# Adaptive Heating for Thermal Compensation in Advanced LIGO

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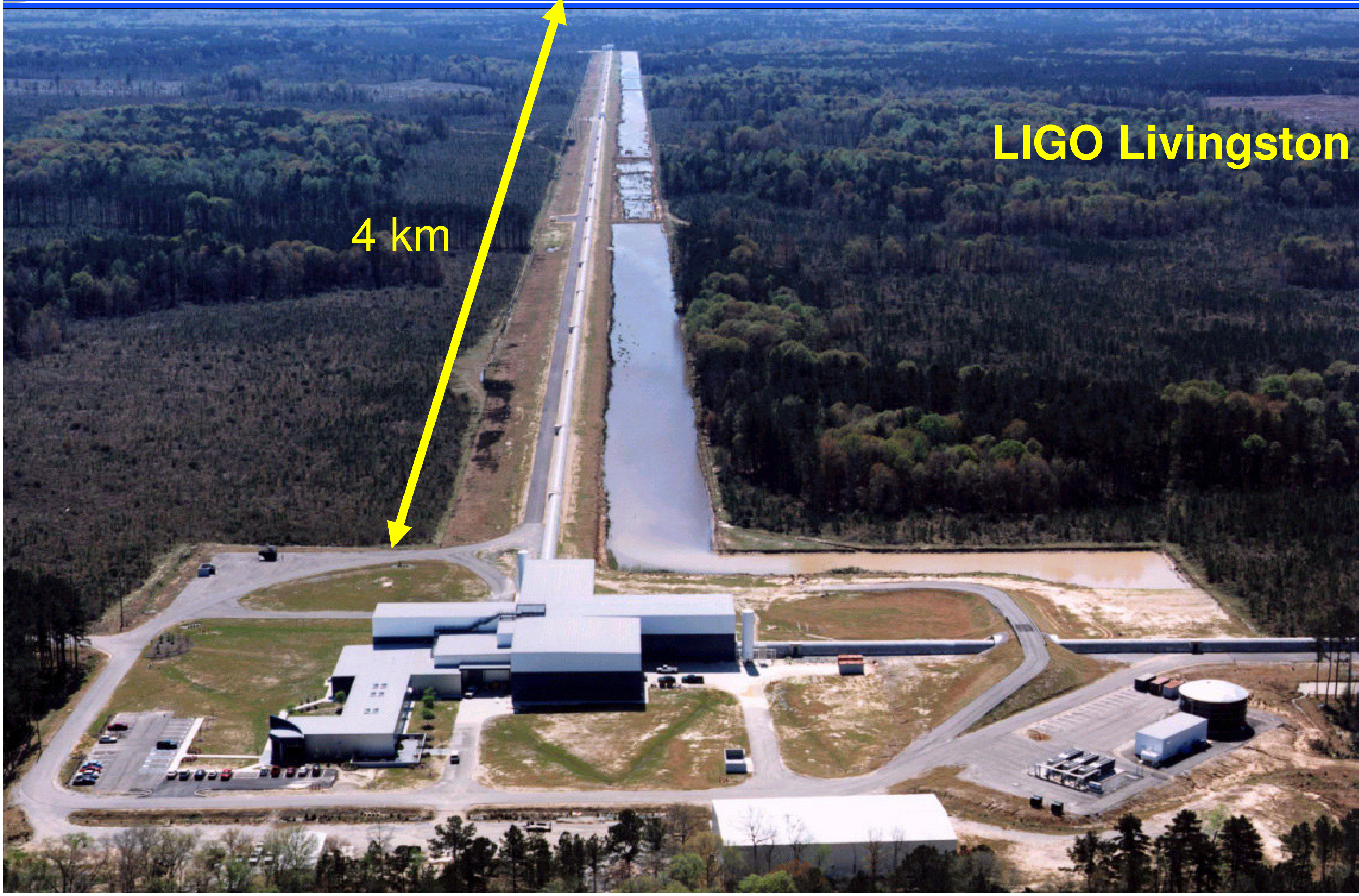
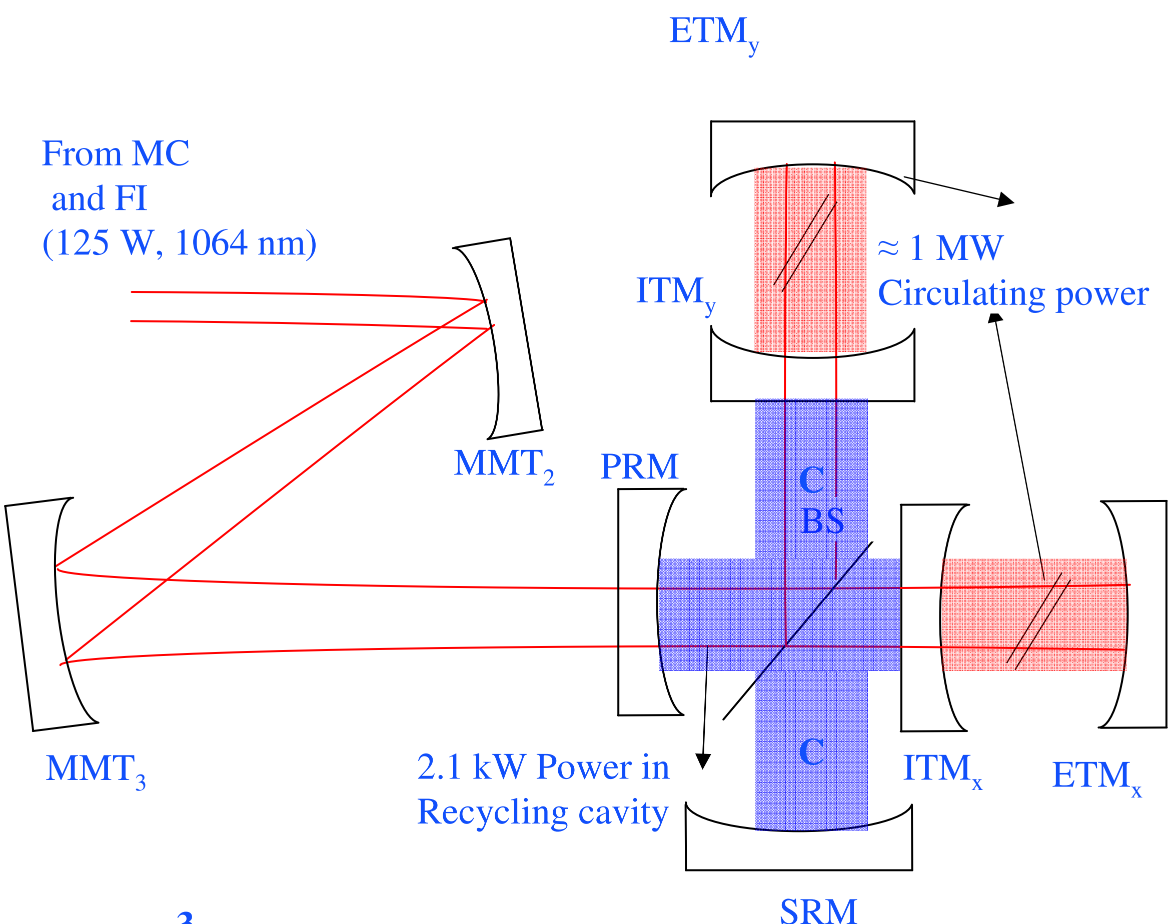
# Initial LIGO-LIGO today



# Advanced LIGO Configuration

## Option 1: Marginally Stable Power Recycling Cavity

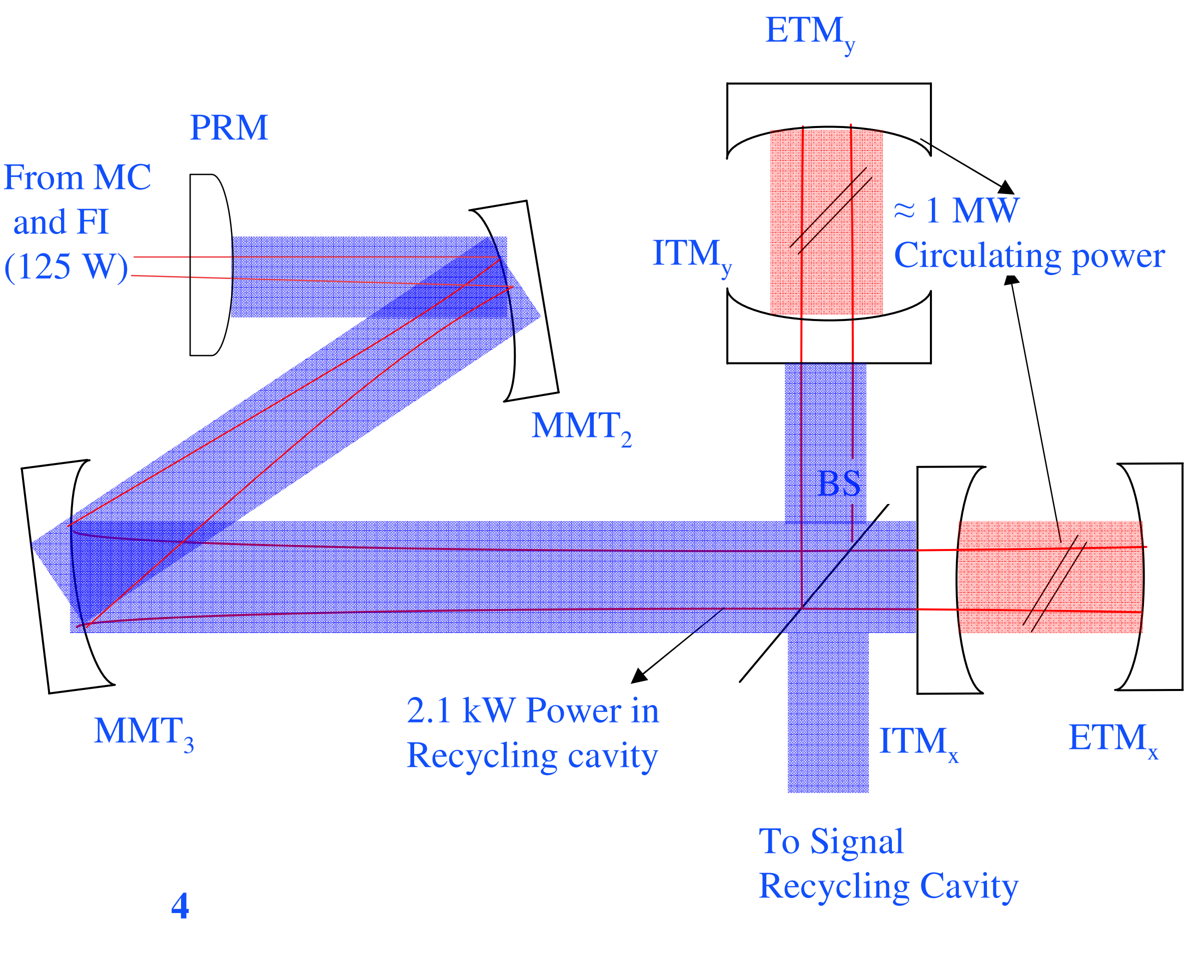



### Important Features:

- 4 km long arm length Michelson Interferometer
- Fabry-Perot cavities in the two arms
- Dual recycled configuration
- Recycling cavity is nearly flat-flat cavity

# Advanced LIGO Configuration

## Option 2: Stable Power Recycling Cavity



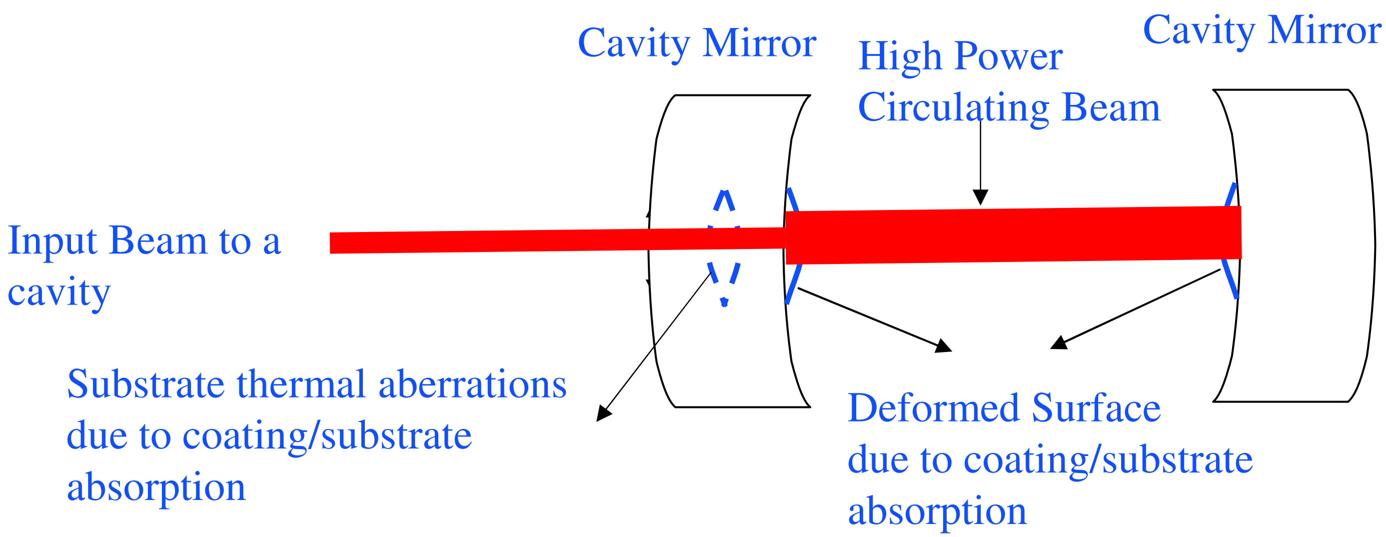

### Important Features:

- Less susceptible to thermal variations
- Uniform build-up of side band power
- Rejection of higher order modes

### Potential Disadvantage

- Alignment Sensing and Control
- Parametric Instabilities

# Problem: Thermal Lensing in High Power cavities

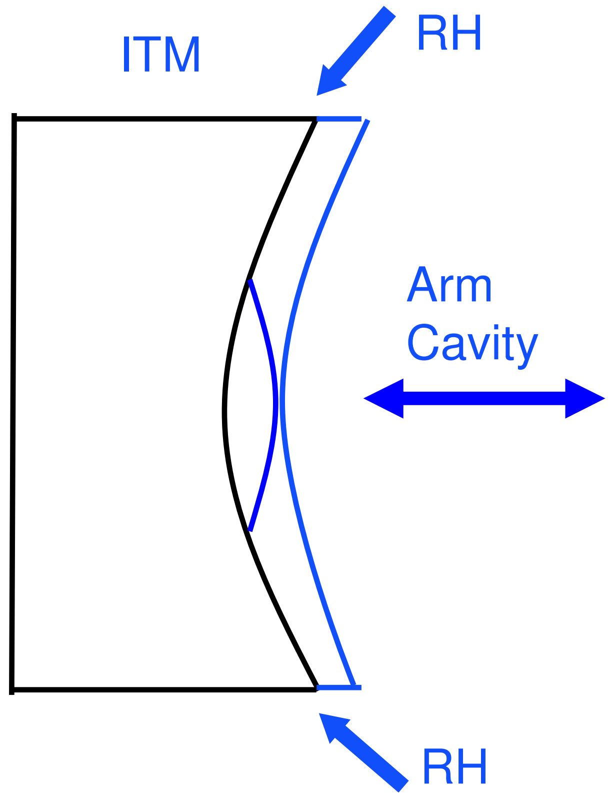



Problems due to High Power Beams

- Reduced coupling from input beam
- Power dependent change in the cavity mode due to surface lensing
- Reduced coupling to the output system
- Higher mode generation due to non-spherical surface profile

# Adaptive Thermal Compensation

## Inside Arm Cavity

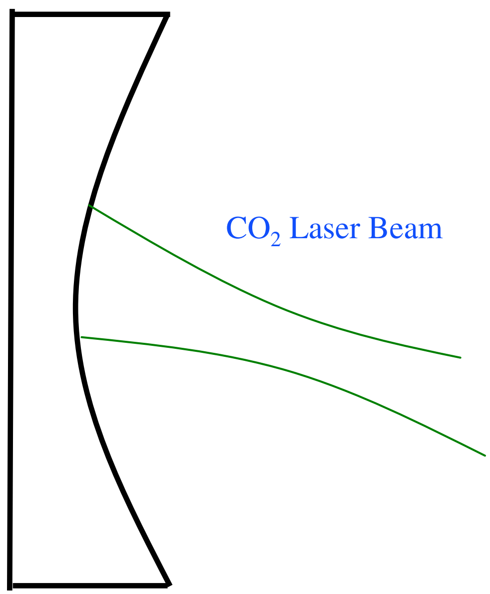


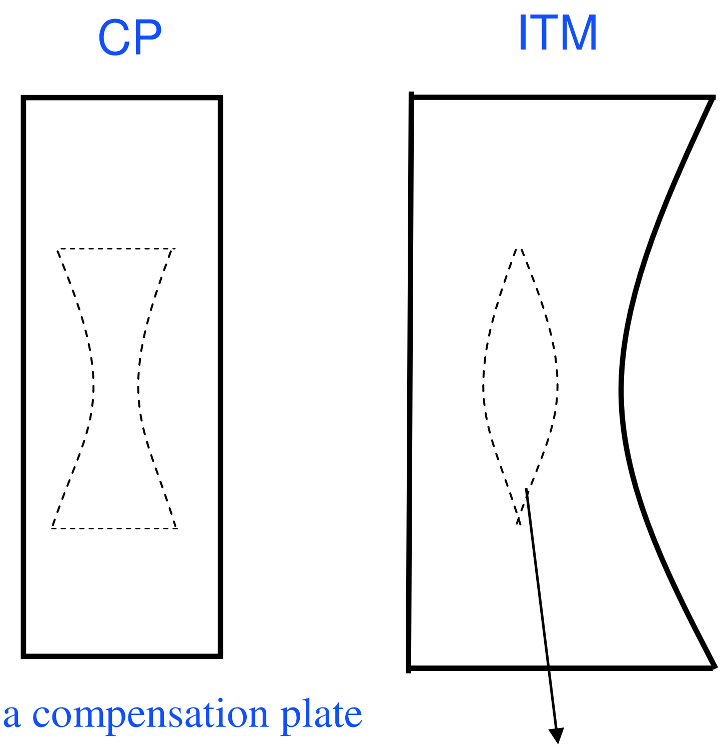

Restores Arm cavity Mode

# Adaptive Thermal Compensation

## Inside Recycling Cavity

Alternate Approach




MMT mirror adaptive heating

(Takes care of common effects)

Heating through $CO_2$ beam produces a negative lens

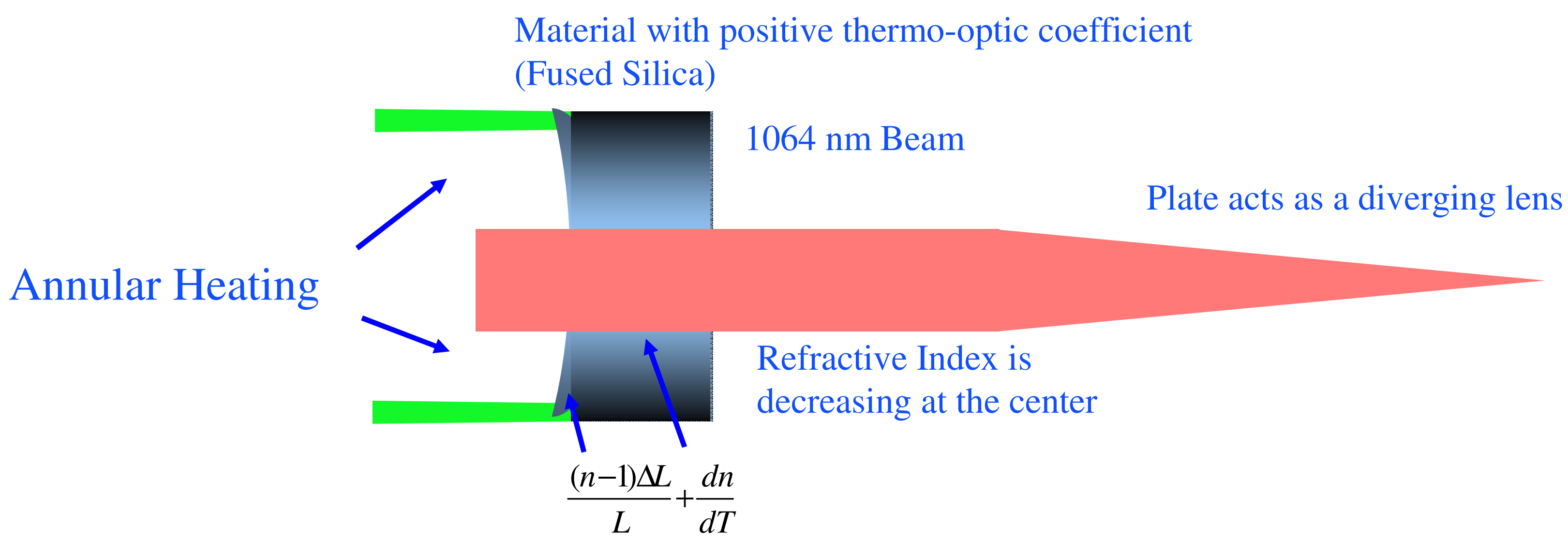
Use a compensation plate

Negative substrate thermal lens through:

1. Annular heating/RH
2. Negative dn/dT material

Positive substrate thermal lens

# Annular & Ring Heater Compensation

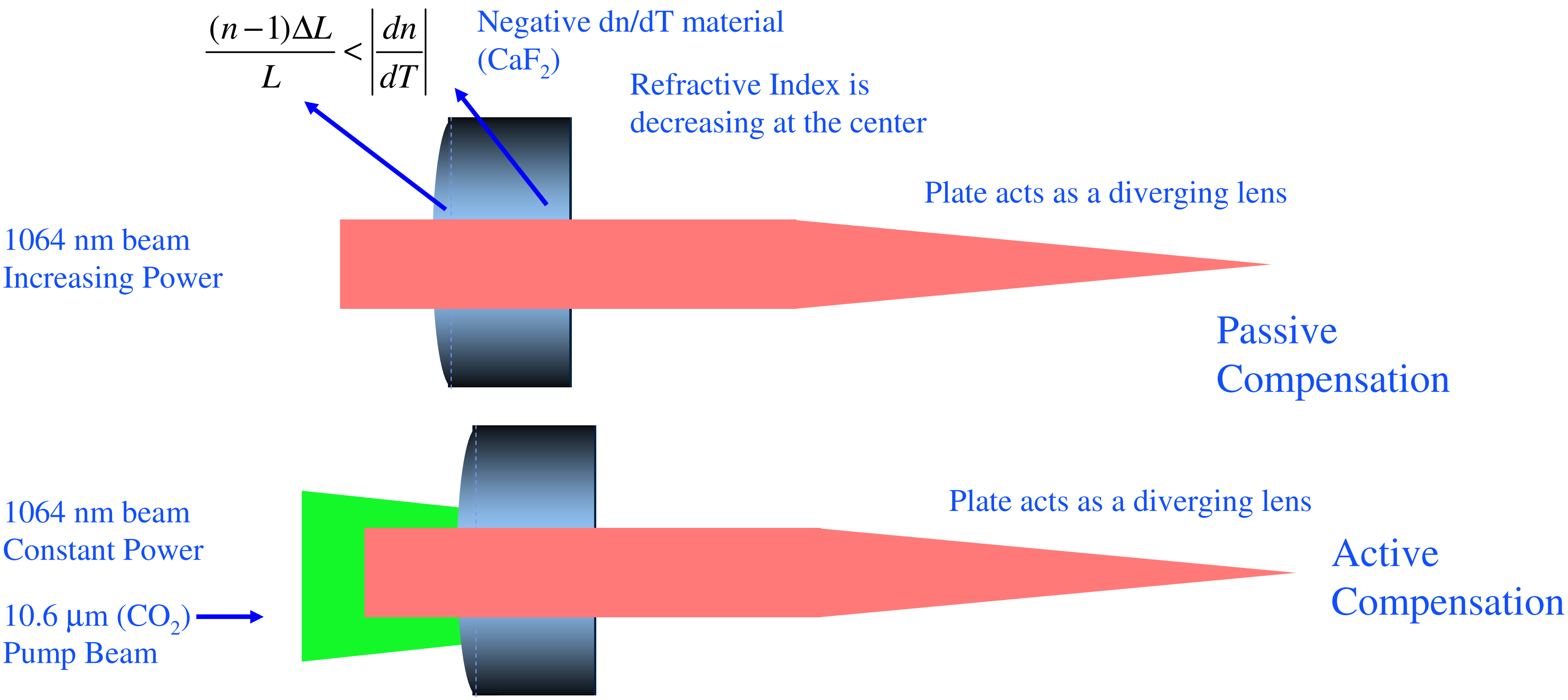



Can be generated through

1. Heating beam and optical masks
   - •Flexible design
   - •Requires stabilized $CO_2$ beams

2. Electrical Ring Heaters
   - •Ease of control
   - •Less flexible

# Negative dn/dT Compensation

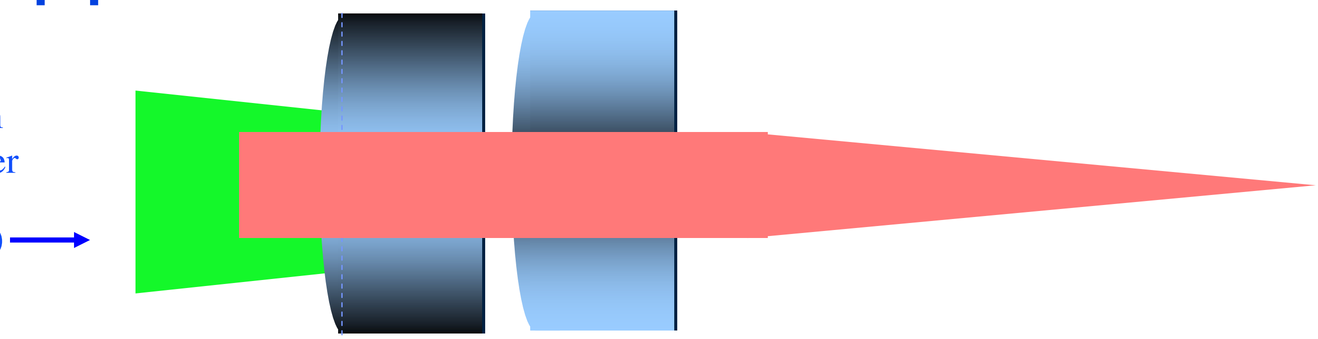


# Negative dn/dT Compensation

## Application in Advanced LIGO

1064 nm beam
Constant Power

10.6 μm ($CO_2$)
Pump Beam

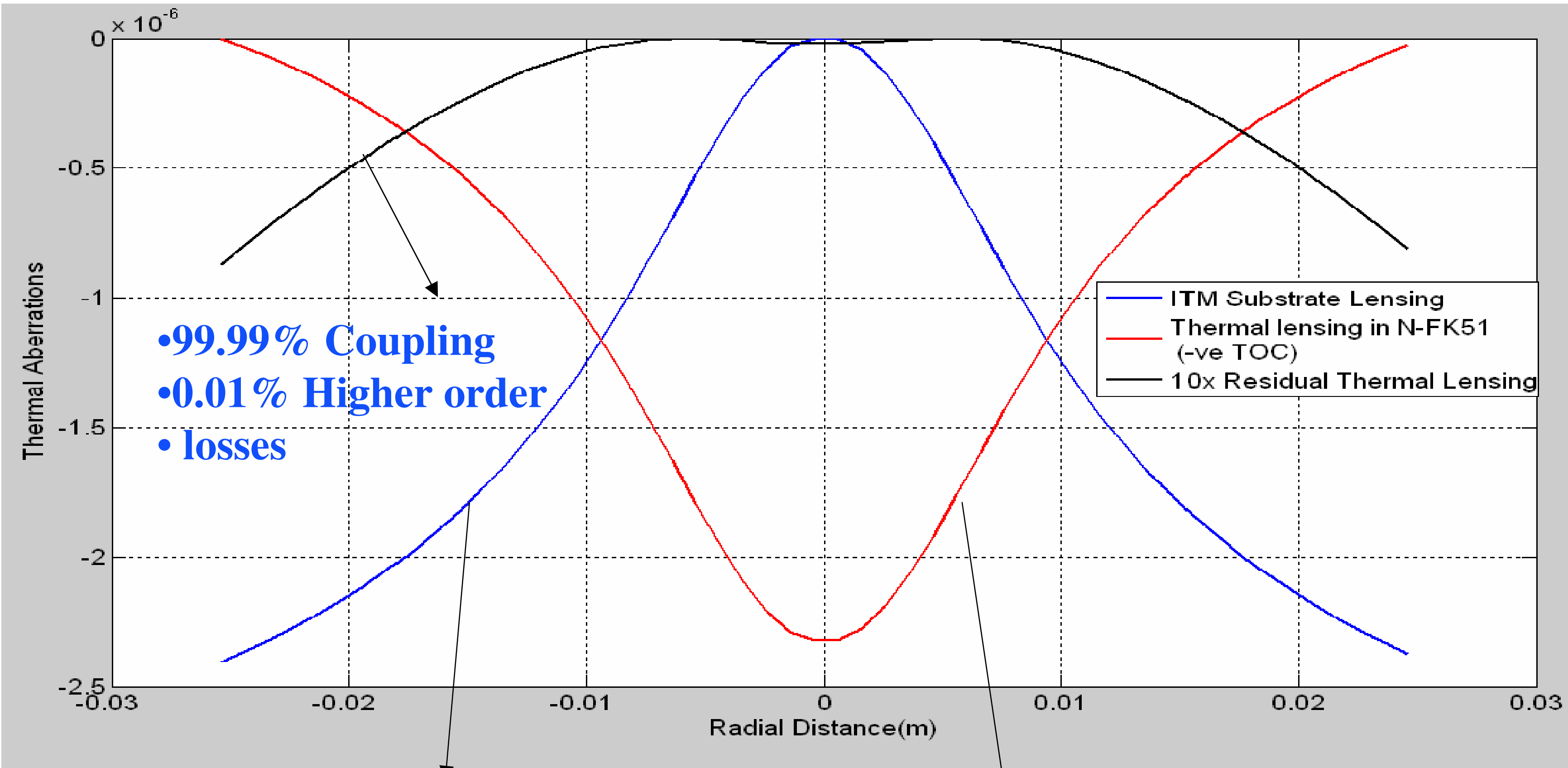


CP ITM

Active
Compensation

Thermal Effects in the
ITM substrate are
cancelled by the CP.

# Negative TOC Material for ITM Substrate Compensation: Simulation

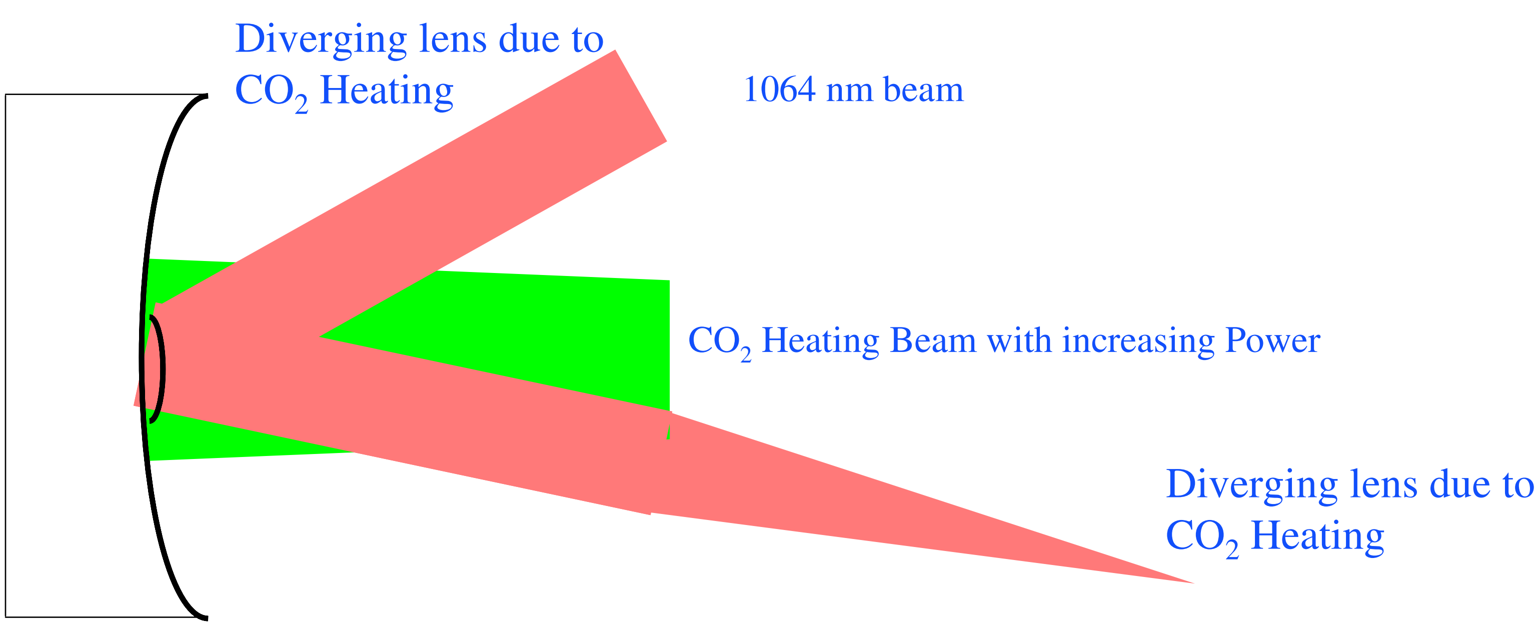



•20% Coupling Drop
•15%Higher order losses due to non-spherical aberrations

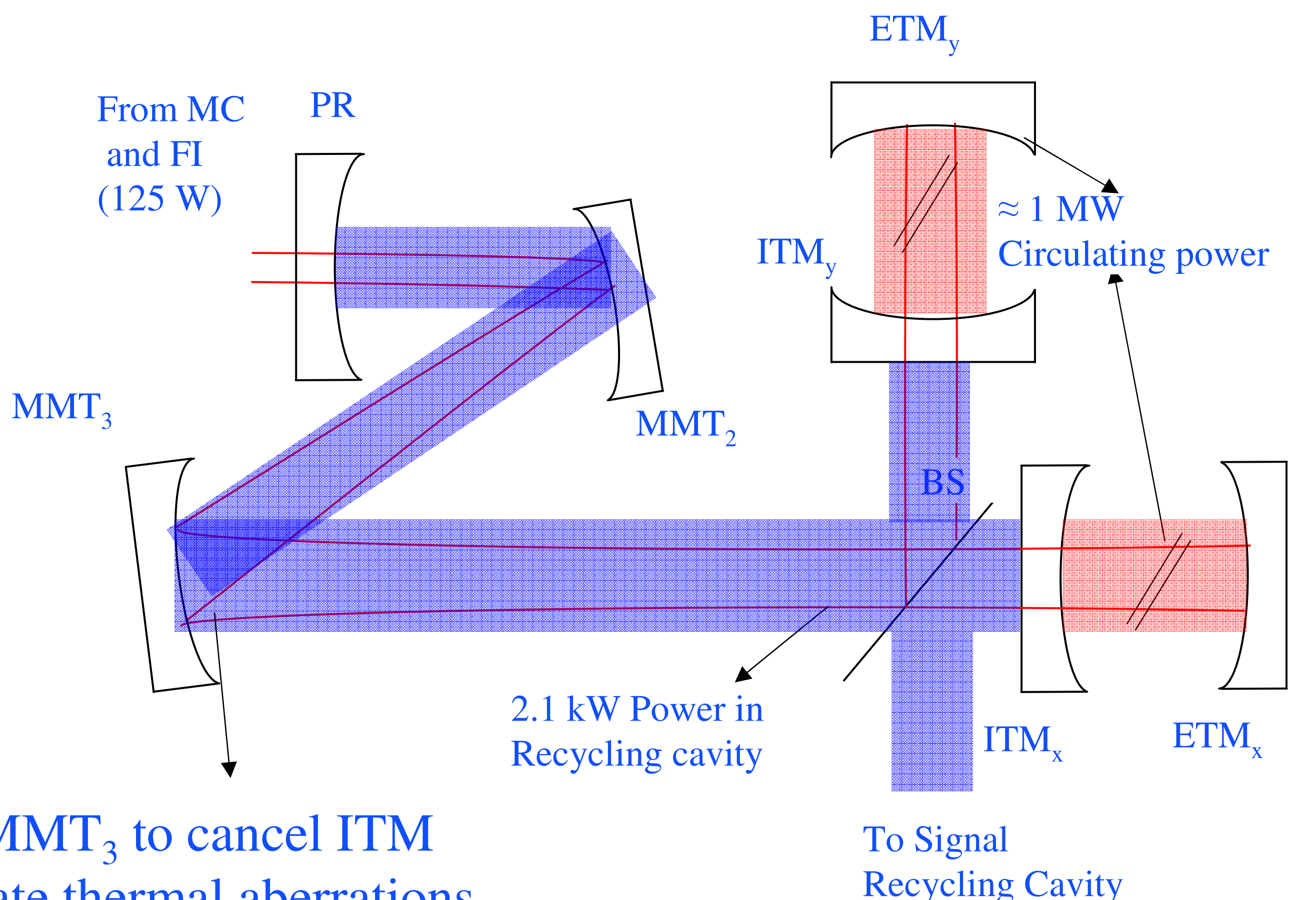
+

•Heating beam on CP optimized to cancel ITM substrate aberrations

# MMT Mirror Heating

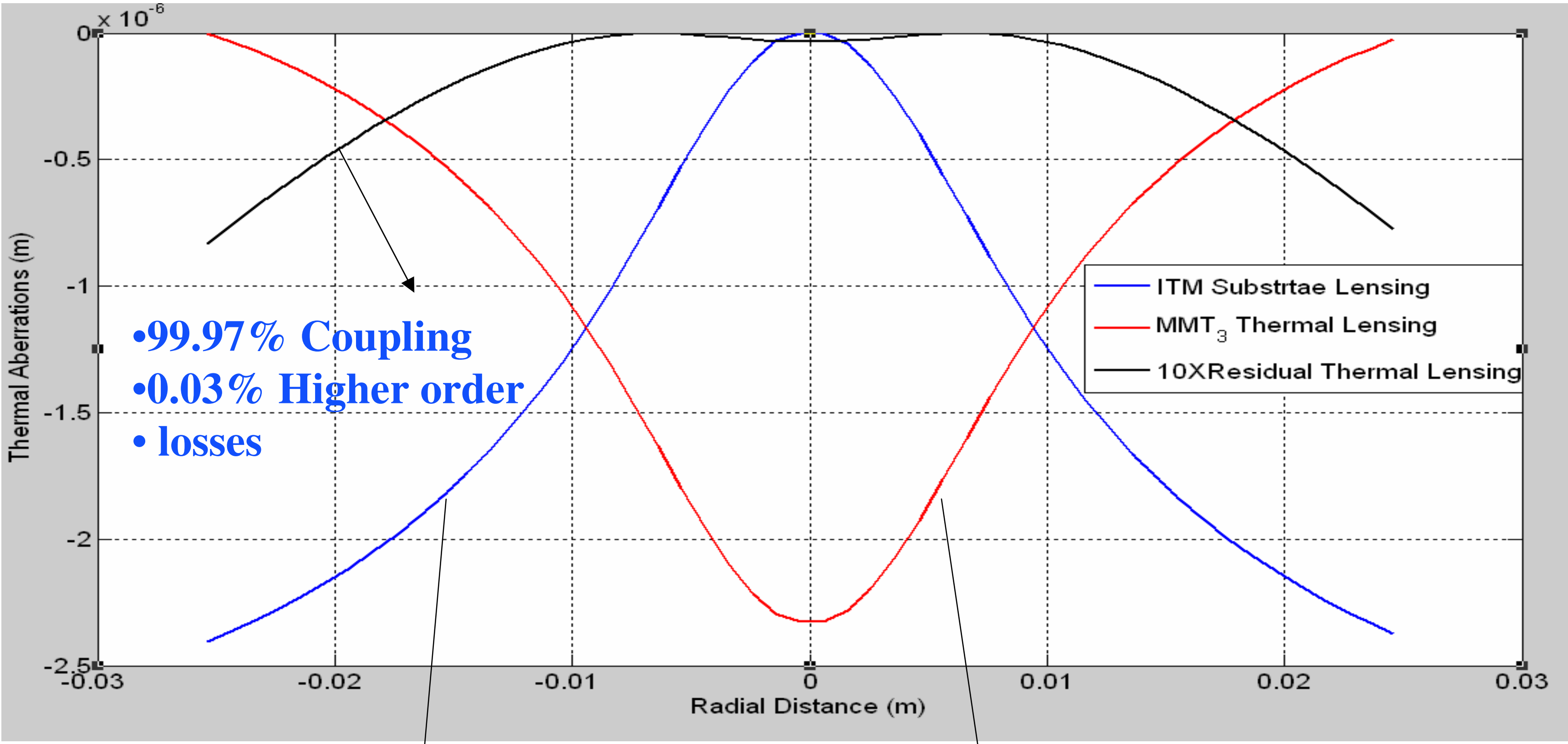


# $MMT_3$ Based Compensation Scheme




Heat $MMT_3$ to cancel ITM substrate thermal aberrations

# $MMT_3$ Adaptive Heating for ITM Substrate compensation: Simulation




- 20% Coupling Drop
- 15% Higher order losses due to non-spherical aberrations

+

- $MMT_3$ produces almost similar thermal aberrations but negative in direction to ITM aberrations

# Thermal Noise in High Power Cavities

## Problem:

- Thermal noise is a major noise source in Gravitational Wave Detectors
  - Thermal noise scales as 1/(beam waist)$^n$ where n depends upon type of thermal noise

## Solution:

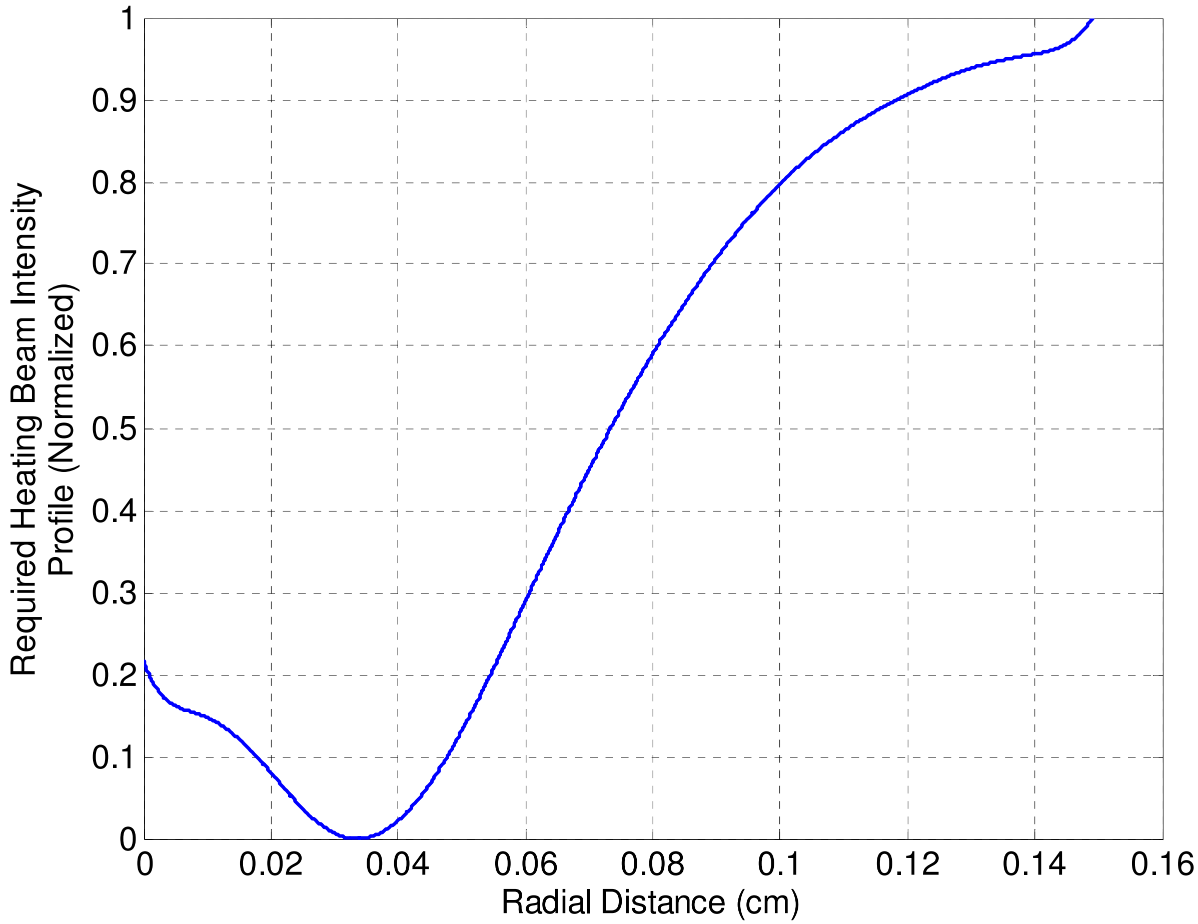
- Increase beam size (limited by diffraction loss)
- Make averaging more effective (requires uniform intensity profile)

Use Flat-top (Mesa) beams that average a larger area as compared to Gaussian beam

Requires Mexican-hat type Mirrors

Mesa Beam Intensity Profile (Normalized)

# Adaptive Heating for Non-spherical Mirrors




Heating beam pattern to be applied to a Fused Silica mirror to produce Mesa beam cavity mirrors

# Summary

- Adaptive heating of optical components is a useful technique for thermal compensation in high power application
- Thermal aberrations in Advanced LIGO can be corrected by adopting:
  - » Annular heating
  - » Negative TOC compensation plate
  - » Mode matching telescope mirror heating
- This can also be used to realize non-Gaussian (e.g., mesa beam cavity mirrors) beam shaping