Higher order Laguerre-Gauss modes in future gravitational wave detectors

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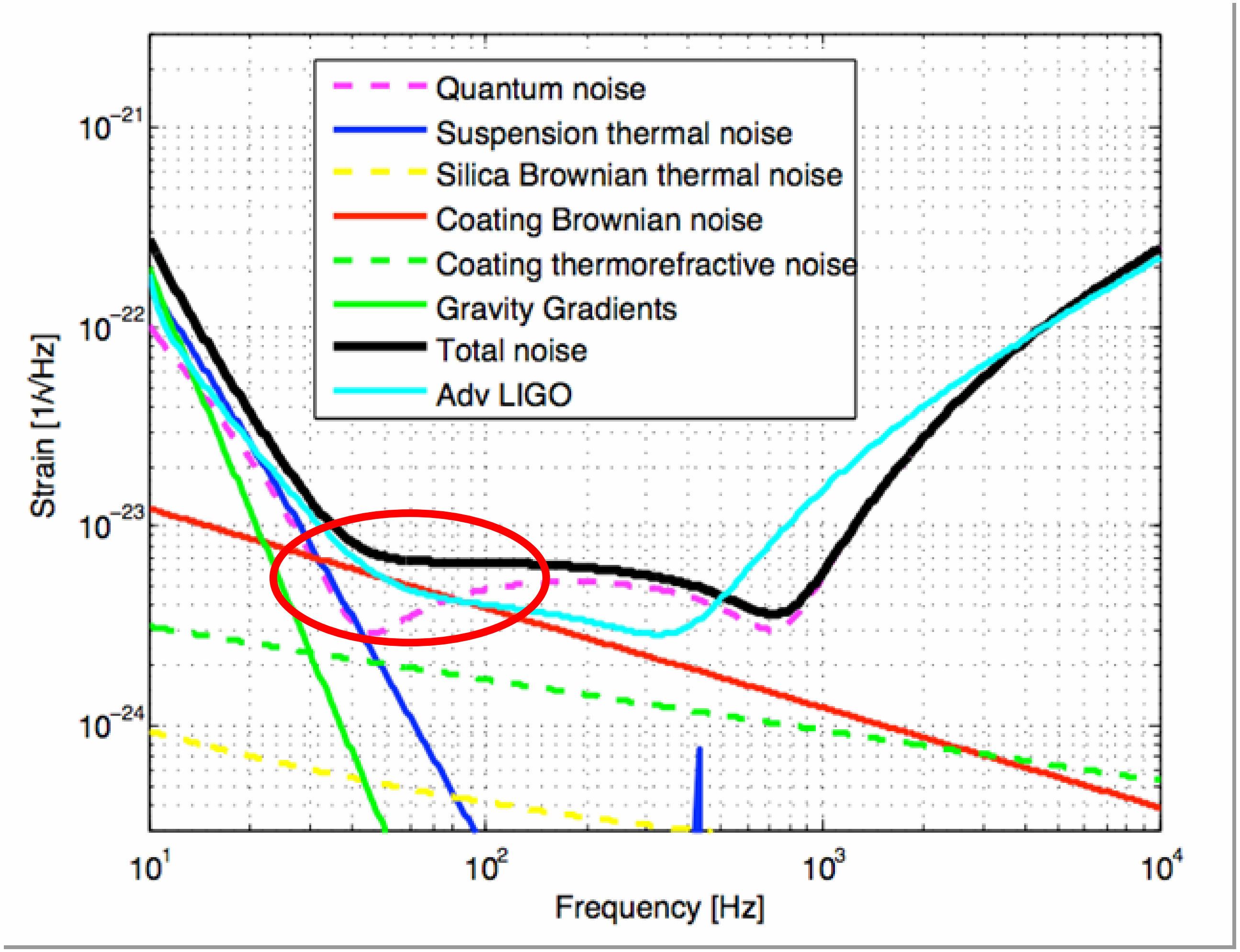
Overview

- Motivation for using Higher-Order Laguerre modes
- Summary of length and alignment sensing with higher order Laguerre-Gauss modes
- Arm cavity mirror radii of curvature trade-off analysis
  - Using advanced Virgo as an example
  - Use inspiral ranges as figure of merit
  - Three scenarios lead to four different comparisons of the fundamental LG_{00} and the proposed LG_{33} mode

Thermal noise in future GW detectors



Advanced Virgo Conceptual Design VIR–042A–07

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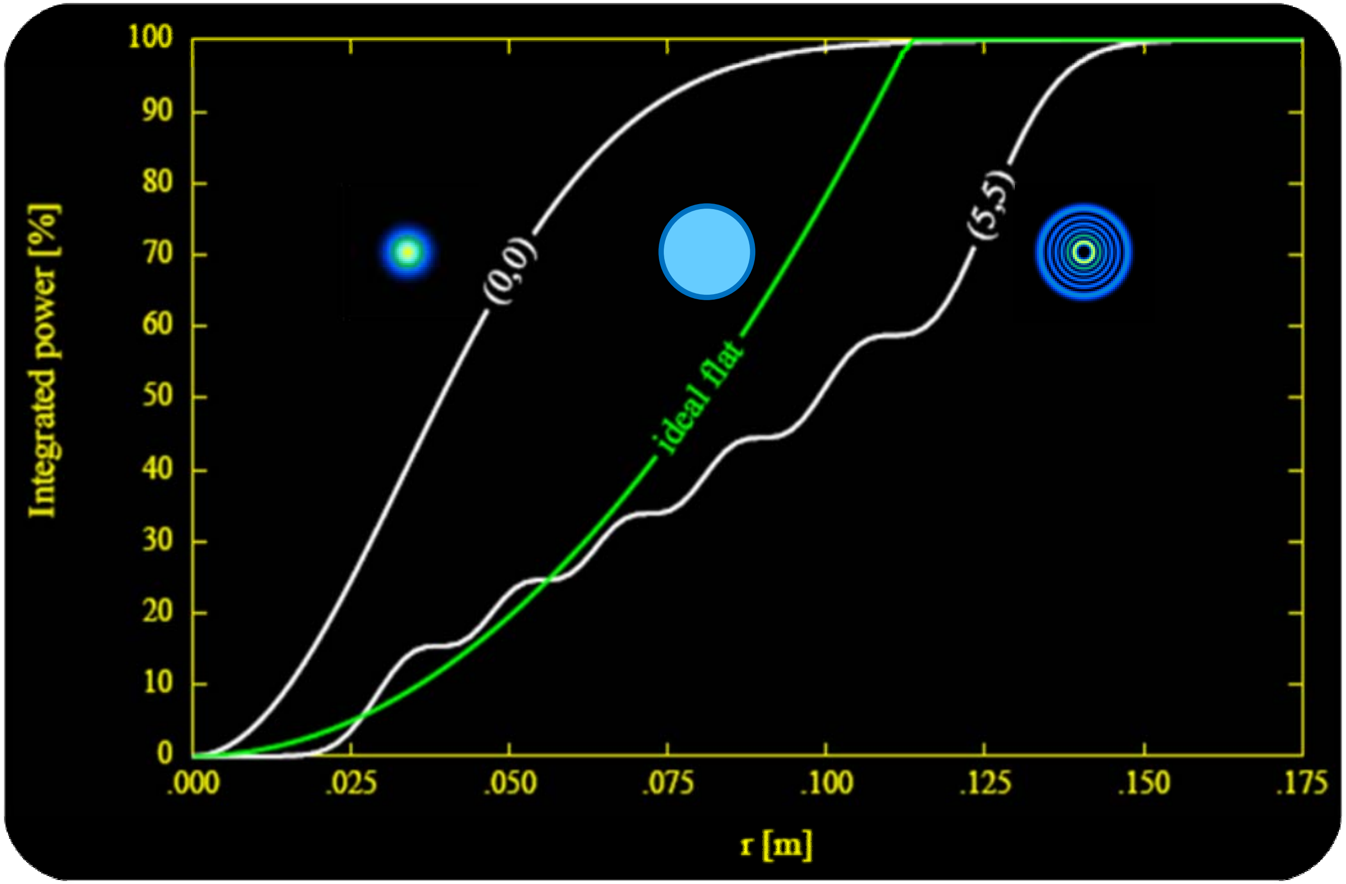
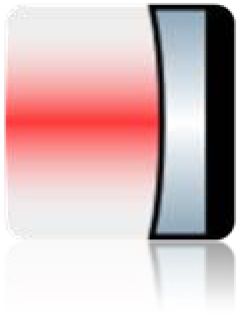
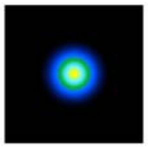
Integrated beam power for modes with 1ppm loss on a mirror with d =35cm





by M. Laval and J.-Y. Vinet

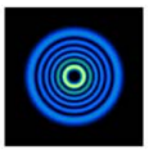
Thermal noise of LG and Flat beams



HG_{00} mode:

Bondu et al. Physics Letters A **246** (1998) 227

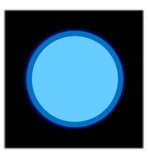
$$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{1-\sigma^2}{2\,\sqrt{\pi}\,Y\,w}$$



LG_{nm} modes:

Bondu et al. Physics Letters A 246 (1998) 227

$$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{1-\sigma^2}{2\,\sqrt{\pi}\,Y\,w}\,\alpha_n^m$$



Flat beams:

J.-Y. Vinet CQG **22** (2005) 1395

$$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{8\,\left(1-\sigma^2\right)}{3\,\pi^2\,Y\,b}$$

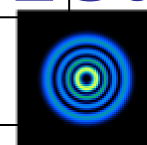
formulas valid for infinite media only

TN scaling factors of LG$_{nm}$ modes

α_n^m

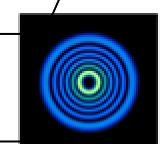
m \ n	0	1	2	3	4	5
0	**1**	**0.69**	**0.57**			
1	**0.60**	**0.50**	**0.44**			
2	**0.46**	**0.41**	**0.37**			
3				**0.31**		
4					**0.27**	
5						**0.25**

LG33



$$h_{33} = \frac{h_{00}}{1.8}$$

LG55



$$h_{55} = \frac{h_{00}}{2}$$

personal communication J.-Y. Vinet

numbers shown are for an infinite mirror size

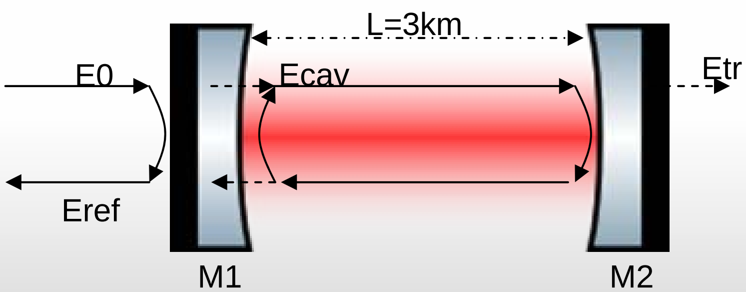
Expected thermal noise improvements

Reduction factor of thermal noise	LG_{00} / HG_{00}	LG_{33}	LG_{55}	Mesa beam
Coating thermal noise	1	~2.2	~2.3	~1.5
Substrate thermal noise	1	~2.7	~2.7	~1.8
Thermo elastic noise	1	~0.6	~0.4	~1.8

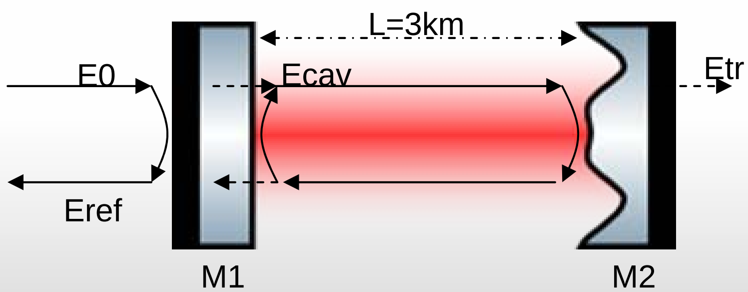
All values given for beam sizes corresponding to 1ppm clipping losses

References:
C. TN: personal communication J.-Y. Vinet
S. TN: Mours *et al.* . CQG 23 (2006),5777
T. E. N: personal communication J.-Y. Vinet

Comparison of LG and Flat beams



HG & LG mode cavity design



Flat top beam cavity design

By M. Laval and J.-Y. Vinet

- Spherical phase fronts
- Compatible with current interferometers

- Beam shape and phase fronts change on propagation
- Mirror surfaces are more complex

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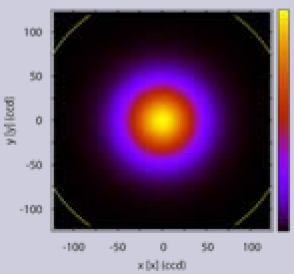
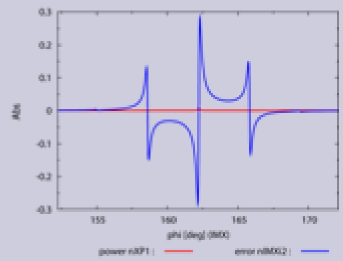
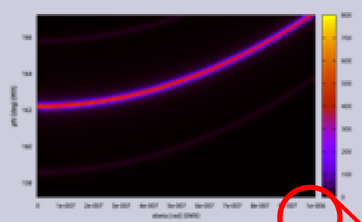
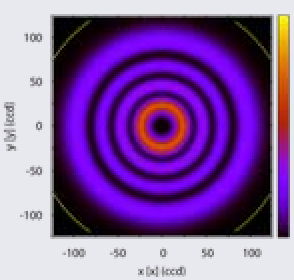
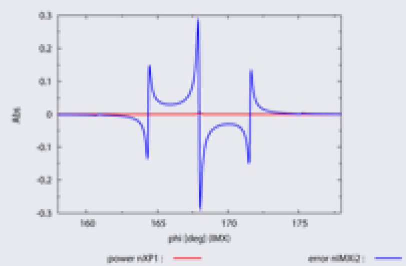
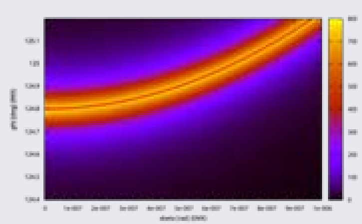
Comparison of length and alignment signals for a single cavity

Transversal mode	Longitudinal error signal	Coupling tilt into longitudinal phase	Control Matrix for alignment signals
LG00 		 $\Delta\phi \approx 5.0^{o}$ 1mrad	$\begin{pmatrix} 1 & 0.862 \\ 0.645 & 0.153 \end{pmatrix}$ $\begin{pmatrix} \text{IMX to Qb} & \text{EMX to Qb} \\ \text{IMX to Qa} & \text{EMX to Qa} \end{pmatrix}$
LG33 		 $\Delta\phi \approx 0.4^{o}$	$\begin{pmatrix} 1 & 2.96e-3 \\ 0.368 & 0.641 \end{pmatrix}$ $\begin{pmatrix} \text{IMX to Qb} & \text{EMX to Qb} \\ \text{IMX to Qa} & \text{EMX to Qa} \end{pmatrix}$

for more details see my Elba talk about higher order LG modes

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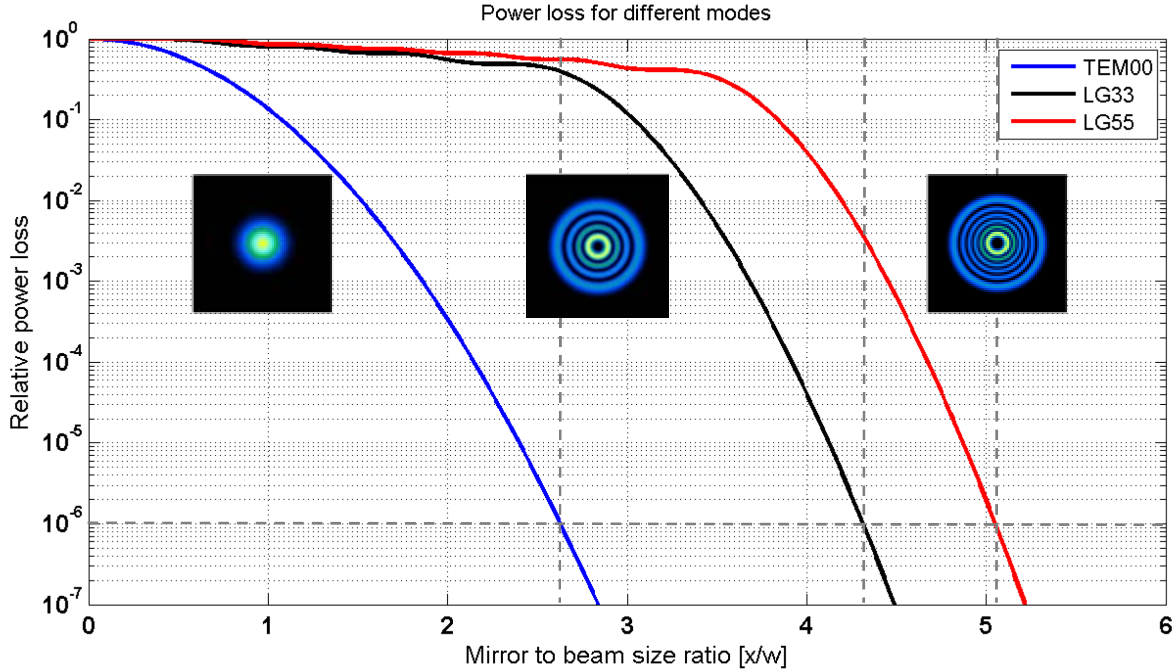
Clipping loss comparison



Mode scaling factors	LG00	LG33	LG55
Mirror size	1	1.64	1.92
Beam size	1	0.61	0.52

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Arm cavity mirror radii of curvature trade-off analysis

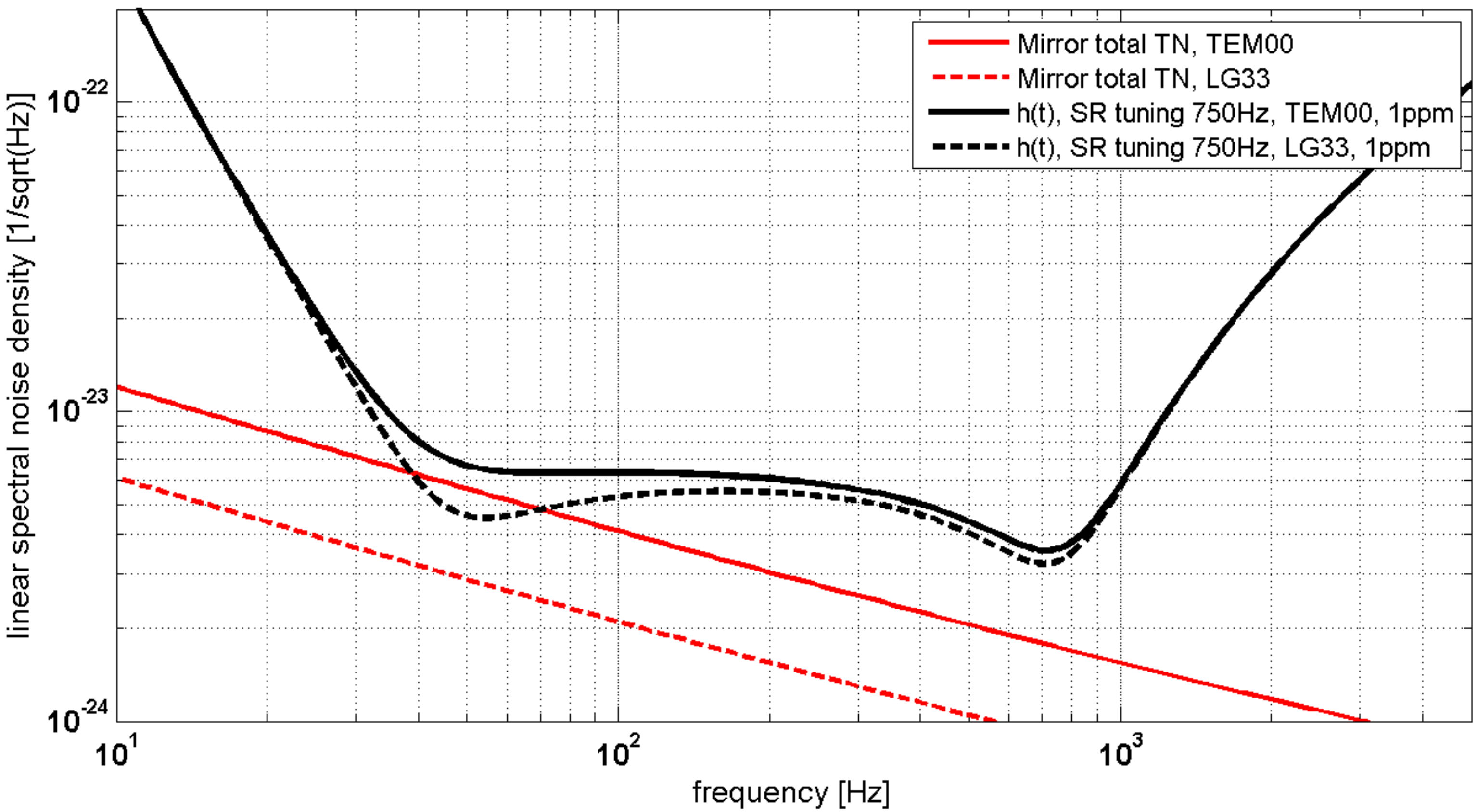
Simulation parameters:

- Bench version 4.1
- Latest IFO model of Adv.Virgo
- Rescaled beam size for LG modes
  - Used thermal noise scaling factor by J-.Y. Vinet
- Thermo-elastic TN compensation included
- Coating radius 17cm according to Virgo note VIR-038A-08 (2008)

Figure of merit:

Inspiral ranges

Advanced Virgo sensitivity



Three Scenarios

1. We buy one a set of optimized mirrors for each mode configuration; same clipping losses

2. We buy mirrors which are compatible with both mode configurations; same radii of curvature

3. We buy mirrors optimized for the LG00 mode and use the TCS system to optimize them later for LG33 and vice versa

Scenario 1: Same clipping losses

Reference configuration

Transversal mode	LG_{00} baseline		LG_{33}	LG_{00}		LG_{33}
SR detuning [Hz]	750		750	300		300
Beam size w [cm]	6.47		3.94	6.47		3.94
Clipping loss [ppm]	1		1	1		1
Radius of curvature [m]	1522.8		1708.4	1522.8		1708.4
NS/NS inspiral range	126	17%	148	130	25%	163
BH/BH inspiral range	900	27%	1143	580	23%	715
NS/BH inspiral range	310	24%	384	280	32%	370

Problem: The mirrors are not compatible!

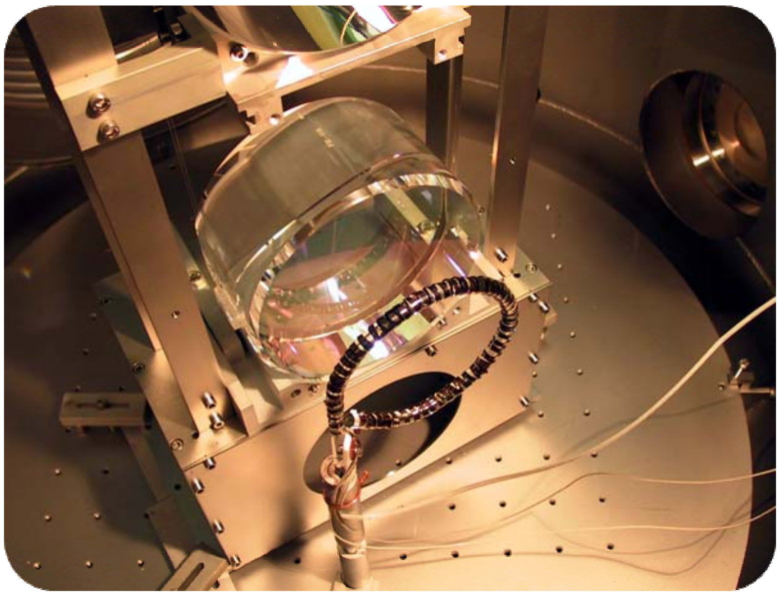
Scenario 2: Same radii of curvature

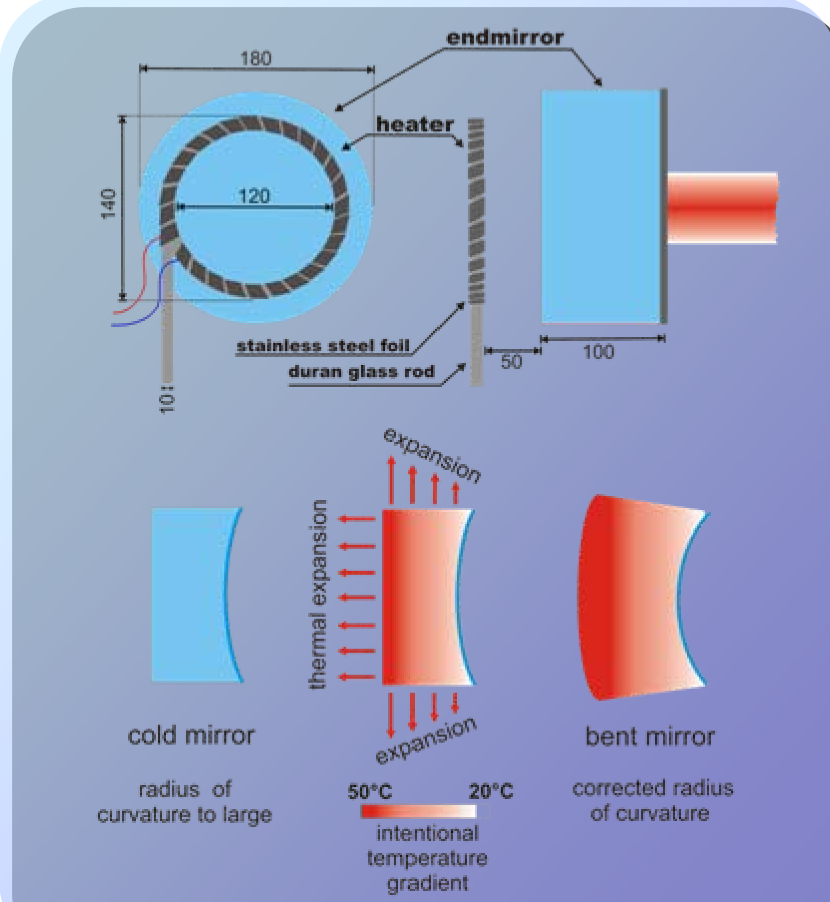
Transversal mode	LG_{00} baseline		LG_{00}		LG_{33}
SR detuning [Hz]	750		750		750
Beam size w [cm]	6.47		4.22		4.22
Clipping loss [ppm]	1		8e-9		30
Radius of curvature [m]	1522.8		1647.2		1647.2
NS/NS inspiral range	126	-21%	100	21%	153
BH/BH inspiral range	900	-24%	680	32%	1187
NS/BH inspiral range	310	-24%	235	28%	398

Not a good option!

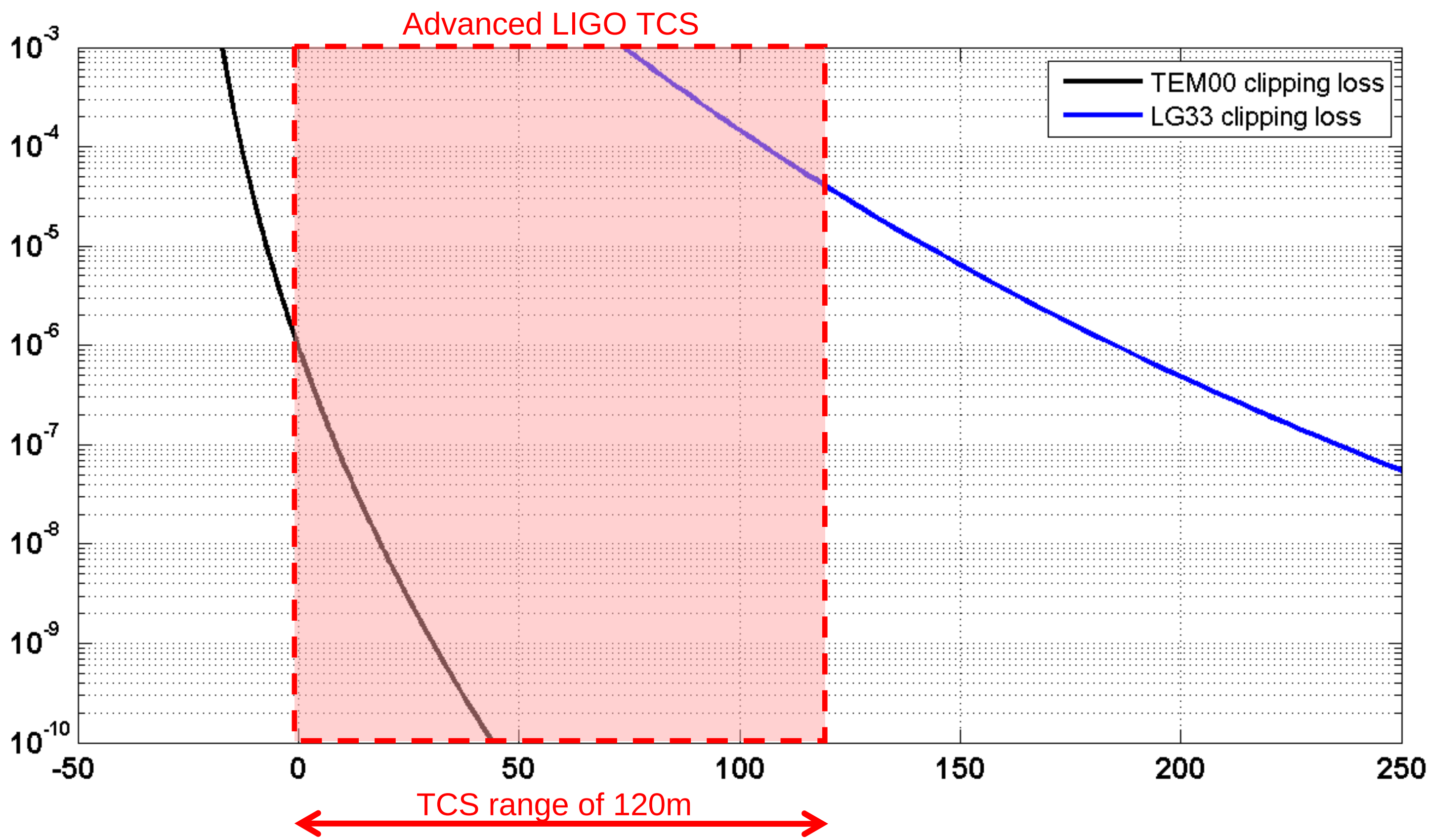
Problem:
- Trade-off concerning clipping loss
- LG_{00} configuration much worse than current baseline

Scenario 3: Use thermal compensation system to the change RoC





Scenario 3a: Use thermal compensation system to the change RoC



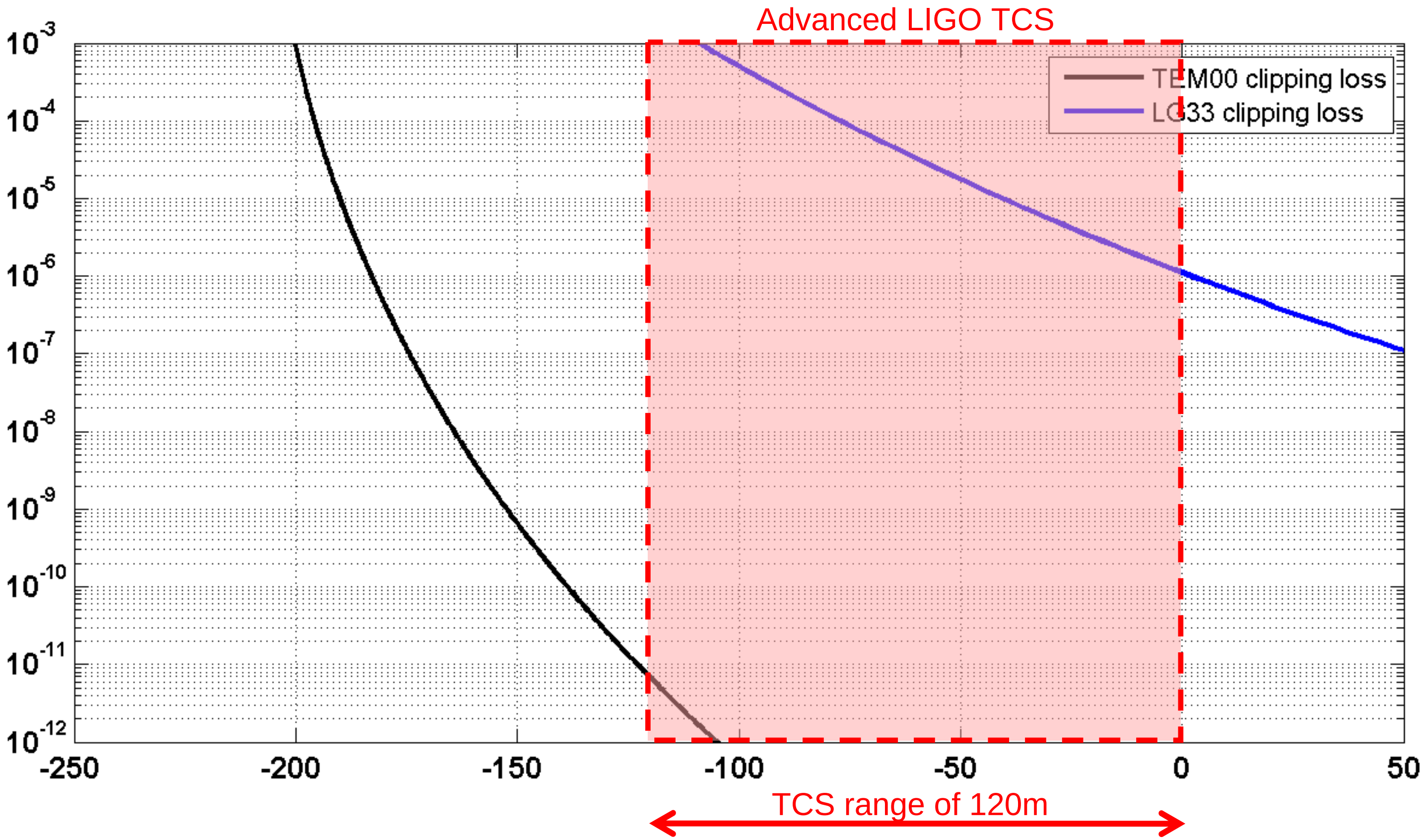
Scenario 3a: Change RoC with TCS, optimisation for fundamental mode

Transversal mode	LG_{00} baseline		LG_{00}		LG_{33}
SR detuning [Hz]	750		750		750
Beam size w [cm]	6.47		6.47		4.25
Clipping loss [ppm]	1		1		40.9
Radius of curvature [m]	1522.8		1522.8		1642.8
NS/NS inspiral range	126	0%	126	21%	153
BH/BH inspiral range	900	0%	900	32%	1192
NS/BH inspiral range	310	0%	310	29%	400

Looks promising!

Problem: Implementation of such TCS might be difficult

Scenario 3b: Use thermal compensation system to the change RoC



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Scenario 3b: Change RoC with TCS, optimisation for LG33 mode

Transversal mode	LG00 baseline		LG00		LG33
SR detuning [Hz]	750		750		750
Beam size w [cm]	6.47		4.71		4.25
Clipping loss [ppm]	1		4.8e-6		1
Radius of curvature [m]	[illegible]		[illegible]		1708.2
NS/NS inspiral range	126	-15%	107	17%	148
BH/BH inspiral range	900	-18%	734	27%	1143
NS/BH inspiral range	310	-18%	254	24%	384

Looks promising!

Problem: Implementation of such TCS might be difficult

Conclusion

- LG modes reduce the thermal noise in the IFO
- LG modes compatible with current IFO designs
- Beam parameters are different
  - RoC have to be matched, or clipping loss are different
- Length and alignment signals of LG_{33} better than LG_{00} for the same mirror sizes
- Inspiral ranges of RoC compatible IFO configuration (Scenario two) are low for fundamental LG_{00} mode
- Best solution uses Thermal Compensation System to adapt RoC to the desired mode

Higher order Laguerre Gauss modes in triangular cavities

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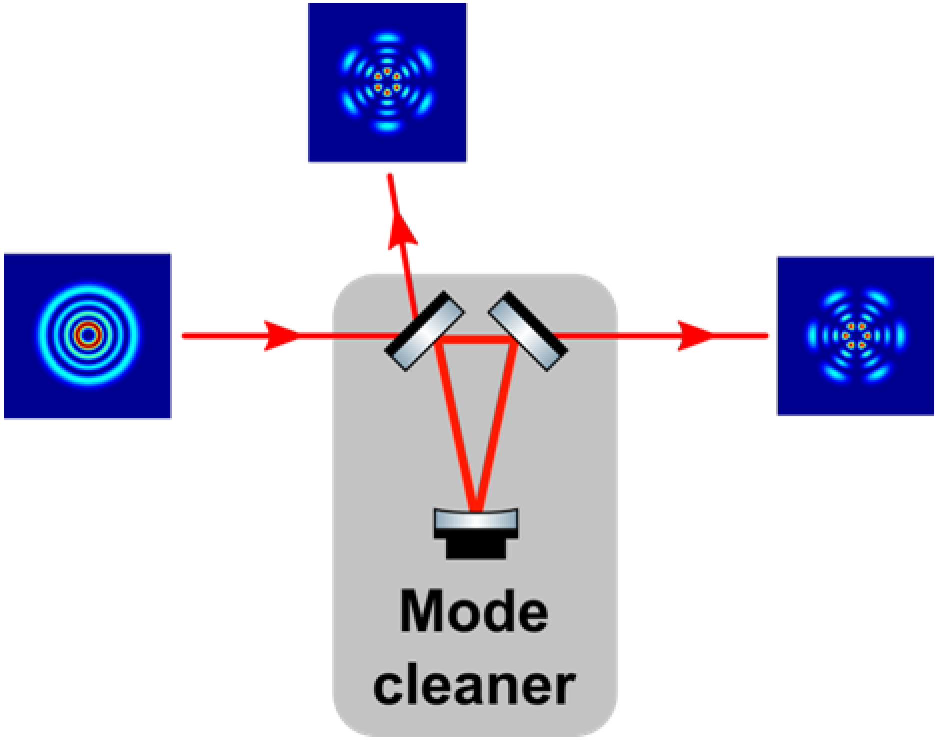
Behaviour of LG modes in triangular cavities

Two possible solutions for this problem

1. Do not use triangular cavities
2. Use sinusoidal LG modes
   - Thermo-elastic noise of sinusoidal LG modes needs to be investigated!



For more details see talk by M. Barsuglia Virgo Biweekly Meeting 1/7/2008

Conclusion

LG modes in triangular cavities

- Helical LG modes are not compatible with triangular cavities
  - Either use sinusoidal LG modes or use modecleaner cavities with an even number of mirrors
- Helical and sinusoidal LG modes have the same brownian thermal noise
- Thermo-elastic noise of sinusoidal LG modes unknown
  - should be investigated