LIGO

Design of Stable Power-Recycling Cavities

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LSC

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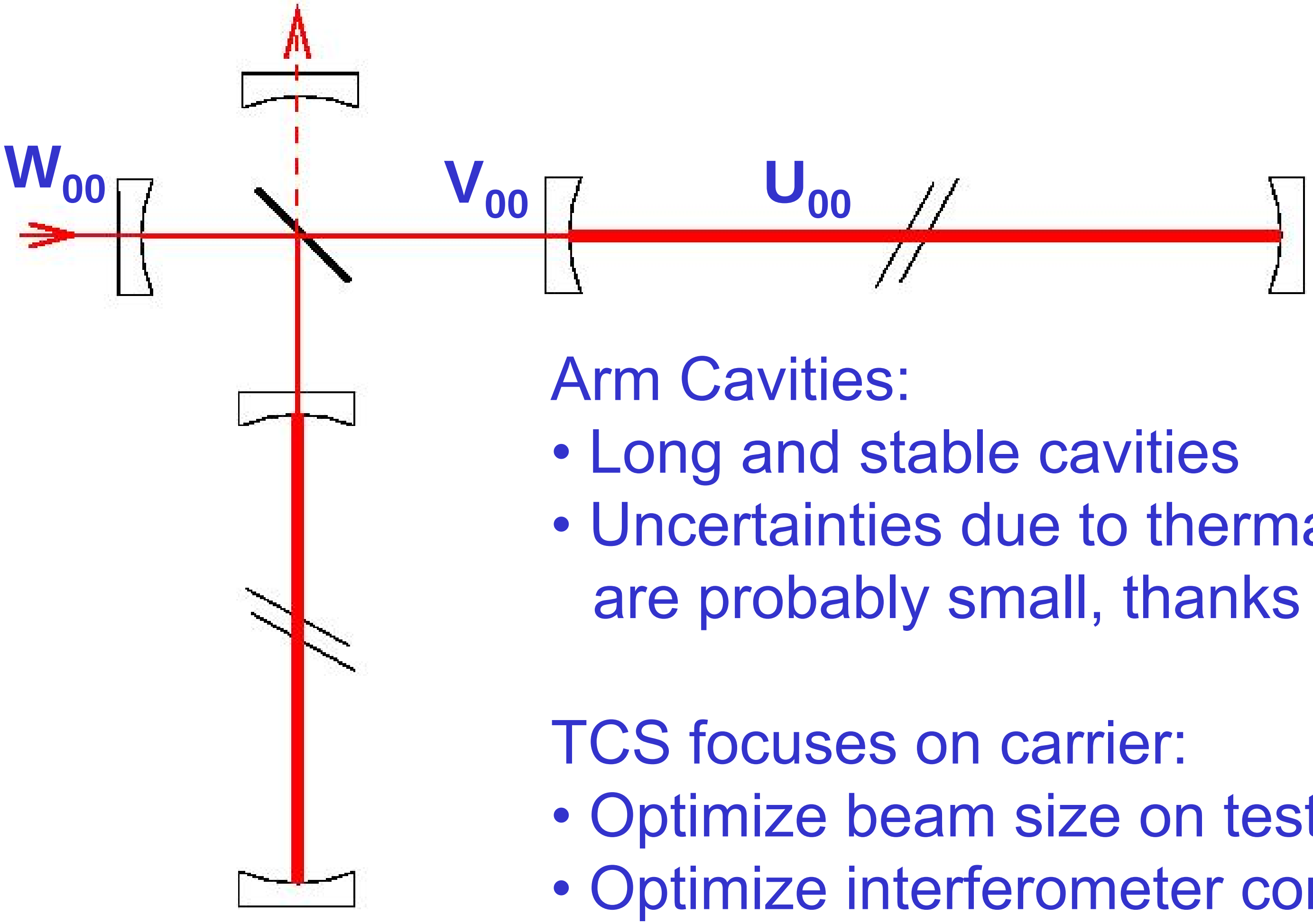
Advanced LIGO – arm cavities



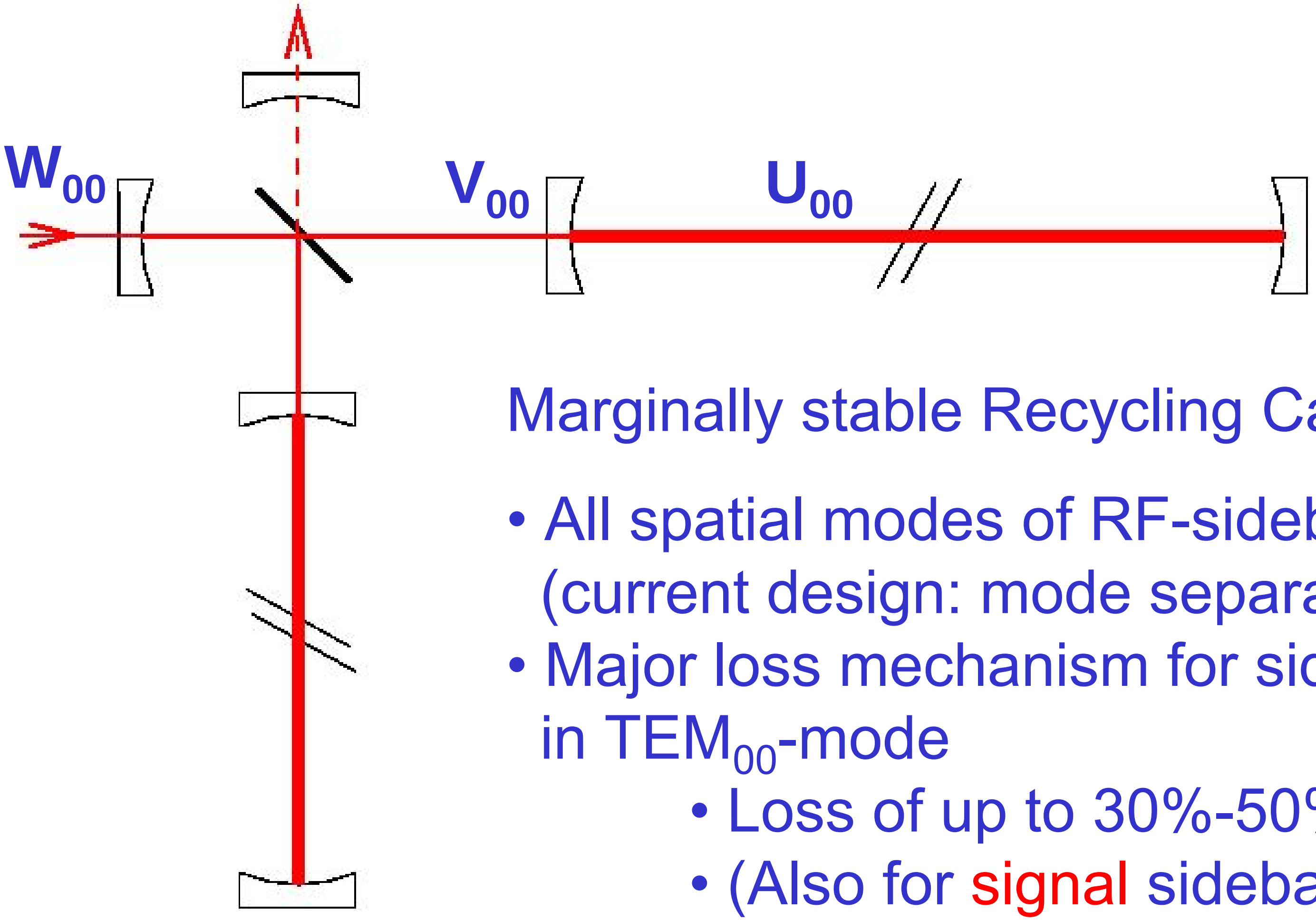
Arm Cavities:

- Long and stable cavities
- Uncertainties due to thermal lensing are probably small, thanks to TCS

TCS focuses on carrier:

- Optimize beam size on test masses
- Optimize interferometer contrast
- Optimize mode matching(?)

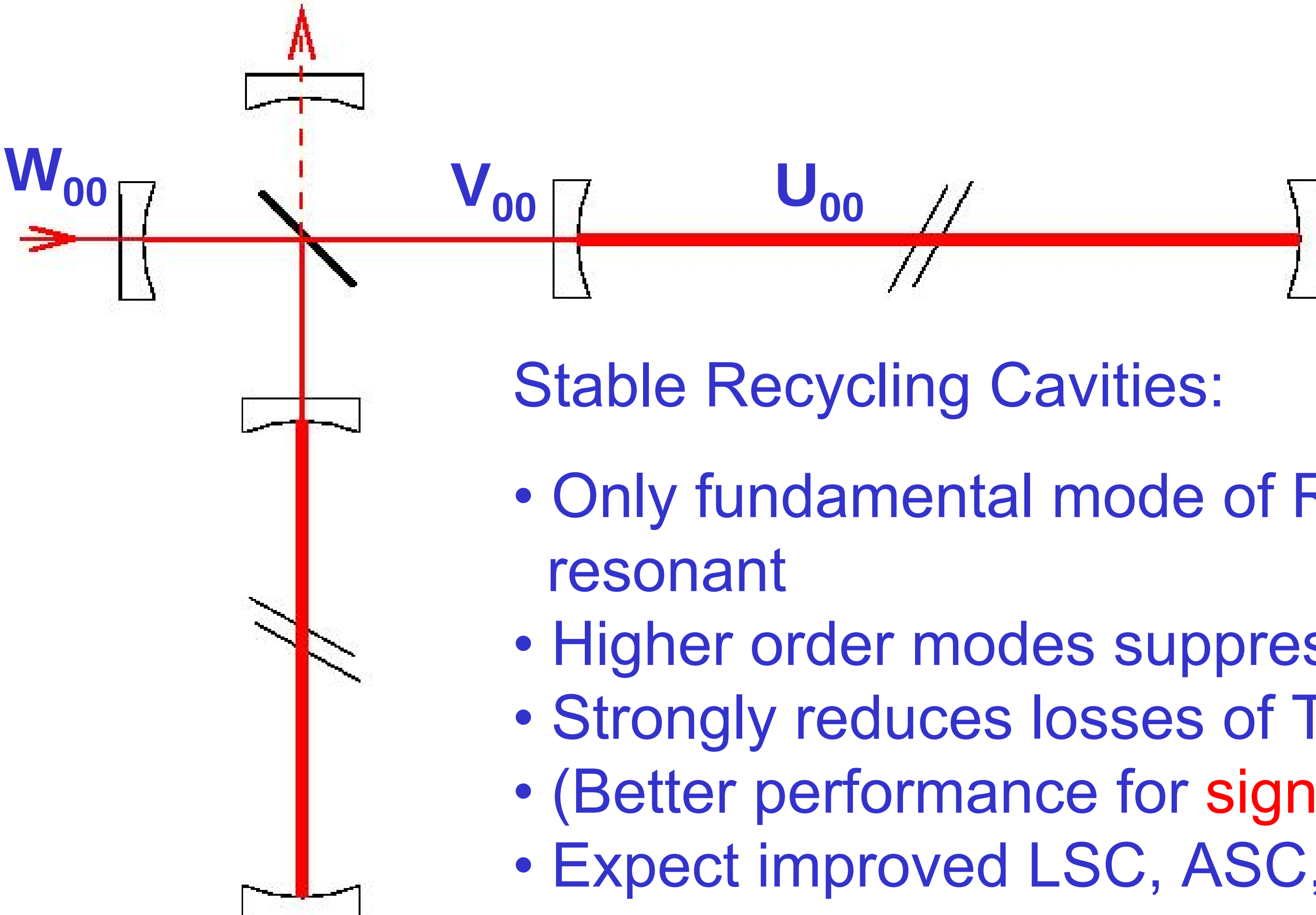
Adv. LIGO
marginally stable recycling cavities



Marginally stable Recycling Cavities:

- All spatial modes of RF-sidebands resonant (current design: mode separation ≈ 4 kHz)
- Major loss mechanism for sidebands in TEM_{00}-mode
    - Loss of up to 30%-50%
    - (Also for signal sidebands!)
- Impact on LSC and ASC

Adv. LIGO stable recycling cavities



Stable Recycling Cavities:

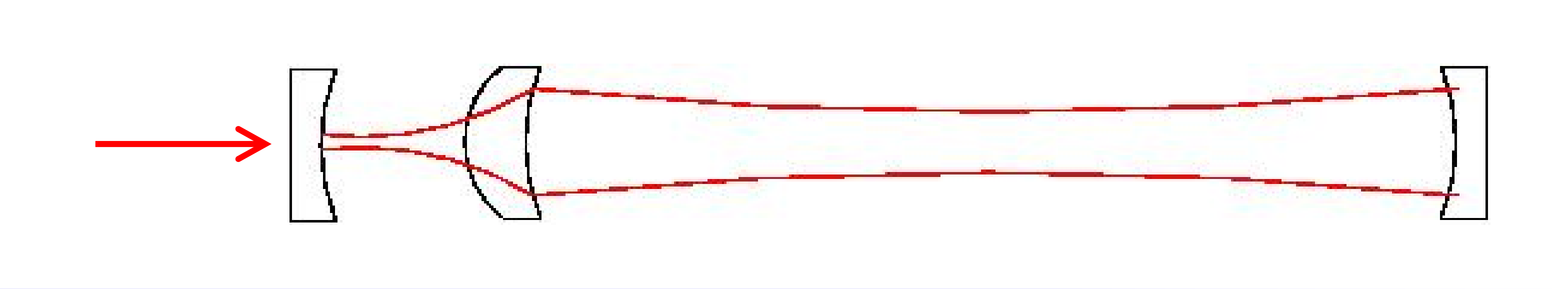
- Only fundamental mode of RF-sidebands resonant
- Higher order modes suppressed
- Strongly reduces losses of TEM_{00}-mode
- (Better performance for signal sidebands)
- Expect improved LSC, ASC, and even Bullseye (mode matching) signals
- Interferometer will be much easier to understand and debug

Stable Rec. Cavities

How? (mirror needed inside the Rayleigh range of the modes)

Solution 1:

- Lens in ITM substrate



Problem:

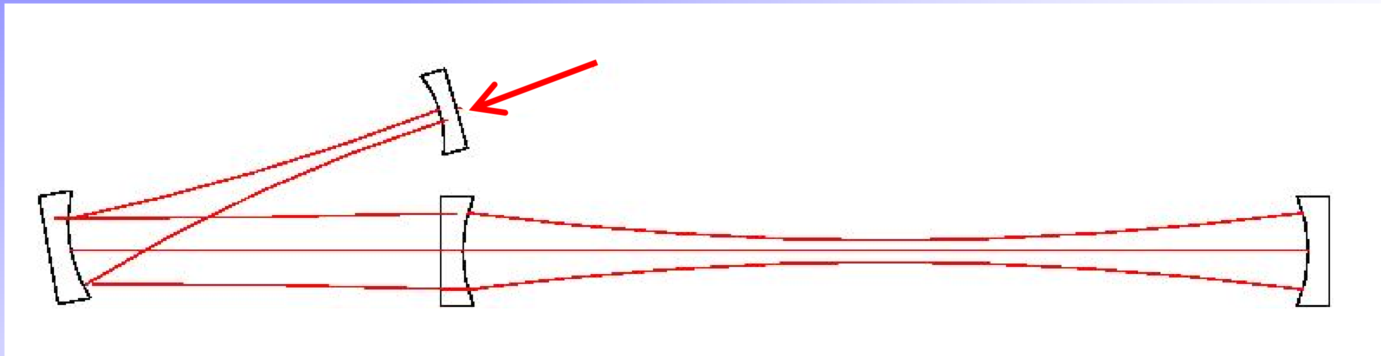
Divergence angle: $\alpha \sim 6$ cm / 8 m ~ 7 mrad

$\rightarrow$ Waist: $w_0 = \lambda/\pi\alpha \sim 50\ \mu m$

Creates sub mm beam size on
Recycling mirror ($\sim 290\ GW/m^2$)

Stable Rec. Cavities – Solution 2

- Two mirror Recycling cavity



Problem:

Divergence angle: $\alpha \sim 6$ cm/16 m ~ 4 mrad

$\rightarrow$ Waist: $w_0 = \lambda/\pi\alpha \sim 90\ \mu m$

Creates sub mm beam size on
Recycling mirror (~ 80 GW/m^2)

Stable Rec. Cavities – Solution 3

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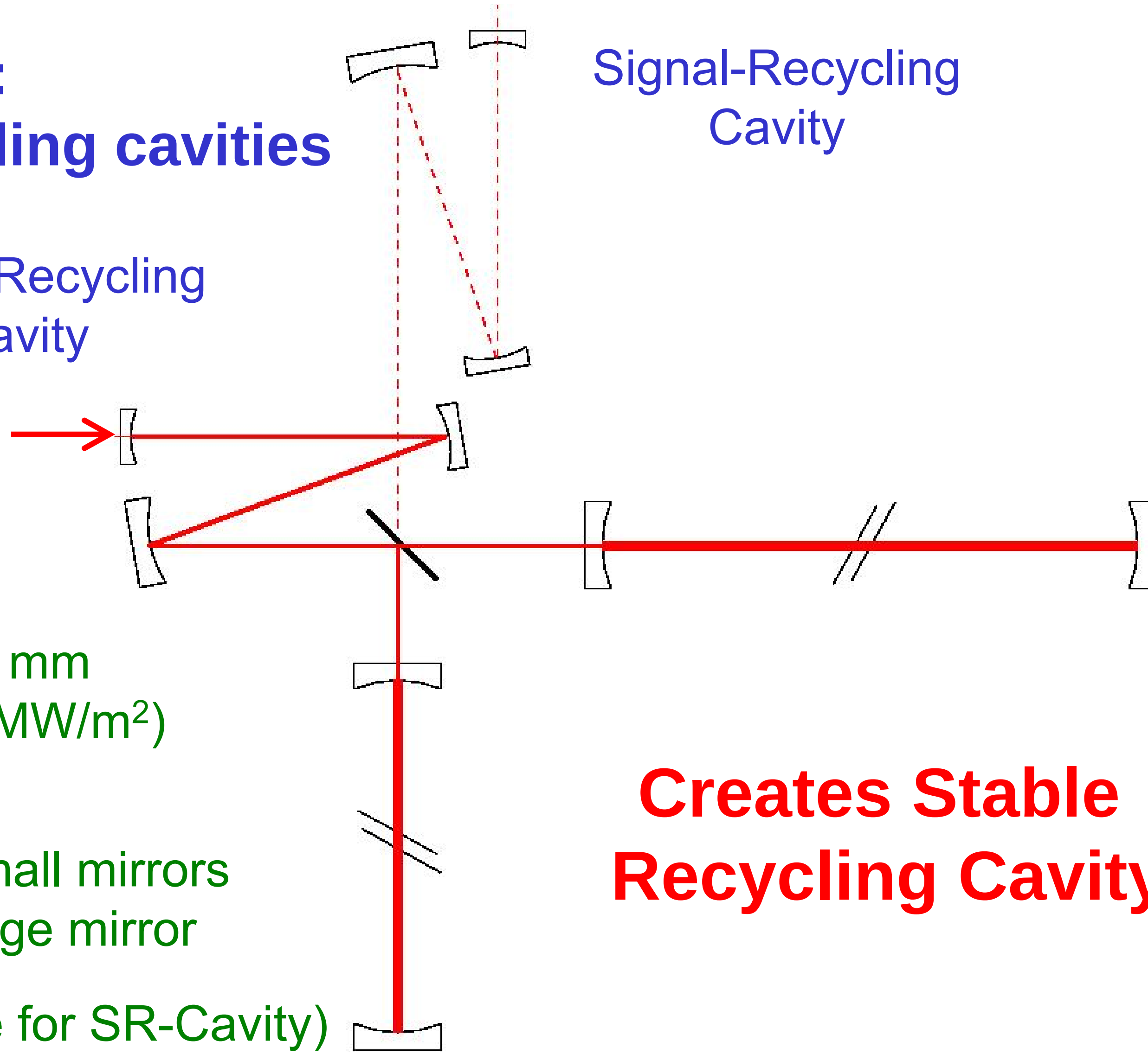
Third option:
folded recycling cavities



This design:
- Beam size > 2 mm
  (Power < 160 MW/m^2)

Design adds:
- 2 additional small mirrors
- Removes 1 large mirror

(Same is possible for SR-Cavity)

Creates Stable Recycling Cavity

Design Drivers

- ✓ Spot Size
- Vacuum envelope
- Seismic Isolation
- Flexibility in mode matching
- Alignment
- Modulation frequency / linewidth effects
- …

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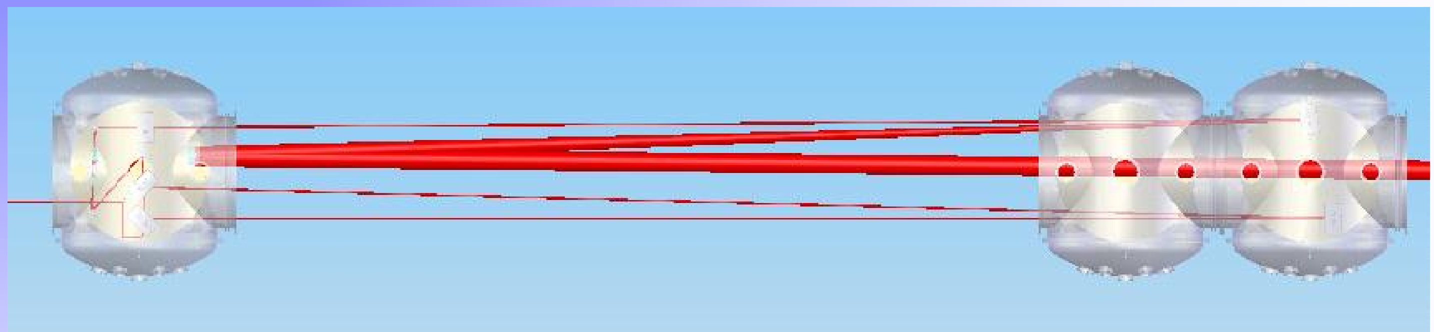
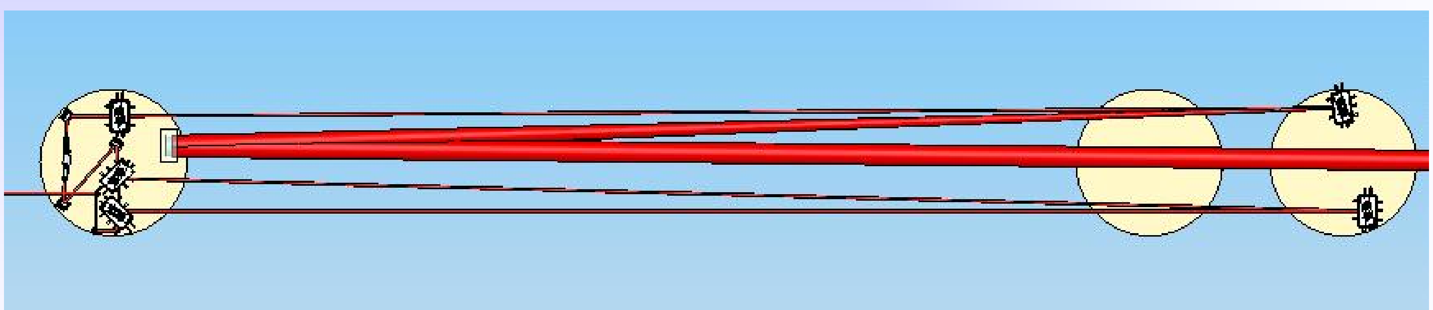
Vacuum Envelope

Top View:

HAM 1 HAM2 HAM3





Vacuum Envelope

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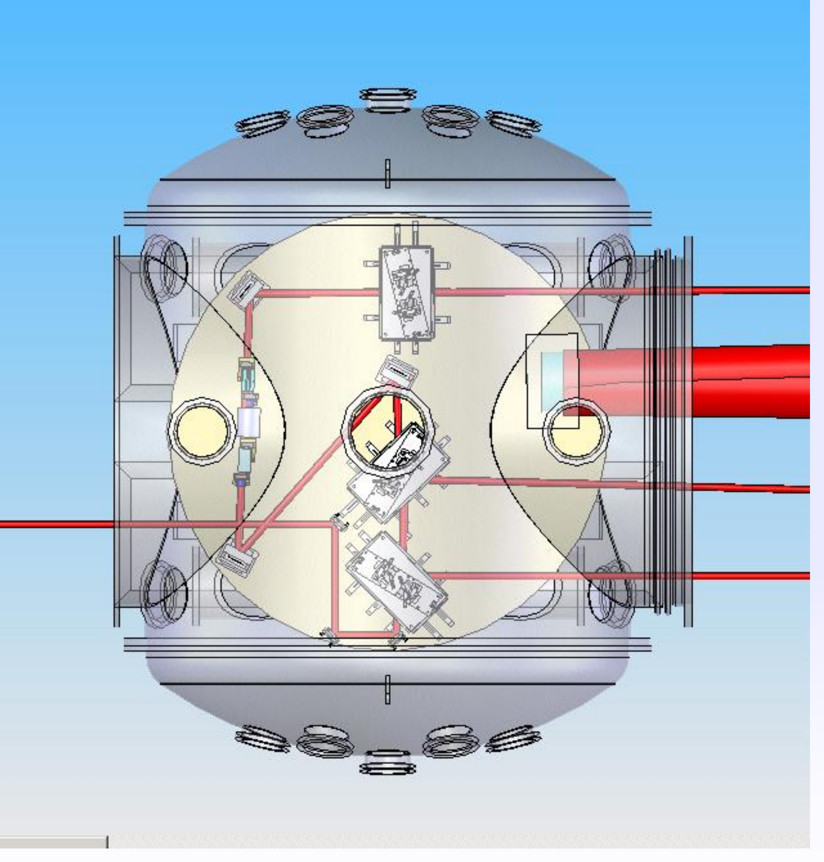
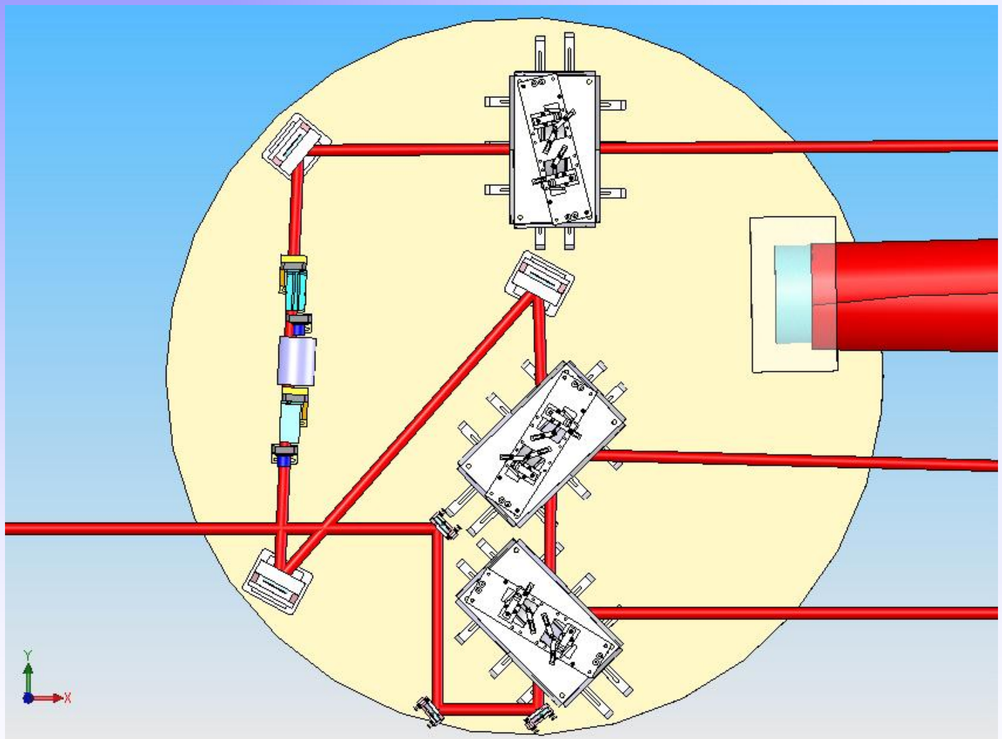
Top View:
HAM 1



Vacuum Envelope

Top View:
HAM 1



Vacuum Envelope

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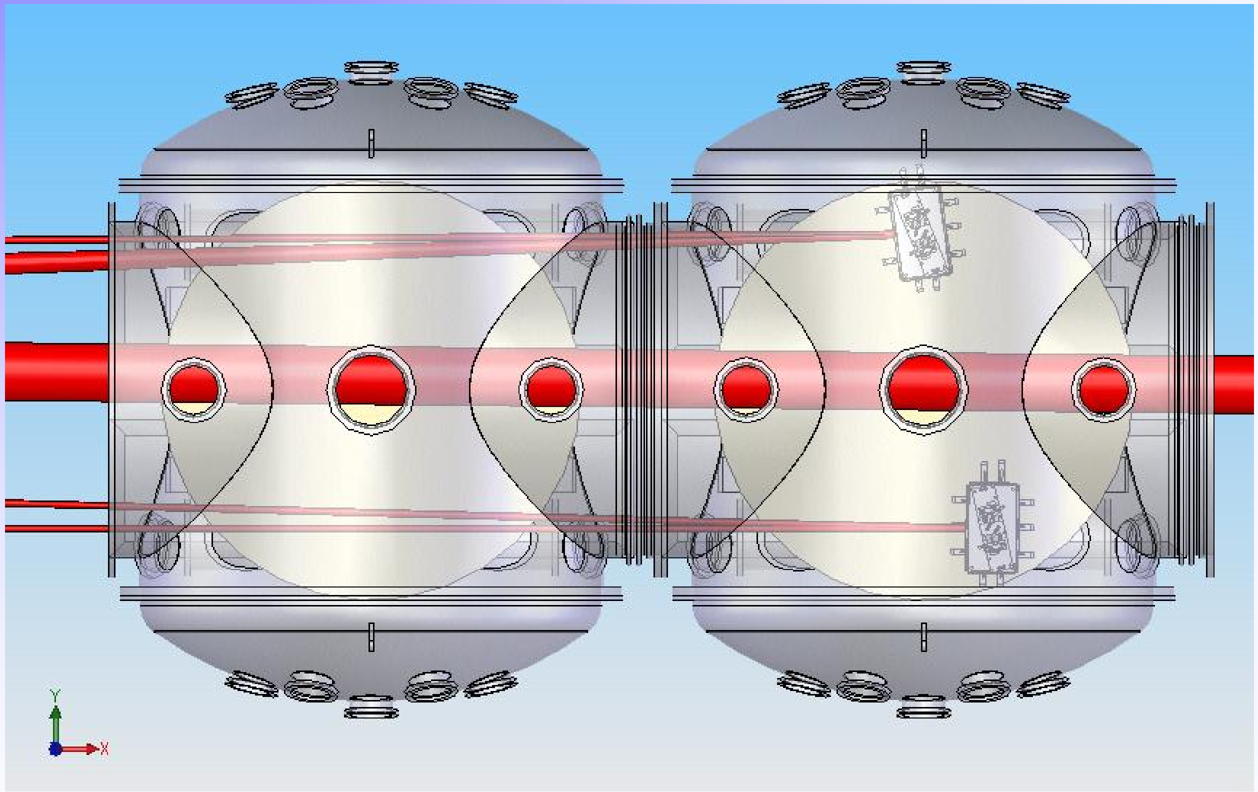
Top View

HAM 2 HAM 3



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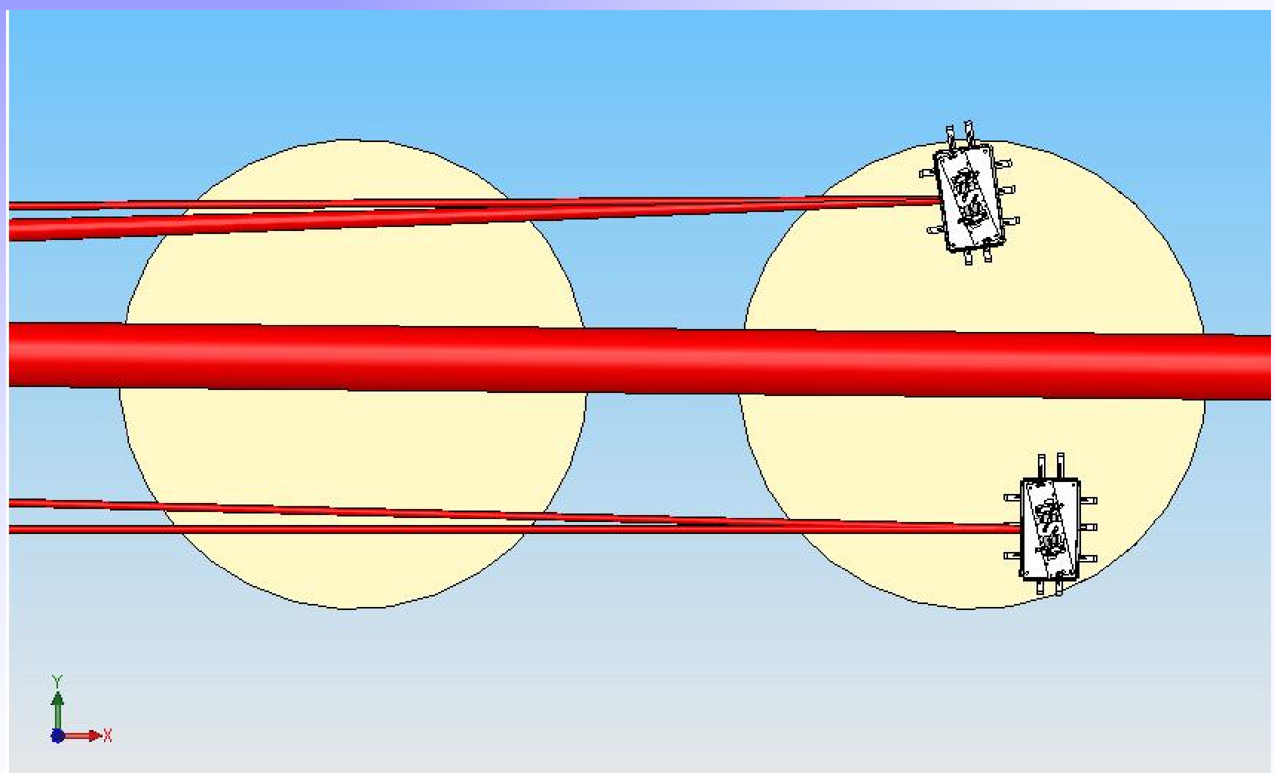
Vacuum Envelope

Top View

HAM 2 HAM 3



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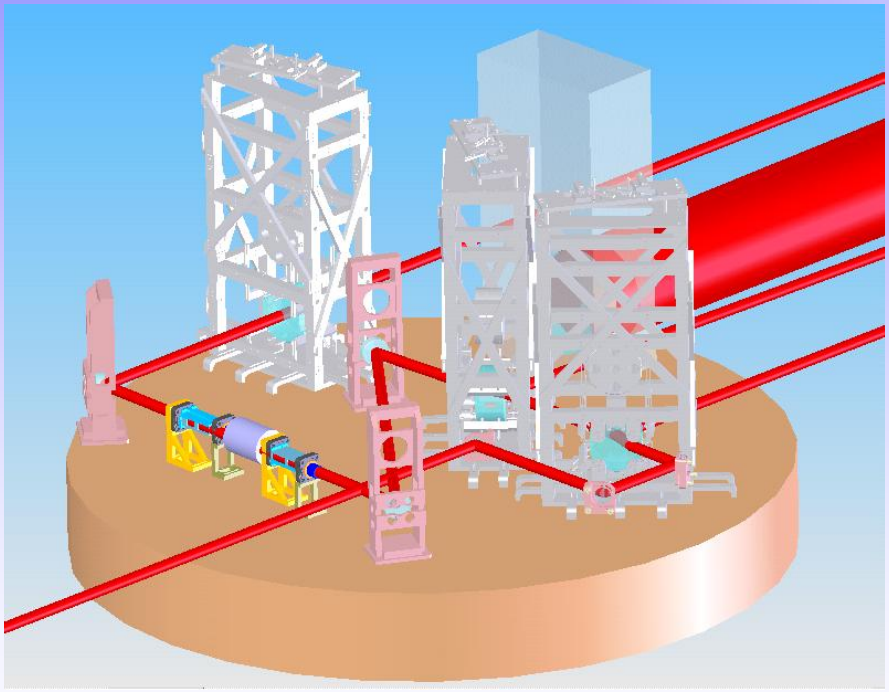
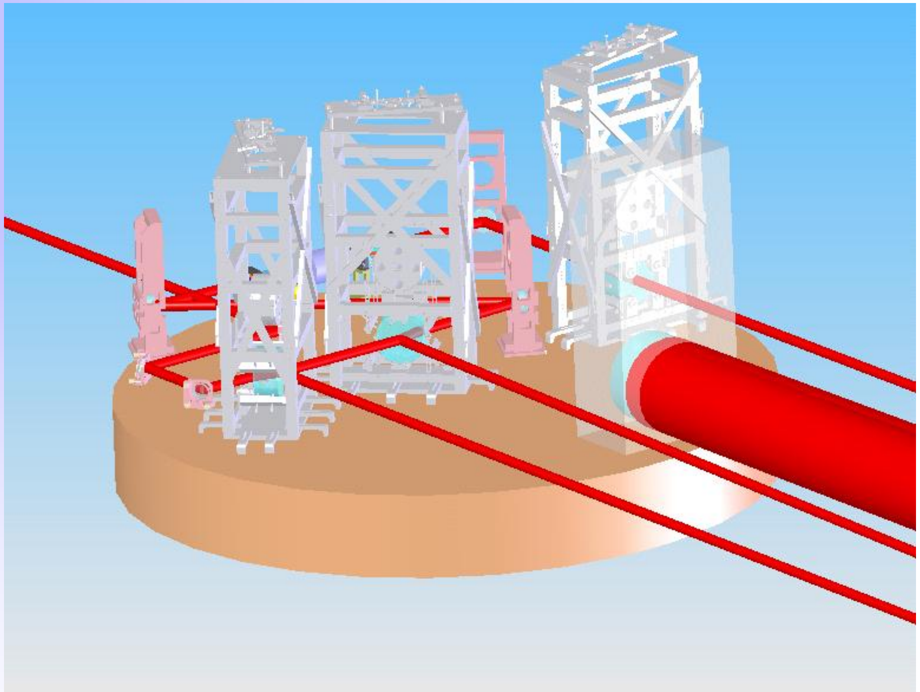
Vacuum Envelope

Side Views from HAM 1





Design Drivers

- ✓ Spot Size
- ✓ Vacuum envelope
- Seismic Isolation
- Flexibility in mode matching
- Alignment
- Modulation frequency / linewidth effects
- …

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Seismic Isolation

Requirements on single PR-mirror [1] :

- 3×10^{-16} m/rHz
  - Driven by sensitivity to frequency noise

Target stability:

- 3×10^{-17} m/rHz
  - Same suspension as Mode cleaner mirrors (triple pendulum)

Necessary changes for New Recycling cavity:

- Move large PR substrate in triple pendulum to MMT3 location
- First small PR mirror in MC-triple pendulum on IO-table
- Second small PR mirror in MC-triple pendulum on PR-table
- Mode matching from MC into Recycling cavity might add two additional small mirrors (single pendulum suspension)

[1] Sources: Seimic Isolation Subsystem Design Requirements Document E990303-03-D
Advanced LIGO Systems Design T010075-00-D

Design Drivers

- ✓ Spot Size
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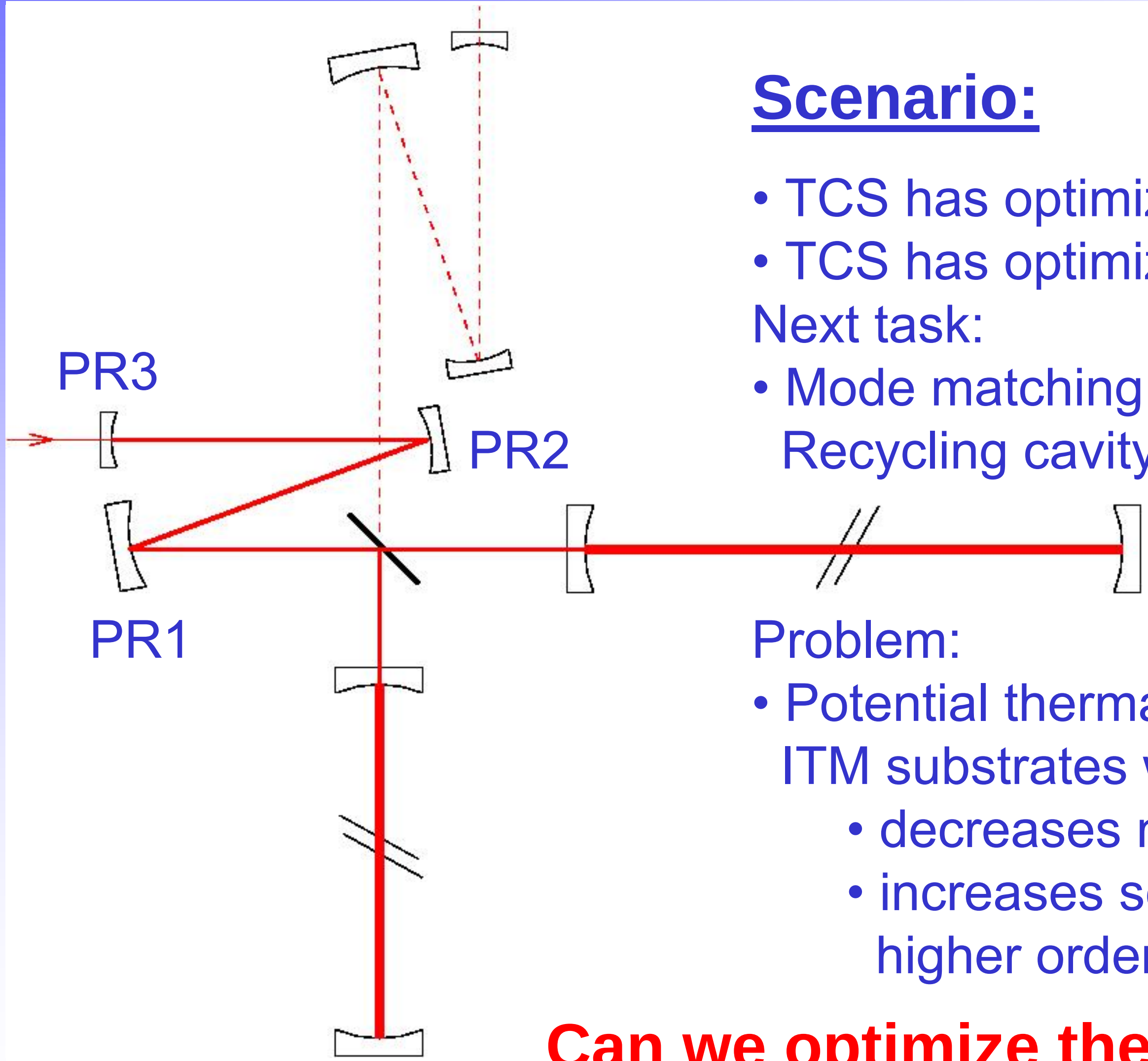
Mode matching



Scenario:

- TCS has optimized beam size in arms
- TCS has optimized contrast in MI

Next task:

- Mode matching between Recycling cavity and arm cavities.

Problem:

- Potential thermal lens in BS and/or ITM substrates which
  - decreases mode matching
  - increases scattering into higher order modes

Can we optimize the mode matching after we know the thermal lens ?

Mode matching

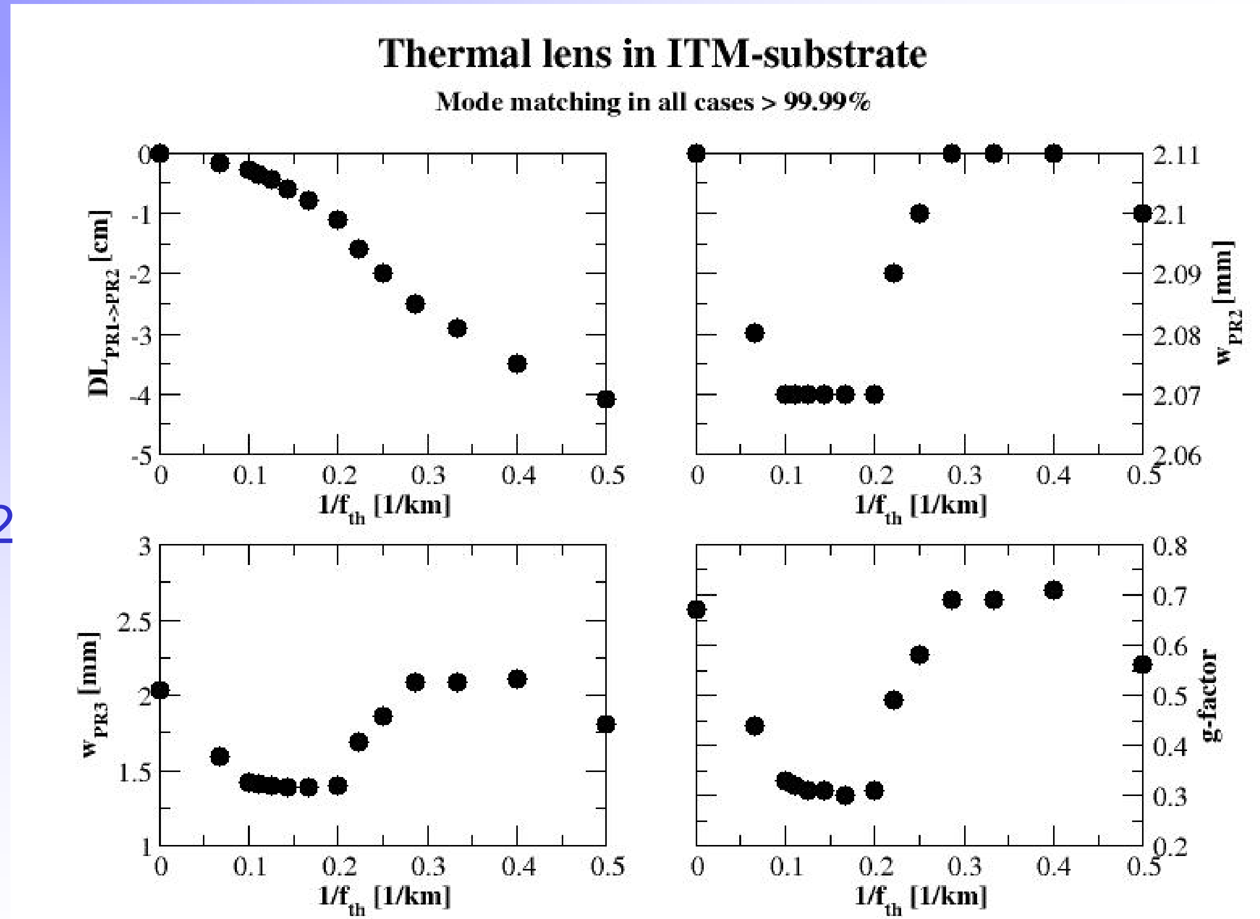
Can we optimize the mode matching after measuring the thermal lens?

Yes!

Even without changing the length of the recycling cavity

How?

- Change distance between PR1 and PR2 until mode matching is optimized
- Compensate change in the length by moving also PR3



Alternative: Adaptive mode matching with thermally induced focal length changes

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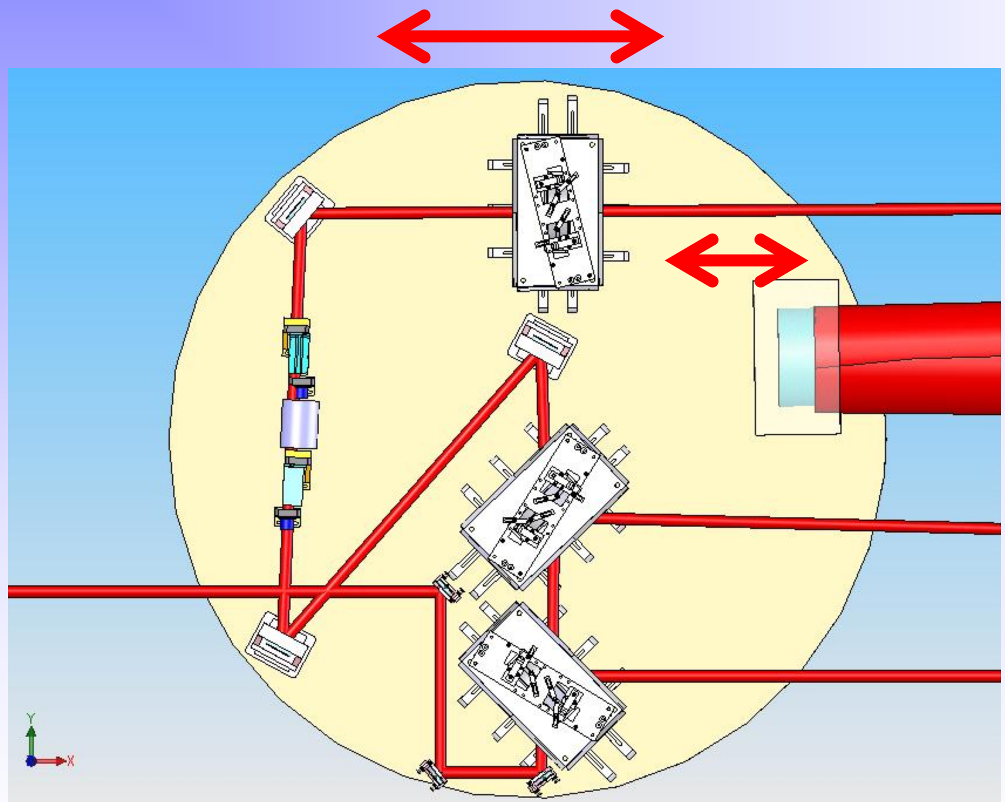
Vacuum Envelope mode matching PR1, PR3

Top View:

Plenty of space for mode matching adjustments



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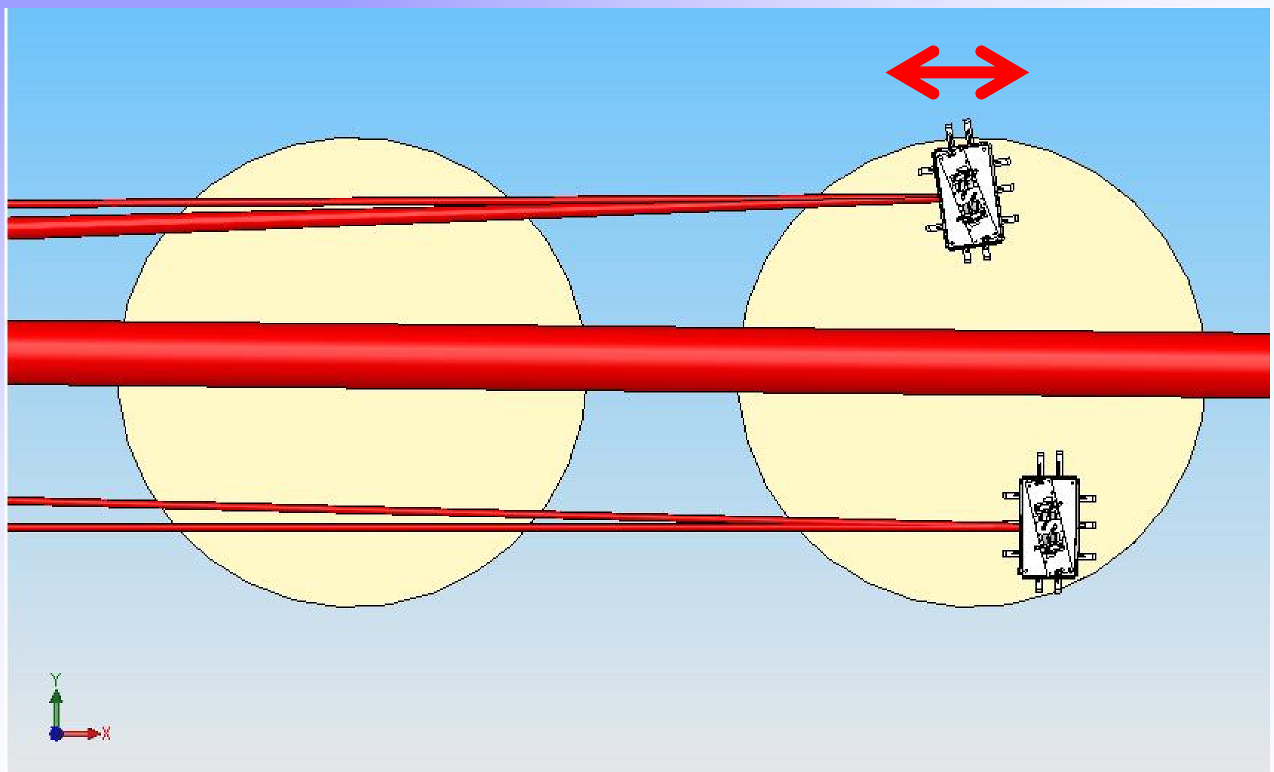
Vacuum Envelope mode matching PR2

Top View

Plenty of space for mode matching adjustments



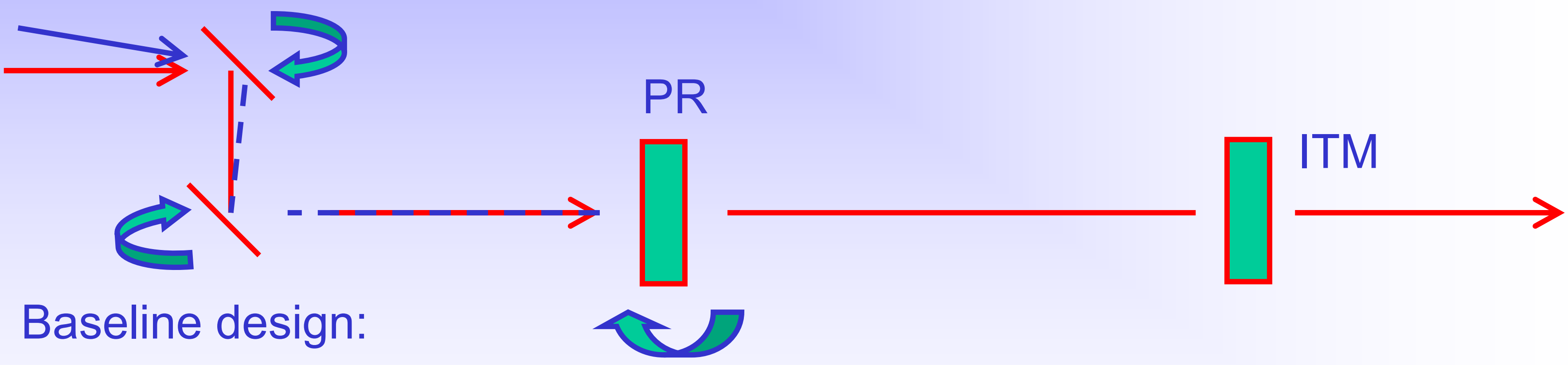
Design Drivers

- ✓ Spot Size
- ✓ Vacuum envelope
- ✓ Seismic Isolation
- ✓ Flexibility in mode matching
- Alignment
- Modulation frequency / linewidth effects
- …

Alignment Issues

Question:
Do we need to worry about additional alignment d.o.f as we have now more mirrors?

- Arm cavities are equal, no difference
- Any difference in Recycling Cavity?



Baseline design:

- Align orientation of PR
- Align propagation direction and position of Input beam

Total: 3 d.o.f. in horizontal and 3 d.o.f. in vertical direction

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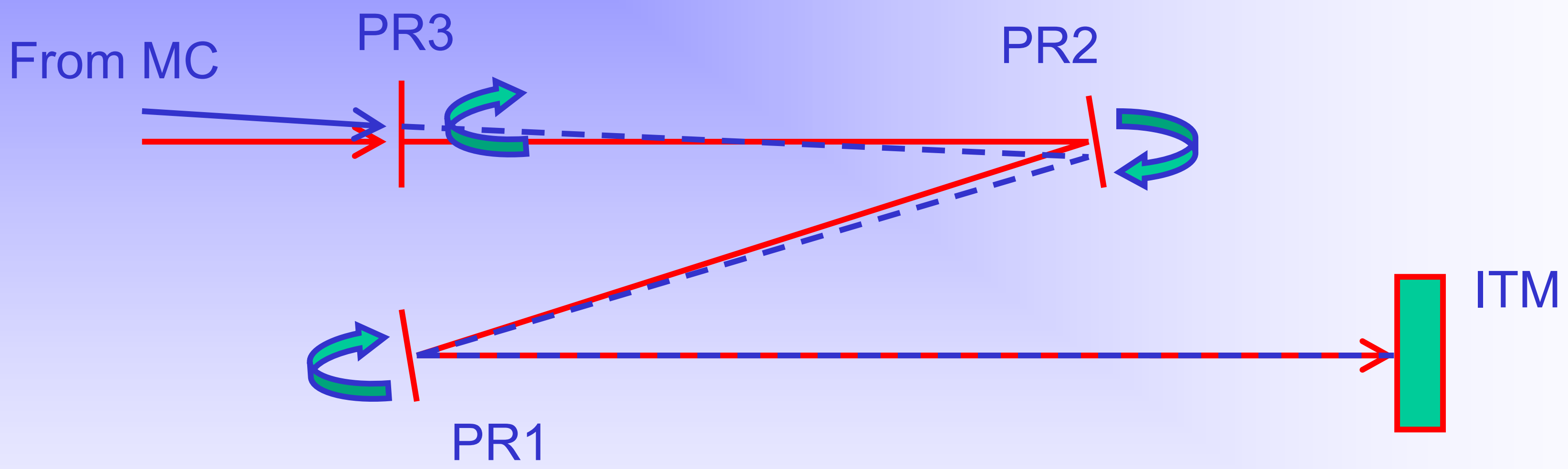
Alignment Issues

Alignment defined by arm cavity:
- Find position on PR1
- Propagation direction from PR1 to ITM1



Change in Input beam also requires adjustment of 3 d.o.f. in horizontal and 3 d.o.f. in vertical direction!

Other Option: Align input beam and only one of the PR mirrors.

Alignment Issues

Alignment sensing matrix: (Work in progress)

• Calculate alignment sensing matrix for Advanced LIGO with and without stable recycling cavities

Intermediate (premature) results:

For Baseline Design:

• Difficult to distinguish between PR and ITM tilts (same Gouy phase)

For New Design:

• Same problem between PR1 and ITM tilts
• Easy to distinguish between PR2, PR3 tilts and ITM tilts

Preliminary conclusion:

Advantage for new design: Larger linear range in ASC-signals
Disadvantage: ?

Design Drivers

- ✓ Spot Size
- ✓ Vacuum envelope
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Modulation Frequencies

Modulation frequency requirements

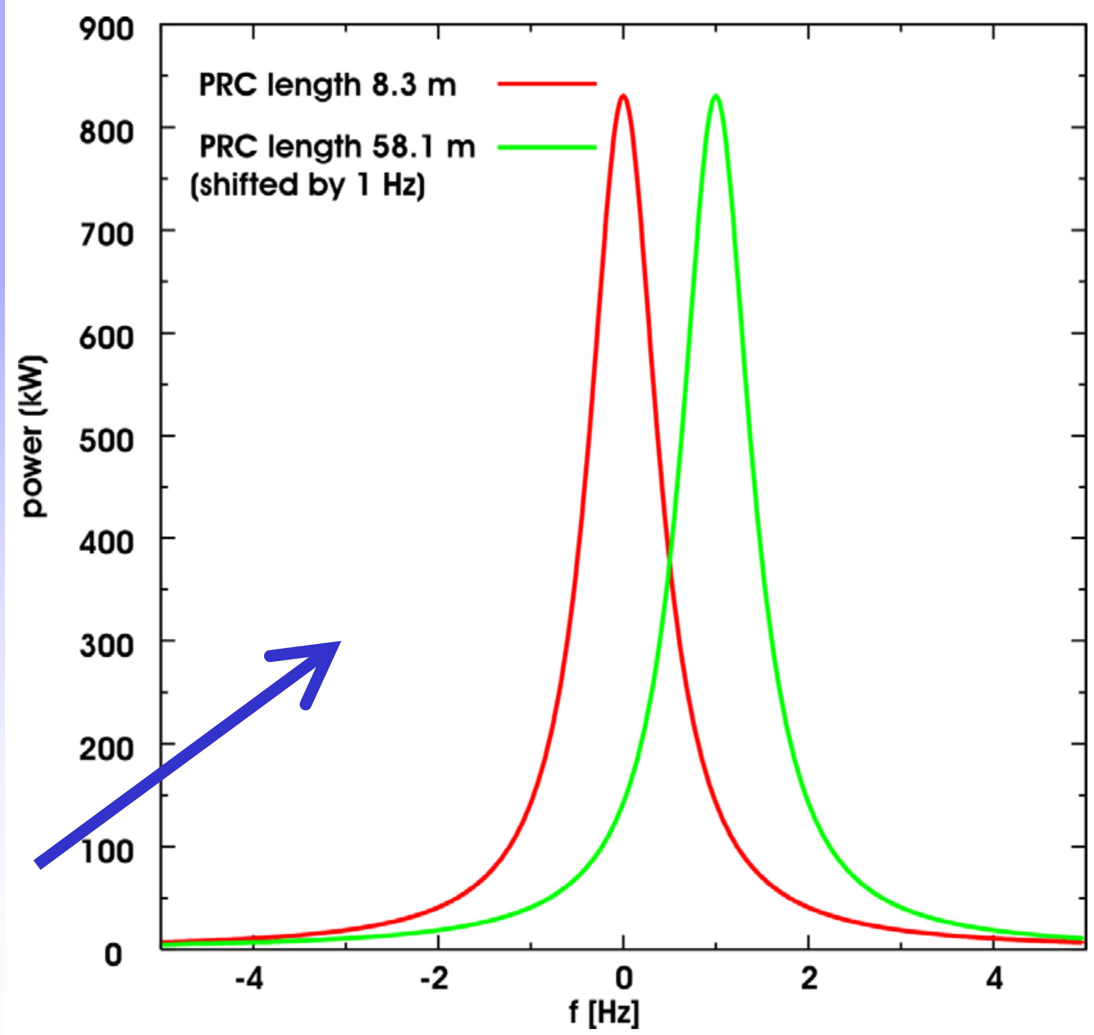
- 180 MHz must pass through MC and PRC and 9 MHz must be anti-resonant for the PRC
(dictated by length of MC = 16.6m, FSR_{MC} = 9 MHz)
- The vacuum envelope changes length of PRC from 8.3 m to 8.3 m + 3*(16.35 m ± x)
(x must be small to fit in HAM chamber)
- With x = 0.25 m => $FSR_{MC} = 3.5 * FSR_{PR}$
FSR_{PR} = 2.57 MHz

Coupled PRC linewidth

- Does changing the length of the PRC have any influence on the linewidth of the coupled power recycling / arm cavity?
- No, the finesse of the Arm cavities dominate the PRC:

$$\Delta\nu_{PRC} = \Delta\nu_{ArmC}\frac{1-\left|\tilde{r}_{ArmC}(0)\right|^2}{2}$$

- No influence of PRC length
- Power vs. frequency in the x-Arm cavity for both PRC length in a finesse plot:



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Conclusions

Stable Recycling Cavity (SRC):

- Suppresses higher order modes of the RF-sidebands
- Increases Power in fundamental mode of sidebands
- (?) Improves alignment sensing (larger linear range of ASC signals)
- Adds flexibility for mode matching

Baseline Recycling Cavity:

- Fewer Components (SRC has more small mirrors, one less large mirror)
- Fewer triple suspensions

Costs:

- Hardware costs probably higher for stable recycling cavity
  - Should fit in current vacuum envelope
- Expect shorter commissioning time for stable recycling cavity design
  - Higher order mode contamination often limits diagnostics