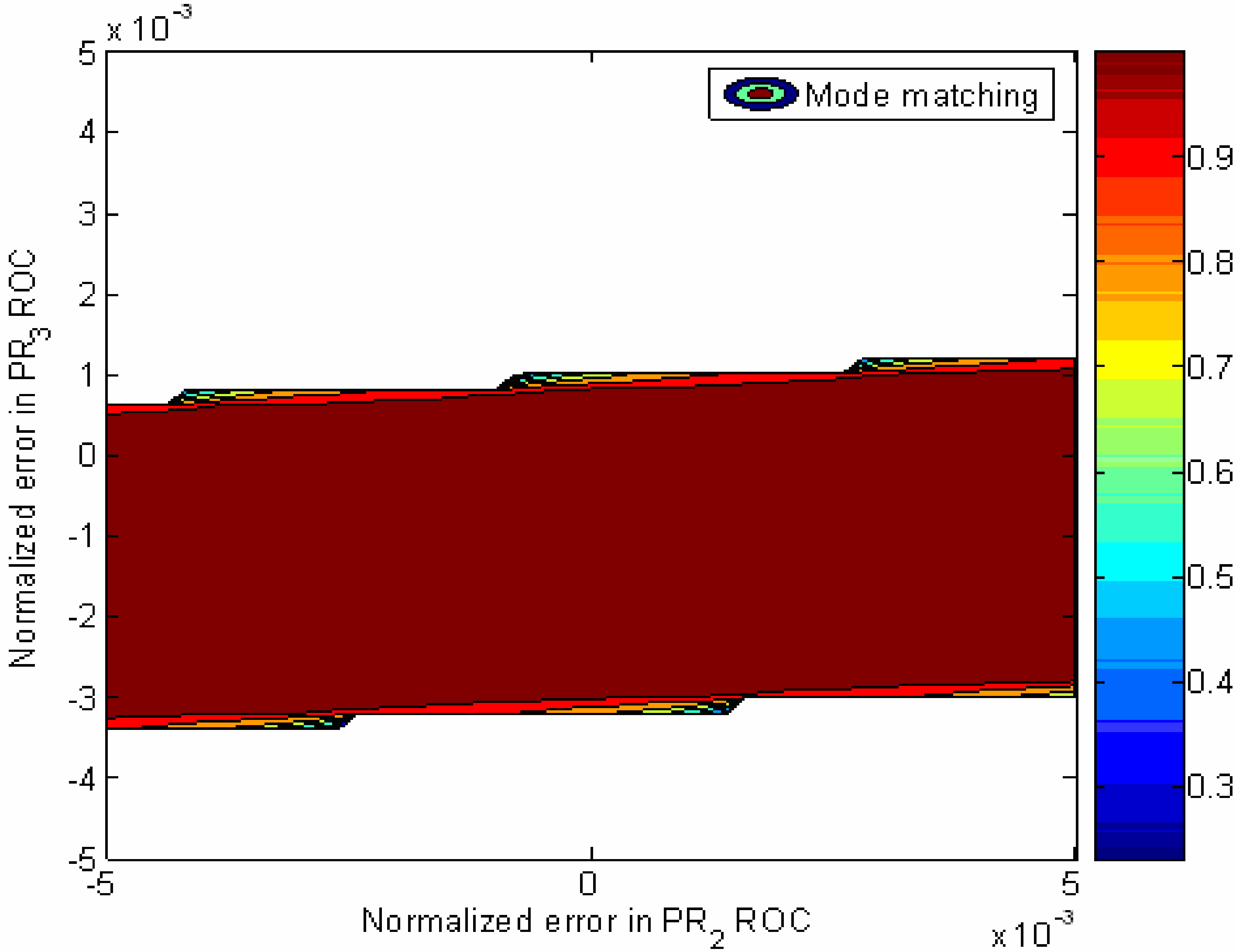
| *Definition* | *Unit* | *PRC* | | *SRC* | |
|---|---|---|---|---|---|
| | | Straight | Folded | Straight | Folded |
| P(S)RM radius of curvature | m | -10.997 | 8.8691 | -5.6938 | -10.4727 |
| Distance b/w P(S)RM and P(S)$R_2$ | m | 16.6037 | 15.7971 | 15.726 | 15.9357 |
| P(S)$R_2$ ROC | m | -4.555 | -4.41 | -6.427 | -4.9260 |
| Distance b/w P(S)$R_2$ and P(S)$R_3$ | m | 16.1558 | 15.2065 | 15.4607 | 16.0016 |
| P(S)$R_3$ ROC | m | 36 | 34 | 36 | 36 |
| Distance b/w P(S)$R_3$ and BS | m | 19.5384 | 19.4204 | 19.368 | 20.0991 |
| BS Effective thickness | mm | 0 | 0 | 131.5 | 132 |
| Distance b/w BS and CPy | m | 4.8497 | 9.4783 | 4.8046 | 9.4330 |
| Distance b/w CP and ITM | mm | 5 | 5 | 5 | 5 |

# A few numbers for Arm Cavity

| Definition | Unit | PRC | | SRC | |
|---|---|---|---|---|---|
| | | Straight | Folded | Straight | Folded |
| ITM ROC | m | 1934 | 1934 | 1934 | 1934 |
| Reqd. beam waist size in arm | mm | 12.0 | 12.01 | 12.0 | 12.01 |
| Spot Size at ITM | cm | 5.30 | 5.31 | 5.30 | 5.31 |
| Beam waist location from ITM | m | 1884.4 | 1885 | 1884.4 | 1885 |
| Arm Cavity Length | m | 3994.5 | 3996.0 | 3994.5 | 3996.0 |
| ETM ROC | m | 2245 | 2245 | 2245 | 2245 |
| Spot Size at ETM | cm | 6.2 | 6.2 | 6.2 | 6.2 |

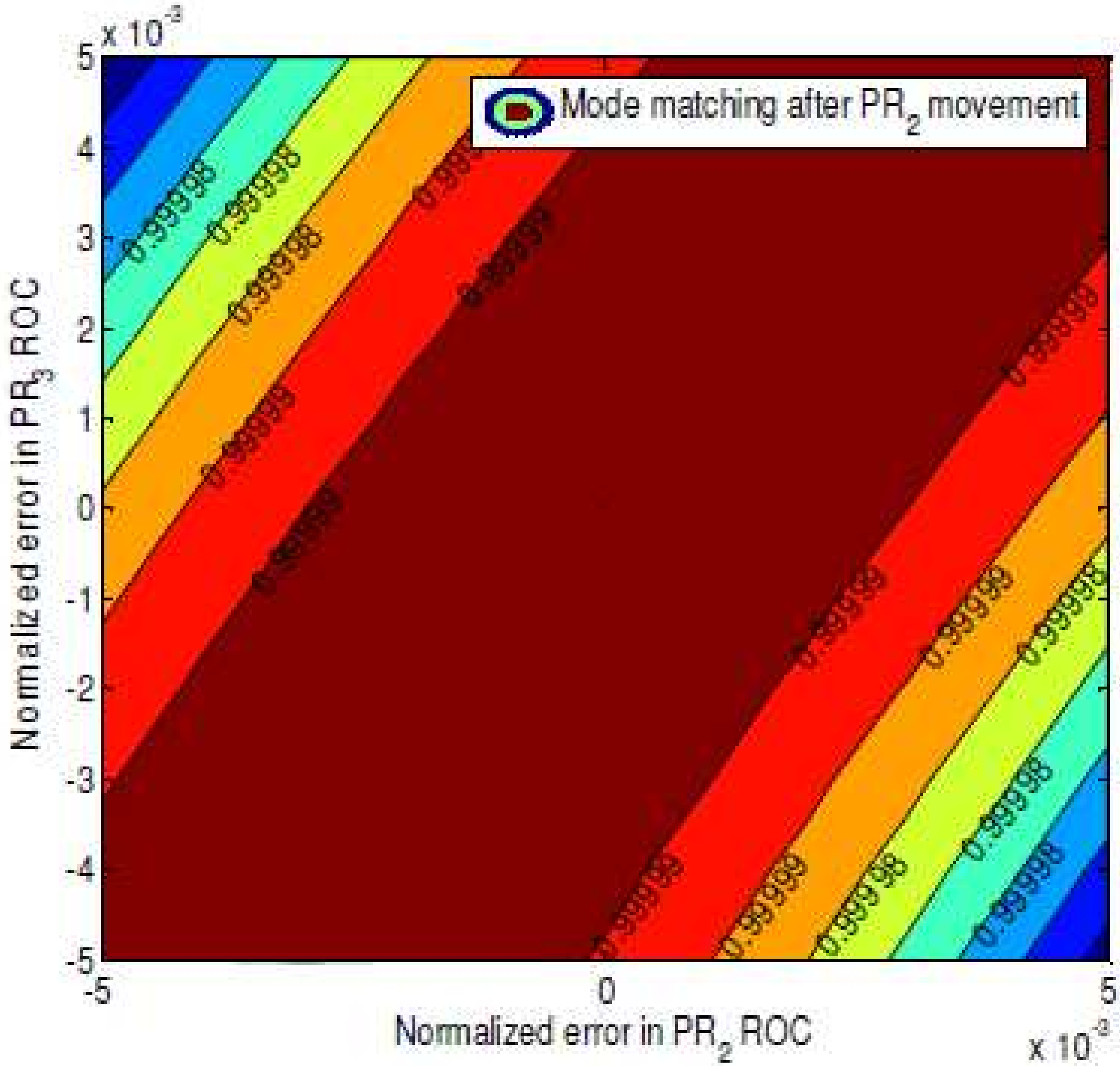
**Beam Size in the arms is unsymmetrical**
**ITM has a lower beam size to reduce diffraction losses in the RC**

# ROC Tolerance of RC Mirrors




- The main ROC tolerance concern is PR3
- White areas represent unstable cavity region

# Compensation of ROC Tolerances




- Mode matching is recovered by moving PR2 mirror
- This requires PRM to be moved twice as much to keep the RC length constant
- This is a burden but is being accommodated in the design

# Summary

- Stable cavity design with PRC $25^0$ PRC and $19^0$ SRC
- Good 'athermal' performance with reasonable ASC
- Distance optimization for ROC tolerances
- Adaptive mode matching from mode cleaner to recycling cavity will help
- Additional mode matching between input optics and recycling cavity
- If interested in latest Advanced LIGO cavity parameters, tune in to **LIGO Technical Note:**

**Optical Layout and Parameters for the Advanced LIGO Cavities, LIGO-T0900043-xx**

# Back up slides

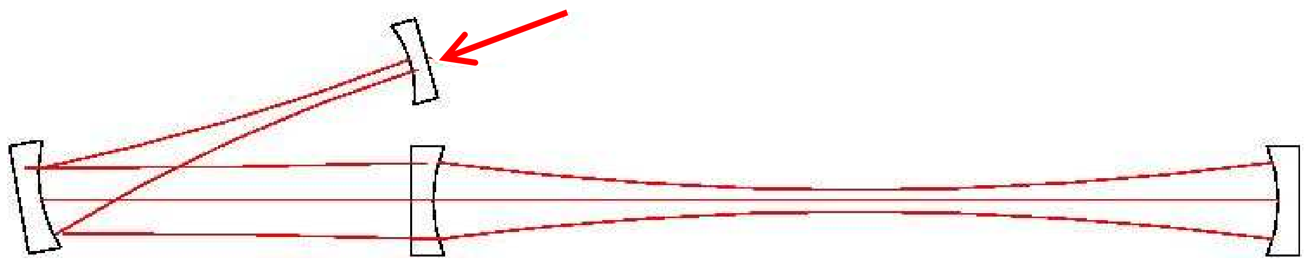
- Option 1: Lens in the ITM [spell out]

**Max distance ~ 25 m**

**Divergence Angle ~ 24 milliradian**

**Beam size ~ 150 micrometer**

- Option 2: Two Mirror RC



**Max distance ~ 40 m**

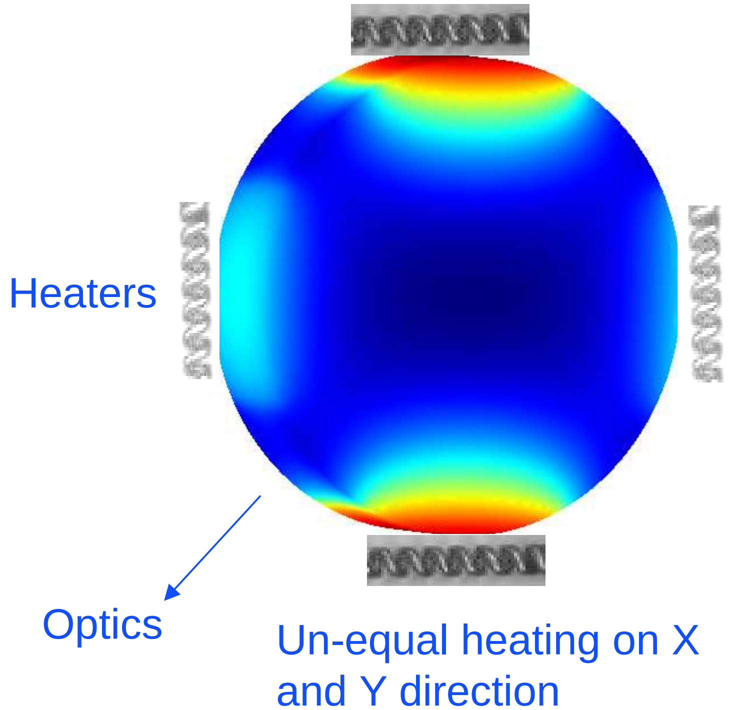
**Divergence Angle ~ 40 milliradian**

**Beam size ~ 240 micrometer**

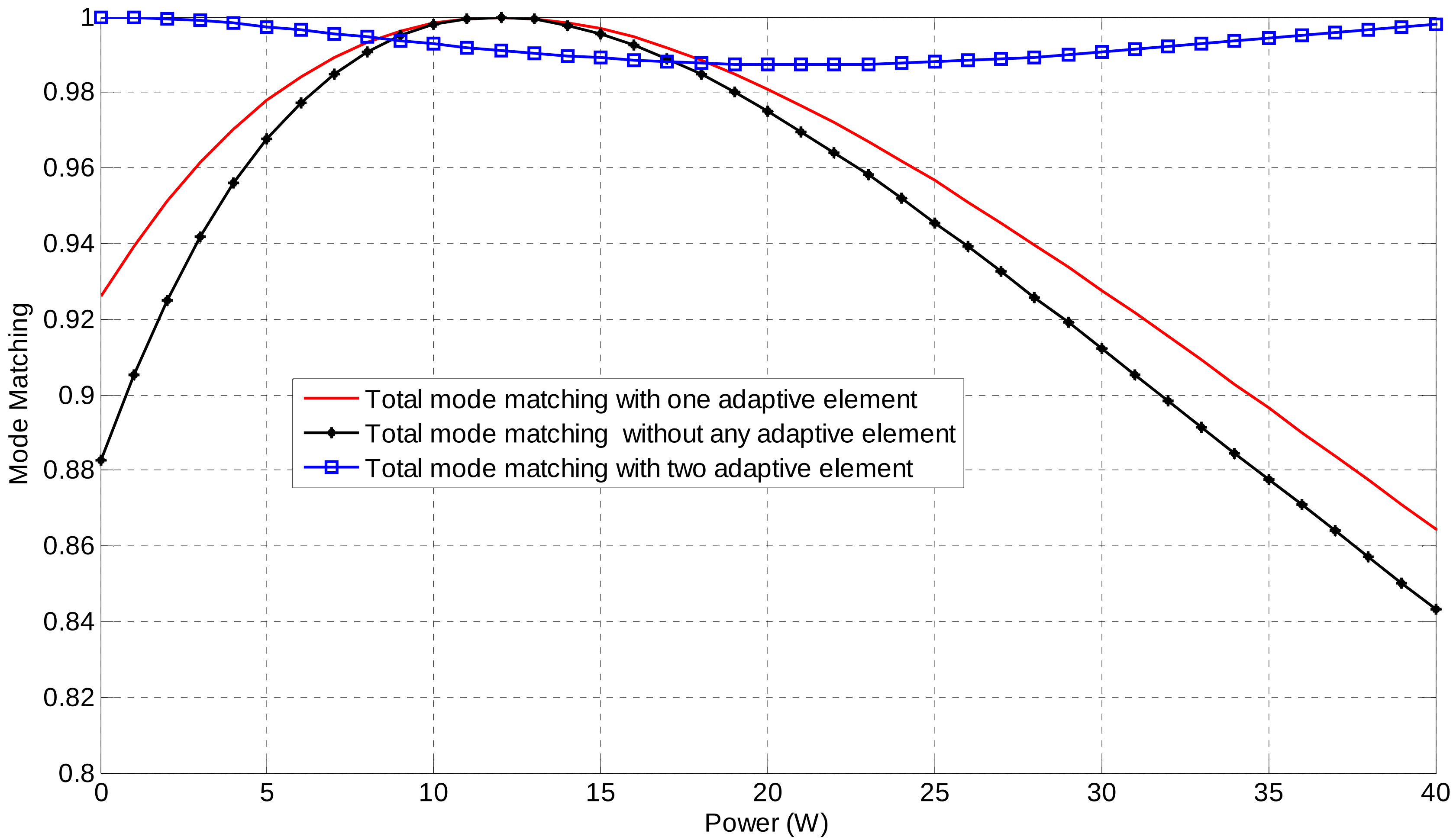
So these options are not feasible

# Adaptive Mode Matching from IO to RC

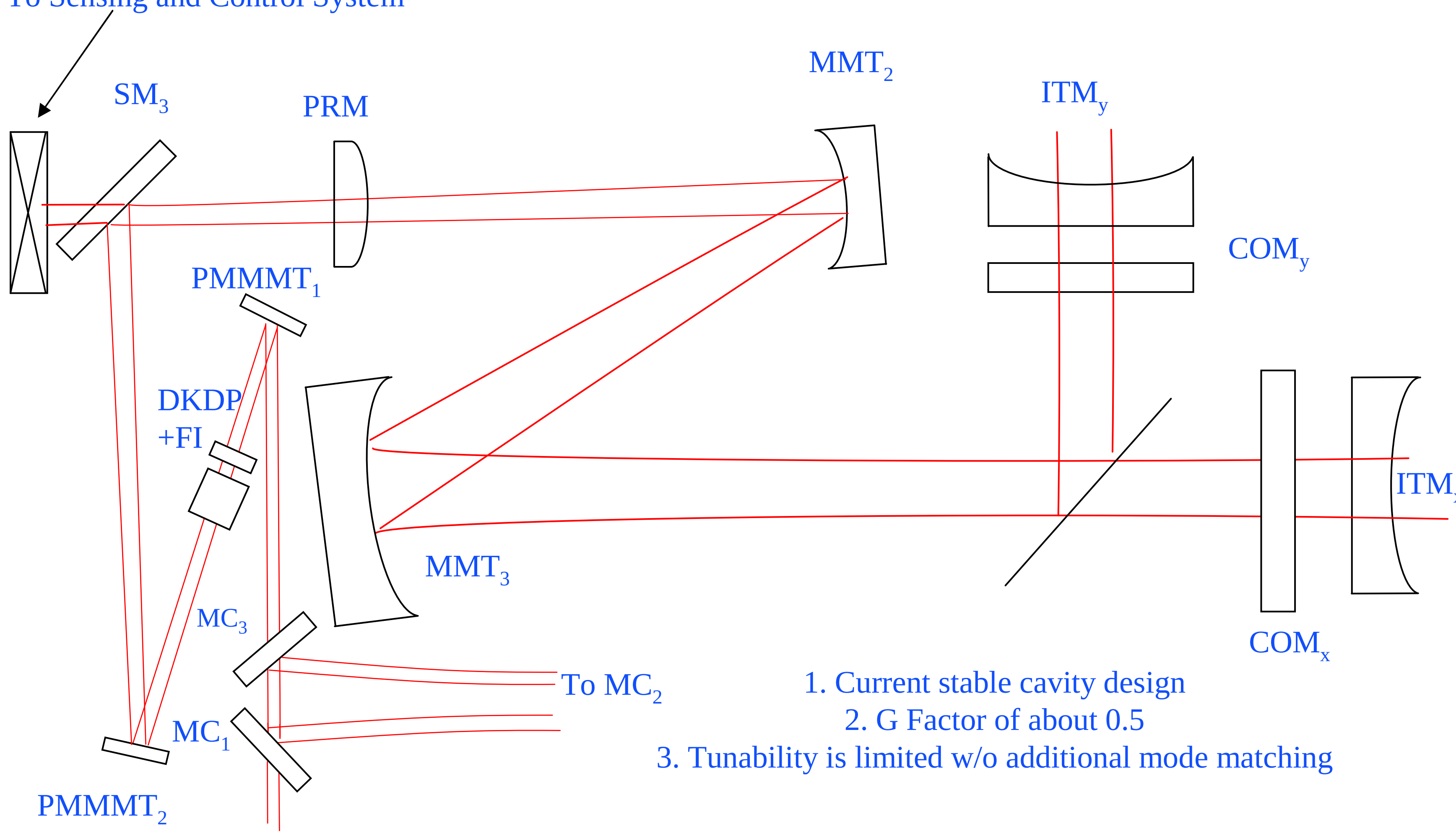
- Optical element heated by four independent heaters for beam shaping
- Material (SF57) having large dn/dT and $\alpha$
- Four heaters can be used for steering too
- We can combine beam steering with thermal lensing
- Opportunity to shape the beam using multi-element heating
- Correction of astigmatism induced by non-normal incidence triangular mode cleaner mirror cavity mirrors



# Mode Matching Improvement with Adaptive lenses



# Details of Input Optics




1. Current stable cavity design
2. G Factor of about 0.5
3. Tunability is limited w/o additional mode matching