Stable recycling cavities for Advanced LIGO

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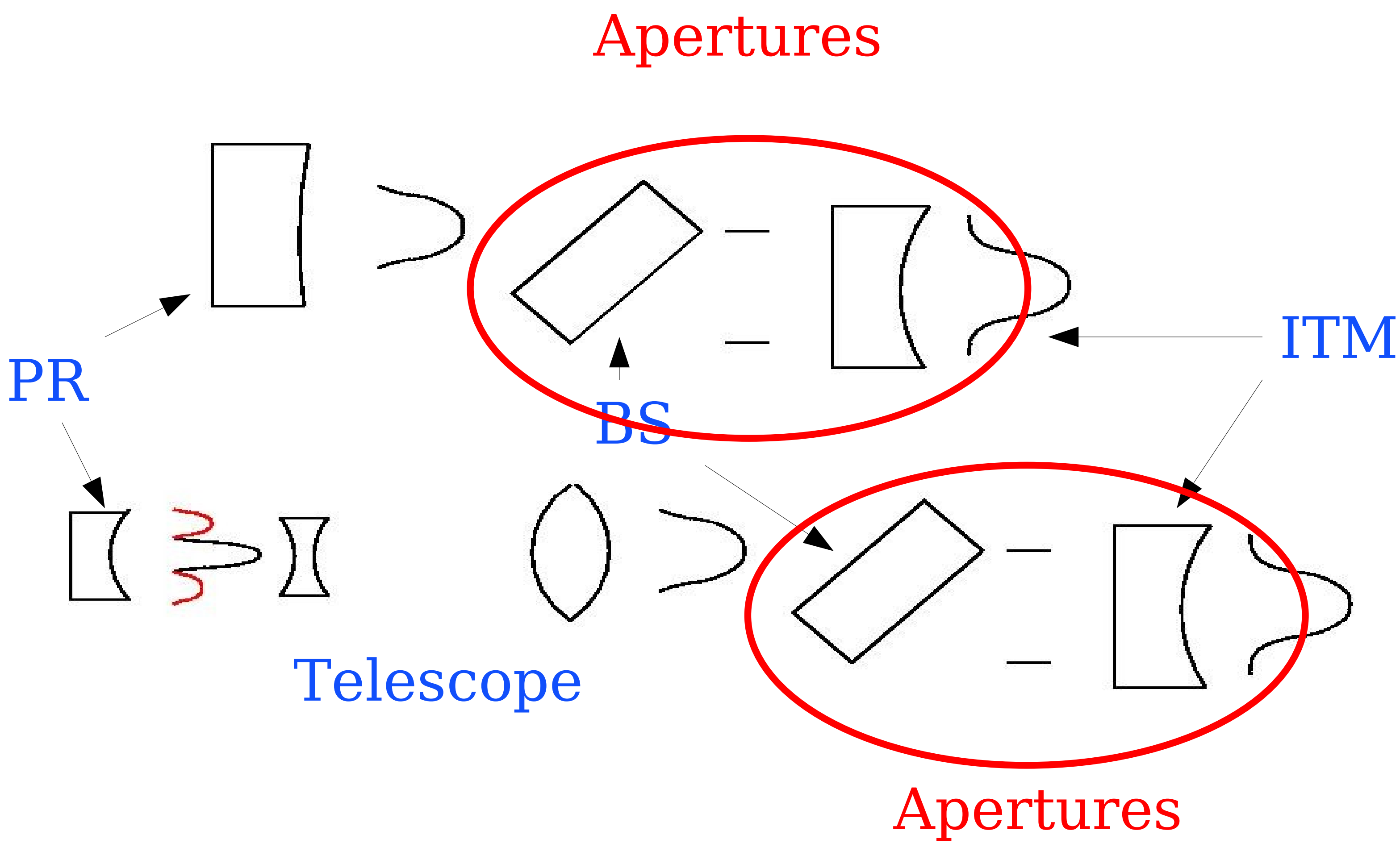
LIGO-G070784-00-Z

LIGO

Areas of concern

- Diffraction (clipping)
- Parametric Instabilities
- ASC

Diffraction



Diffraction

Explanation:

- **Telescope-type discussion:**
  - » **Flat top beams create an ring pattern in diffraction limited telescopes**
    - – Point spread function
  - » **Apertured Gaussian will also create ring pattern**

- **Modal picture (just to get an idea)**
  - » **Aperture might be described by additional very high order modes**
    - – one with maxima at the edges to destructively interfere with 00-mode
    - – several others to suppress the additional fringes in the non-apertured area
  - » **HOMs will be out of phase with carrier after one roundtrip**

    --> interferes now constructively with 00 mode and create real intensity at edges which will be cut off by aperture

Diffraction

Stable Recycling Cavity increases diffraction losses

Hiro's FFT results (work in progress):

Signal sideband

- 6cm: 230ppm x recycling gain $>$ 1%
- 5.5cm: 65ppm x recycling gain $<$ 1%

+ Carrier scatter in PR-cavity of same order

Assumes mode matched recycling cavities

Diffraction

Mode mismatch between Recycling cavities and arm cavities:

- Modal model:

$$LG^{In}_{00} = LG^{Cav}_{00} + (\Delta w/w + i\Delta z/z_R)\, LG^{Cav}_{10}$$

Δw, Δz: measure for mismatch

will be reflected at the cavity

$$LG^{Out}_{00} = LG^{Cav}_{00} - (\Delta w/w + i\Delta z/z_R) LG^{Cav}_{10}$$

Pending on sign of Δw and Δz either

the In or the Out mode will be larger than the cavity mode

--> More diffraction losses

Details require FFT code (Hiro) but

stable recycling cavities will require careful mode matching

Areas of concern

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Parametric Instabilities

Parametric Instabilities

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

Could build-up as Pis inside the arm cavities if

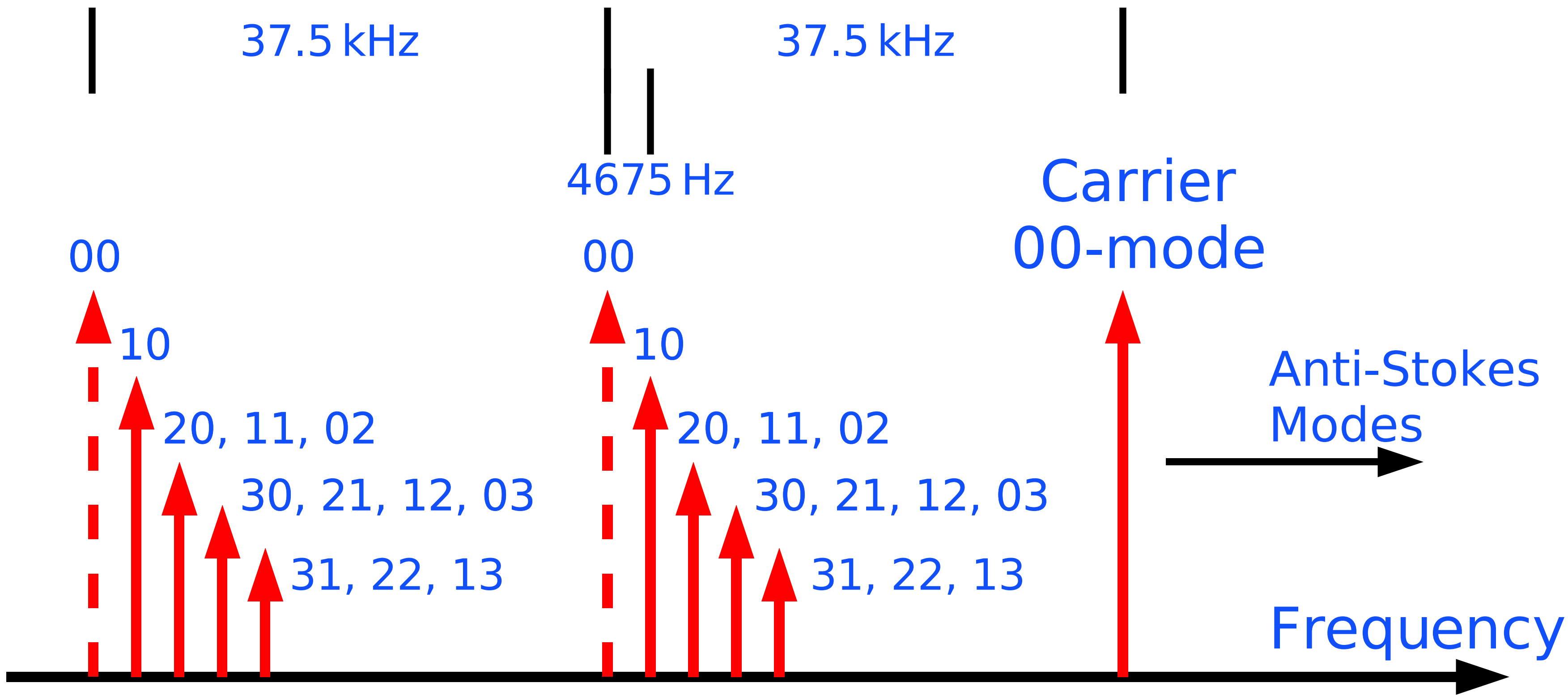
  - » the optical losses are smaller than the opto-mechanical gain

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

Ideal: Resonant sideband extraction for the PI mode

Stable Recycling Cavities

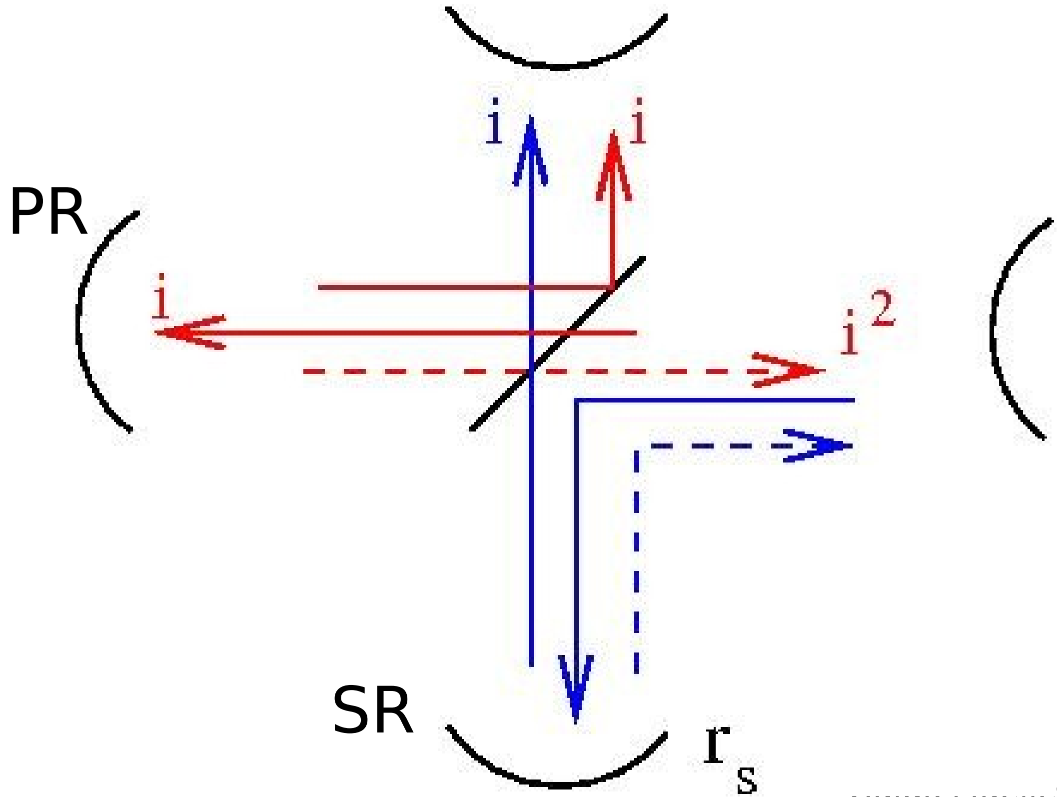
PI-Spectrum:



My understanding: PI limited to Hermite-Gauss modes up to n and m < 5
Higher order modes have Diffraction losses > ITM transmission

Simulation

- **Start discussion with following configuration:**
  - » **symmetric BS: $t_{BS} = r_{BS}$, no Gouy phases in recycling arms**
  - » **PR mirror is power recycling the carrier**
  - » **SR mirror is extracting the signal mode (RSE configuration)**

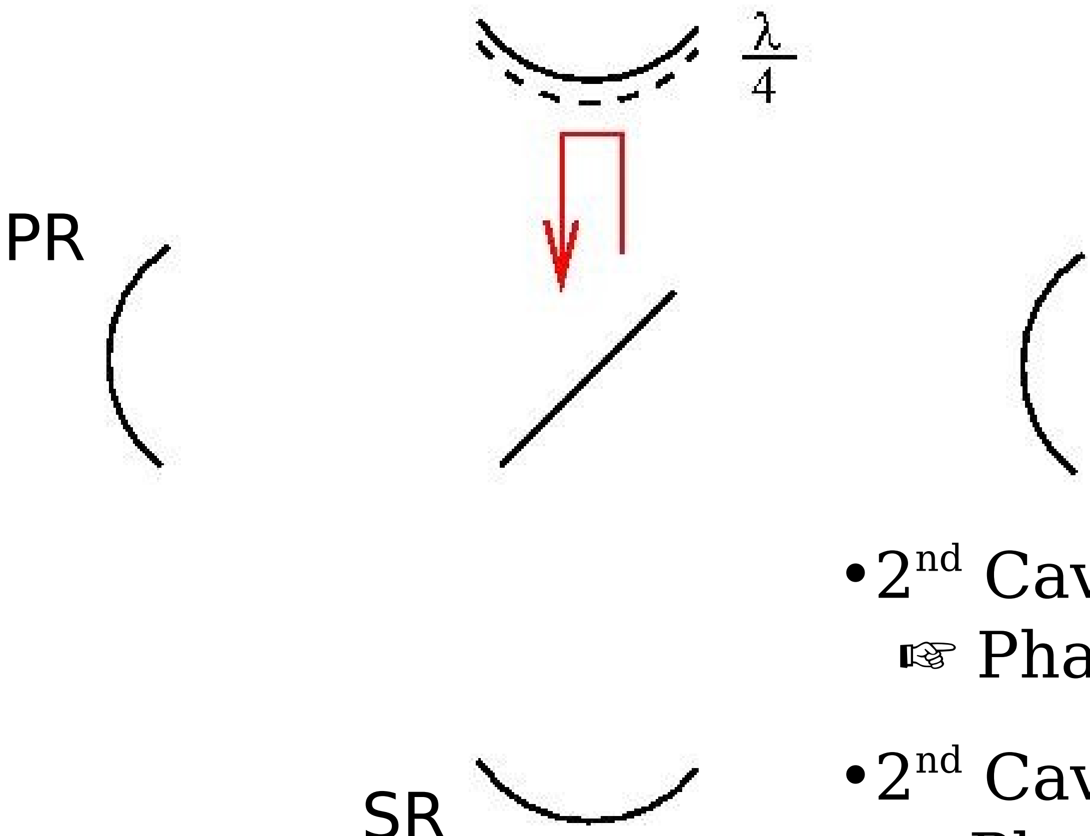


Recycling arm Michelson IFO would be bright!

☞ PI-mode travels mainly to 2nd Cavity

Simulation

2^{nd} Cavity moved by $\lambda/4$ compared to
1^{st} cavity to have MI dark (compensates the $(it)^2$ in BS)



- 2^{nd} Cavity off-resonant
  - ☞ Phase shift: π
- 2^{nd} Cavity on-resonance
  - ☞ Phase shift: 2π

LIGO

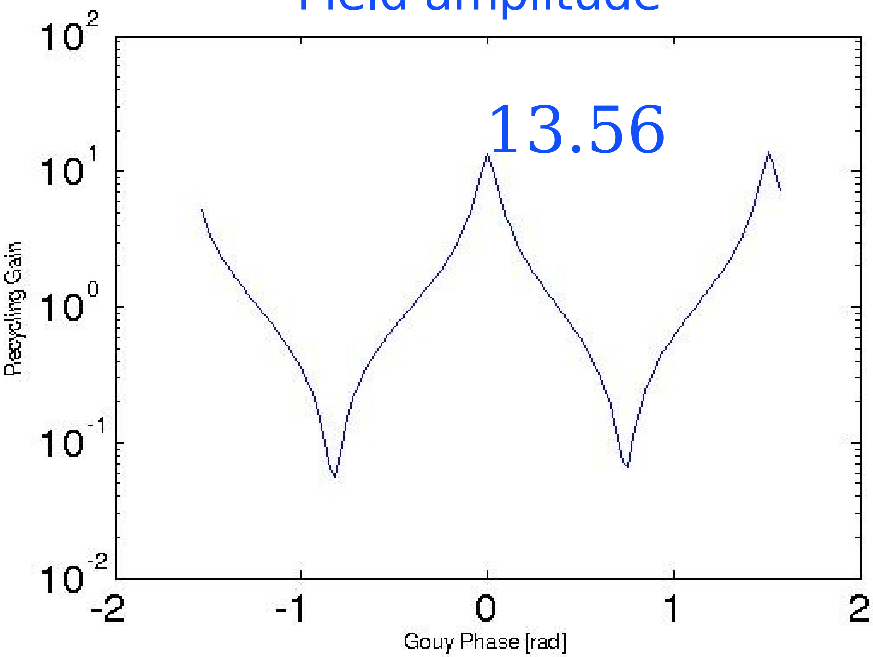
Simulation

1st Case:

- 2nd Cavity resonant with PI mode (unlikely):
  - Light reflects back into short recycling cavity MI
  - Picks up another 90deg phase shift

relative recycling gain:

Field amplitude



- ☞ **Round trip phase shift is 180deg ☞ signal <u>recycling</u> (very bad)**
- » **Add now identical Gouy phases to recycling cavities**
  - – recycling cavity MI stays bright
  - – move from signal recycling to signal extraction

Simulation

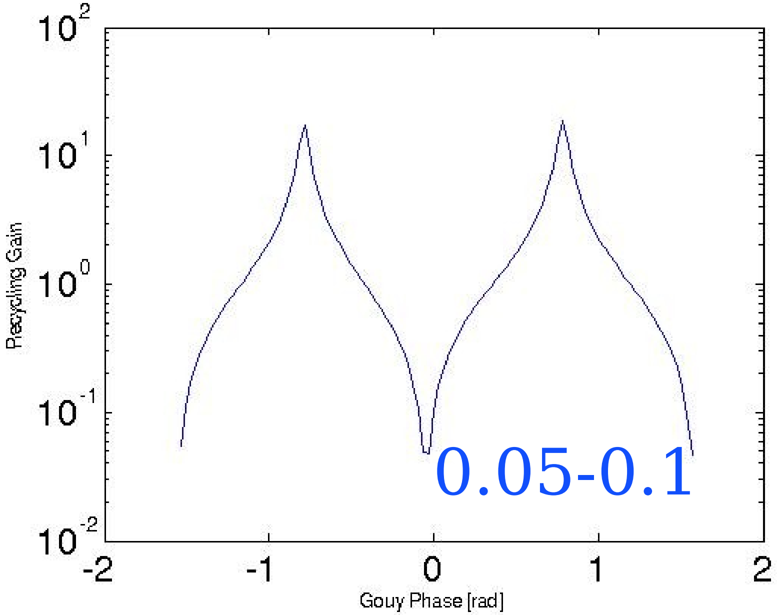
2^{nd} Case:

- 2^{nd} Cavity non-resonant with PI mode (likely):
  - Picks up 180deg phase shift at 2^{nd} Cavity
  - Light reflects back into short recycling cavity MI
  - Picks up another 90deg phase shift

- ☞ **Round trip phase shift is 360deg ☞ signal extraction (very good)**
- » **Add now identical Gouy phases to recycling cavities**
  - – recycling cavity MI stays bright
  - – move from signal extraction to signal recycling

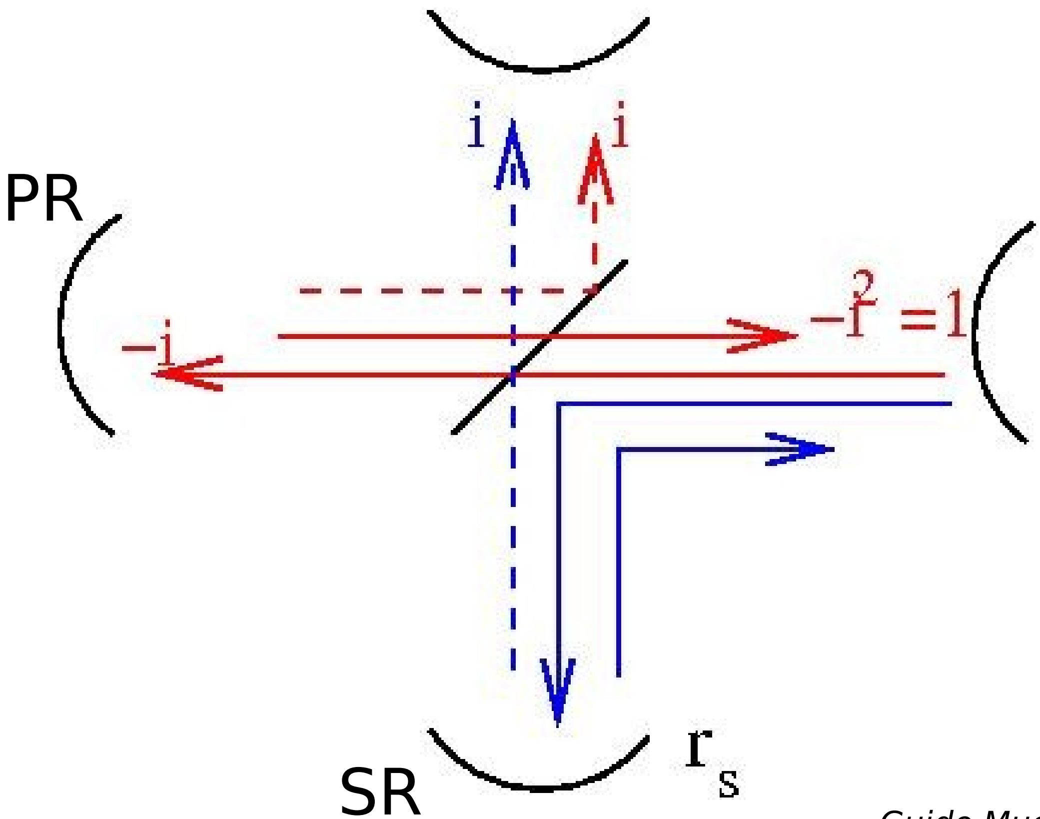
relative recycling gain:

Field amplitude



Simulation

- **Optimized for alignment sensing (detect the 10-mode):**
  - **PR recycling cavity would have $\psi_G \sim \pi/2$ (to extract the 10-mode)**
  - **SR mirror is extracting signal mode (RSE configuration)**



Recycling arm
Michelson IFO
is dark for odd modes!

☞ 2nd Cavity doesn't matter anymore

Note:
Nothing has changed for even modes!

LIGO

Simulation

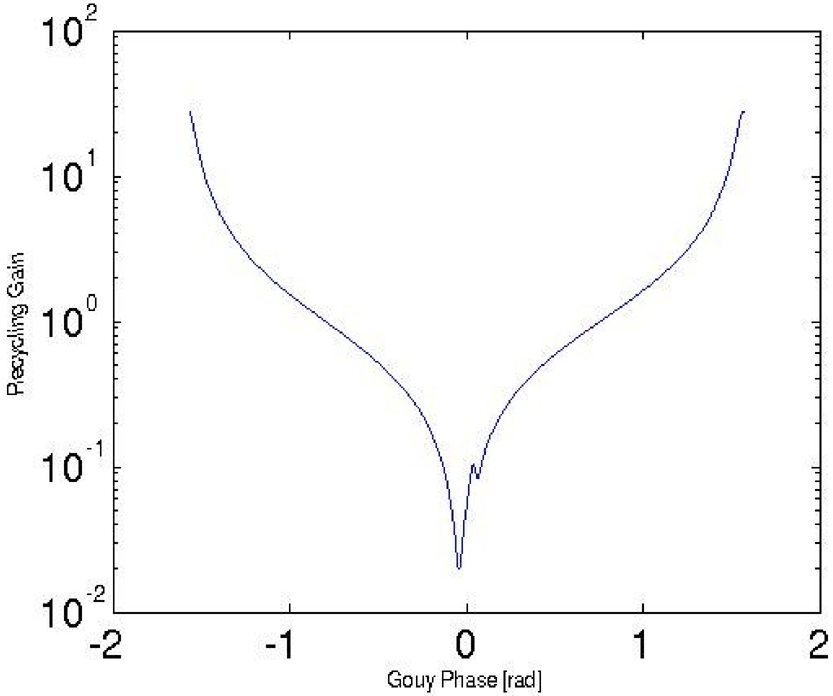
Only new case: (Odd modes only, max gain higher because they see PR/SR only once per roundtrip)

- ☞ **Round trip phase shift is 360deg ☞ signal extraction (very good)**
- » **Add now identical Gouy phases to recycling cavities**
  - – recycling cavity MI stays dark
  - – move from signal extraction to signal recycling

(Structure in center caused by SR-detuning)

relative recycling gain:

Field amplitude

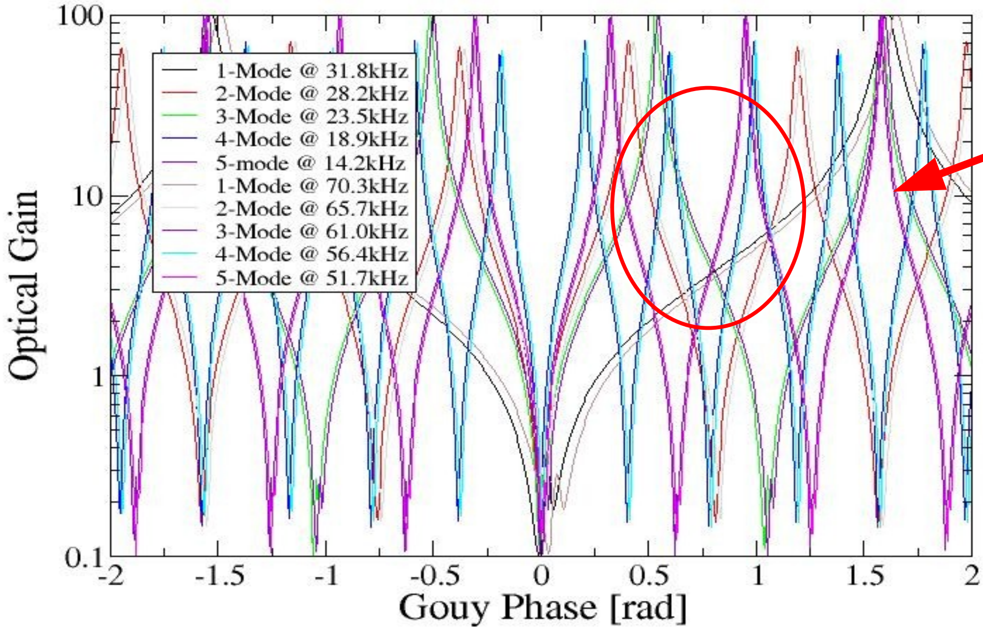


Parametric Instabilities

Optical gain (compared to no recycling) as a function of Ψ_g (Power recycling: $\pi/2+\Psi_g$)

Assumes arm cavities are <u>NOT</u> identical and PI mode from one cavity is not entering second cavity.

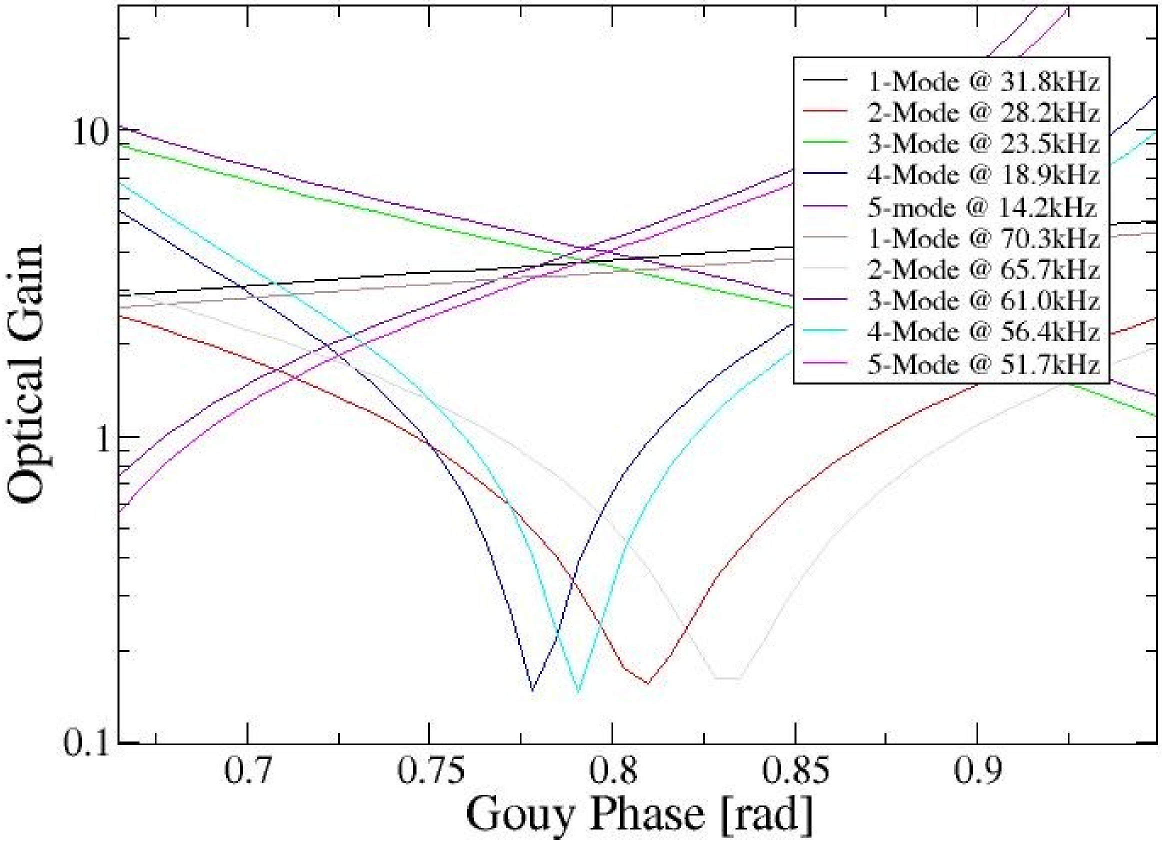
Parametric gain for modes with mode number $m+n < 6$



Window of opportunity: $\sim \pi/4$

Warning:
All these peaks will move for high SR detunings!

Parametric Instabilities



Window of opportunity: $\sim \pi/4$

still good at 0.7
main problem are the 30, 21, 12, 03 modes.

LIGO

Parametric Instabilities

- Like to have the Gouy phases in PR and SR cavities equal or different by pi/2
  - » Allows to track the spatial modes better
- Prefer non-identical arm cavities
  - » Transversal mode spacing changes by 30Hz/m difference in ITM ROC
    - – 10m difference should have no significant impact on mode matching
  - » Having second cavity on or near resonance adds a large and very sensitive phase shift to HOM -> changes resonance condition fast
    - – or could this be used to tweak optical gain of PI?
- All this needs to be confirmed for
  - » arm cavities with 5.5cm beam size on ITM
  - » new reflectivities (T_{ITM}=1%, T_{PR}=3.6%, T_{SR}=11.8%)

Areas of concern

- Diffraction (clipping)
- Parametric Instabilities
- ASC

Simulation

- **Based on new Length Sensing Scheme (T06xxxx)**
  - **T_{ITM} = 1% T_{PR} = 3.6% T_{SR} = 11.8%**
  - **Schnupp asymmetry: 5cm**
  - **L_{PR} = 55.815m L_{SR} = 57.410m**
  - **f_1 = 9.4MHz f_2 = 5xf_1 = 47MHz**

- **3 Modes of operation**
  - **Low Power Case: P_{in}=4W, ΔL_{SR} : 177nm (Detuning)**
    - $\Gamma_1 = 0.14$ $\Gamma_2 = 0.14$ (0.2 inside MZ)
  - **RSE-Case: P_{in}=125W, ΔL_{SR} : 0nm (Detuning)**
    - $\Gamma_1 = 0.14$ $\Gamma_2 = 0.14$
  - **NS/NS-Case: P_{in}=125W, ΔL_{SR} : 29.5nm (Detuning)**
    - $\Gamma_1 = 0.14$ $\Gamma_2 = 0.14$

Requirements

Displacement:

- BH/BH total
  - » TM: 8×10^{-19} m/rtHz @ 10Hz, 3×10^{-20} m/rtHz @ 30Hz, 1.4×10^{-20} m/rtHz @ 50Hz
  - » RM: 3×10^{-16} m/rtHz @ 10Hz
- RSE
  - » TM: 8×10^{-19} m/rtHz @ 10Hz, 4×10^{-20} m/rtHz @ 30Hz, 2.3×10^{-20} m/rtHz @ 50Hz
  - » RM: 3×10^{-16} m/rtHz @ 10Hz
- NS/NS
  - » TM: 8×10^{-19} m/rtHz @ 10Hz, 4×10^{-20} m/rtHz @ 30Hz, 2×10^{-20} m/rtHz @ 50Hz
  - » RM: 3×10^{-16} m/rtHz @ 10Hz

Requirements In-Band

- Angular stability requirements scales with centering with respect to angular actuator axes of rotation
  - assume Δl = 100um
- BH/BH total
  - » TM: $8x10^{-15}$rad/rtHz @ 10Hz, $3x10^{-16}$rad/rtHz @ 30Hz, $1.4x10^{-16}$rad/rtHz @ 50Hz
  - » RM: $3x10^{-12}$rad/rtHz @ 10Hz (independent of beam size!)
- RSE
  - » TM: $8x10^{-15}$rad/rtHz @ 10Hz, $4x10^{-16}$rad/rtHz @ 30Hz, $2.3x10^{-16}$rad/rtHz @ 50Hz
  - » RM: $3x10^{-12}$rad/rtHz @ 10Hz (independent of beam size!)
- NS/NS
  - » TM: $8x10^{-15}$rad/rtHz @ 10Hz, $4x10^{-16}$rad/rtHz @ 30Hz, $2x10^{-16}$rad/rtHz @ 50Hz
  - » RM: $3x10^{-12}$rad/rtHz @ 10Hz (independent of beam size!)

No safety margin! Independent of beam size!

Requirements RMS

- RMS-Stability (T070999-00-I, Rana, Peter):
  - Test mass angles: 10^{-9}rad rms
  - BS and RC-mirrors: 10^{-8}rad rms
    - Driven by Beam Jitter coupling
      - scales with 1/beamsize = as do ASC signals
      - → Invariant to beam size
    - What other effects (especially some which don't scale)?

Requirements

- Sensor has to meet the following requirements
  - RMS:
    - Has to provide an error signal for all mirrors which is clearly below the rms requirement. Need to check:
      - Shot noise limit of WFS
      - Saturation
  - In Band (only test masses, ASC BW on RC < Adv.LIGO band):
    - Has to meet requirements up to ~3xUGF of the ASC servo loops
      - at 3UGF we can roll the gain down faster than $1/f^2$ (~LIGO sensitivity slope)
  - UGF has to be above Sidles-Sigg instability
    - Low Power (BH/BH) Case: P_{in}=4W → UGF ~ 3Hz (above pendulum freq.)
      - Sensor needs to meet requirements up to ~10Hz (?)
    - RSE and NS/NS case: P_{in}=125W → UGF ~ 10Hz
      - Sensor needs to meet requirements up to ~30Hz

Requirements

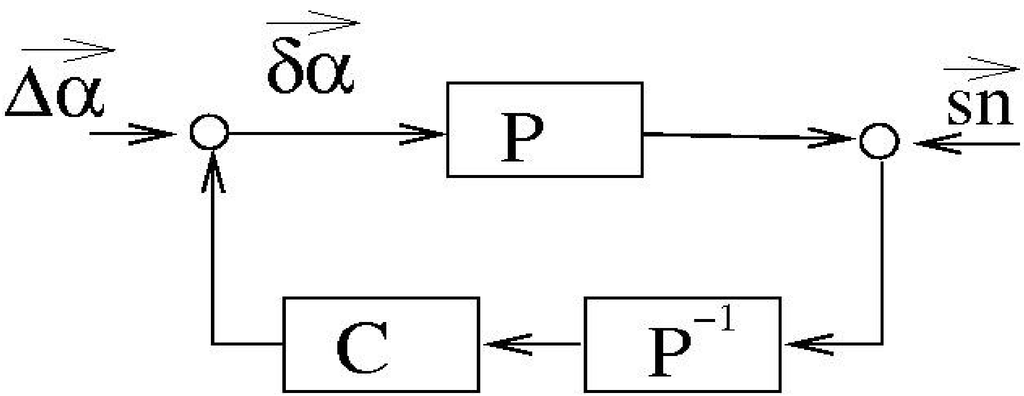
- Sensor has to meet the following requirements
  - » RMS:
    - – Has to provide an error signal for all mirrors which is clearly below the rms requirement. Need to check:
      - Shot noise limit of WFS
      - Saturation

All this assumes that the suspension system keeps the mirrors quiet enough in the Adv. LIGO Band!

pendulum freq.)
      - Sensor needs to meet requirements up to ~10Hz (?)
    - – RSE and NS/NS case: P_{in}=125W → UGF ~ 10Hz
      - Sensor needs to meet requirements up to ~30Hz

Simulation

- **Based on Valera's code**
  - **all signals still scaled with 6cm beam size**
    - results for stable recycling cavity mirrors need to be multiplied by ~30 (beam size ratio on mirrors)
  - **Shot noise not correct**
    - Still some factor 2 type uncertainty
    - have the theory but didn't implement it yet



$$\vec{\delta\alpha} = \frac{\vec{\Delta\alpha} + CP^{-1}\vec{sn}}{1+C}$$

Simulation

$\Delta\alpha$: Fluctuations w/o feedback

In-band:

- Should be lower than requirements

Below band:

- Sidles-Sigg (~4Hz at 125W, Test masses only)
- Suspension Eigenfrequencies (pendulum frequency)

Loop Gain (Test masses)

- About 2-3 at Sidles Sigg instability
- Roll-off with 1/f to 3xUGF
  - UGF @ 125W: ~10Hz
    - 1/f slope until ~30Hz (Most difficult part)
- Above that with $1/f^{2+}$, faster than Adv. LIGO sensitivity

Loop Gain (RM, TM at low power (?))

- Pendulum frequencies (~1Hz)
  - UGF: 3Hz, slope of 1/f until 10Hz, then $1/f^{2+}$

Simulation

- **Low Power Case: P_{in} = 4W**
  - **DC-Power (TEM00 in mW, divide by 10 for pick off):**

Port	CR	SBu1	SBl1	SBu2	SBl2	DC
Dark	10.4	0.1	0.0	0.2	0.2	10.9
Refl	1.6	19.6	19.7	19.5	19.6	80.0

  - **RF-Power (TEM00 in mW, divide by 10 for pick off):**

Port	f1	f2	2xf1	2xf2	f2-f1	f2+f1
Dark	0.9	2.6	0.1	0.4	0.3	0.2
Refl	11.0	8.1	39.3	39.1	64.9	78.1

Simulation

- **Low Power Case: P_{in} = 4W (Current status)**
- **Loop Gain**
  - **3Hz = 1 (UGF)**
  - **10Hz = 0.3**
  - **30Hz = 0.03**

Requirements (frad/rtHz):
- 10Hz: 8 (TM)
- 30Hz: 0.3 (TM)
- 10Hz: 3000 (RM)

frad/rtHz	Port	Sensor	3Hz	10Hz	30Hz
PR	BP f1	7.8	3	1.8	0.23
SR	DP f2	6110	3055	1410	178
DITM	DP f2	2.7	1.3	0.6	0.08
CITM	BP f2	0.1	0.05	0.02	0.003
DETM	DP f2	7.7	3.8	1.8	0.22
CETM	BP f1	0.8	0.39	0.18	0.02

Note that PR and SR angles x30 for stable rec.

Simulation

- **RSE Case: P_{in}=125W**
  - » **DC-Power (TEM00 in mW, divide by 10 for pick off):**

Port	CR	SBu1	SBl1	SBu2	SBl2	DC
Dark	82	0.2	0.2	543.9	543.9	1170.5
Refl	12.5	615.7	615.7	76.9	76.9	1397.8

  - » **RF-Power (TEM00 in mW, divide by 10 for pick off):**

Port	f1	f2	2xf1	2xf2	f2-f1	f2+f1
Dark	0.8	416.8	0.5	1088	3.6	44.3
Refl	173	61.9	1231	154	846	871

Simulation

- **RSE Case: P_{in} = 125W (Current status)**
- **Loop Gain (RM)**
  - » **3Hz = 3 (1)**
  - » **10Hz = 1 (0.3)**
  - » **30Hz = 0.3 (0.03)**

Requirements (frad/rtHz):
- 10Hz: 8 (TM)
- 30Hz: 0.4 (TM)
- 10Hz: 3000 (RM)

frad/rtHz	Port	Sensor	3Hz	10Hz	30Hz
PR	BP f1	2.1	1.1	0.5	0.06
SR	DP f2	71	35	16	2.1
DITM	DP f2	1	0.8	0.5	0.24
CITM	BP f1	0.8	0.6	0.4	0.18
DETM	DP f2	1.4	1	0.7	0.31
CETM	BP f1	0.5	0.4	0.3	0.12

Note that PR and SR angles x30 for stable rec.

Simulation

- **NS/NS Case: P_{in}=125W**
  - » **DC-Power (TEM00 in mW, divide by 10 for pick off):**

Port	CR	SBu1	SBl1	SBu2	SBl2	DC
Dark	85	0.3	0.2	140	99.7	325
Refl	12.9	615	615	477	51.9	2240

  - » **RF-Power (TEM00 in mW, divide by 10 for pick off):**

Port	f1	f2	2xf1	2xf2	f2-f1	f2+f1
Dark	0.9	190	0.5	236	5.9	9.6
Refl	176	1222	1231	995	1893	1818

LIGO

Simulation

- **NS/NS Case: P_{in} = 125W (Current status)**
- **Loop Gain (RM)**
  - » **3Hz = 3 (1)**
  - » **10Hz = 1 (0.3)**
  - » **30Hz = 0.3 (0.03)**

Requirements (frad/rtHz):
- 10Hz: 8 (TM)
- 30Hz: 0.4 (TM)
- 10Hz: 3000 (RM)

frad/rtHz	Port	Sensor	3Hz	10Hz	30Hz
PR	BP f1	0.8	0.4	0.2	0.03
SR	DP f2	105	52	24	3
DITM	DP f2	0.3	0.26	0.17	0.08
CITM	BP f1	0.9	0.7	0.47	0.22
DETM	DP f2	0.1	0.09	0.06	0.03
CETM	BP f1	1.6	1.2	0.8	0.37

Note that PR and SR angles x30 for stable rec.

Simulation

- **Further necessary improvements:**
  - » Need to check if expected fluctuations $\Delta\alpha$ of recycling mirrors is really low enough
  - » Try to improve WFS using:
    - – Double demod signals
    - – Pick off signals from recycling cavities
  - » Fix shot noise
  - » Check for different Gouy phases
  - » Try to understand why the signals are what they are
  - » ...

LIGO

First Recommendation

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

- **ASC**
  - » **Nearly there. Fairly optimistic**
- **Beam Jitter**
  - » **Coupling increases by ~1.5 compared to marginally stable cavity**
- **Signal loss**
  - » **No low order HOM on resonance.**
- **Parametric Instabilities**
  - » **Additional optical gain for all except the 3-modes at or below 3.**
    - – 3-Modes have gain of ~8 (compared to gain in non-recycled cavities).
  - » **Prefer non-identical cavities (ROC mismatch of order 5m)**
  - » **Need to be checked for new transmissivities**