Stable recycling cavities for Advanced LIGO

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LIGO-G070691-00-D

with input/material from
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David Ottaway, Muzammil Arain,
Yi Pan, Peter Fritschel, and
many others

Stable Recycling Cavities

Original Motivation:

Define the spatial mode in the recycling cavities

- Clean up the RF sidebands
- Keep sidebands symmetric
  - at least for RSE (non-detuned SR)
- Better understanding of what is going on inside the IFO

About a year later (Yi Pan, Kip Thorne):

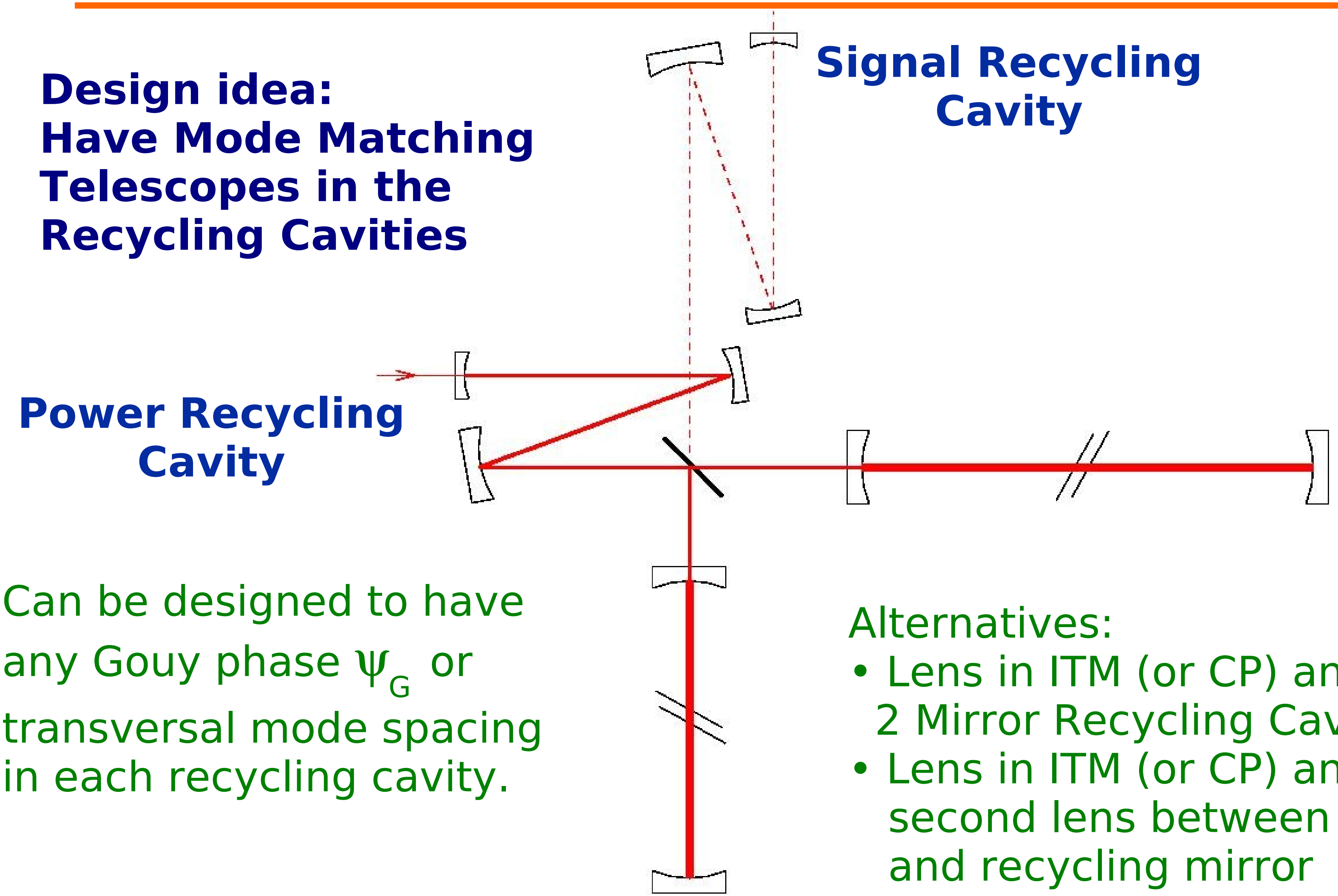
- Reduce the scatter losses of the signal sideband

Basic Idea:

- Keep higher order modes non-resonant
- All this is based on modal model (Gauss modes)

Stable Recycling Cavities

Design idea:
Have Mode Matching Telescopes in the Recycling Cavities



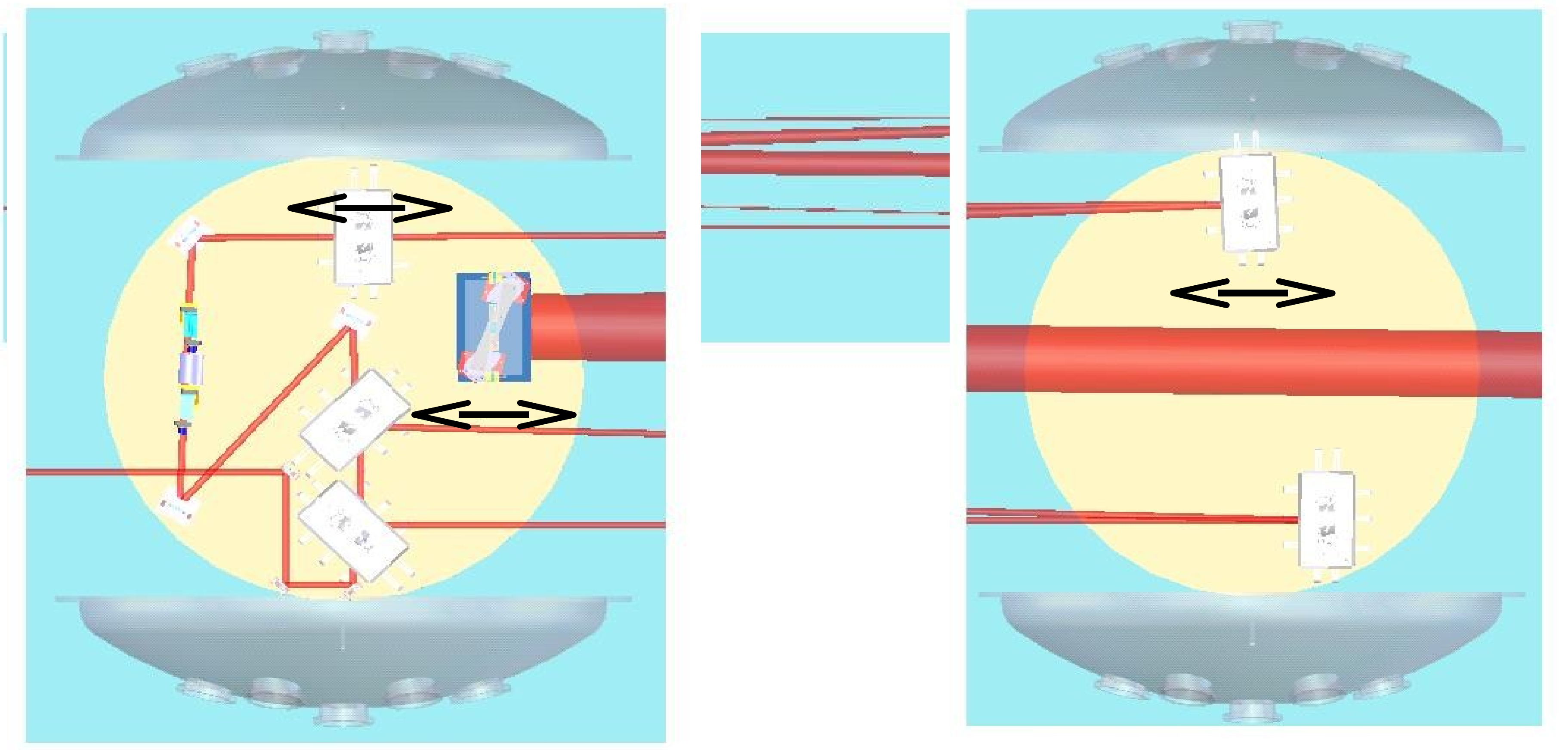
Can be designed to have any Gouy phase ψ_G or transversal mode spacing in each recycling cavity.

Alternatives:
- Lens in ITM (or CP) and 2 Mirror Recycling Cavity
- Lens in ITM (or CP) and second lens between BS and recycling mirror

Stable Recycling Cavities

Stable Recycling Cavities

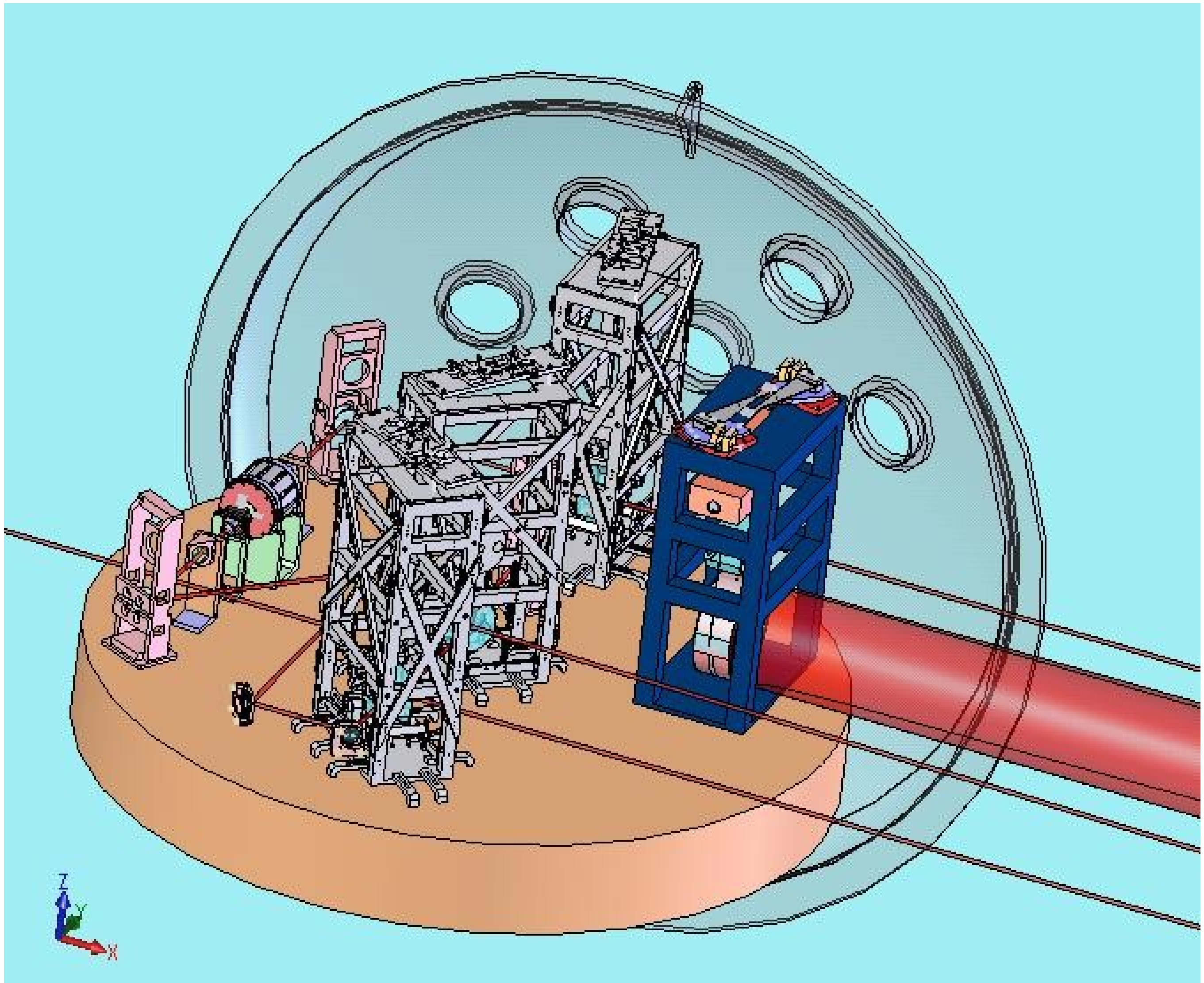
Enough range for mode matching adjustments



Stable Recycling Cavities

HAM 2:

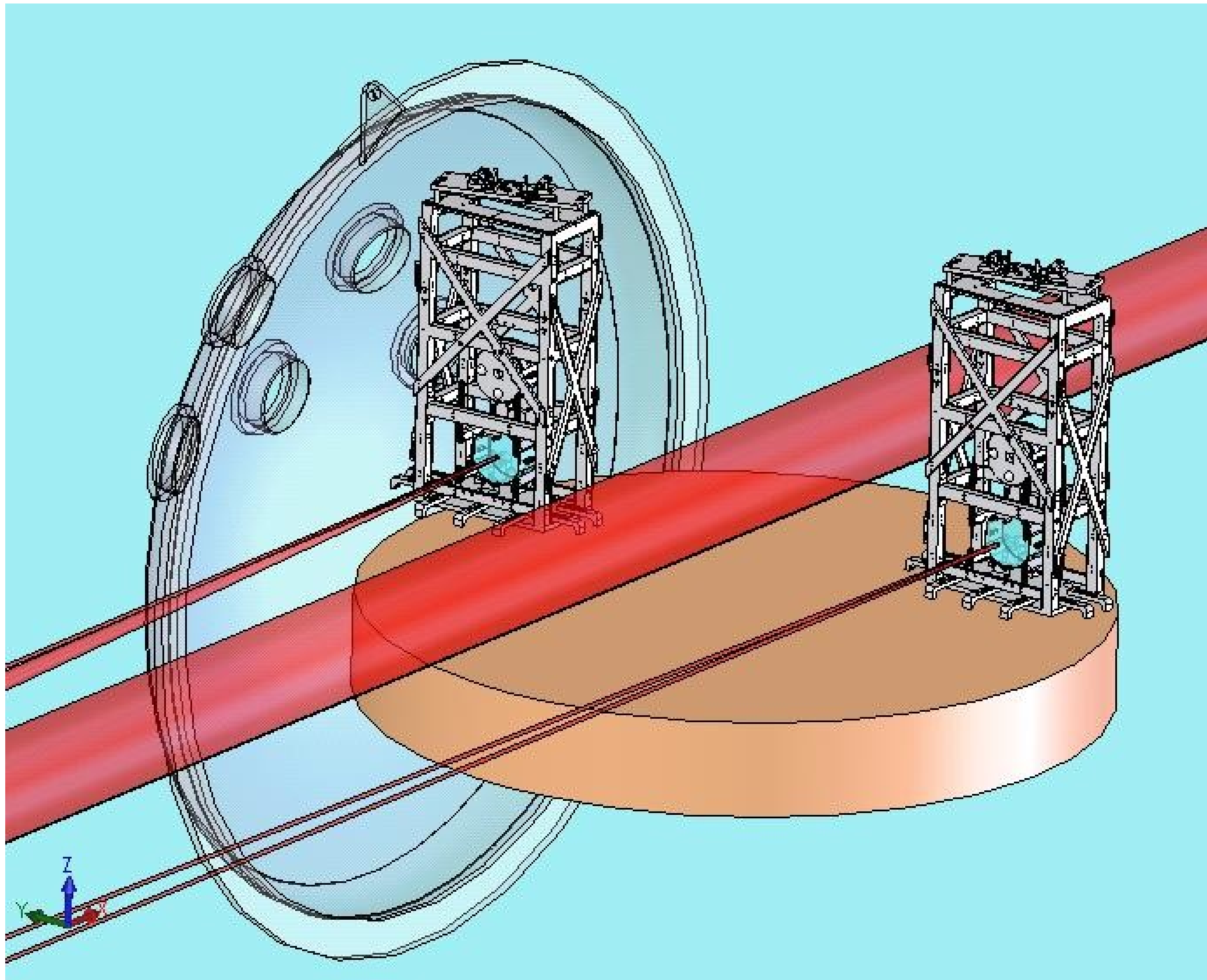
- MC 1+3
- PR 1+3
- FI
- + auxiliary optics to route all pick offs (not shown)



Stable Recycling Cavities

<u>HAM 3:</u>

- MC 2
- PR 2
- + auxiliary optics to route the all pick offs +TCS optics (not shown)



Stable Recycling Cavities

Typical values:

- **Beam size on large PR3 mirror $\simeq$ beam size on ITMs**
- **Beam size on small PR2 and PR1 mirrors $\simeq$ 2-4 mm**
- **No limitations on value of Gouy phase in recycling cavity**
  - **Pick one and we design the telescope accordingly**
  - **Very sensitive to mode mismatch in telescope but recovers also when we recover the mode matching**
    - fast telescopes are very sensitive to **relative** mismatches between distance and radii of curvatures
- **Mode matching will not change when TM ROCs are off by 1%**
  - **Based on Modal model (no diffraction)**
  - **Need TBC by FFT-code (Diffraction is an issue)**

Areas of concern

- **ASC**
  - **Aligning the test masses and recycling mirrors**
    - The 10-mode has to be extracted from the arm cavities
    - Distinguish between all d.o.f.
- **Beam Jitter**
  - **10-mode in input field scatters into 00-mode at tilted TM and RM**
    - The 10-mode should be rejected by the interferometer
- **Signal loss**
  - **HOMs in the signal recycling cavity should be suppressed**
    - HOMs round trip phase should **not** be multiple of 2π
- **Parametric Instabilities**
  - **Avoid 'signal recycling' of HOM's generated inside arm cavities**
- **Diffraction**

ASC

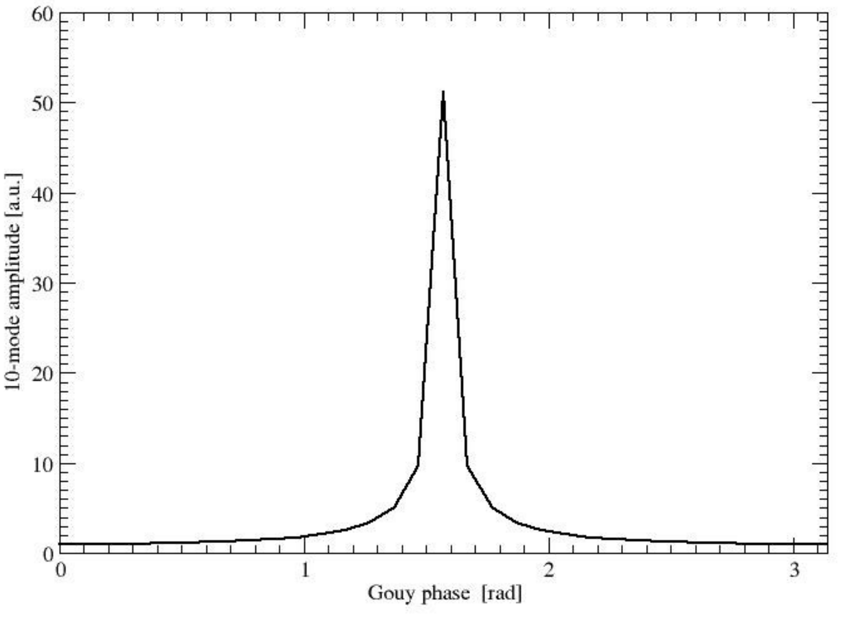
ASC

- The 10-mode has to be extracted from the arm cavities

Ideal:

- **Power recycling cavity:**
  $\Psi_g = \pi/2$
- **Signal recycling cavity:**
  $\Psi_g \sim 0$ (comp. detuning of SR)

➢ **10-mode build-up: ~50 inside recycling cavities**



ASC

ASC

- The 10-mode has to be extracted from the arm cavities
- Distinguish between all degrees of freedom

Apparent advantage for marginally stable SR-cavity could not be confirmed in simulations (at least not factor 50):

- Likely reason: Other d.o.f. mess up sensing matrix
- Have now a first ASC sensing matrix for stable cavities which appears to work (virtually no margin)
- will be difficult in all cases but doesn't look impossible
- does not show a strong preference for any design
- work in progress (Presentations in WG meeting tomorrow)

Beam Jitter

Ideal:

- Power recycling cavity: $\Psi_g = 0$
  - 10-mode anti-resonant in PR cavity
    - **Good for Beam jitter**
    - **Rather bad for ASC and Parametric Instabilities**

How bad is it for other Gouy phases?

- **~ Factor of a few more sensitive**
  - ➔ **We will have enough margin in the IO and PSL to handle this**

If $\Psi_g = \pi/2$ in PR-cavity (ASC-Optimum)

we would be ~50 times more sensitive to jitter (not good)

Signal Loss

Signal Loss

- **The low order modes which are generated by mode mismatches and figure errors between the arm cavities should be suppressed in the signal recycling cavity (and probably also in PR cavity)**

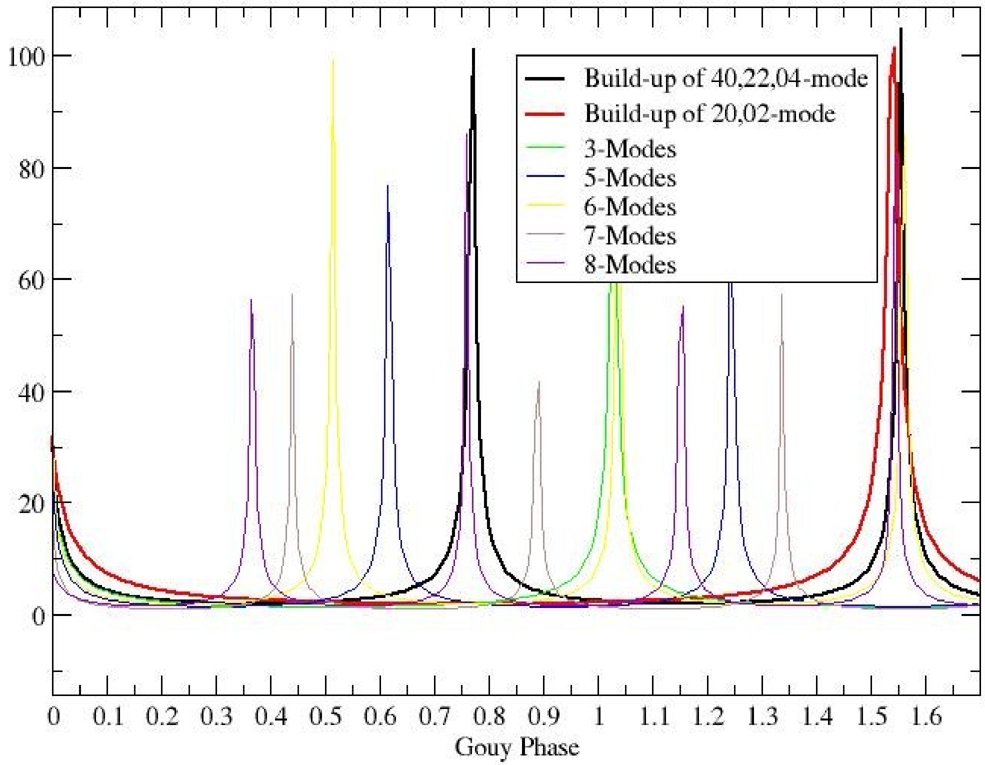
Ideal:

- Signal recycling cavity: $\Psi_g = \pi/4$
  would make the 20-mode (ROC mismatch) anti-resonant in the signal recycling cavity (but the 40 mode would be resonant).
- Yi Pan: $\Psi_g = 0.2 .. 1.3$ (avoid resonance of other HOM)

Signal Loss

Build-up of higher order scatter modes

Most critical: 20,02 and 40,22,04 modes



Good ranges:

~0.25 rad

~0.7 rad

Need to check

for larger SR detunings

For PR-cavity:

Shift the curve

by $\pi/2$ wg. tuning

Signal Loss

Only half of the story:

- **Diffraction** can not be described by modal picture
- **Have intra-cavity diffraction at the beam splitter and ITMs**

Apertured Gaussian beams develop rings in the far field

- **Marginally stable cavity is staying in near field**
- **Stable recycling cavity will develop diffraction rings**
  - **increases diffraction losses (see Diffraction)**

Parametric Instabilities

Parametric Instabilities

- Low order modes driven by the
  - » 00-mode inside arm cavities
  - » mechanical resonances of the mirrors substrates

mainly low order modes with n, m $\lesssim$ 4

Could build-up as PIs inside the arm cavities if

- » the optical losses are smaller than the opto-mechanical gain

➔ Don't want to do signal recycling on the PI modes

Ideal: Resonant sideband extraction for the PI mode

Complex issue:

- » Literature assumes worst case (marginally stable PR-cavity, identical cavities) for optical gain. Stable recycling PR cavity helps. Doesn't solve the problem!

Arm Cavities

A short side note:

How different will the arm cavities be?

- **ROC specification: ~1% or 10-20m**

Transversal mode spacing:

- **Changes by ~30Hz/m (ROC)**
- **FWHM (Power) of cavity: ~30Hz (T_{ITM}= 0.5%)**

➡ **resonant HOM in one cavity will probably not be resonant in other cavity**

TCS will correct ROC mismatches to some degree!
This could become a trade-off (tweak everything)

Areas of concern

Optimum Gouy phases:

- ASC
  - Optimum: PR: $\Psi_g = \pi/2$ SR: $\Psi_g = 0$ (assuming close to RSE)
  - Amplitude of 10-mode reduces by factor ~50 when $\Psi_g = 0$ (in PR)
- Beam Jitter
  - Optimum: PR: $\Psi_g = 0$, Worst case: $\Psi_g = \pi/2$
- Signal loss
  - Optimum: SR: $\Psi_g = 0.2 .. 1.3$
  - avoid resonances of HOMs: at $\Psi_g \sim \pi/4$ build-up of 40-mode
- Parametric Instabilities
  - Optimum: PR: $\Psi_g = \pi/2$ SR: $\Psi_g = 0$,
  - Window at PR: $\Psi_g \sim 3\pi/4$ SR: $\Psi_g \sim \pi/4$

Recommendation

PR: $\Psi_g = \pi/2+0.7$ SR: $\Psi_g = 0.7$

- ASC
  - Have now a first set of ASC-signals which appear to be OK (no margin)
- Beam Jitter
  - Coupling increases by ~1.5 compared to marginally stable cavity
- Signal loss
  - No low order HOM on resonance.
- Parametric Instabilities
  - Parametric gain for all modes except for 3-modes at or below 3. 3-Modes have gain of ~8 (compared to gain in non-recycled cavities).
  - Need non-identical cavities!
- Need to optimize the mode matching between PR, SR, and arms

Diffraction

Main outstanding issue (in my opinion):

- **Diffraction losses turn into signal loss and carrier scatter**
  - » **marginally stable cavity**
    - – diffraction loss dominated by arms ~ 0.6ppm x Gain + additional ~ 0.3%

Preliminary results from Hiro's FFT model (see his talk):

- **6cm beam size on ITM:**
  - » **Roundtrip losses: 230ppm --> Signal loss: 230ppm x recycling gain**
  - » **Also increased scattered light in central chamber from carrier resonating in PR cavity**
- **5.5cm beam size on ITM (~6.4cm on ETM):**
  - » **Roundtrip losses: 65ppm --> Signal loss: 65ppm x recycling gain**
- **Diffraction is sensitive to mode matching**
  - » **Work in progress**