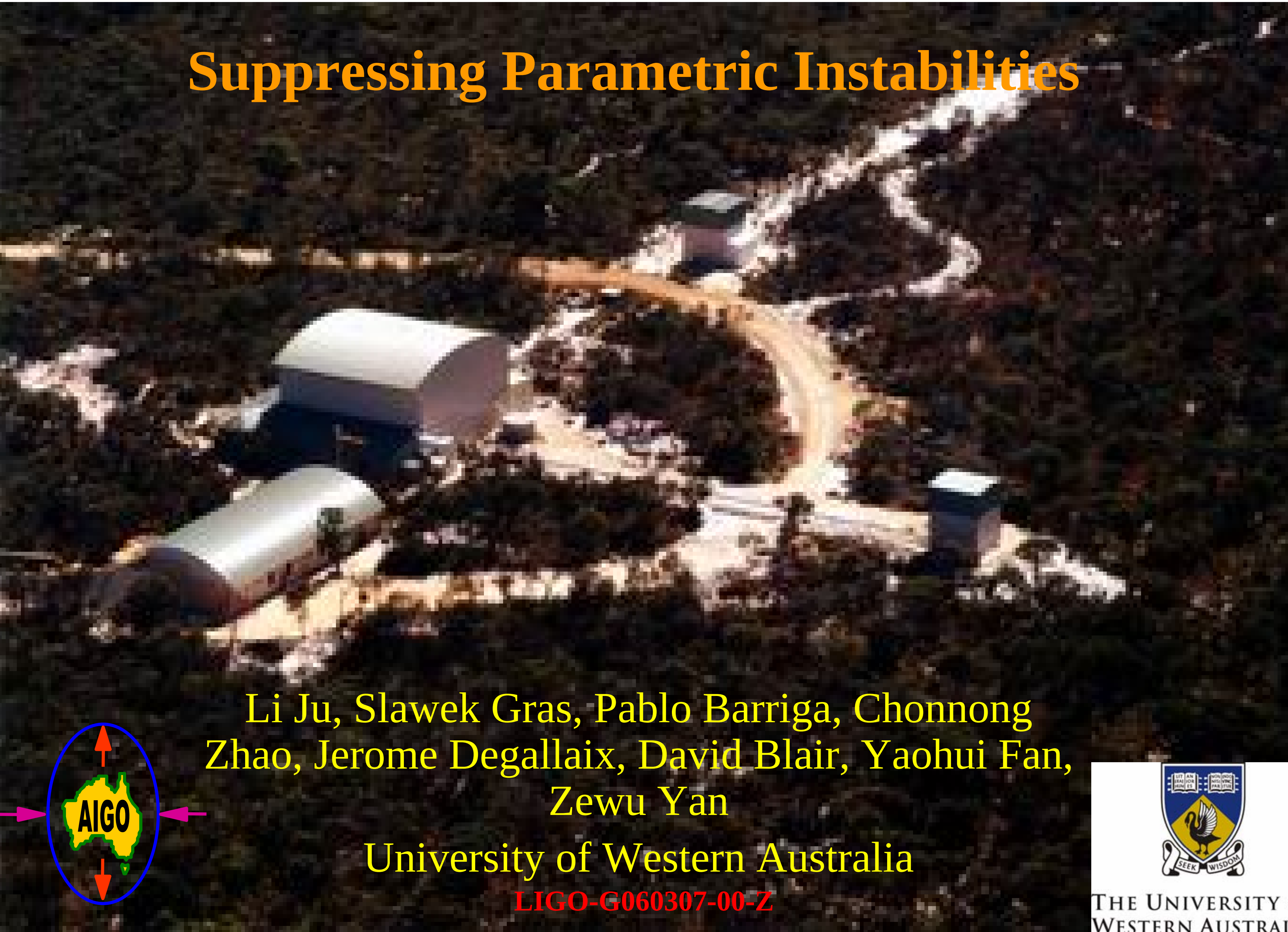


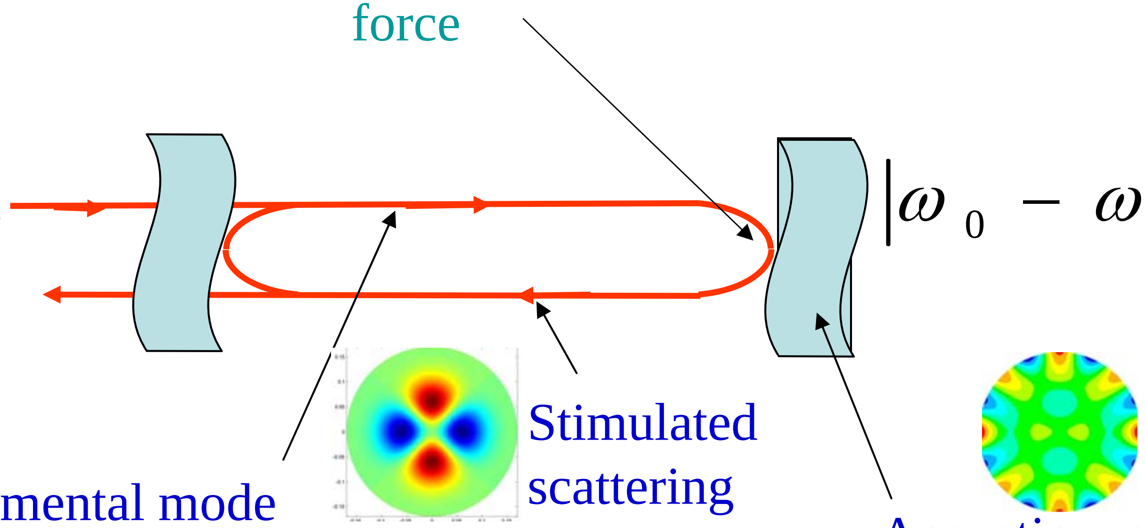
Suppressing Parametric Instabilities

Li Ju, Slawek Gras, Pablo Barriga, Chonnong Zhao, Jerome Degallaix, David Blair, Yaohui Fan, Zewu Yan

University of Western Australia

LIGO-G060307-00-Z

Parametric Instability



Radiation pressure force

input frequency ω_o

$$|\omega_0 - \omega_1| = \omega_m$$

Cavity Fundamental mode (Stored energy ω_o)

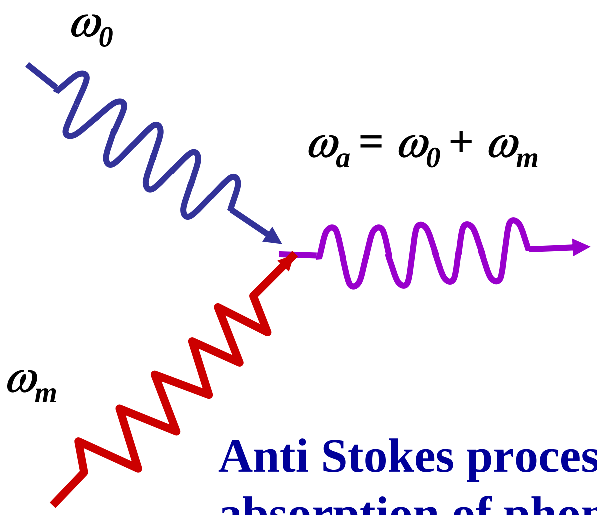
Stimulated scattering into ω_1

Acoustic mode ω_m

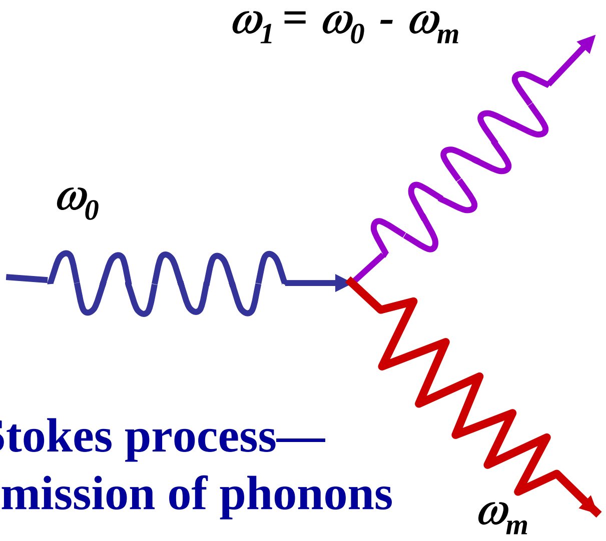
Photon-phonon scattering

Instabilities from photon-phonon scattering

- A test mass phonon can be **absorbed** by the photon, increasing the photon energy (damping);
- The photon can **emit** the phonon, decreasing the photon energy (potential acoustic instability).



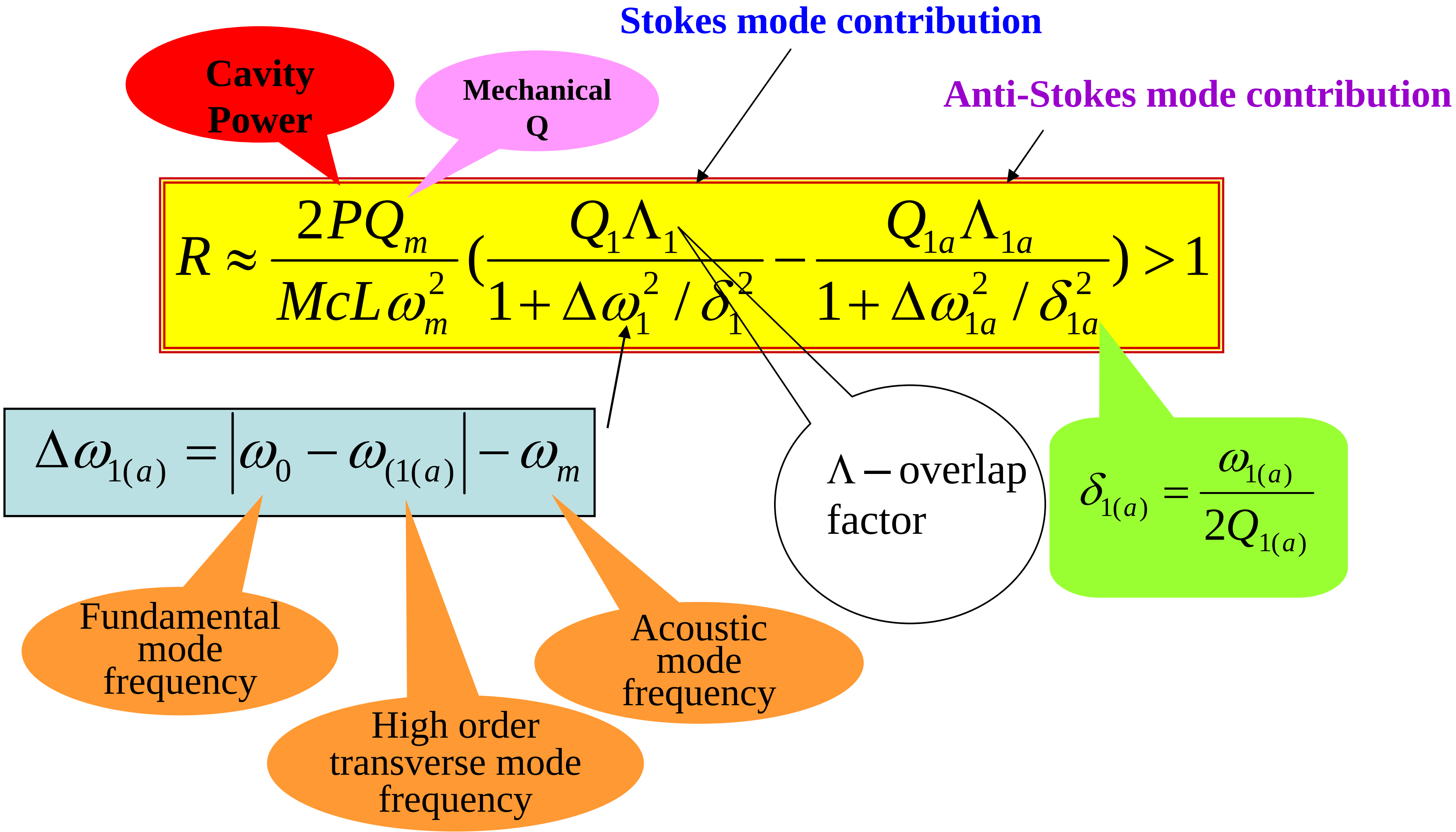
Anti Stokes process—absorption of phonons



Stokes process—emission of phonons

Instability Condition

Parametric gain[1]



Stokes mode contribution

Anti-Stokes mode contribution

Cavity Power

Mechanical Q

$$R \approx \frac{2PQ_m}{McL\omega_m^2}\left(\frac{Q_1\Lambda_1}{1+\Delta\omega_1^2/\delta_1^2}-\frac{Q_{1a}\Lambda_{1a}}{1+\Delta\omega_{1a}^2/\delta_{1a}^2}\right)>1$$

$$\Delta\omega_{1(a)}=\left|\omega_0-\omega_{(1(a)}\right|-\omega_m$$

$\Lambda -$ overlap factor

$$\delta_{1(a)}=\frac{\omega_{1(a)}}{2Q_{1(a)}}$$

Fundamental mode frequency

High order transverse mode frequency

Acoustic mode frequency

[1] V. B. Braginsky, S.E. Strigin, S.P. Vyatchanin, *Phys. Lett. A*, 305, 111, (2002)

Parametric Instability Condition

$$\boxed{R = \sum \frac{4PQ_{m\,j}}{McL\omega_{mj}^{2}}\left(\frac{Q_{1i}\Lambda_{1i}}{1+\Delta\omega_{1i}^{2}/\delta_{1i}^{2}}\times\Omega_{1i} - \frac{Q_{1ai}\Lambda_{1ai}}{1+\Delta\omega_{1ai}^{2}/\delta_{1ai}^{2}}\times\Omega_{1ai}\right)}$$

Anti-Stokes contribution

Stokes contribution

related to the power recycling cavity

- Stokes and Anti-Stokes modes usually do not compensation,
- $R \propto Q_{mech}, Q_{opt}$
- $\Delta\omega$ is a function of RoC
- Total parametric gain is the summation over all the unstable modes

Parametric instability is a reality

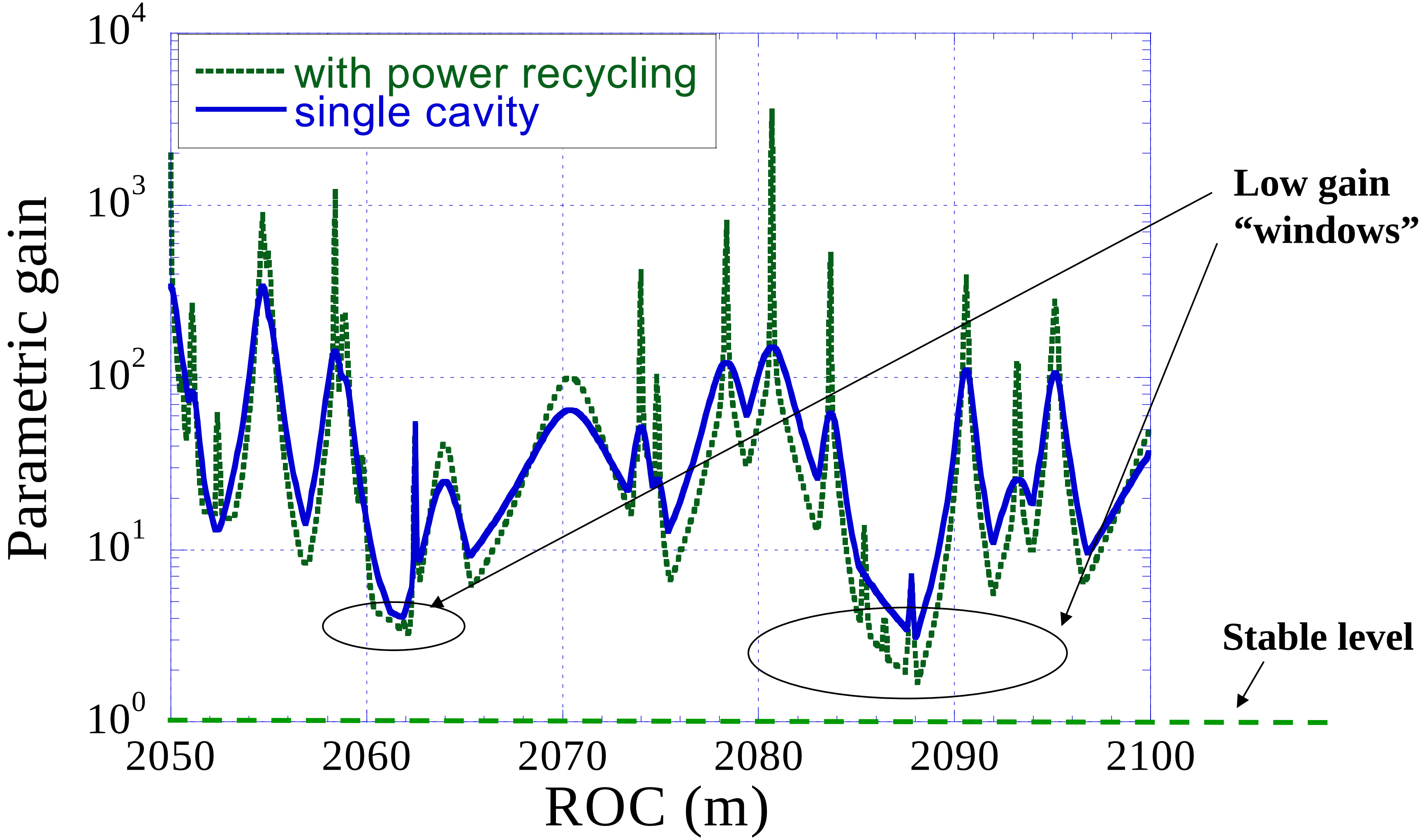
Low frequency parametric instability observed (f_{mech} <FSR)

- MIT experiment (reported by Tomas Corbitt on Sunday)
- LIGO recent observation of mechanical Q change of 37.8kHz mode (H1 at Hanford, A.C. Melissinos and S. Giampanis, February 27, 2006)

High frequency parametric instability

- Stokes & anti-Stokes are not balanced

Parametric Gain Changes with RoC

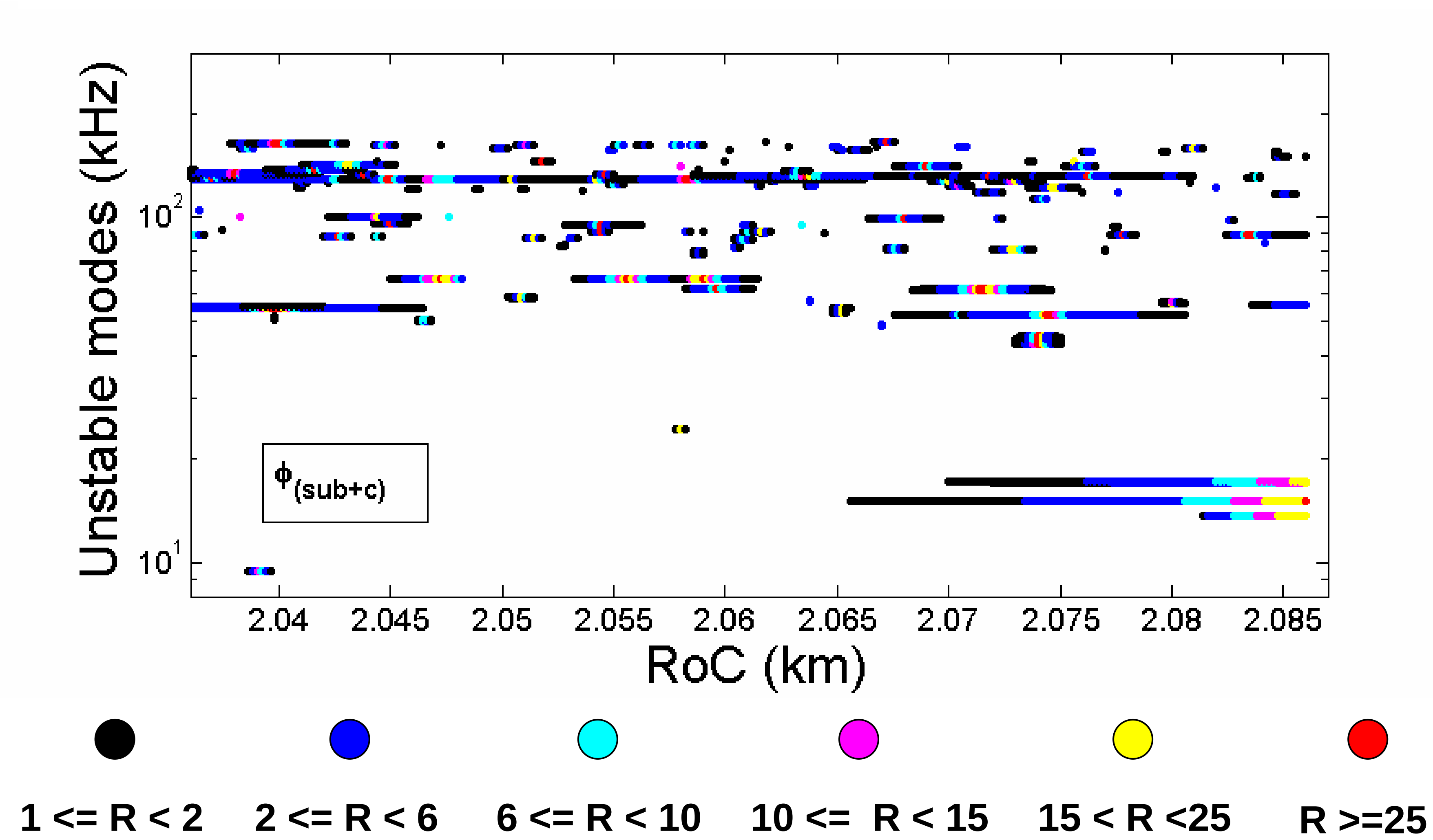


Low gain "windows"

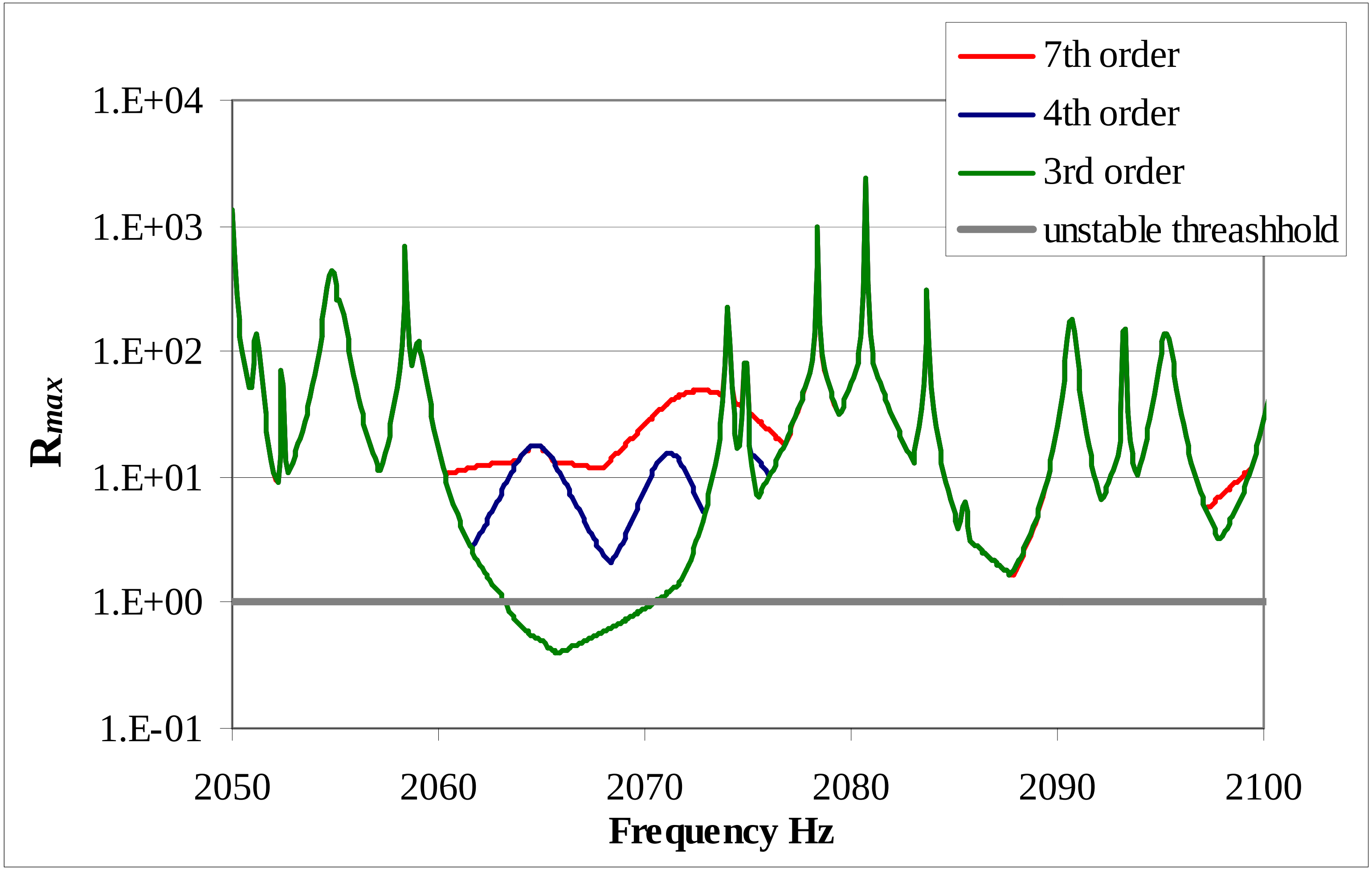
Stable level

Unstable modes

Selected from 1000 acoustic modes. For the test mass with a substrate and coating loss source there are 317 of unstable modes in the range of the RoC 2.039km – 2.086km.



Higher order optical modes contribution



Explore the low gain "window"

- High order optical mode loss
  - Correct calculation of diffraction loss
  - Can we increase higher order mode loss by non-uniform coating?

Diffraction loss investigation

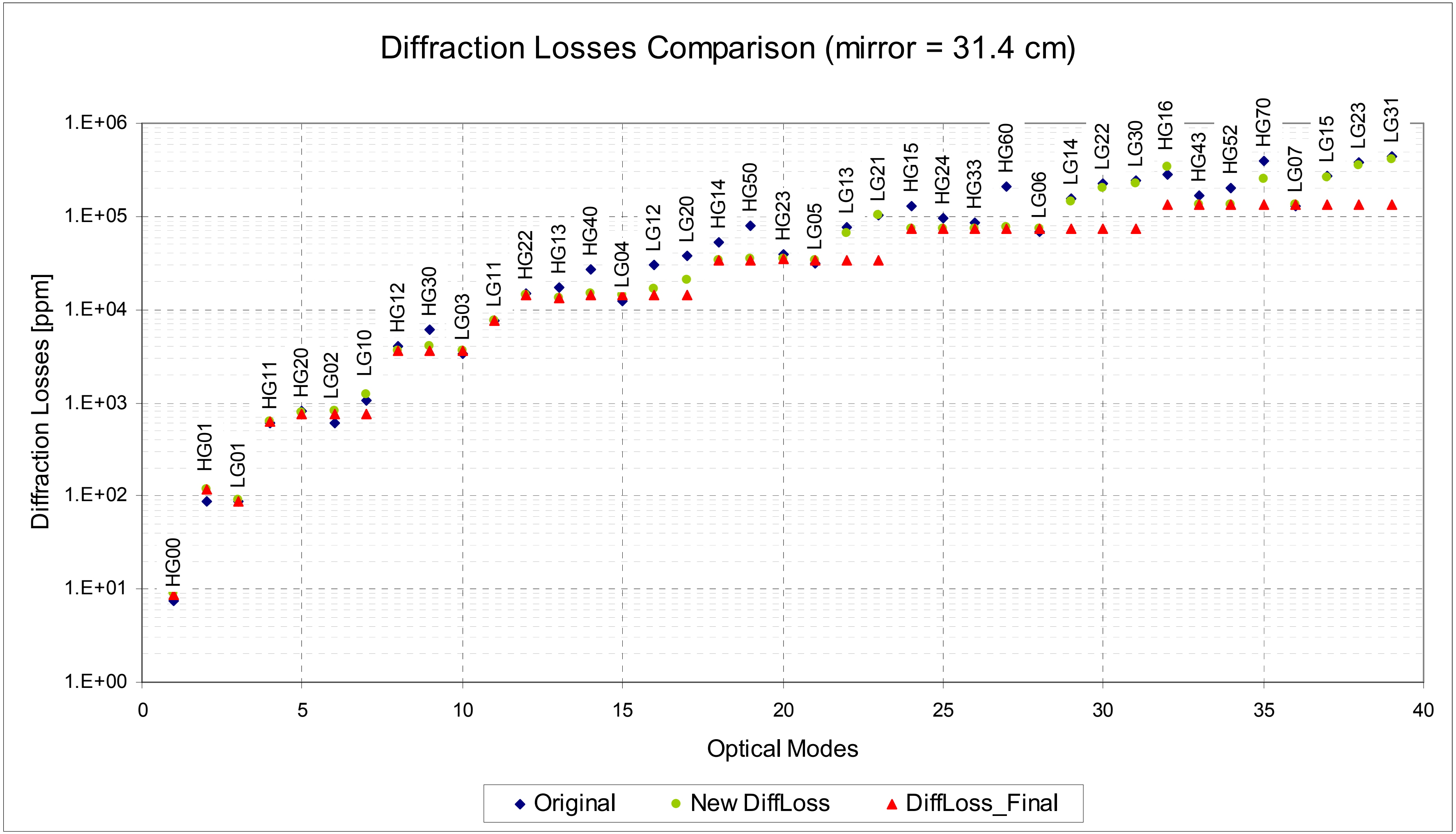


Figure 1: Comparison of the diffraction losses results for an Advanced LIGO type cavity with test masses of diameter 31.4 cm.

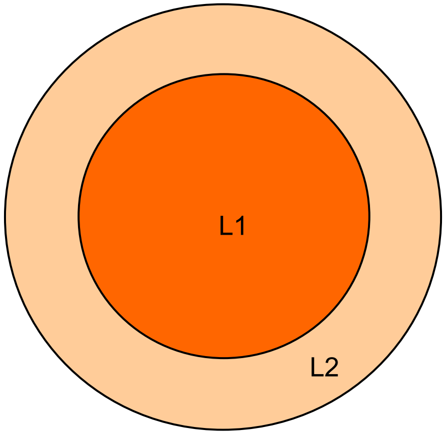
Bablo Barriga with collaboration with LIGO

- Cannot ignore higher order modes contributions

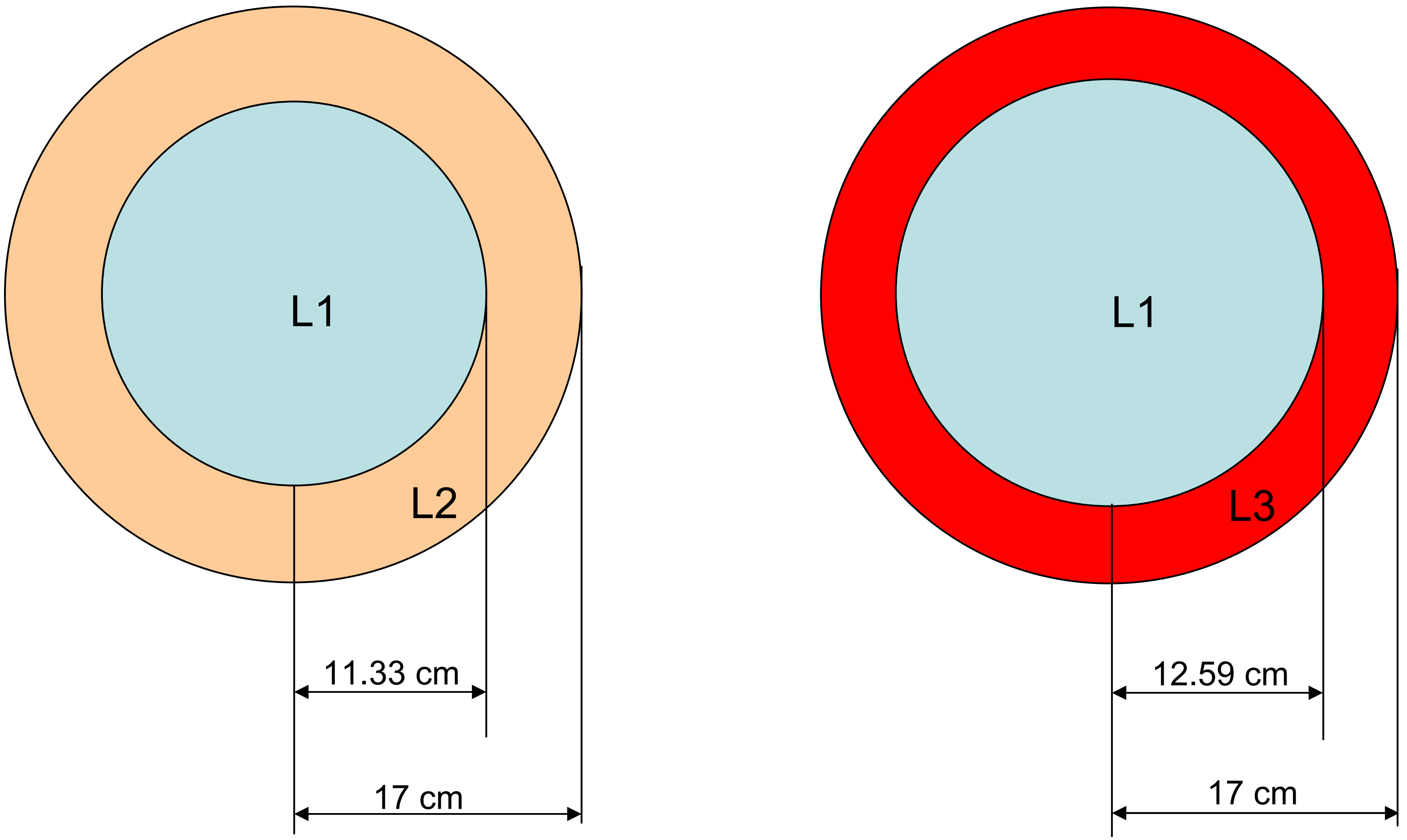
Increase high order modes loss by differential coating?

Suggested by Reccardo DeSalvo, analyzed by Pablo Barriga

- Reduce the parametric gain by increasing the higher order mode loss while maintaining the fundamental mode loss <1ppm

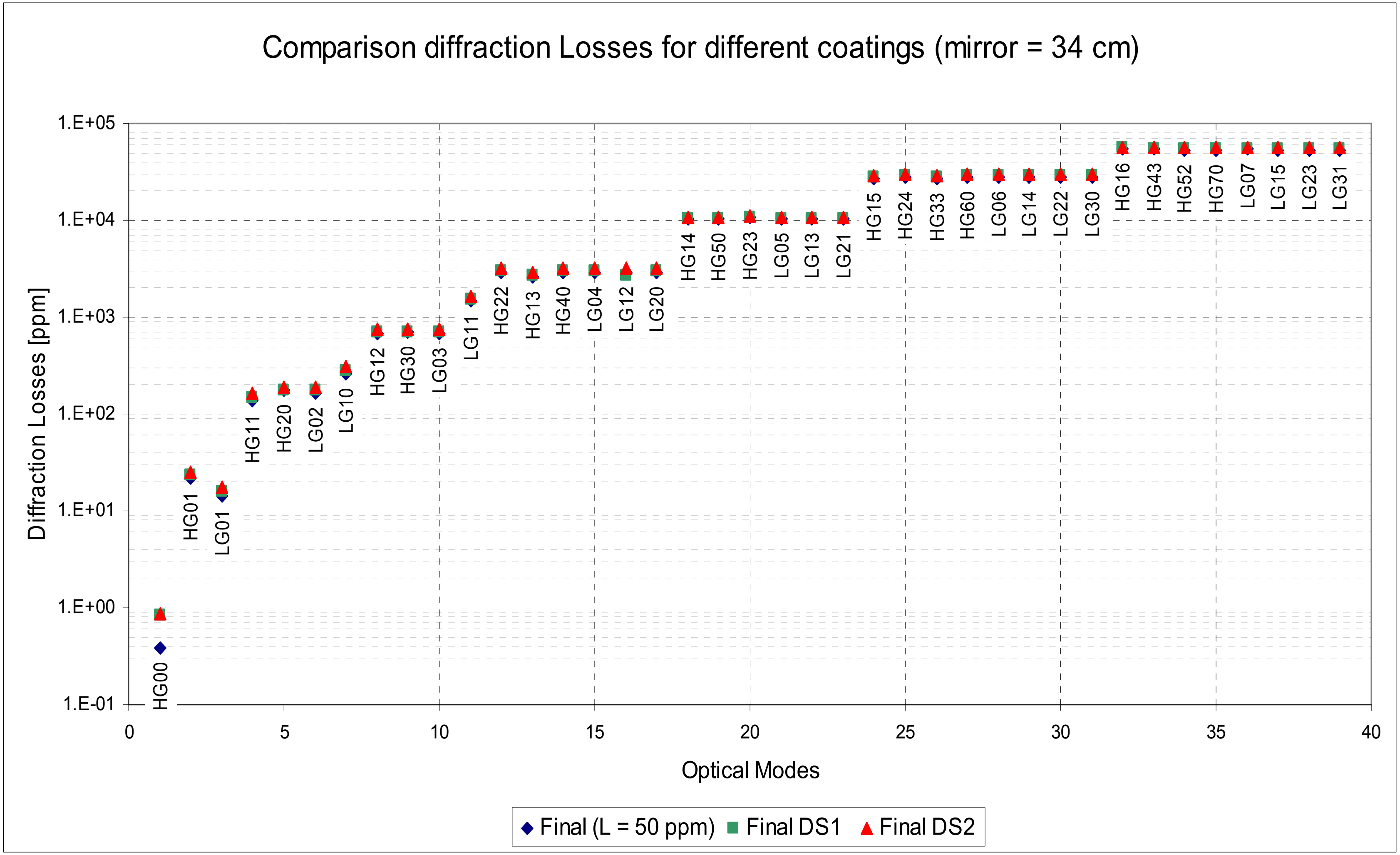


Differential Coating



L1=50ppm, L2=25,000ppm, L3=100,000ppm

Differential Coating



L1=50ppm, L2=25,000ppm, L3=100,000ppm

- No significant difference of diffraction loss between the homogeneous and the differential coatings

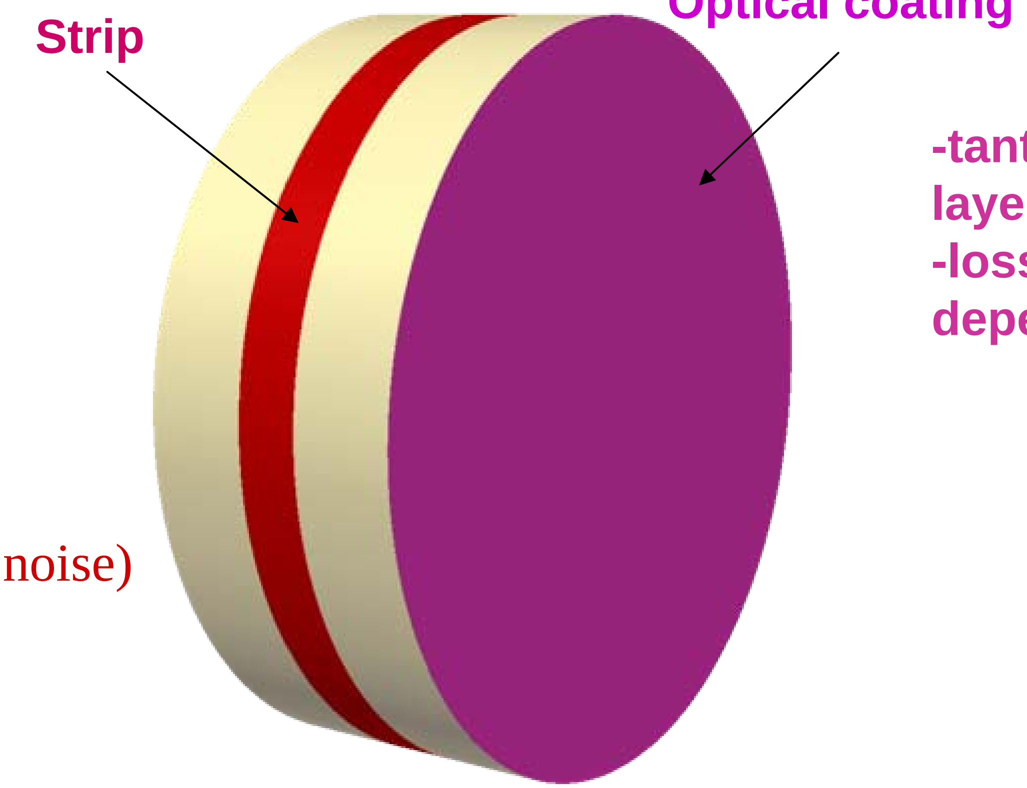
Ring damper—reducing the mechanical Q

- Introduce local damping (rim of the test masses) far away from the centre of the mirror
  - reduce mechanical mode the mechanical modes Q of the test mass without degrading thermal noise (much)

(Reccardo, Gretarsson, UWA)

  - Tests with a rubber o-ring and tape on a test mass at Caltech thermal noise facility

Test mass with ring damper model

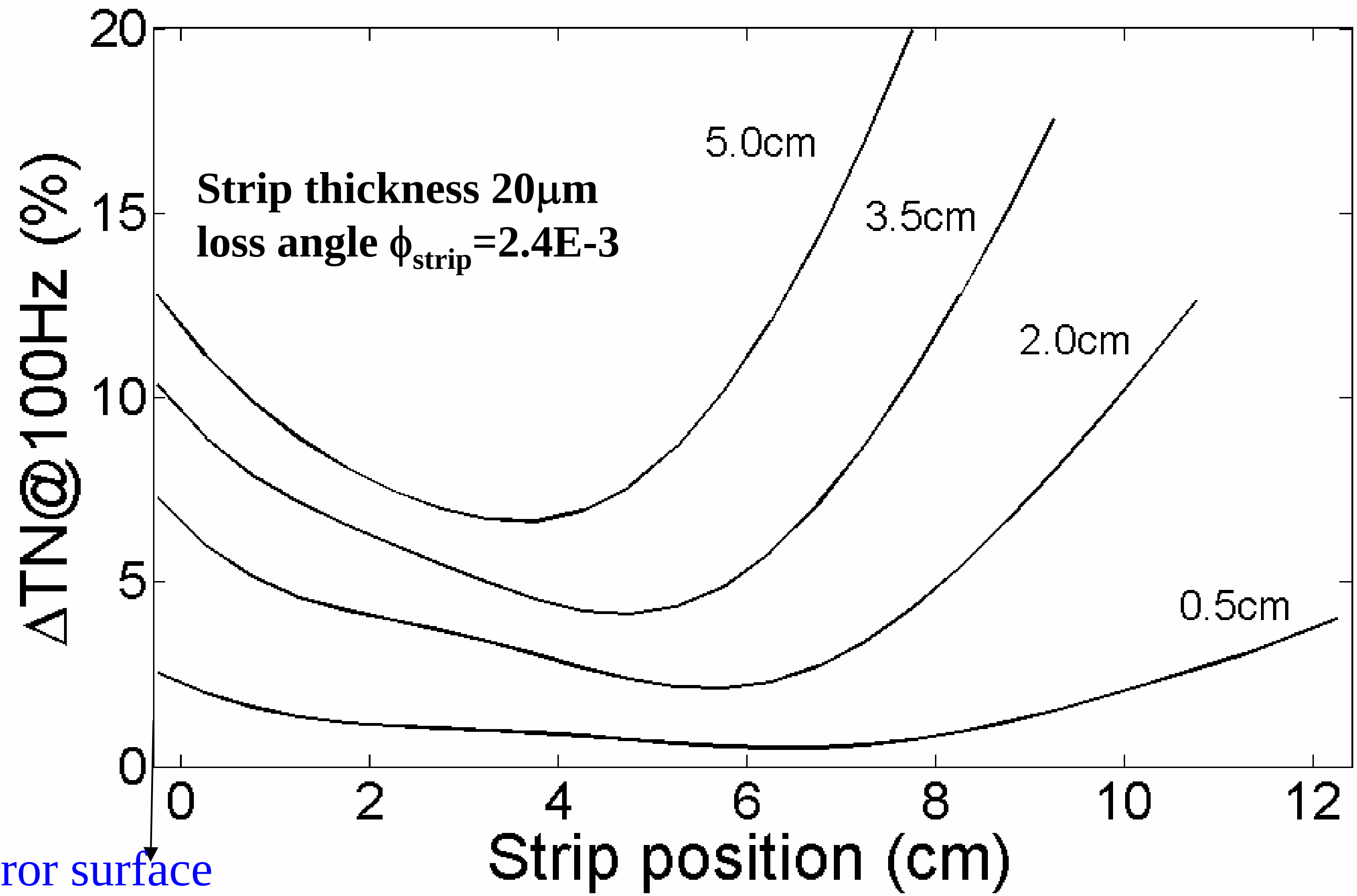


-tantala/silica layers
-loss freq. dependent

Strip variables:
- position
- dimensions:
  - -thickness
  - -width
- loss angle (thermal noise)

Test mass radius r = 0.157m
Thickness d = 0.13m

Ring damper position and width vs thermal noise degradation



Strip thickness 20μm
loss angle ϕ_{strip}=2.4E-3

Mirror surface

There exist a strip position where the thermal noise change is minimal

S. Grass, UWA

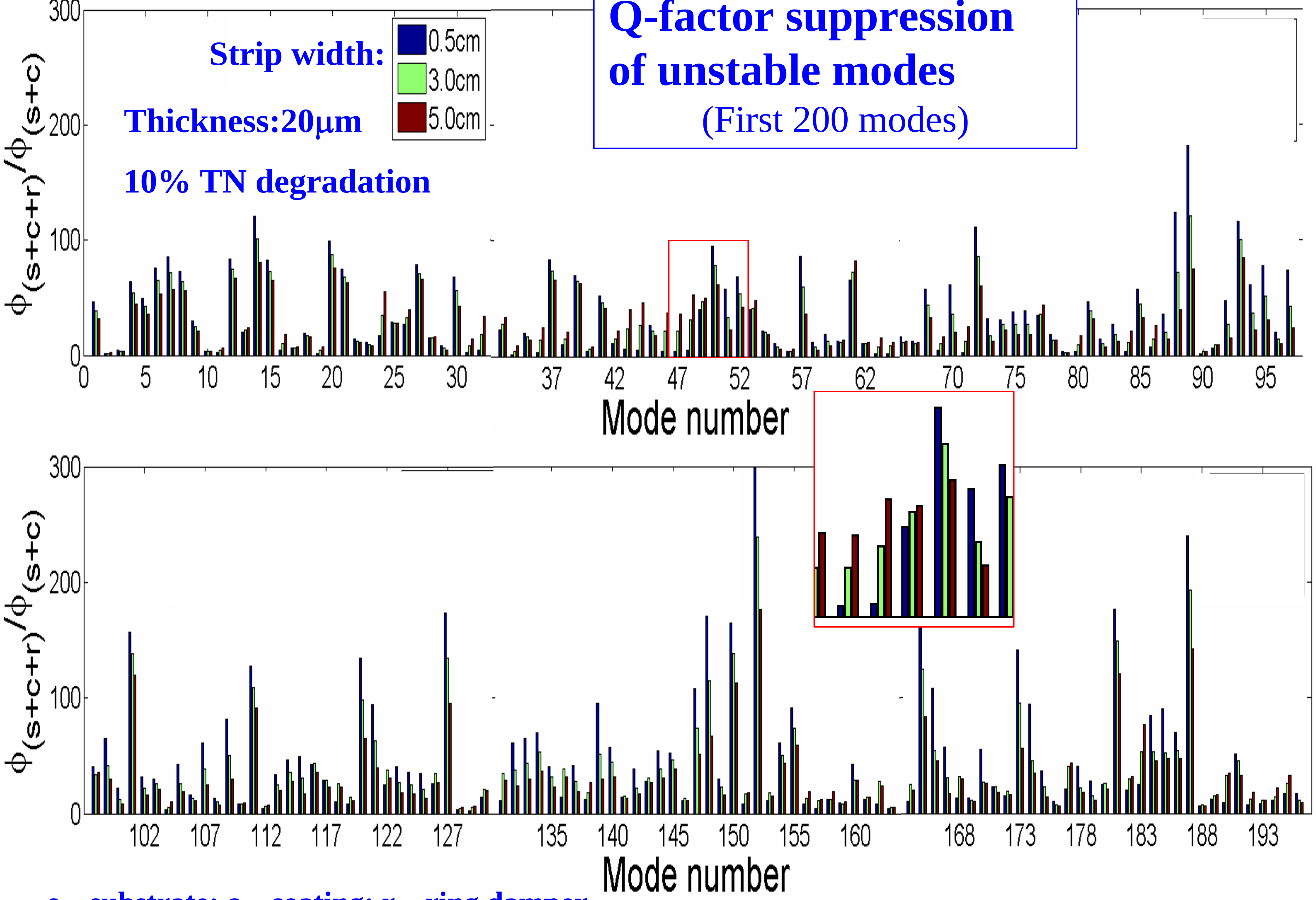
Q-factor suppression of unstable modes

(First 200 modes)

Strip width:

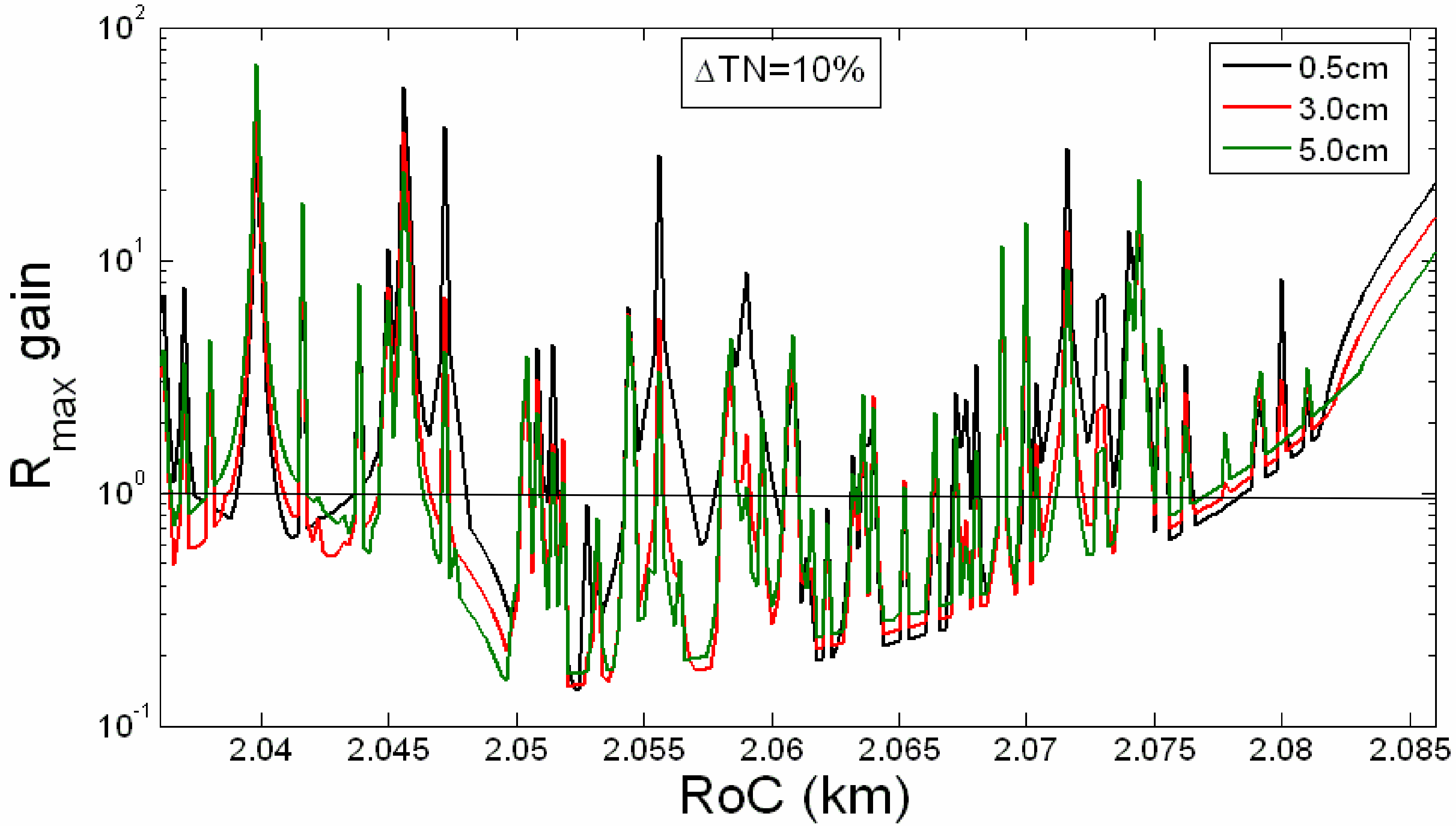
Thickness:20μm

10% TN degradation



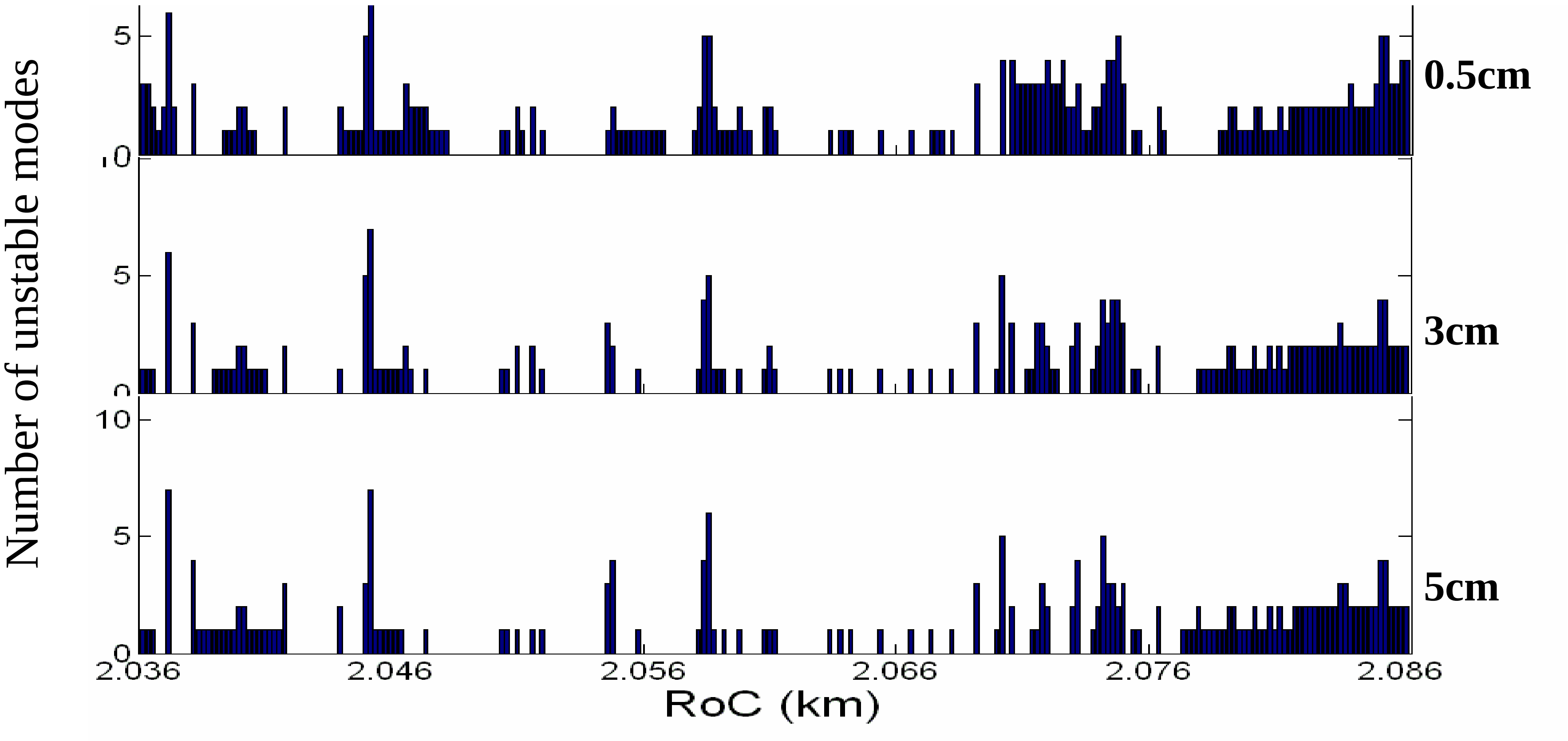
s—substrate; c—coating; r—ring damper

Effect of different strip width (fixed ΔTN)



ΔTN=10%

Strip width



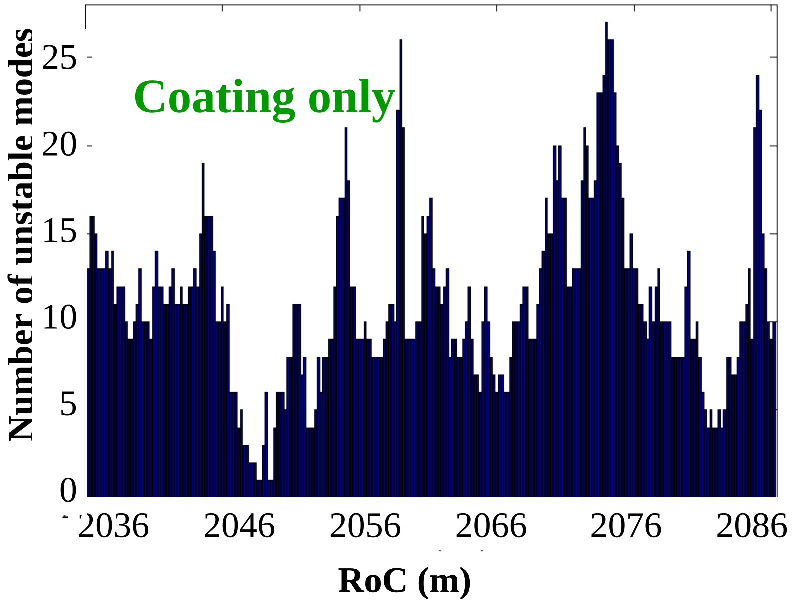
0.5cm

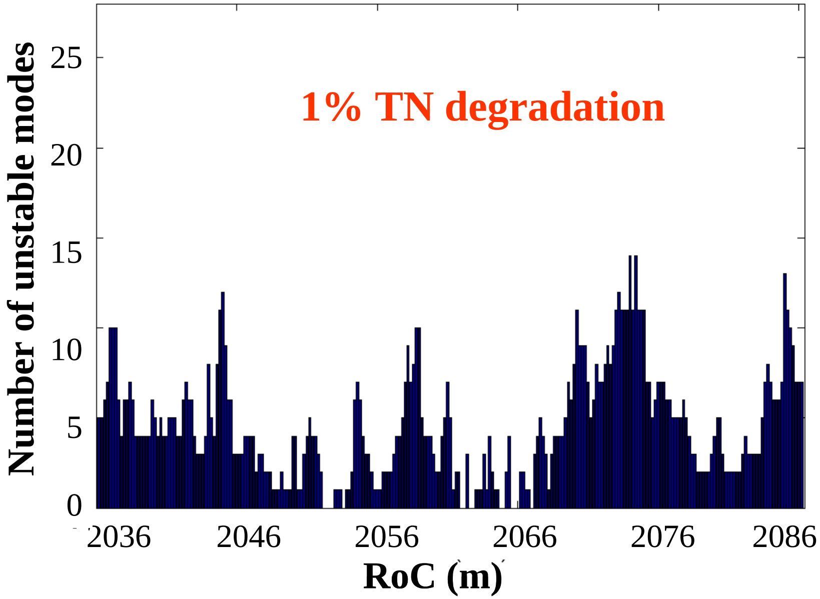
3cm

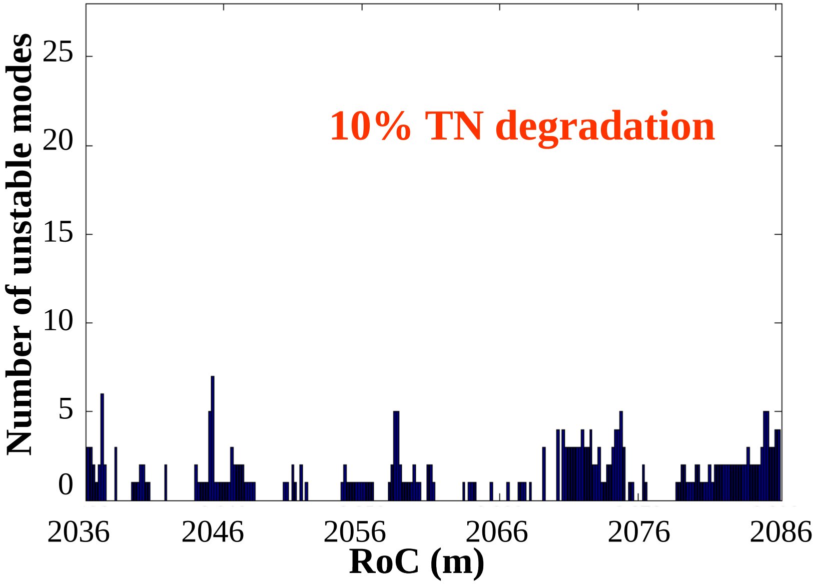
5cm

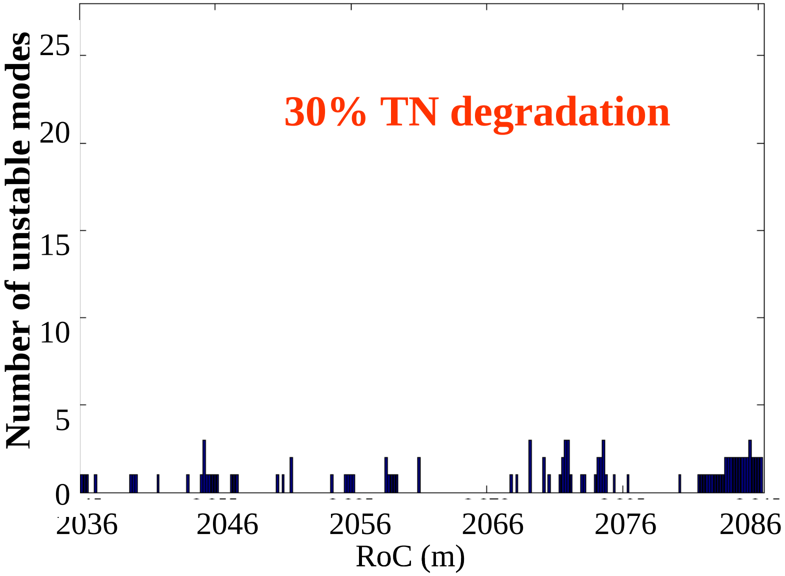
Unstable mode (R>1) with different thermal noise degradation

(5mm strip width with different material loss angle)

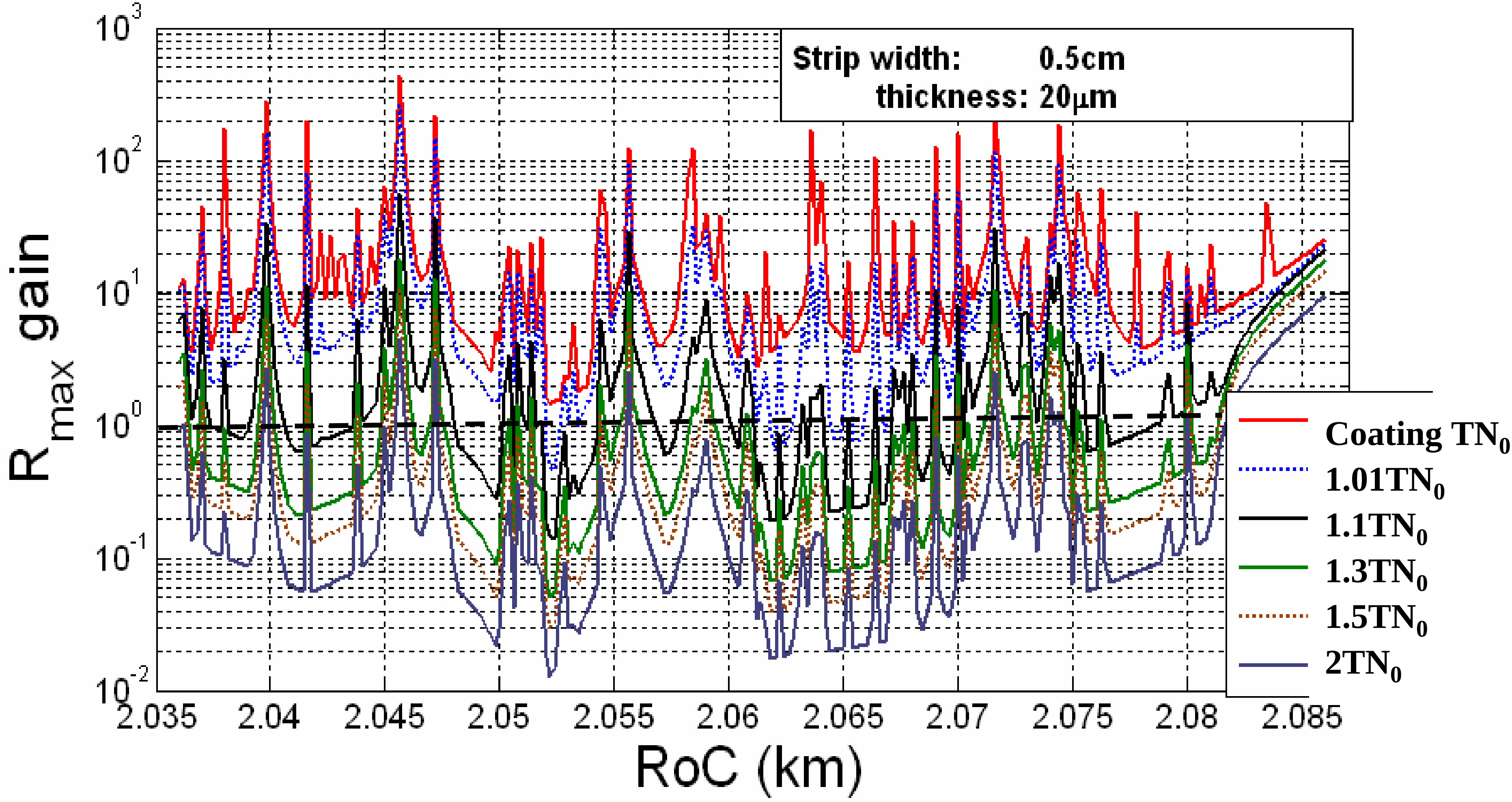






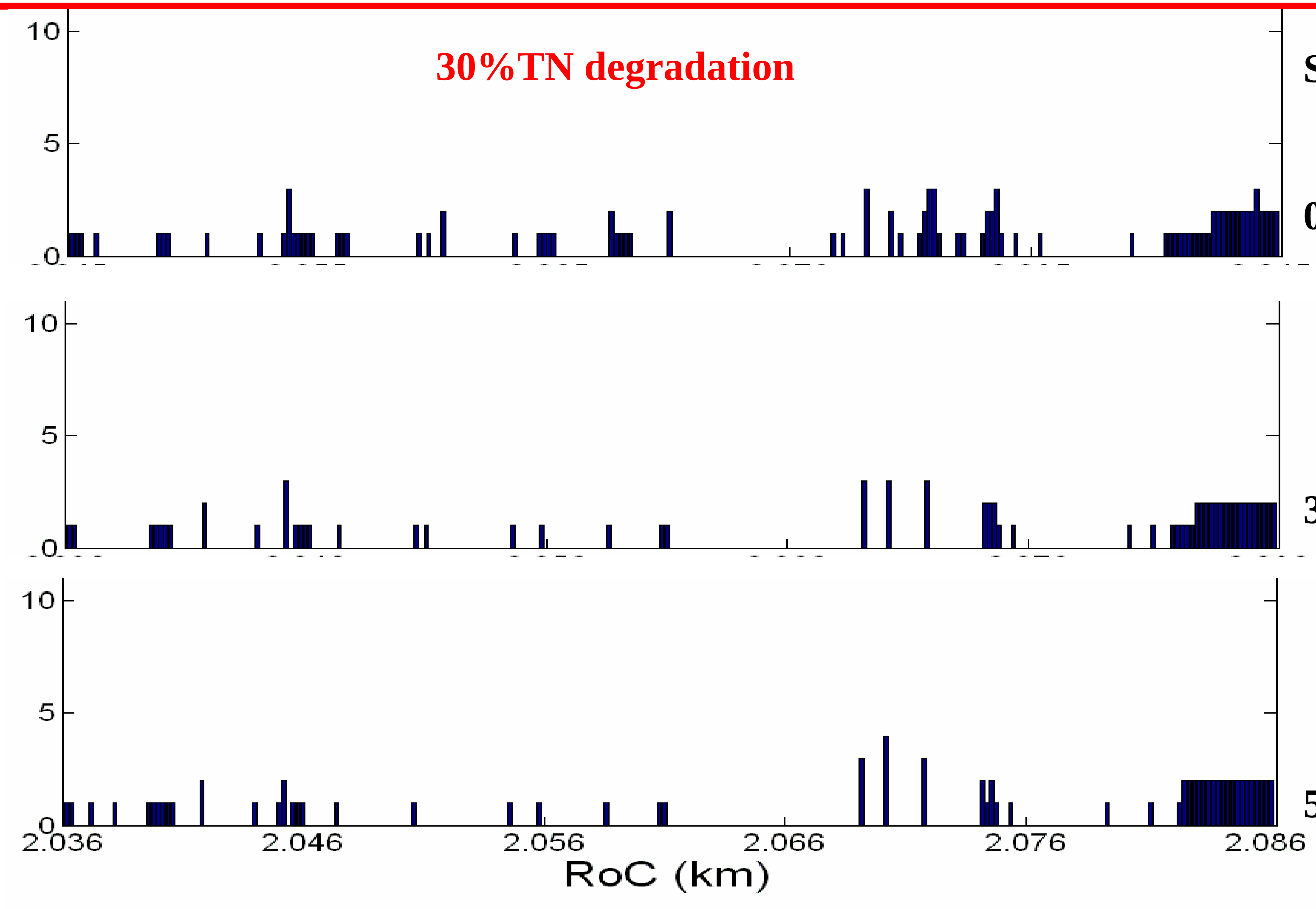


Parametric gain reduction with ring damper



30%TN degradation

Number of unstable modes



Strip width

0.5cm

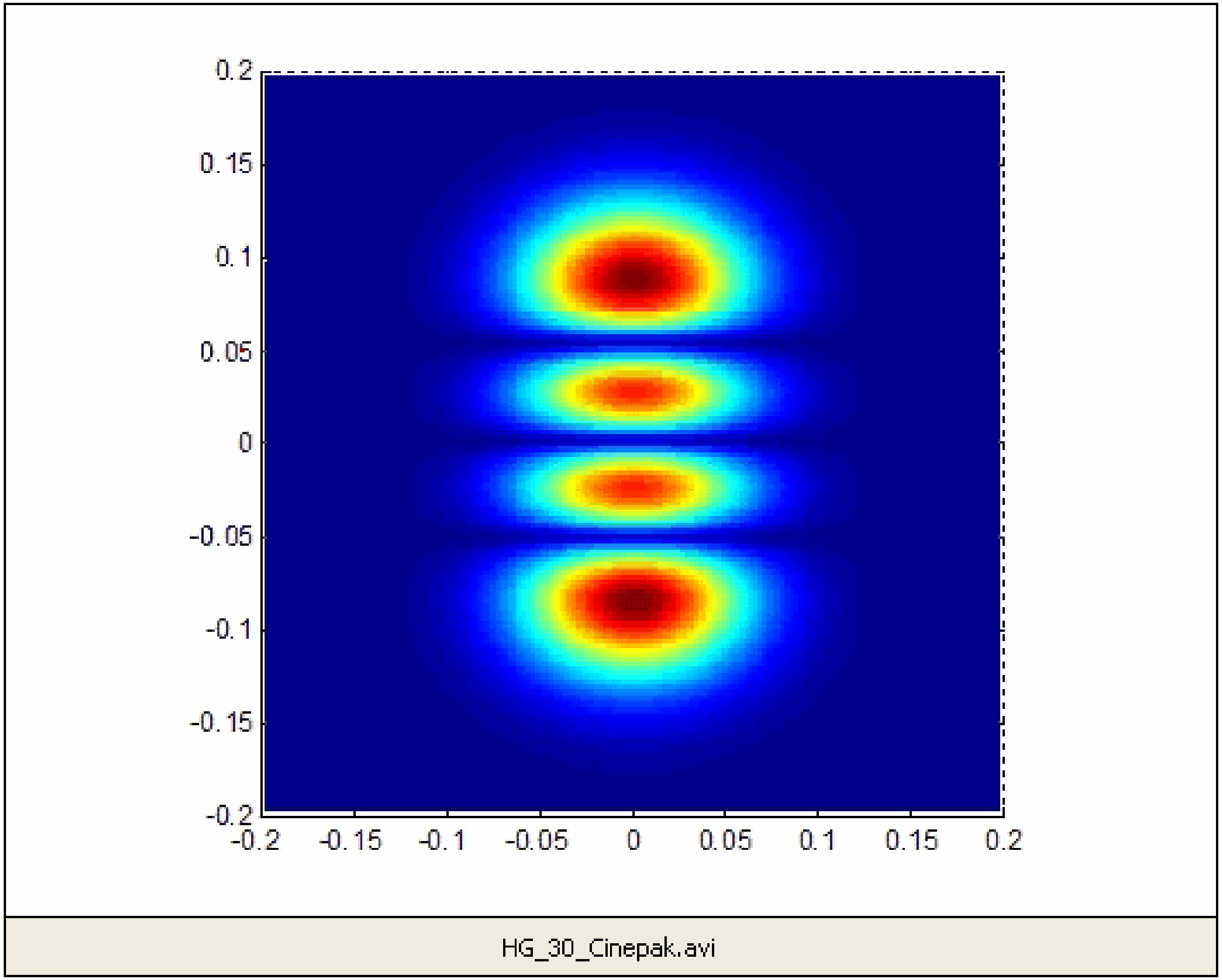
3cm

5cm

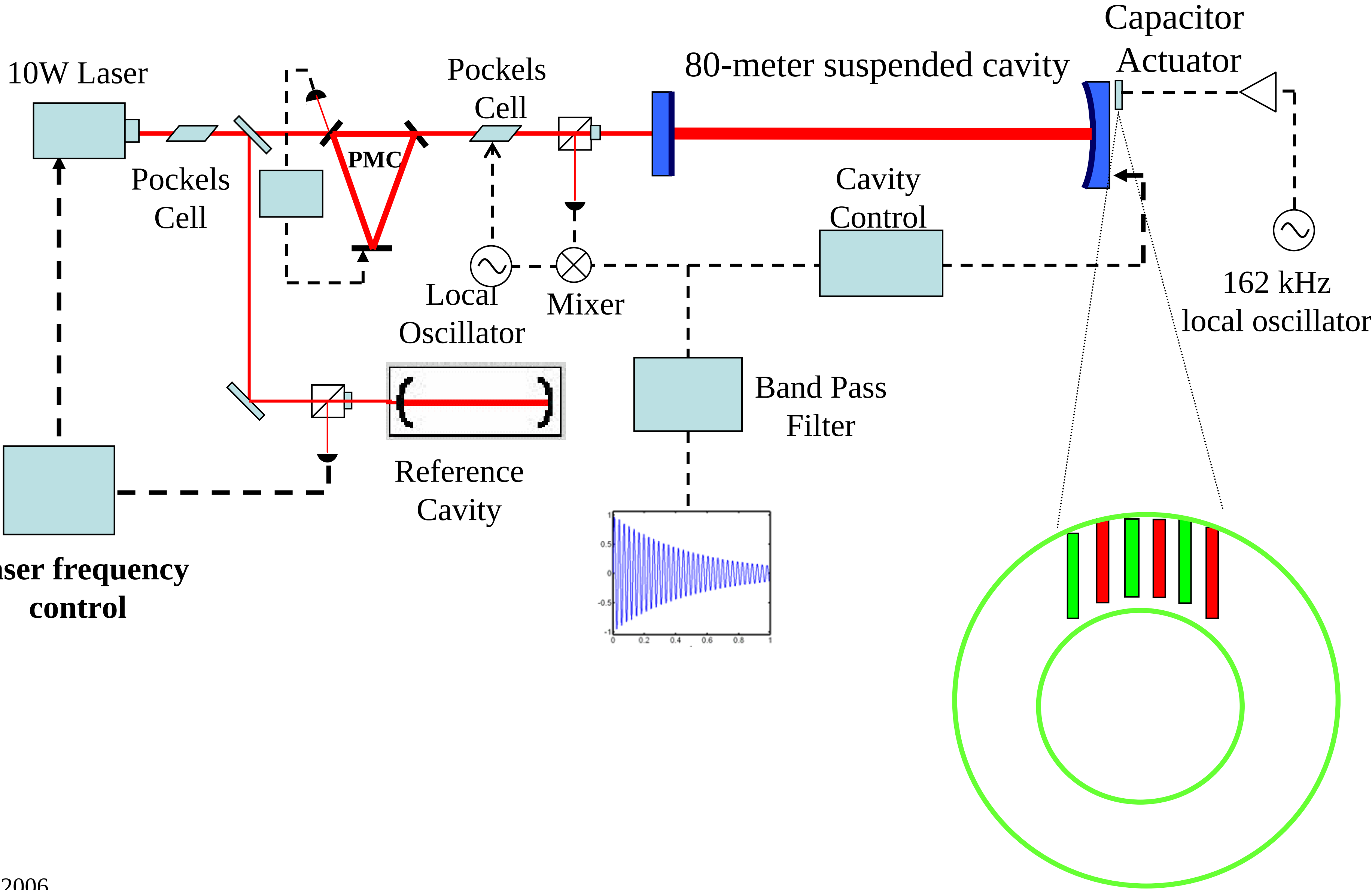
Conclusion

- Ring damper is an effective method to open up stable operation window, at a price of increased thermal noise
  - How much thermal noise increase is tolerable?
- Other possible solution
  - Active feedback (complicated)
- Gingin high power facility will investigate PI experimentally

Mode


0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
HG_30_Cinepak.avi

Active feedback to suppress parametric instability



10W Laser

Pockels Cell

PMC

Pockels Cell

80-meter suspended cavity

Capacitor Actuator

Cavity Control

Local Oscillator

Mixer

162 kHz local oscillator

Reference Cavity

Band Pass Filter

Laser frequency control

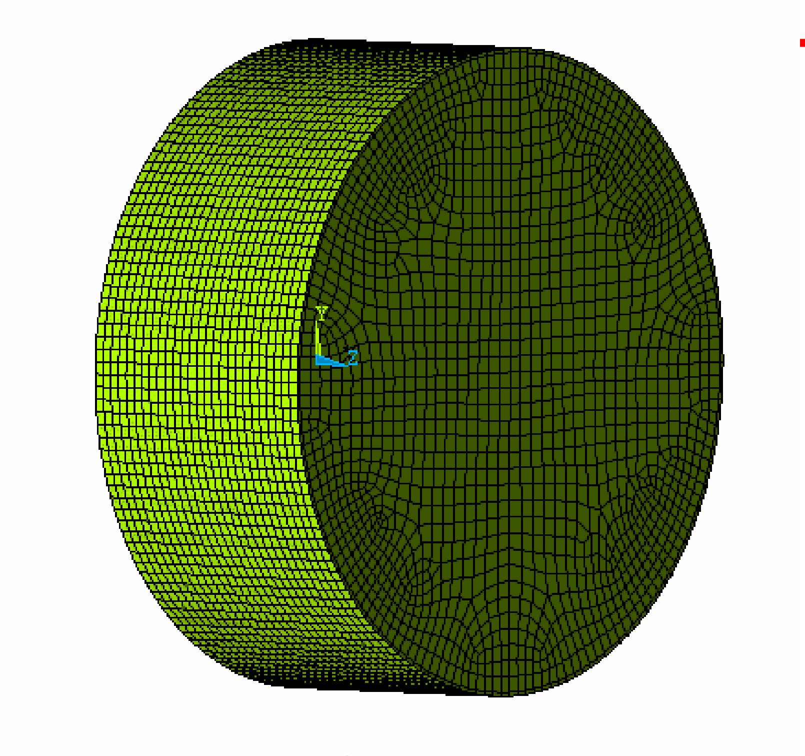
FEM analysis

Substrate: Al_2O_3

- solid95, 21725 elements
-assumed isotropy
-loss angle φ = 1E-08
Young modulus E = 400E09
Poisson ratio p = 0.23
Density ρ = 3983 kg/m3

Coating: SiO_2/Ta_2O_5

-solid46, 869 elements
-30 layers of SiO2/Ta2O5
-thickness 30(λ/4+λ/4) = 15μm
-assumed loss isotropy $\varphi_{\|} = \varphi_{\perp}$
-loss frequency dependent (*)
φ = 4.0E-05 + f 2.7E-09
φ = 4.2E-04 + f 0.4E-09
SiO_2: Young modulus E = 70E09
Poisson ratio p = 0.17
Density ρ=2200 kg/m3
Ta_2O_5: Young modulus E = 140E09
Poisson ratio p = 0.23
Density ρ = 8200 kg/m3



FEM model of the test mass

Strip:

-Material properties like for Al_2O_3 (still good approximation)
-Various loss angles, various thickness and width for desired thermal noise level

* Harr G M,… et al. 2004 Proceedings of the SPIE 5527 33