Study of coating mechanical losses for gravitational wave detectors

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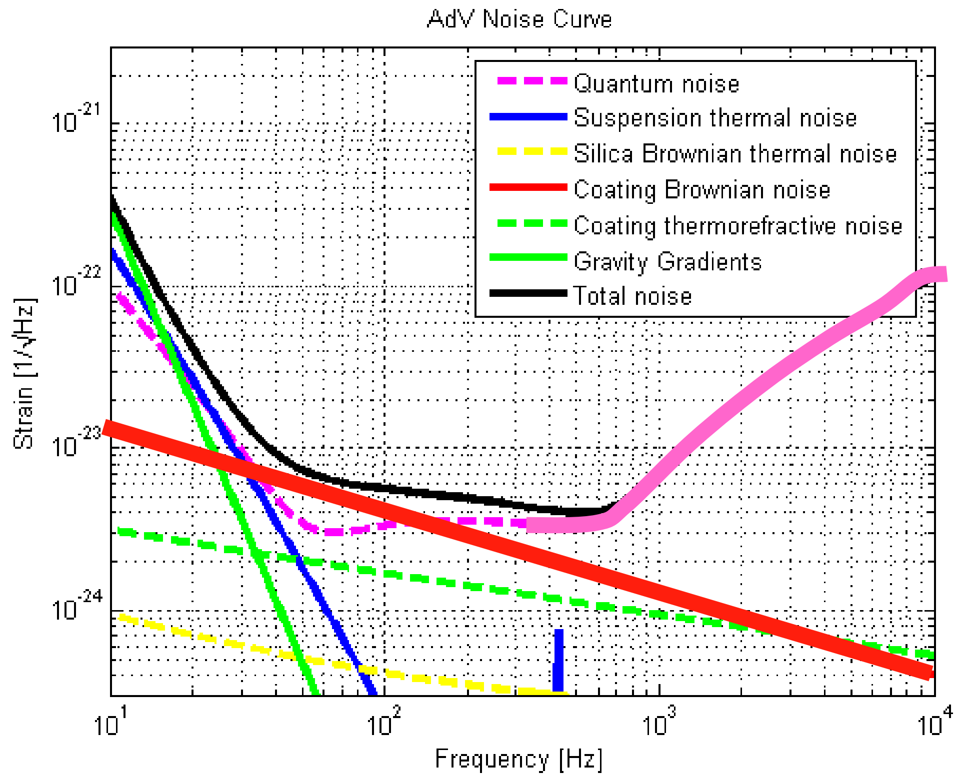
Motivations of the study

- Mechanical losses from dielectric mirror coatings are a significant source of thermal noise in the more crucial frequency range (~ 100 Hz)

Limit the design sensitivity for advanced detectors



- Coating optical absorption
  - ⇨ Thermal lensing
    - ⇨ limits the power injected in the cavity

Limits the reduction of the Shot noise at high frequency

Mechanical losses

- Ta_2O_5 is the dominant source of dissipation in current SiO_2 / Ta_2O_5 coatings

Ratio ~ 6 between silica and tantala

$\Phi_{SiO2} \sim 0.5\ 10^{-4}$

$\Phi_{Ta2O5} \sim 3\ 10^{-4}$

Goal : Improve the mechanical quality factor of the high index material

- The stress of the coating must be controlled
  - Deformation of the surface
  - Adherence of the coating
  - Formation of defects (bubbles)

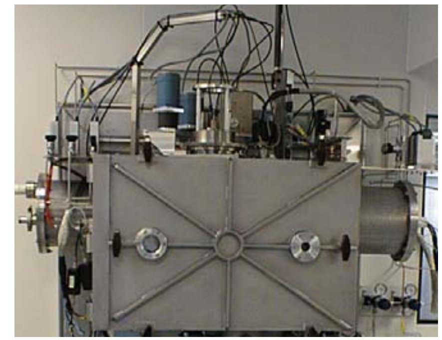
typical stress values : -300 MPa Ta_2O_5 and 200 MPa for SiO_2

LMA IBS (Ion Beam Sputtering) deposition Facilities

IBS technique is the deposition process to obtain optical stacks with the lower optical losses on large surface

- Small IBS coater : DIBS
  - Able to coat homogeneously up to 3“ substrates
    - ✓ Continual upgrades since 1990 : now equipped with an RF ion source (filament ion source before) like in the large coater
  - Very flexible machine ⇒ ideal for prototyping

Small IBS coater



- Large IBS coater : GC
  - ✓ 2,2 m X 2,2 m X 2,0 m inner deposition chamber
  - ✓ Designed to coat substrates up to 1 meter diameter
  - ✓ Used for VIRGO large mirrors since 2001
    - ❖ Periodic quarter wave doublet stacks (Ta_2O_5 and SiO_2)
    - ❖ Between 130 and 180 nm layer thickness

350 mm diameter VIRGO mirrors

Large IBS Coater

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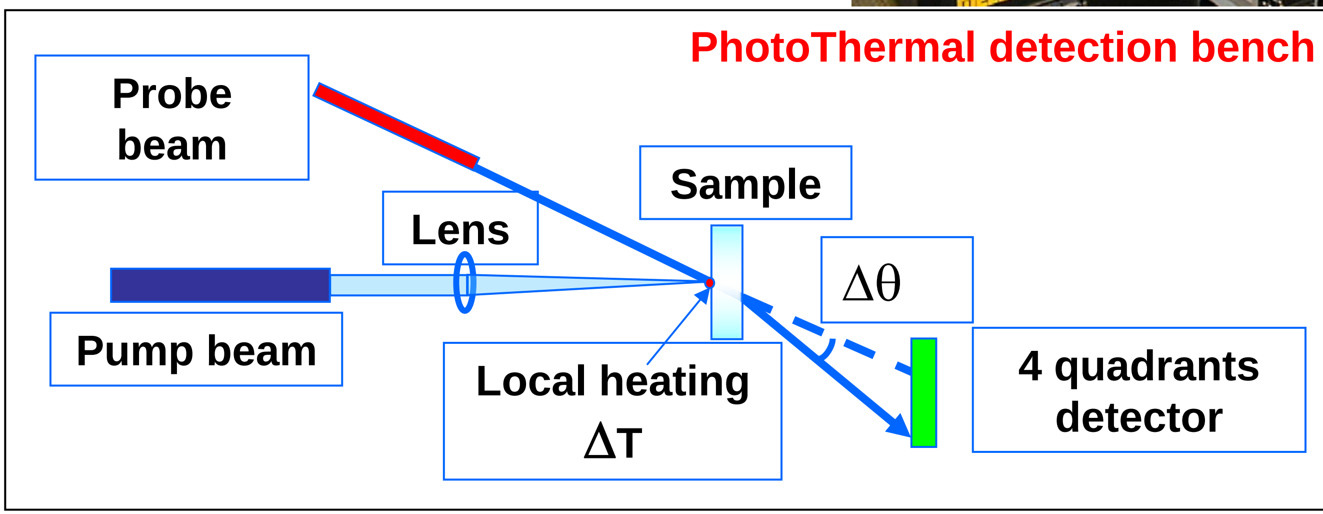
Optical losses measurement bench

- **2 Absorption measurement benches at LMA**

Over Ø Few inches

Over Ø 400 mm

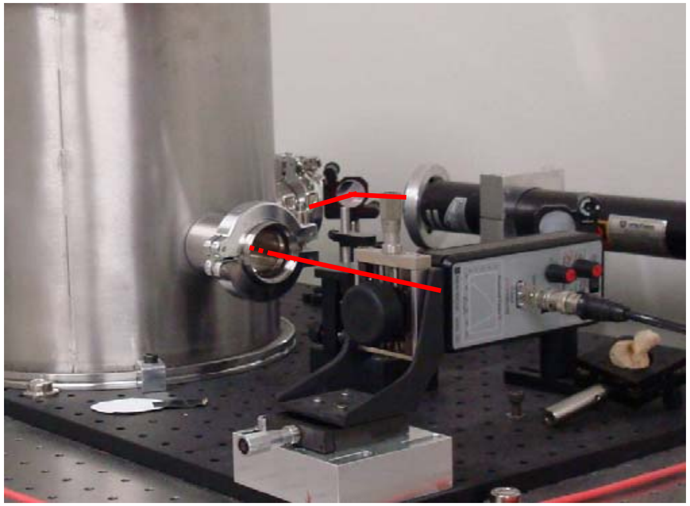


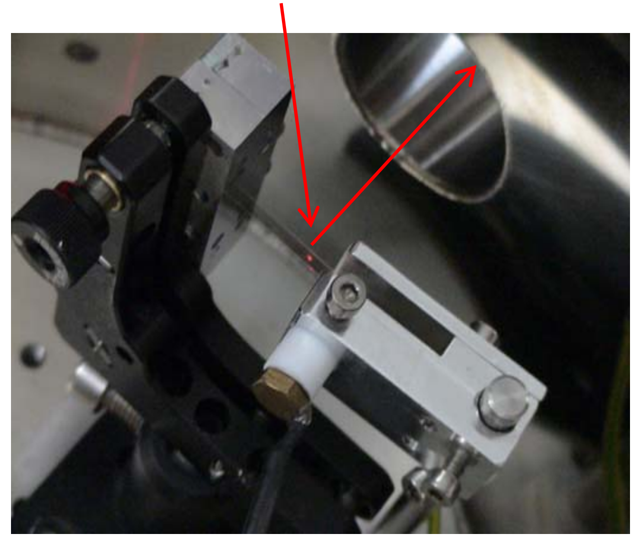
Bulk absorption resolution : 0.01 ppm/cm

Surface absorption resolution (coatings) : 0.02 ppm

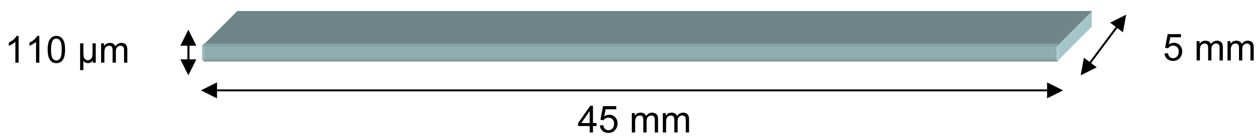
LMA Q measurement bench

Collaboration with INFN (PERUGIA)





- Cantilever : Silica *SUPRASIL 311* from *HERAEUS*

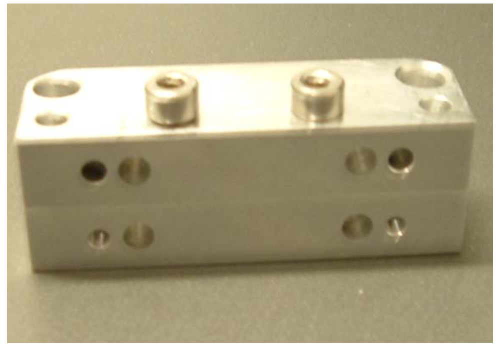


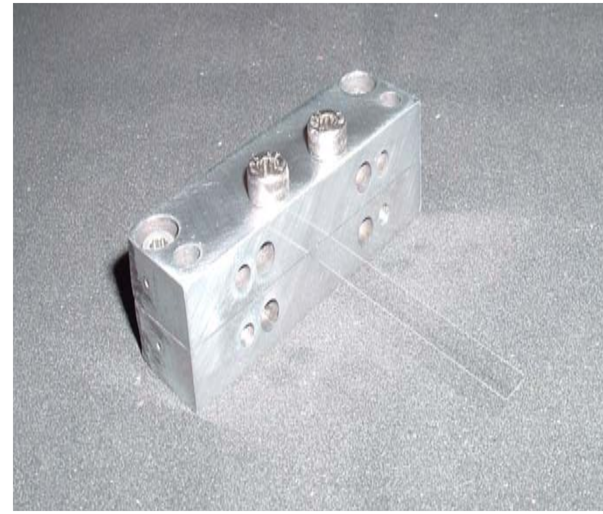
Goal: Have a quick and low cost measurement for the LMA coatings

- Measurement at low frequency (60 Hz – 1000 Hz)

LMA Q measurement bench

- Polishing + working on the vice
  ⇨ minimize clamping losses





- Cleaning of the cantilever
  ↳ Remove the polishing impurities
- Long annealing of the cantilever
  ↳ Cure some cracks of the sub-surface

Improvement of 25 % of the Q factor

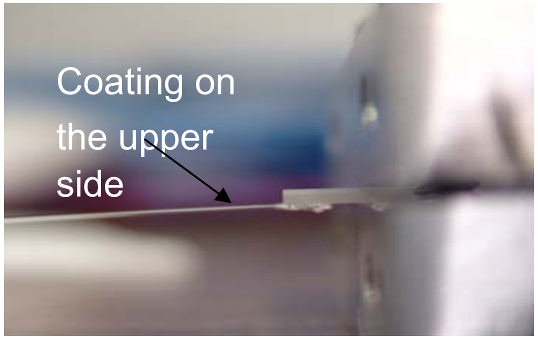
Measured Suprasil membrane losses : $\Phi = 4.10^{-6}$

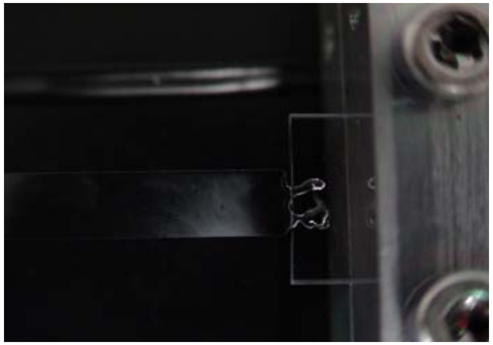
Determines minimum measurable losses

Samples

Collaboration with IGR (University of Glasgow)

LMA membranes, CO_2 laser welded in Glasgow





Free vibration length : 45 mm - Thickness membrane : 104 µm

Goal : Minimize the clamping losses

suspicious white marks near the welding point : (silica vapor) ?

Naked silica membranes mechanical losses

Not welded	welded
4.10^{-6}	**$< 3.10^{-6}$**

New high optical index coating materials : ZrO_2 (DIBS) & Nb_2O_5(DIBS)

ZrO_2 (DIBS)

Coating *	Optical index	Absorption (ppm)	Losses	Stress (Mpa)
ZrO_2	2.1	11	$2.3.10^{-4}$	~ - 1780
ZrO_2 : Ti	2.15	37	$6.8.10^{-4}$	~ - 180
ZrO_2 : W	2.12	10	$2.8.10^{-4}$	~ - 600

* Monolayer thickness : 500 nm

⊕
- **Easy to synthetize by IBS**
- **High index : > 2.1**
- **Promising mechanical losses : Ø ~ $2.3.10^{-4}$**

⊖
- **Very stressed material > 1-2 GPa**
- **High absorption : ~ few tens of ppm**

ZrO_2 study ⇨ No relation : Stress – Mechanical Losses

Nb_2O_5(DIBS)

Coating	Optical index	Scattering (ppm)**	Absorption *(ppm)	Losses*
Nb_2O_5	2.21	10	2.25	$4,6.10^{-4}$

* Monolayer thickness : 820 nm & ** $L(HL)^{15}$ HH L @ 1064 nm

- Absorption on complete mirror L(HL)15 HH L : **2,25 ppm**

New high optical index coating materials : doped:Ta_2O_5 (DIBS)

Coating *	Optical index	Absorption (ppm)	Losses	Stress (Mpa)
Ta_2O_5	2.035	1.22	3.10^{-4}	~ - 225
Ta_2O_5 : Co	2.11	5 000 !	11.10^{-4}	NA
Ta_2O_5 : W	~ 2.07	2.45	$7.5.10^{-4}$	NA
Ta_2O_5 : W+Ti **	2.05<n<2.1	1.65	$3.28.10^{-4}$	NA
Ta_2O_5 : Ti	2.07	1.7	$2.4.10^{-4}$	NA

* Monolayer thickness : 500 nm

** Absorption too high for a complete mirror (>80ppm)

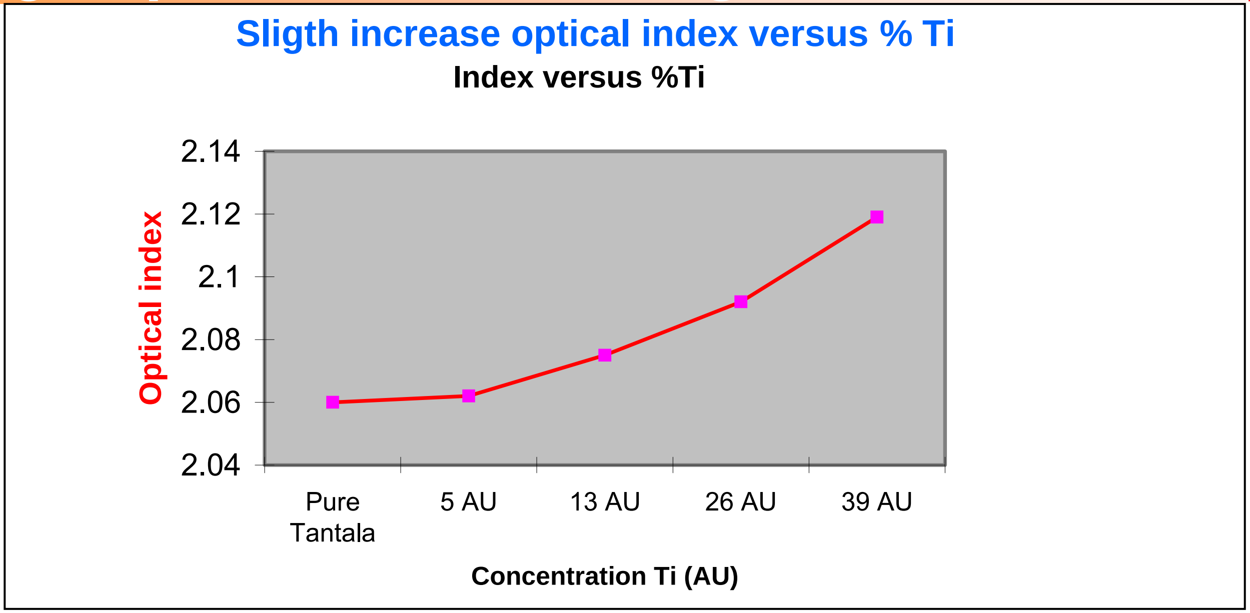
- Doping increases index contrast between high and low index materials

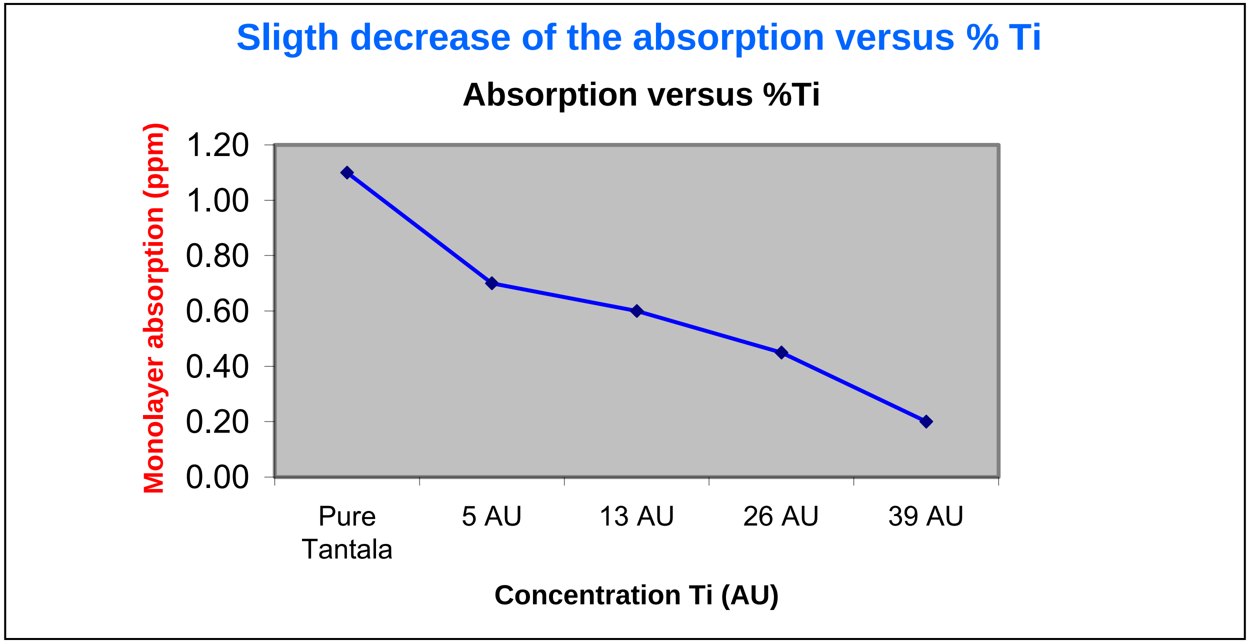
  ⇨ may lower the coating brownian noise

- It is not easy to lower the mechanical loss without increasing the absorption

The best doping for Tantala coating is the Titanium

New high optical index coating materials : $Ti:Ta_2O_5$ (DIBS)





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Ti : Ta_2O_5 (Large Coater)

Ta_2O_5

$\Phi_{Ta2O5} = 3\ 10^{-4}$

Ti doping

$\Phi_{Ta2O5} = 2.4\ 10^{-4}$

+ ~ 22 %

Optimization of process parameters

$\Phi \sim 1.9\ 10^{-4}$

+ ~ 26 %

Monolayer (500 nm) @ 1064 nm

Refractive index ~ 2.065
Monolayer absorption : 1,5 ppm
Mechanical losses : $1{,}9.10^{-4}$

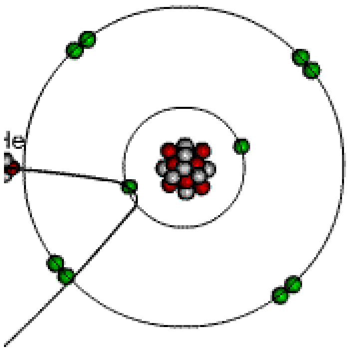
Complete mirror $(HL)^{19}$ HLL @ 1064 nm

Optical properties unchanged compare to pure Tantala mirror

Absorption : 0.5 ppm

Diffusion < 5 ppm

Principle of the méthod : RBS is used to determine the structure and composition of materials by measuring the backscattering of a beam of high energy ions impinging on a sample



Back-Scattered ion energy : $E=k^2E_0$

E_0 : Incident particles Energy

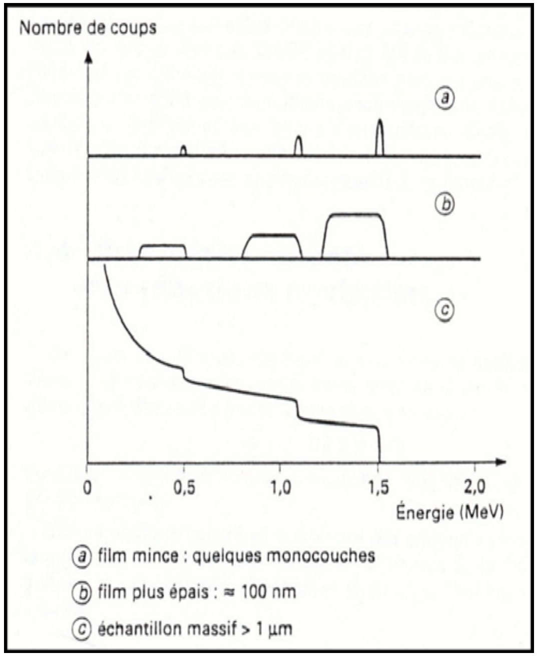
k : Kinematic factor

$$k = \frac{m_1\cos\theta+(M_2^2-m_1^2\sin^2\theta)^{1/2}}{m1+M2}$$

m_1: Mass of the incident particle

M_2 : Mass of the target atom

θ : detection angle



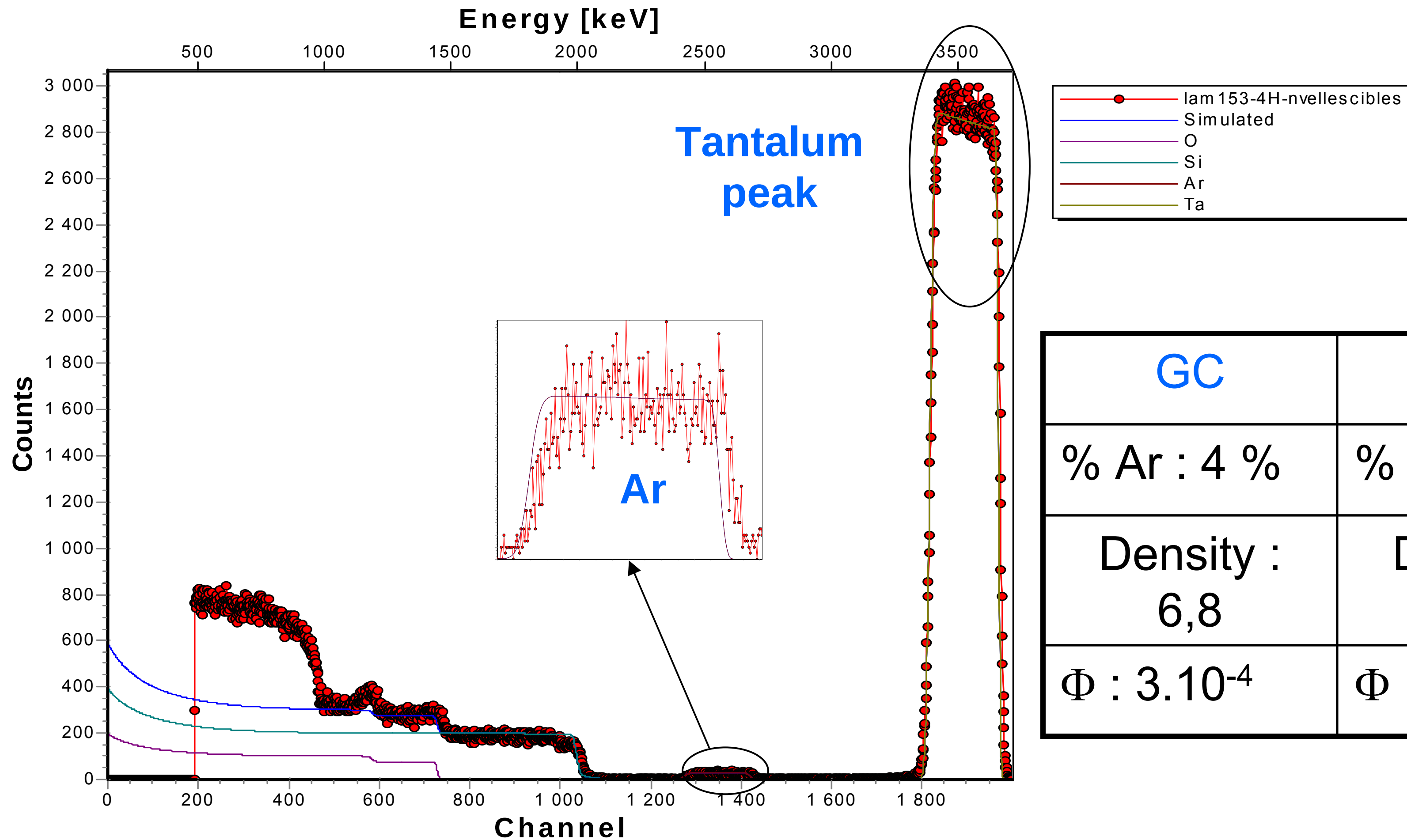
Method performances : the analysis is more sensitive when you analyse a heavier material into a lighter matrix

Incident ions beam He^{4+} Energy 2.5 MeV

Interesting data : ⇨ quantify the element concentration

⇨ gives the density of the layer

RBS analysis on Tantala coatings : Pure Ta_2O_5

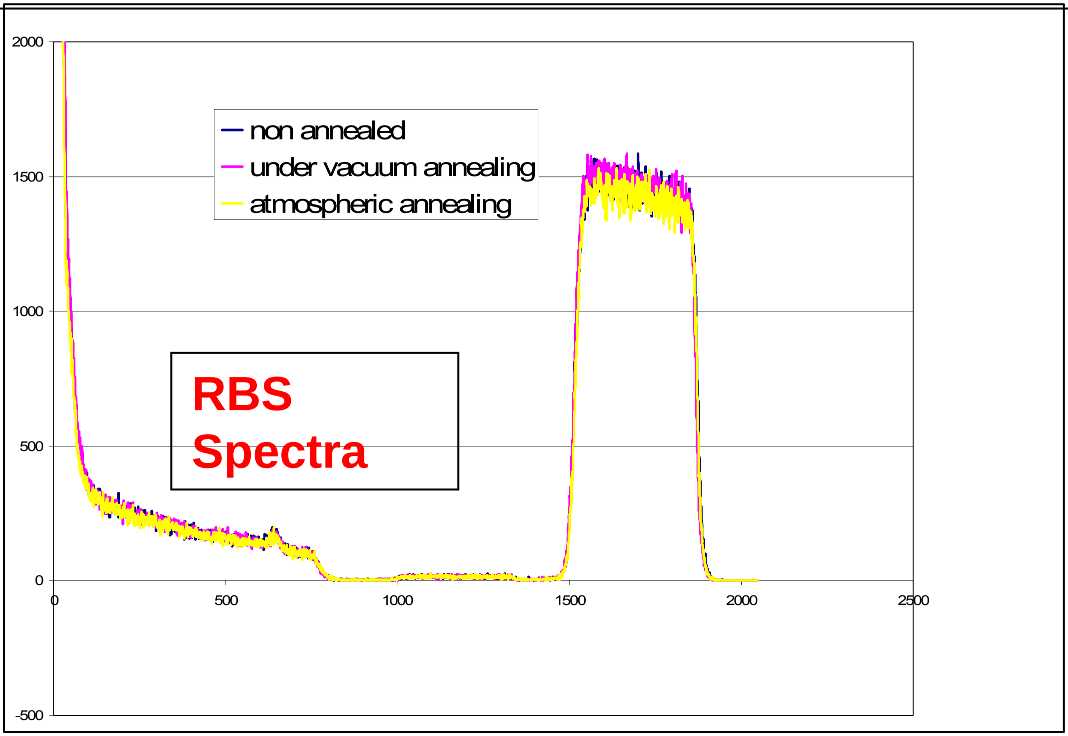


GC	DIBS
% Ar : 4 %	% Ar : 2,8
Density : 6,8	Density : 7,1
Φ : 3.10^{-4}	Φ : 3,7.10^{-4}

- **Stoechiometry respected**
- **Presence of Ar (Gas used in the ion source)**
- **Density can be increased**

Annealing study : first tests on pure Ta coating

Annealing test under vacuum on membrane and 1" silica substrate



Preliminary results on vacuum annealing :

✓ **No composition differencies (% Ar, Density)**

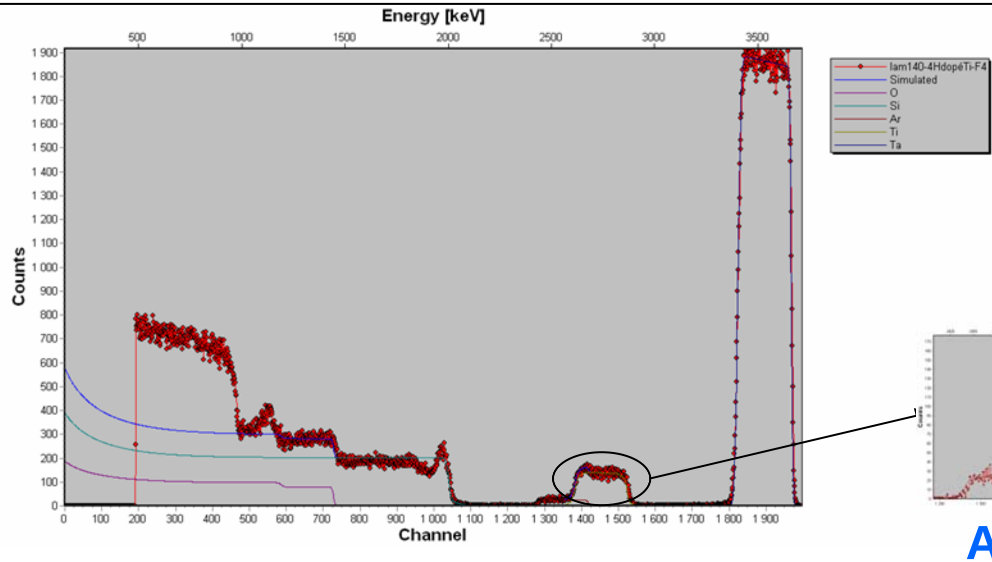
✓ **increased mechanical losses : $4{,}3.10^{-4}$ compared to 3.10^{-4} (air annealing)**

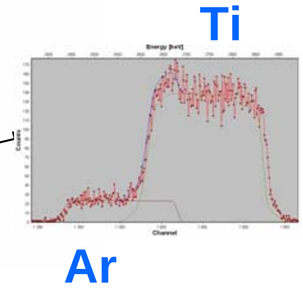
✓ **optical losses : absorption some tens of ppm**

Oxydation during air annealing ⇨ interest in controlled atmosphere annealing

RBS analysis on Tantala coatings Ti:Ta_2O_5 (Large Coater)

Formula 4





Ti doped Tantala

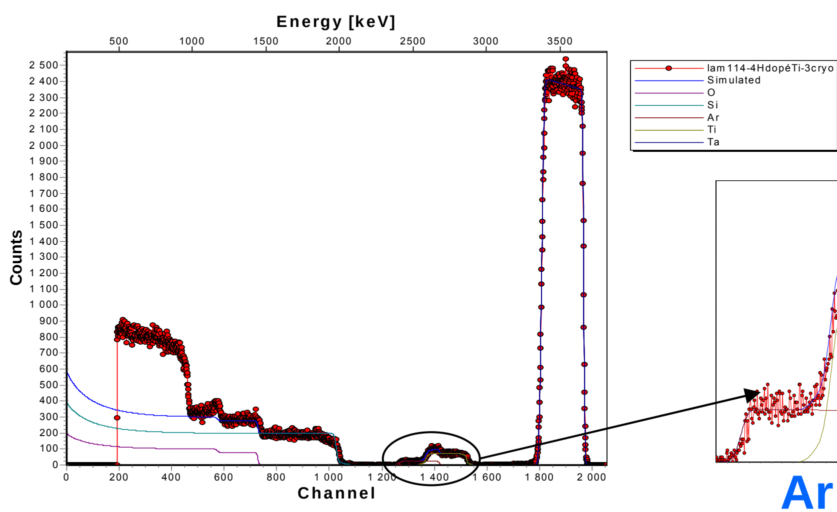
Ratio Ta/Ti : 1,25

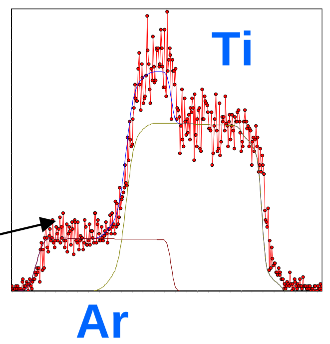
Density = 5,50

N = 2.18

Φ = 2,2.10^{-4}

Formula 5





Ti doped Tantala

Ratio Ta/Ti ~ 3

Density = 6,40

N = 2.065

Φ = 2.10^{-4}

Reference coating: quarter wavelength mirror $(HL)^{19}$ HLL

H: Ta_2O_5 $n_H \sim 2.035 - i.3.10^{-8}$ @ 1064 nm & $\Phi \sim 2.10^{-4}$ @ 60 Hz

L: SiO_2 $n_L \sim 1.472 - i\, 4.10^{-8}$ @ 1064 nm & $\Phi \sim 5.10^{-5}$ @ 60 Hz

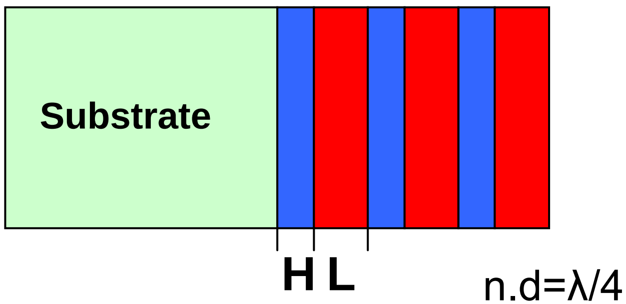
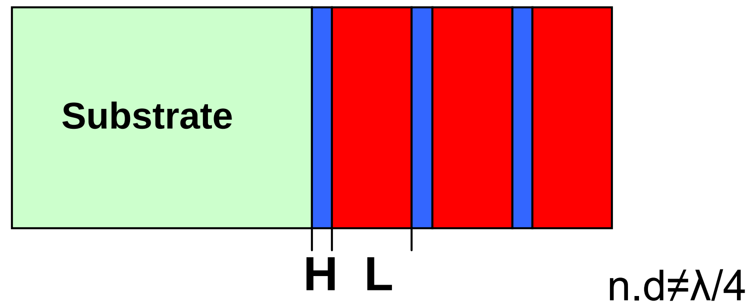
Reference coating losses : $8.39.10^{-9}$

	N_H=2.035	N_H=2.06		N_H = 2.10		N_H=2.14		N_H=2.18
Stack (Number of doublets)	**19**	**19**	**18**	**18**	**17**	**17**	**16**	**16**
Transmittance	6.33 ppm	3.88 ppm	7.60 ppm	3.7 ppm	7.45 ppm	3.78 ppm	8 ppm	4.25 ppm
Φcoating/ Φref	1	0.99	0.94	0.93	0.88	0.87	0.82	0.81
ΦH so Φcoating/ Φref = 1	$2,00.10^{-4}$	$2,02.10^{-4}$	$2,16.10^{-4}$	$2,20.10^{-4}$	$2,35.10^{-4}$	$2,40.10^{-4}$	$2,56.10^{-4}$	$2,61.10^{-4}$

The best material is a compromise between Index, mechanical losses, optical losses

Optimized coatings

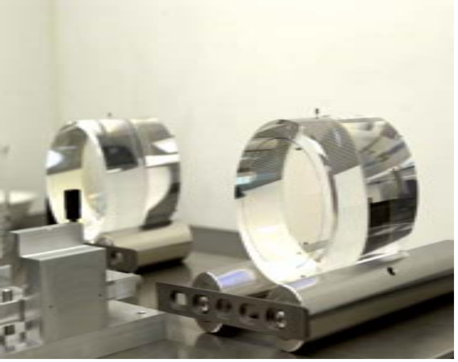
Modify the physical stack without changing the optical response

Mirror transmission : 278 ppm H:Ta205 (n : 2.035-i.3.10^{-8}, Φ : 3.10^{-4}) L:SiO2 (n:1.465-i.4.10^{-8}, Φ : 5.10^{-5})	
QWL mirror	Lowest noise end tweaked stacked doublet (PINTO-University of Sannio)
	
$(HL)_{13}$ HLL	$0.56H(1.38\ L0.62H)_{16}\ 0.16L$
Ta_2O_5 thickness : 1830 nm SiO_2 thickness : 2722 nm	Ta_2O_5 thickness : 1347 nm SiO_2 thickness : 4032 nm
Relative PSD (Power Spectral Density) : 1	Relative PSD : 0.83

Optimized coatings

✓ **Optimized stacks has been coated on 4 inches silica substrates for the TNI***

(Thermal Noise Interferometer)project (E. BLACK – LIGO) with good results



Courtesy E.BLACK & A. VILLAR

$$\frac{PSD_{opt}}{PSD_{qwl}} = \frac{\Phi_c^{opt}}{\Phi_c^{QWL}} = 0.85$$

$$(0.83\,,\,0.86)$$

In very good agreement with expected theory (See Akira's talk)

✓ **Unsuccessfull attempt to coat an optimized stack on thin silica membranes**

- **Exploded Ar bubbles (surface scratches, cleaning …)**
  - ⇨ **Tests of new polished silica Suprasil 311 membranes :**

    Roughness: <1 Å RMS (Gooch & Housego)

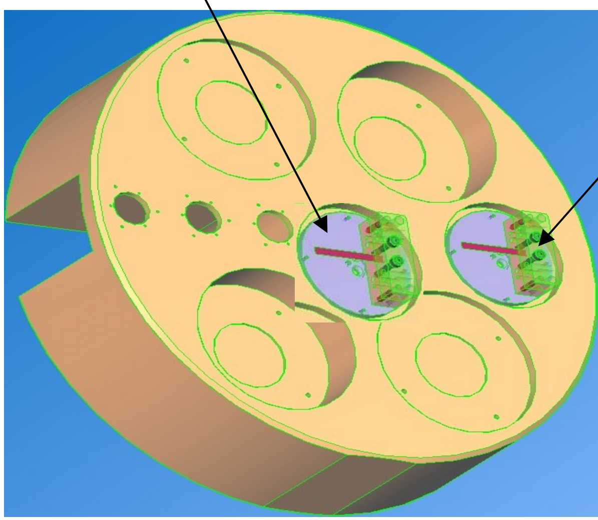
Next step : coat optimized stack with Ti : Ta_2O_5

Mechanical losses homogeneity

Study on the homogeneity of the mechanical losses

Membrane at the center

Eccentric position : 12 cm
from the center



350 mm diameter substrate holder

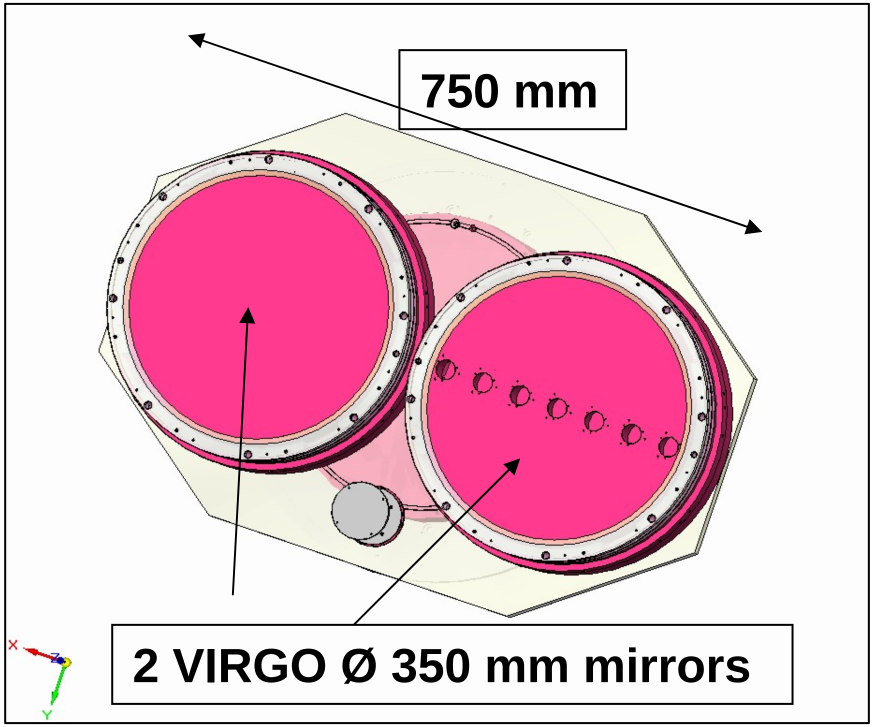
Eccentric position	Membrane at the center
After annealing	After annealing
$\Phi_{Ta2O5} \sim 2.96\ 10^{-4}$	$\Phi_{Ta2O5} \sim 3.02\ 10^{-4}$

Good homogeneity

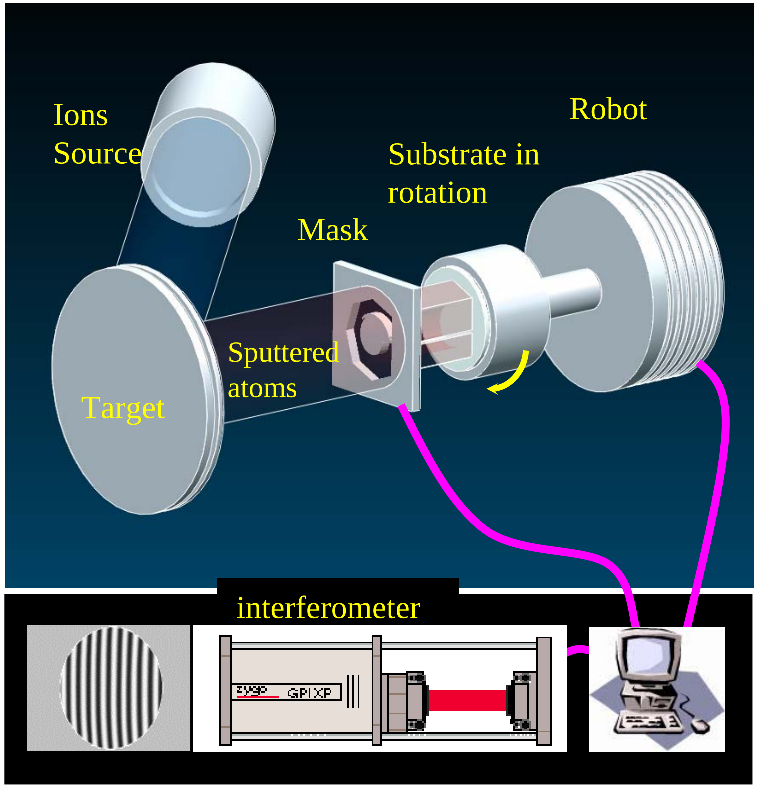
➡ Homogeneous losses for a 350 mm diameter mirror

Coating uniformity and losses

Goal : **coat homogeneously 2 VIRGO mirrors in the same run with Tl doped Ta_2O_5**



Masking technique by IBS (Ions Beam sputtering)



No effect of the masking technique on the mechanical losses : $\varnothing=2.10^{-4}$ ($Ti:Ta_2O_5$) and absorption

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Summary

- Need to improve coating mechanical losses while keeping sub ppm optical losses
- Several coating materials tested at LMA
  - ZrO_2 (with and without doping)
  - Nb_2O_5
  - Doped Ta_2O_5
- Ti doped Ta_2O_5 still the best solution
- RBS characterization confirms
  - good stoechiometry of doped and un-doped Ta_2O_5
  - presence of Ar
- Optimized coating (I. Pinto)
  - first coating with Ta_2O_5 produced
  - Next to come: with Ti:Ta_2O_5
- Masking technique does not affect mechanical properties of high index material
  - Next: produce two input mirrors for Virgo+ (twin mirrors)
- Prospective at LMA : extend investigations to low temperatures