Pushing the boundary: mirror requirements for the Speed Meter proof of concept experiment

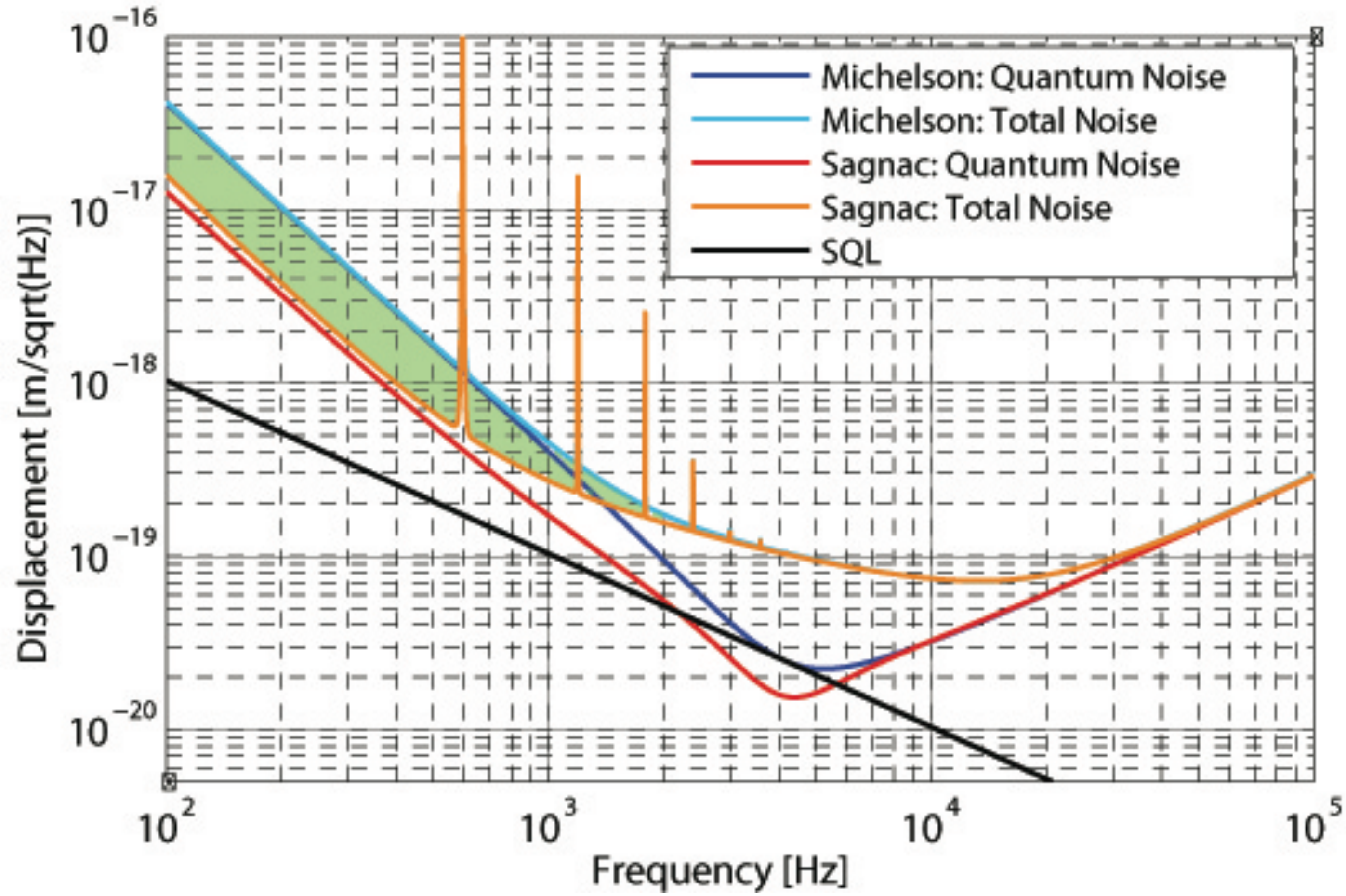
Daniela Pascucci

for the Glasgow Speed Meter team

LVC - Budapest, 31st August - 3rd September 2015

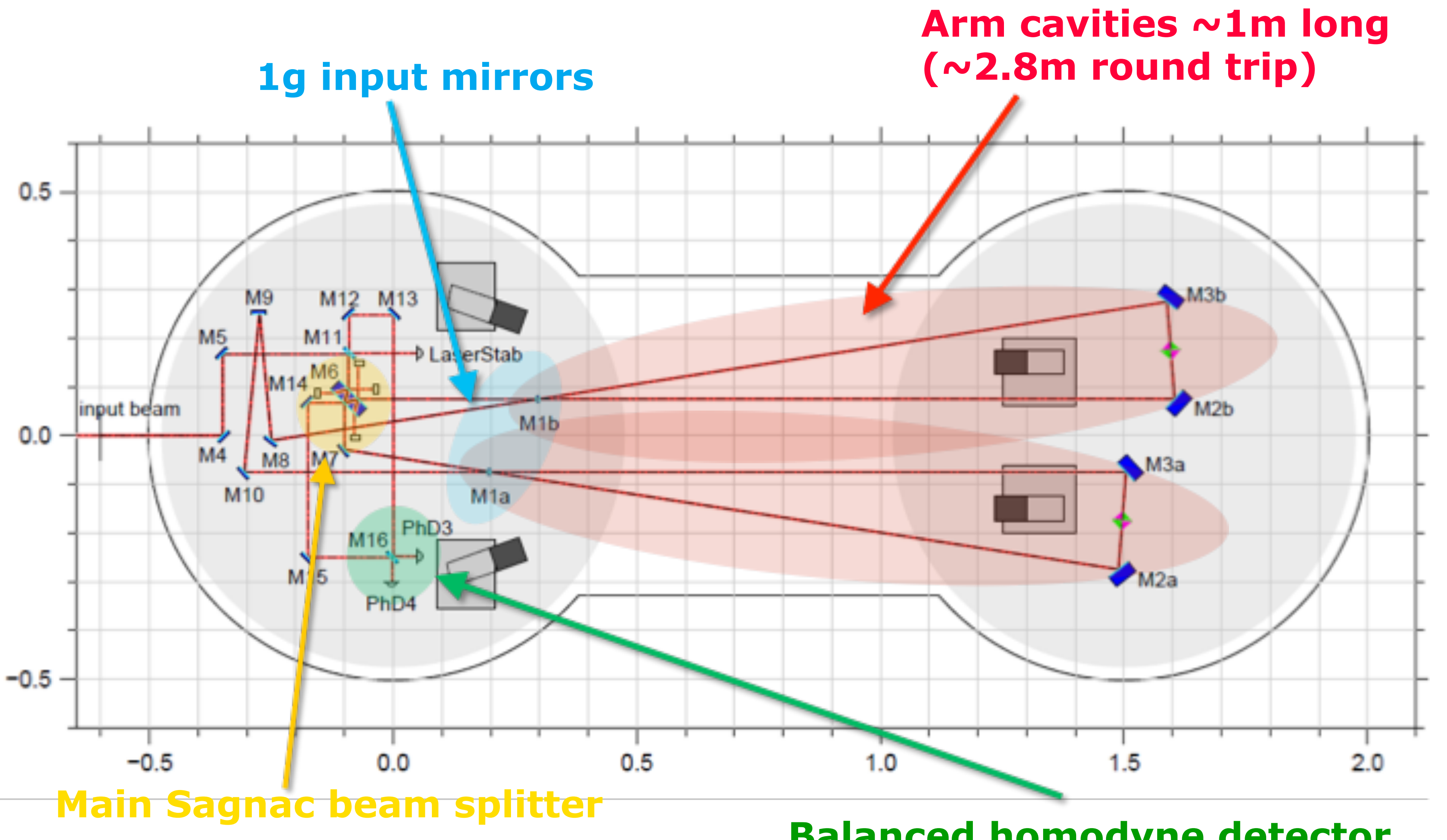
Michelson vs Sagnac

Aim of Glasgow Speedmeter proof of concept experiment: Show reduced back-action noise compared to Michelson configuration with the same parameters



source: [Graef et al.]()

Speedmeter layout

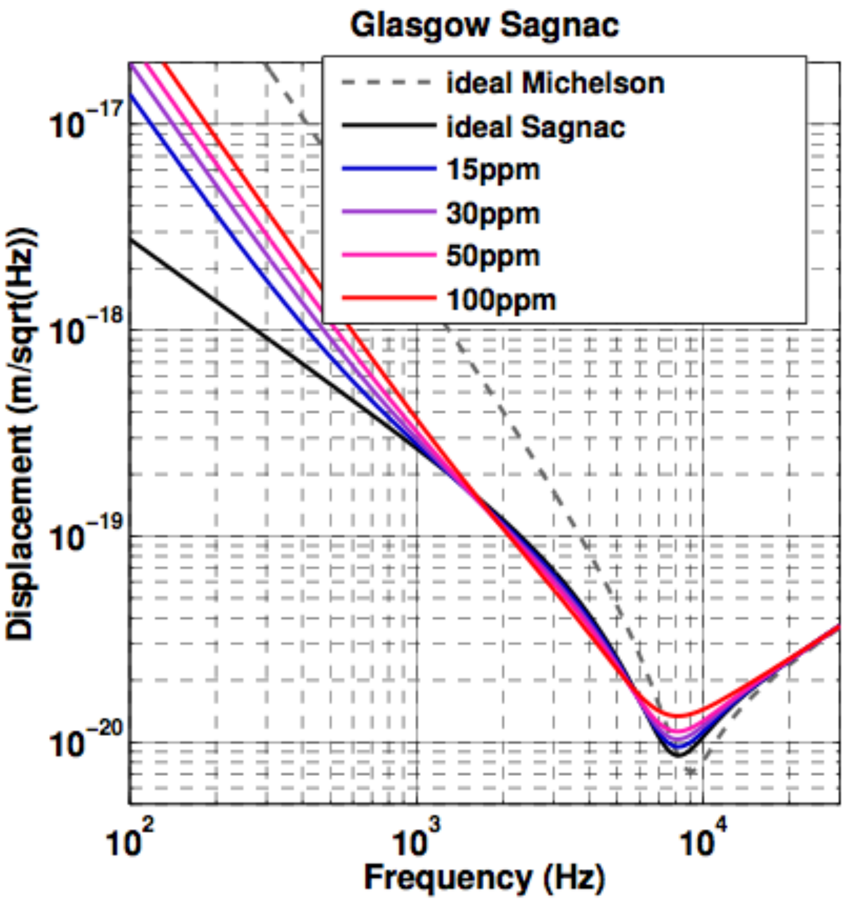


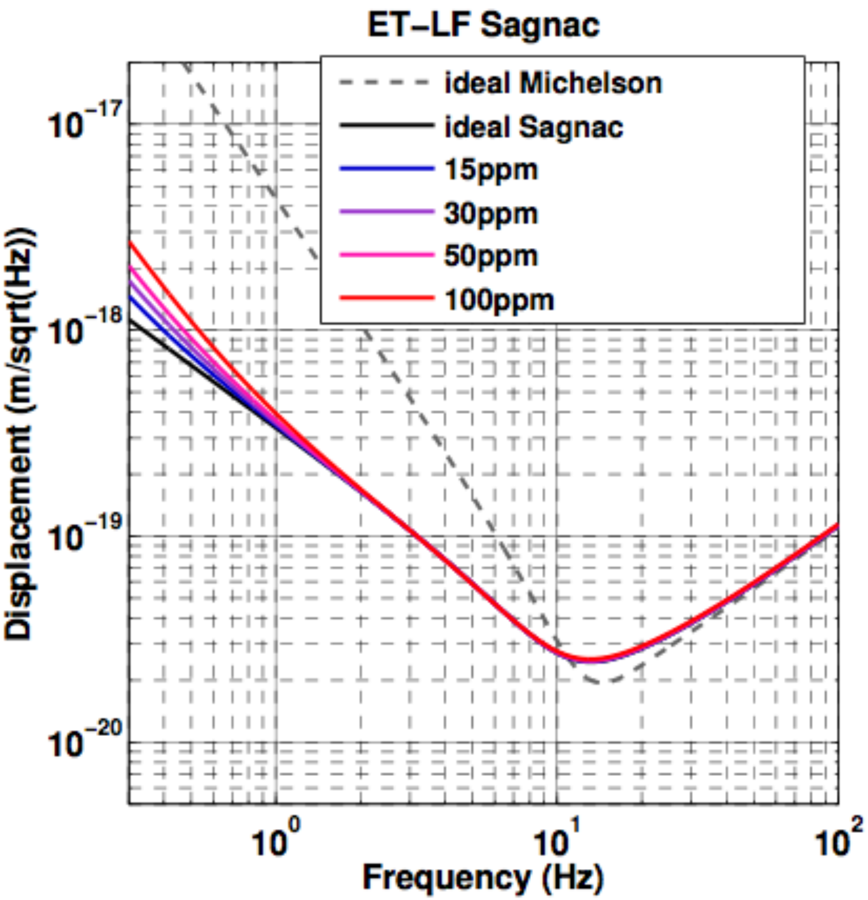
source: [Graef et al.]()

Arm cavity loss requirement

Goal for experiment: keep the loss below ~30 ppm

Note: This stringent requirement is special to our setup (short arm + want to demonstrate back action reduction at audio band frequencies), but full scale Sagnacs are much less sensitive to loss.





source: [Danilishin et al.]

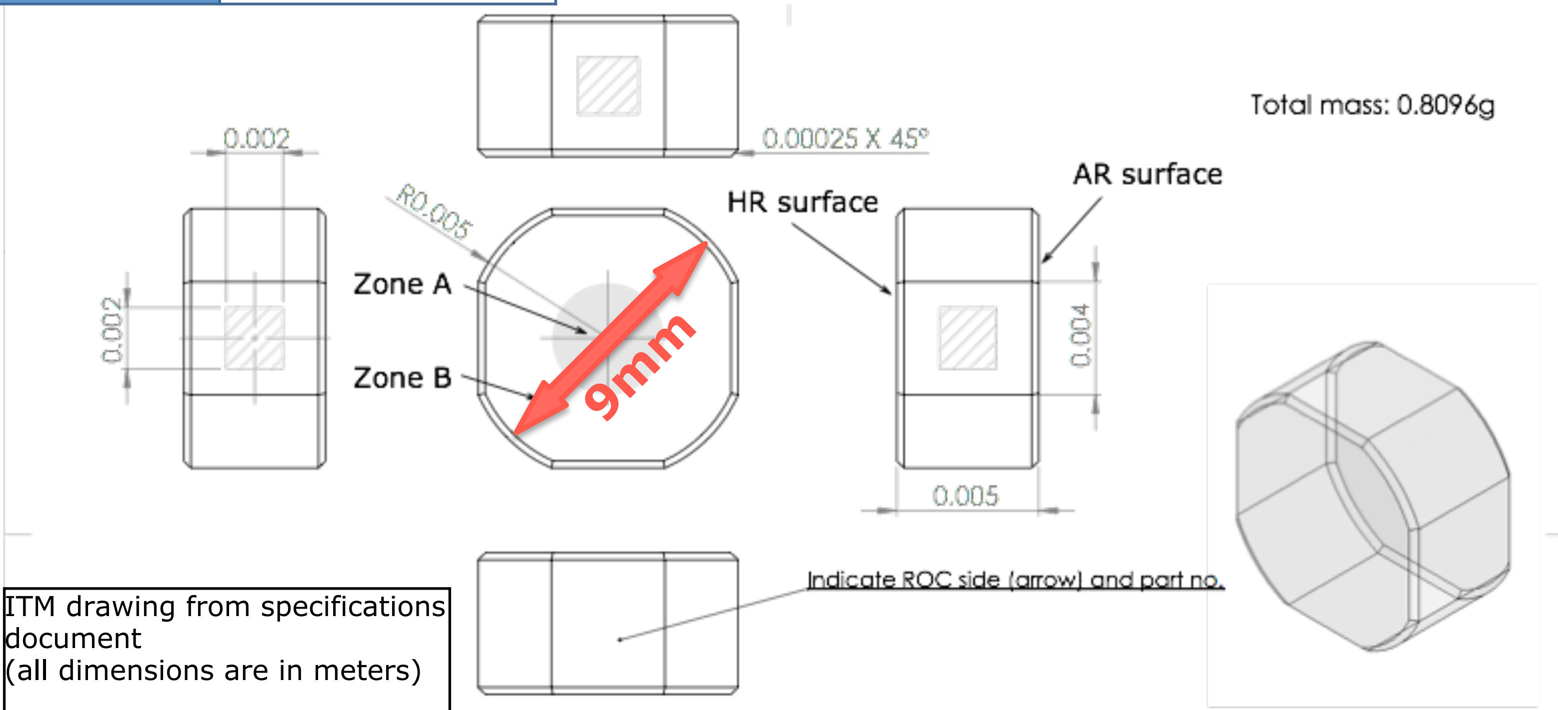
Aim of my studies: Derive Mirror surface requirements!

Input power	*1.7 W*
Circulating power	*4800 W*
Cavity finesse	*8850*
ITM mass	*0.8 g*
ETM mass	*100 g*
ITM transmissivity	*700 ppm*
ETM transmissivity	*2 ppm*

With such small dimensions the scatter due to surface deformation could be very significant.

The scattered light propagates in the opposite direction of the circulating beam and large scattering angles should be avoided

This is the reason why the requirements for the test masses surfaces have to be restrictive.



ITM drawing from specifications document
(all dimensions are in meters)

Zones

Since the central zone of the surface affects much more the loss, we divided the mirror surface in zones.

For example for the ITM, which has a radius of 5mm, we chose:

- Zone A: inside a radius of 3mm

- Zone B: outside a radius of 3mm

So we can make the analysis for the two zones in order to set requirements more restrictive in the central zone.

Surface errors

We considered the following errors of the mirror surface:

- Flatness
- Radius of curvature
- Astigmatism
- Surface errors at discrete spatial frequencies
- Point defects

Tools

OSCAR*

Simulations were made with OSCAR (Optical Simulation Containing Ansys Results), a Matlab code that uses the FFT to simulate cavities with arbitrary mirror profiles.

Simtools**

Simtools is collection of custom made Matlab files which can be used for optical simulations.

*http://uk.mathworks.com/matlabcentral/fileexchange/20607-oscar
**http://www.gwoptics.org/simtools/

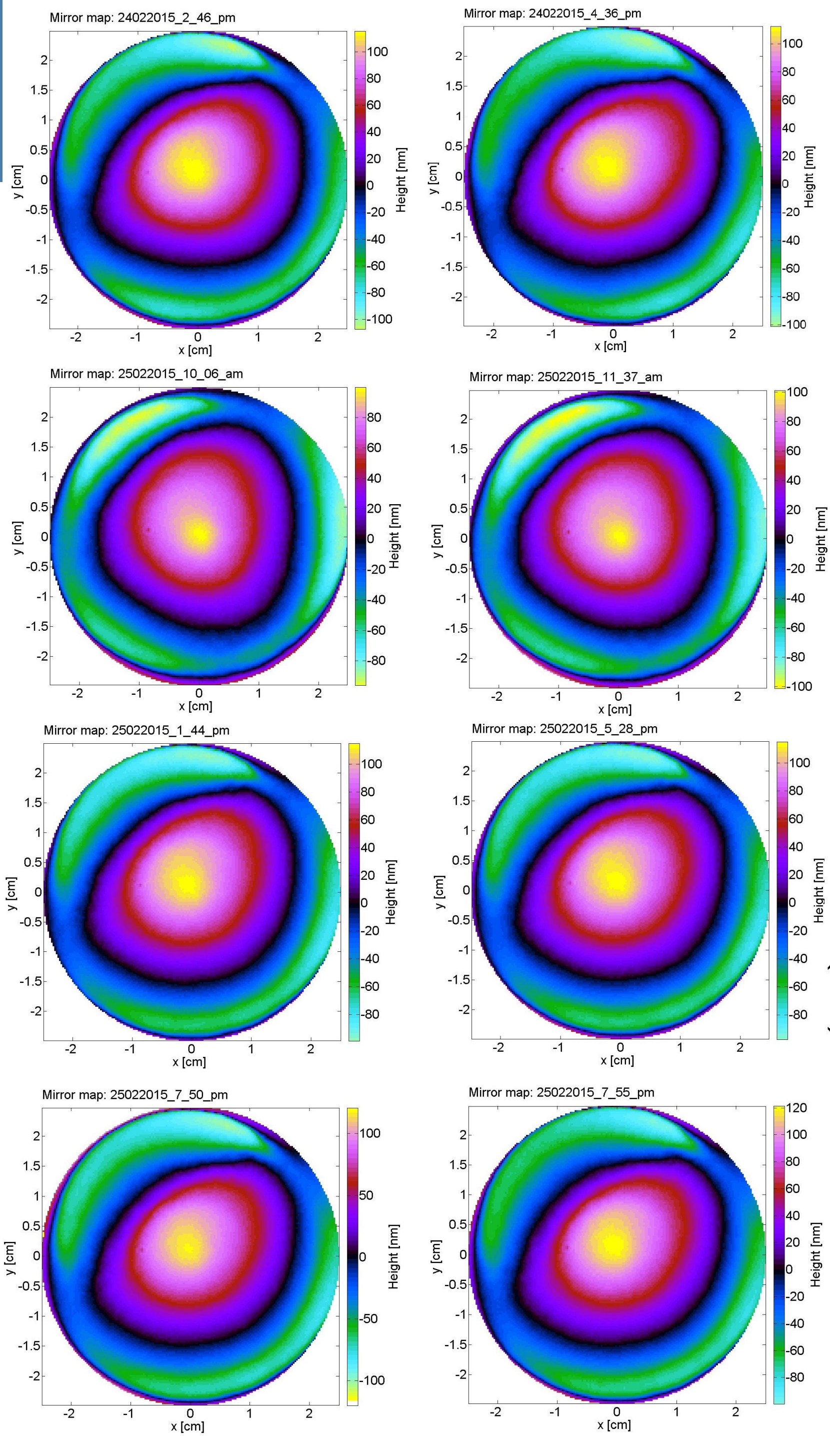
Maps

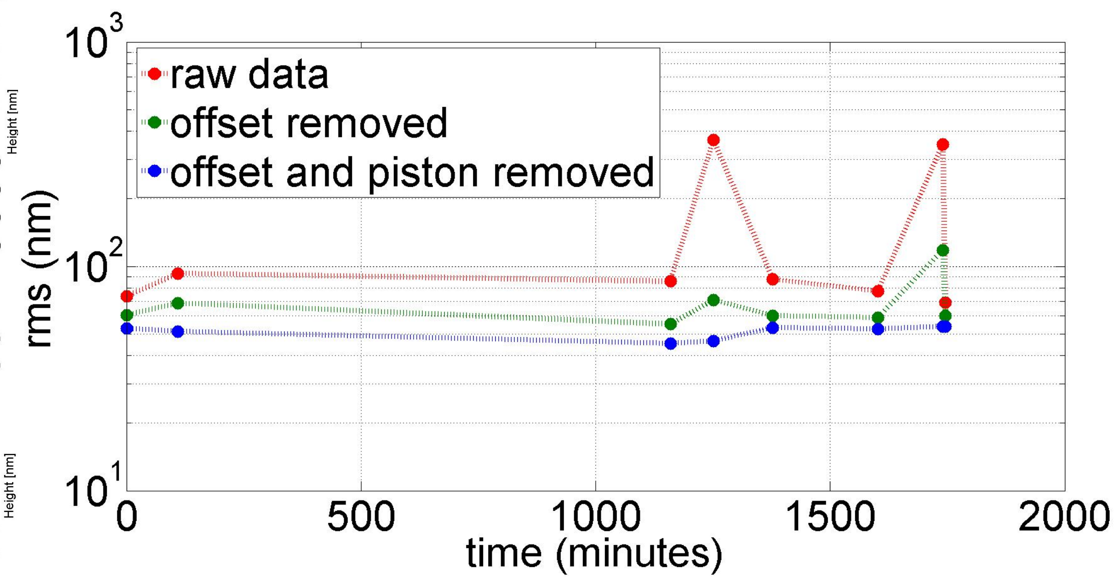
Since the big difference in the dimensions, the map obtained for LIGO cannot be used for the simulation, because the rescaling will be drastic.

Using a super-polished flat mirror with a diameter of 50mm, the measurements of the mirror surface flatness were made with our Zygo.

The mirror was in the set up for about 30 hours and different measurements were made during this period.

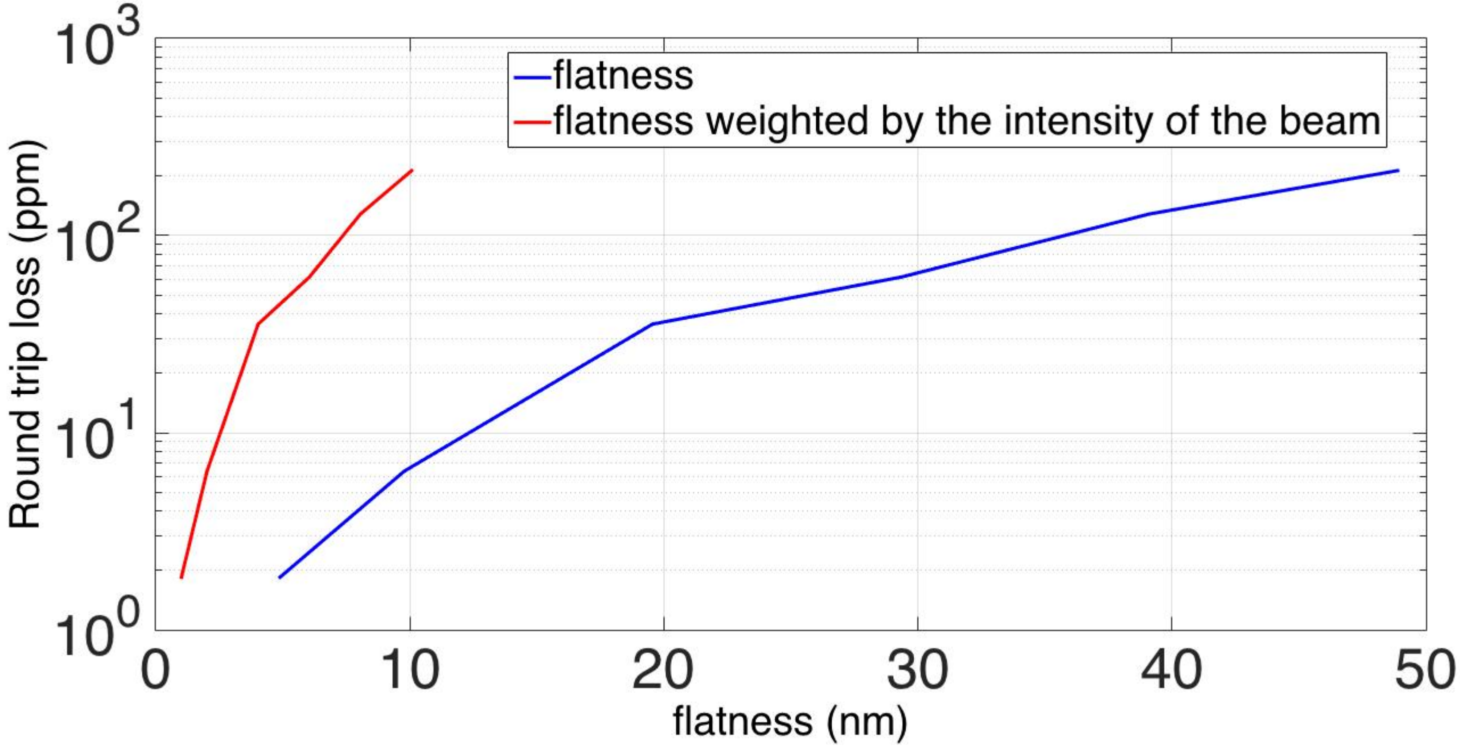
The analysis of these maps was made with SimTools, in order to check the reproducibility of the measurements.





Flatness

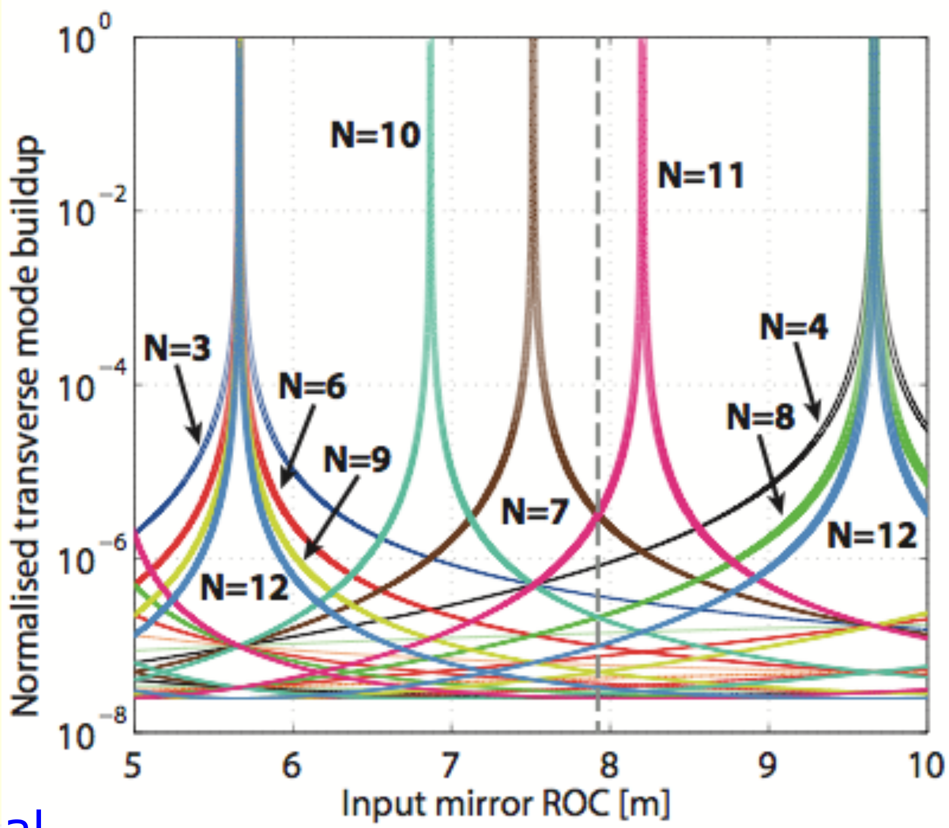
One of the maps measured with Zygo was added to the ITM and the the flatness and the round trip loss was calculated with different scales of the map through OSCAR



Radius of curvature

A radius of curvature of the ITM is chosen to be 7.91m (dashed line in the plot), in order to have low loss from HOMs resonance.

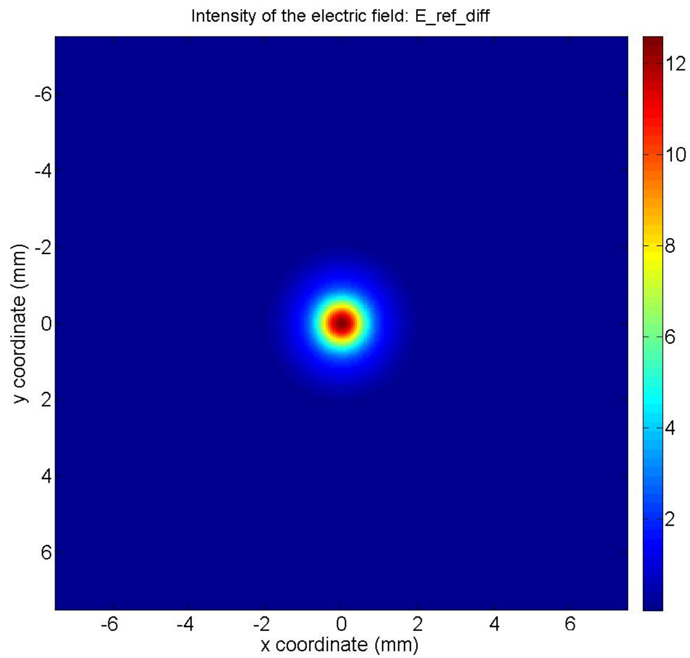
An error too large could lead to an excessive increase of the loss.

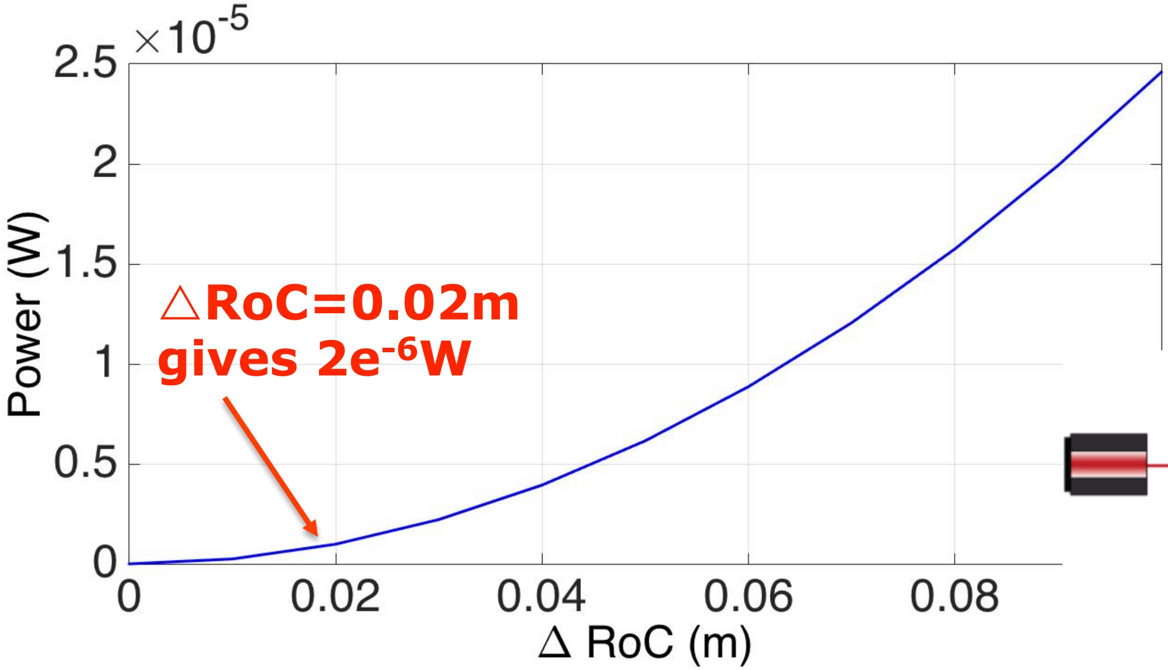


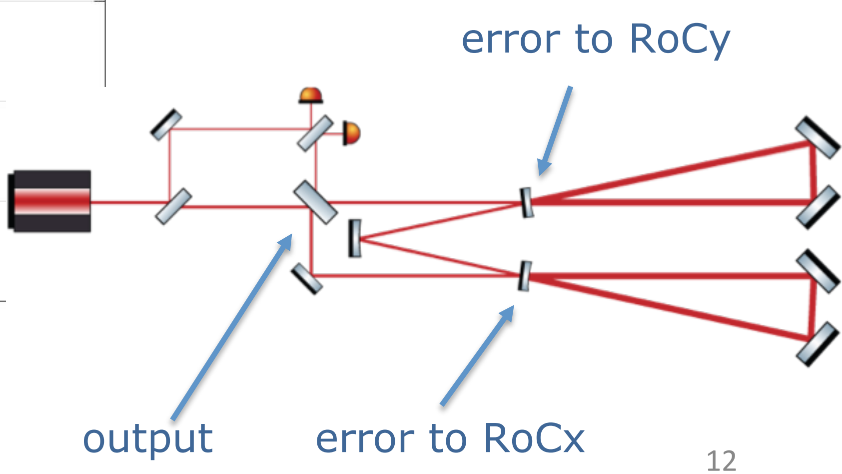
source: [Graef et al.]()

Differential radius of curvature

- Define two cavities
- Add an error equal and opposite to the ITM's RoC of the two cavity (one along x and one along y)
- Make the difference between the two beams that exit from the cavities
- Calculate the lost power due to interference

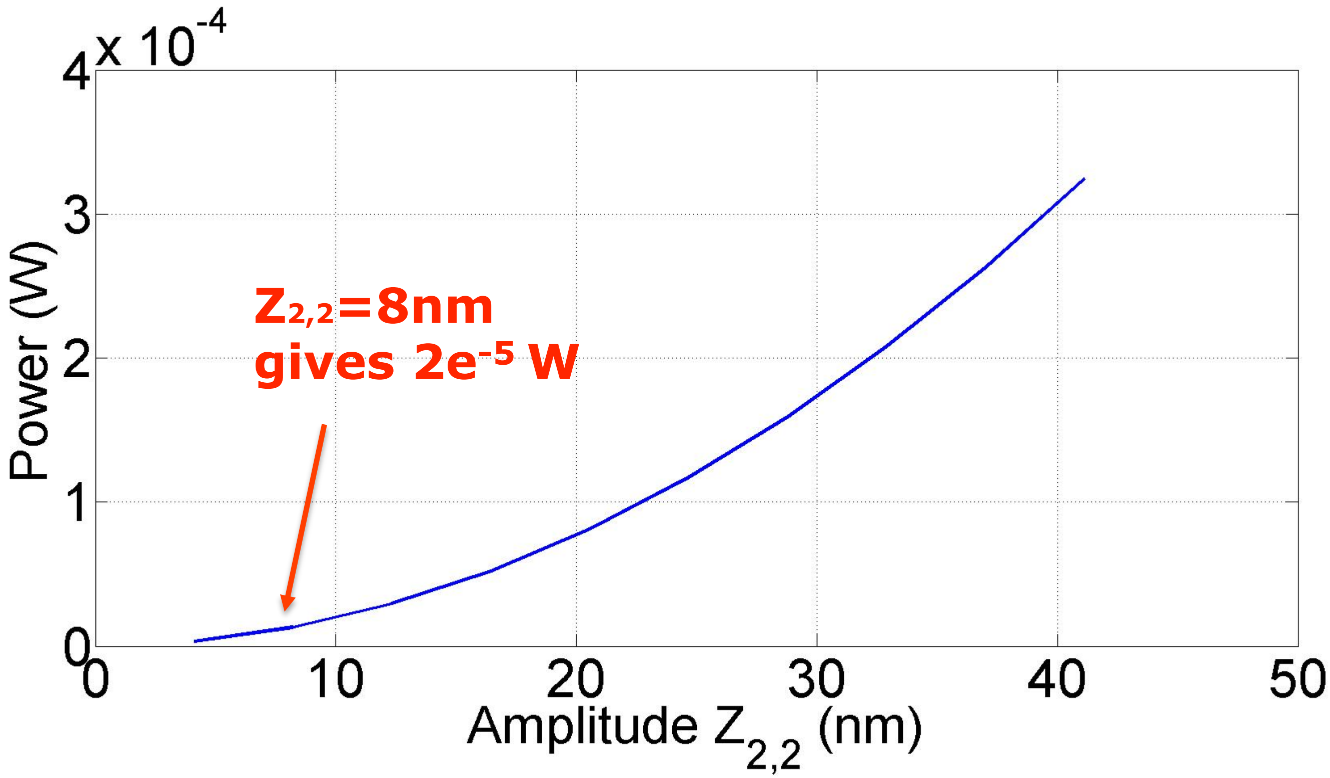






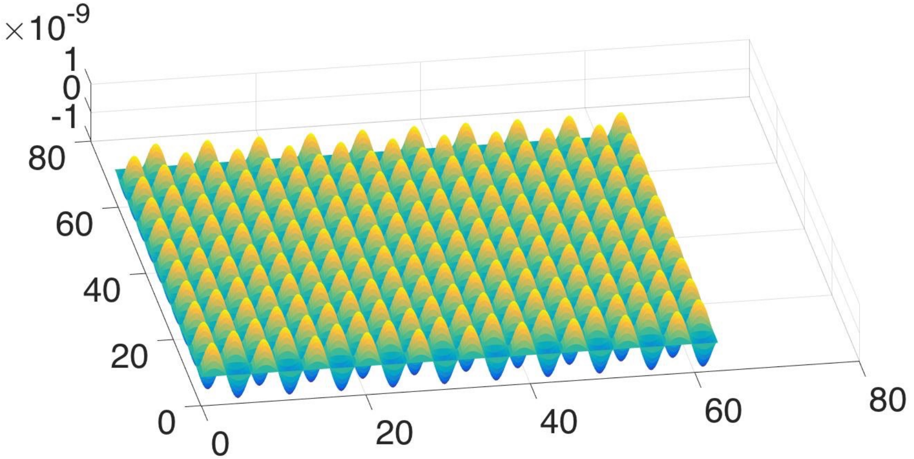
Differential astigmatism

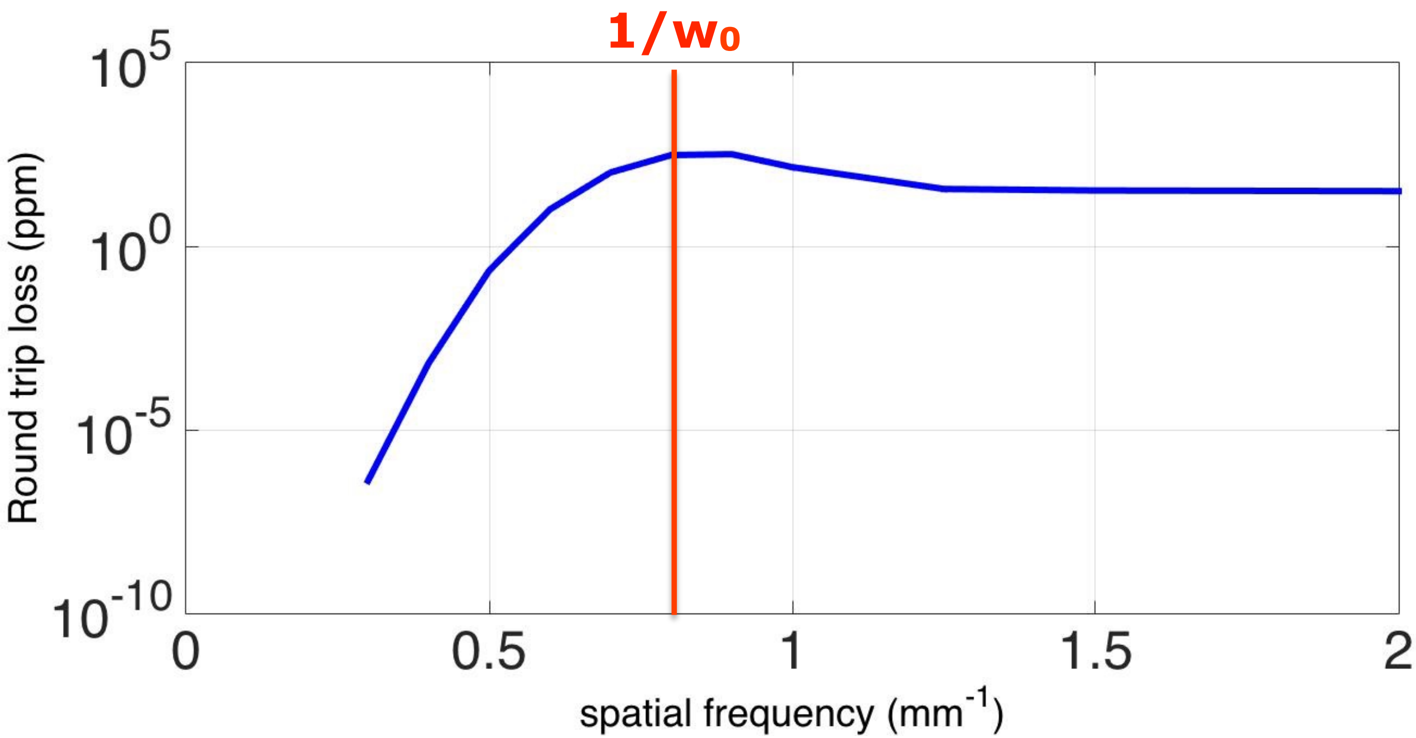
- Added an error to the radius of curvature of the two ITMs with equal and opposite values
- Made the difference between the reflected beams and calculated the power of this difference.
- Calculated the amplitude of the Zernike 2,2 polynomial relative to the error added to the radius of curvature.



Error at discrete spatial frequencies (I)

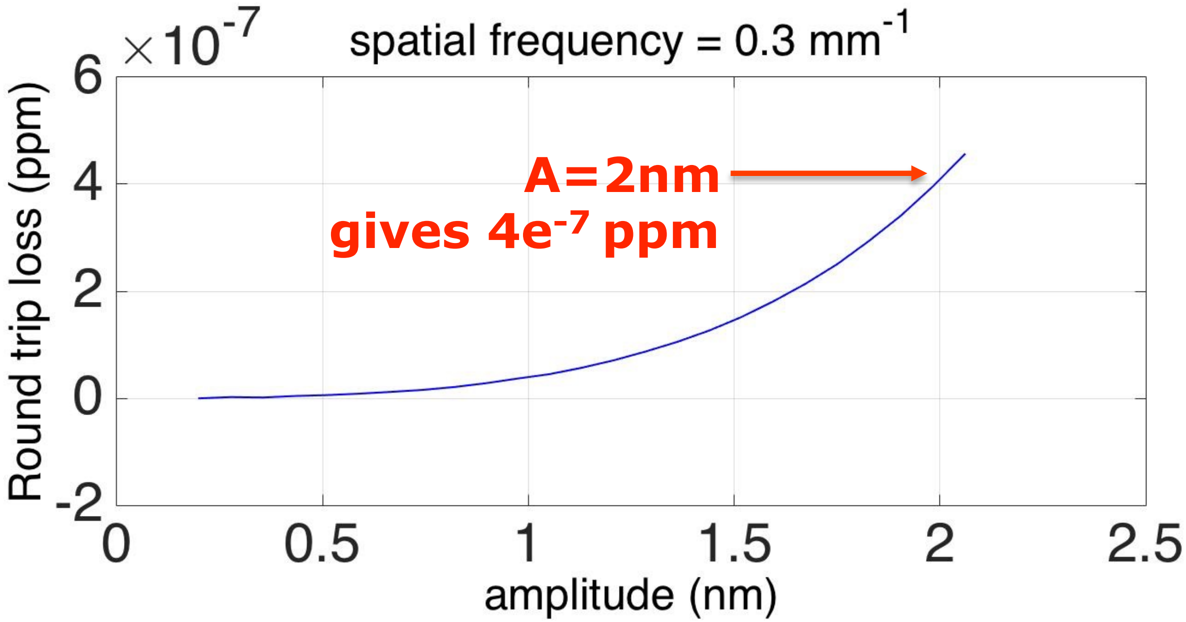
- Define a sinusoidal map
- Add the map to the mirror
- Calculate the round trip loss with OSCAR changing the spatial frequencies of the map

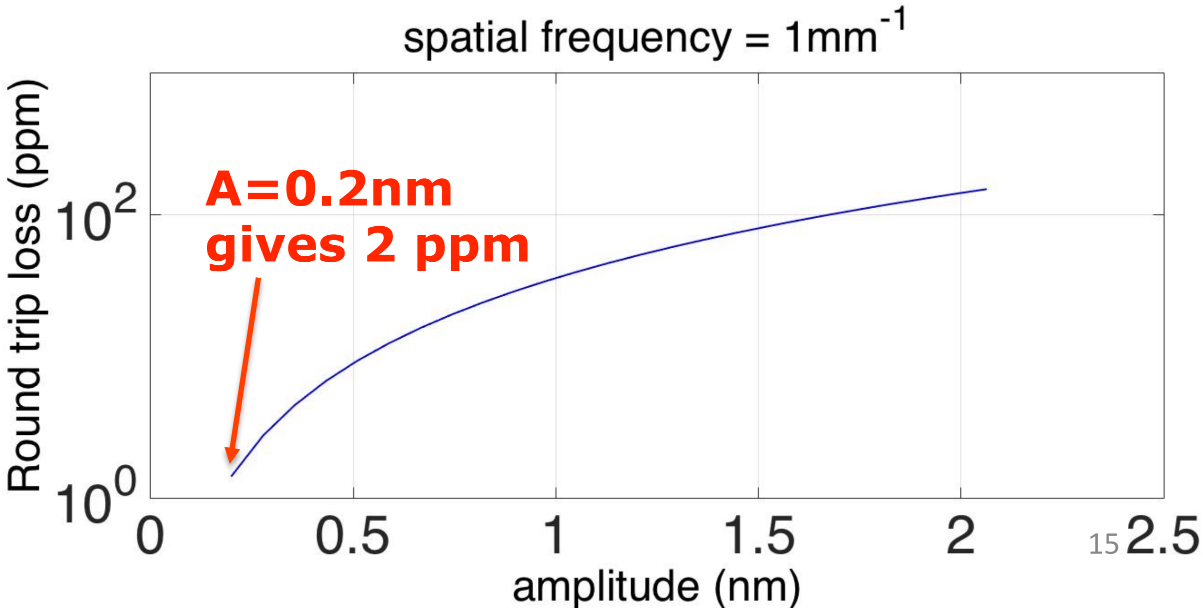




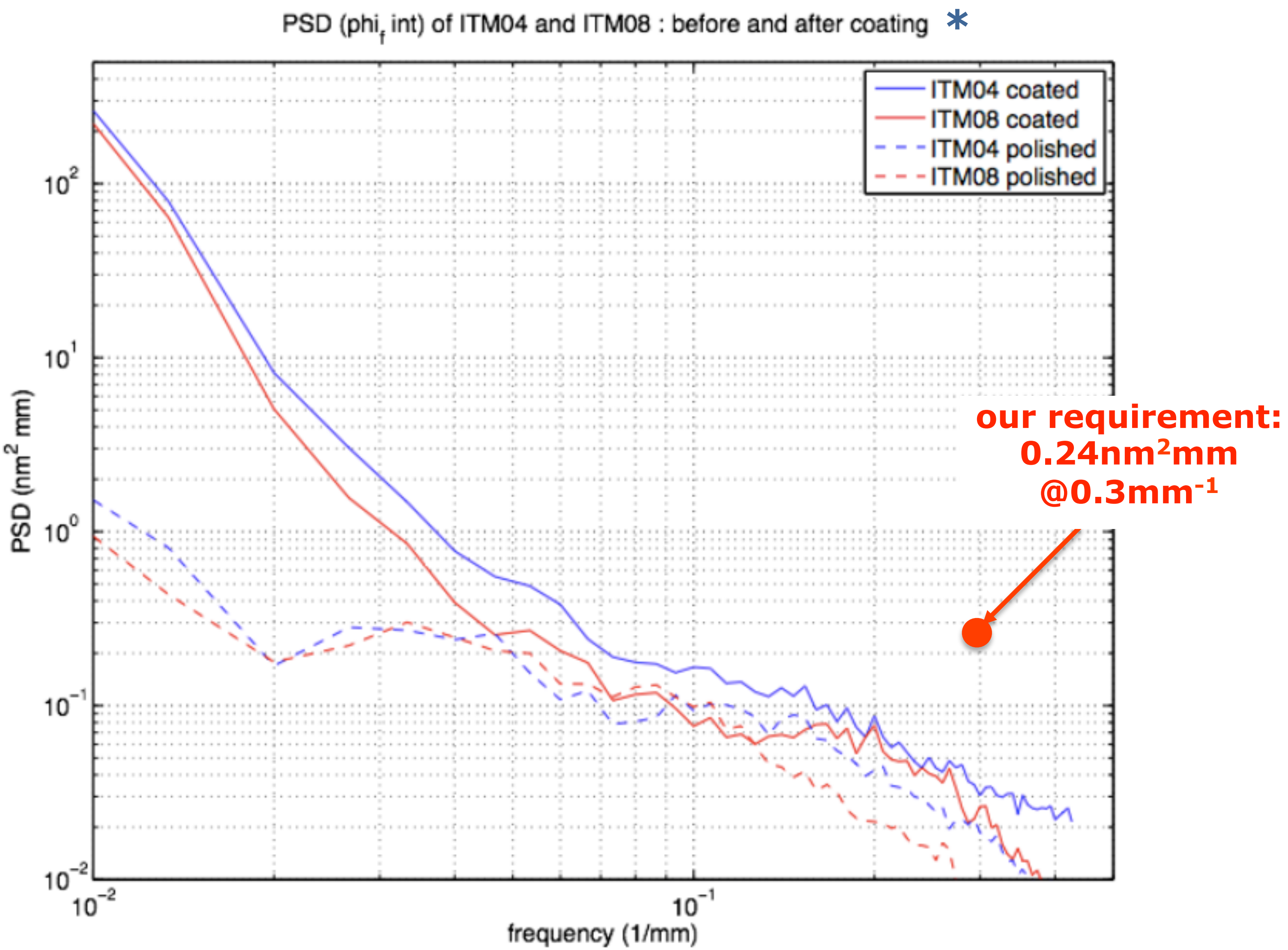
Error at discrete spatial frequencies (II)

The simulations were performed for a fixed spatial frequency and changing the amplitude



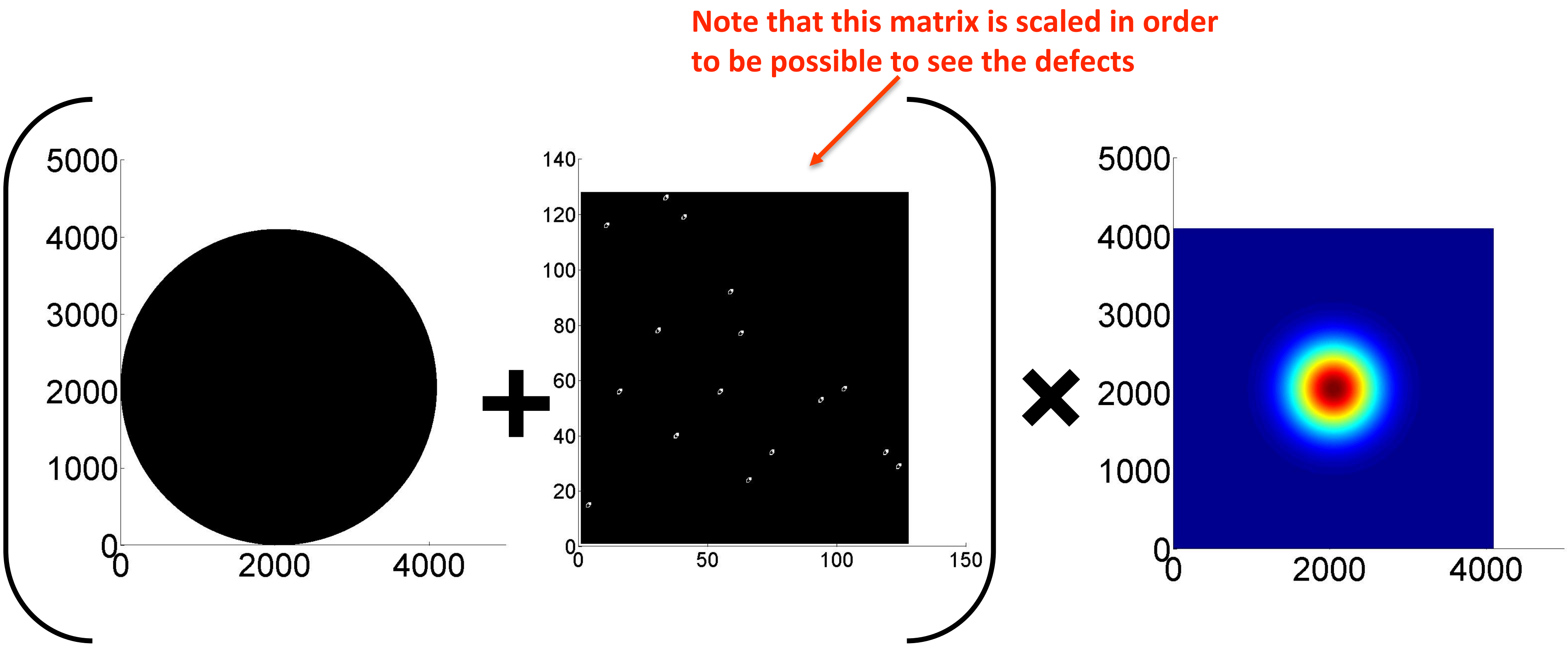


PSD of the surface



*[Source:Yamamoto](#)

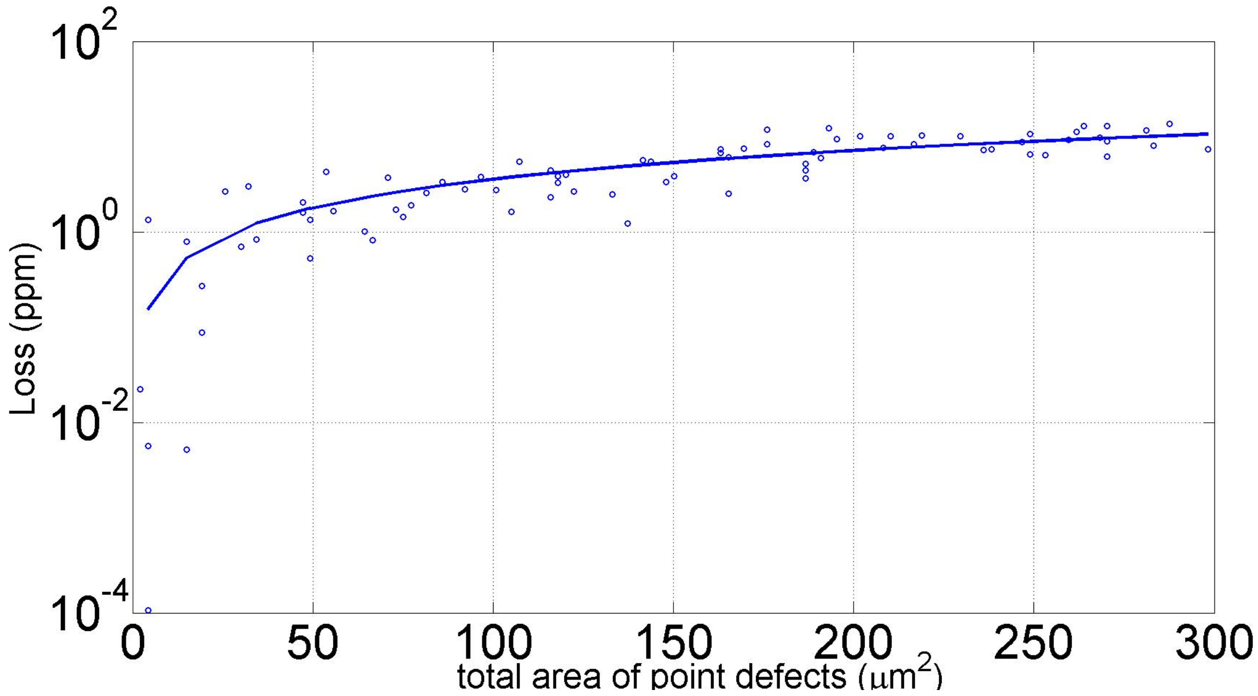
Point defects



- Define the mirror considering that the grid must have the value 0 inside the radius and NaN outside
- The defects were represented by a matrix with only 1 and 0 elements. The position of the 1 values are randomly set in the matrix.
- Calculated the power inside each pixel corresponding to a point defect and summed all these values to have the total power loss.

Loss vs area of point defects

Fitted the results with the equation for the loss obtained by Yamamoto ([T1000154-v5](T1000154-v5)) choosing the height of the point defects (in this case h=85nm)



$$Point\_loss = \frac{32\pi a^2 h^2}{(w\lambda)^2}$$

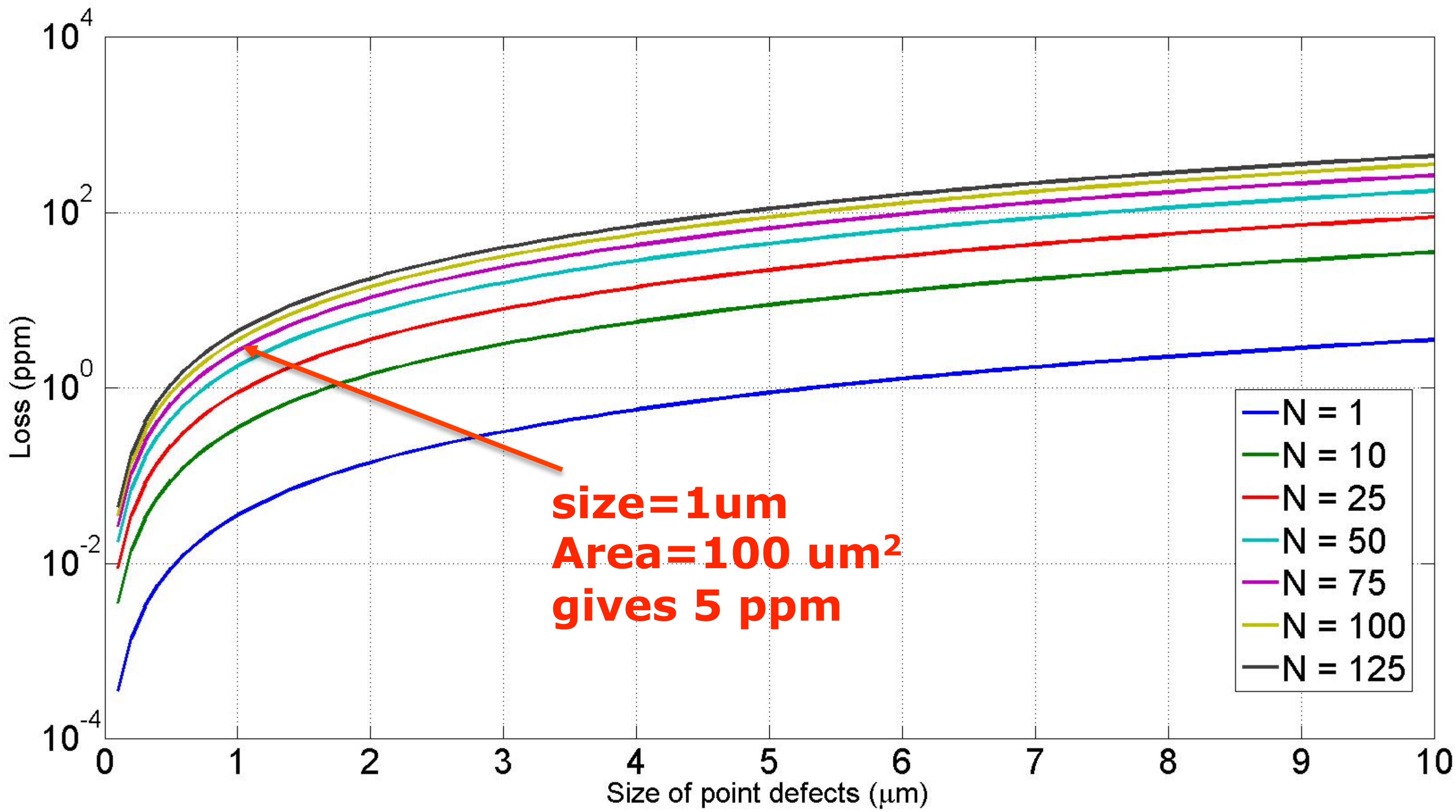
$$Total\_Loss = \int\int dx\,dy \cdot Point\_Loss \cdot e^{\left(-2\frac{x^2+y^2}{w^2}\right)} \times N$$

where:

- a and h are the size and the height of digs respectively,
- w is the beam radius,
- λ is the wavelength,
- N is the density of the digs

Loss vs size of point defects

Plot of the Yamamoto equation using the value of the height found for the fit and changing the number and the size of point defects.



Results

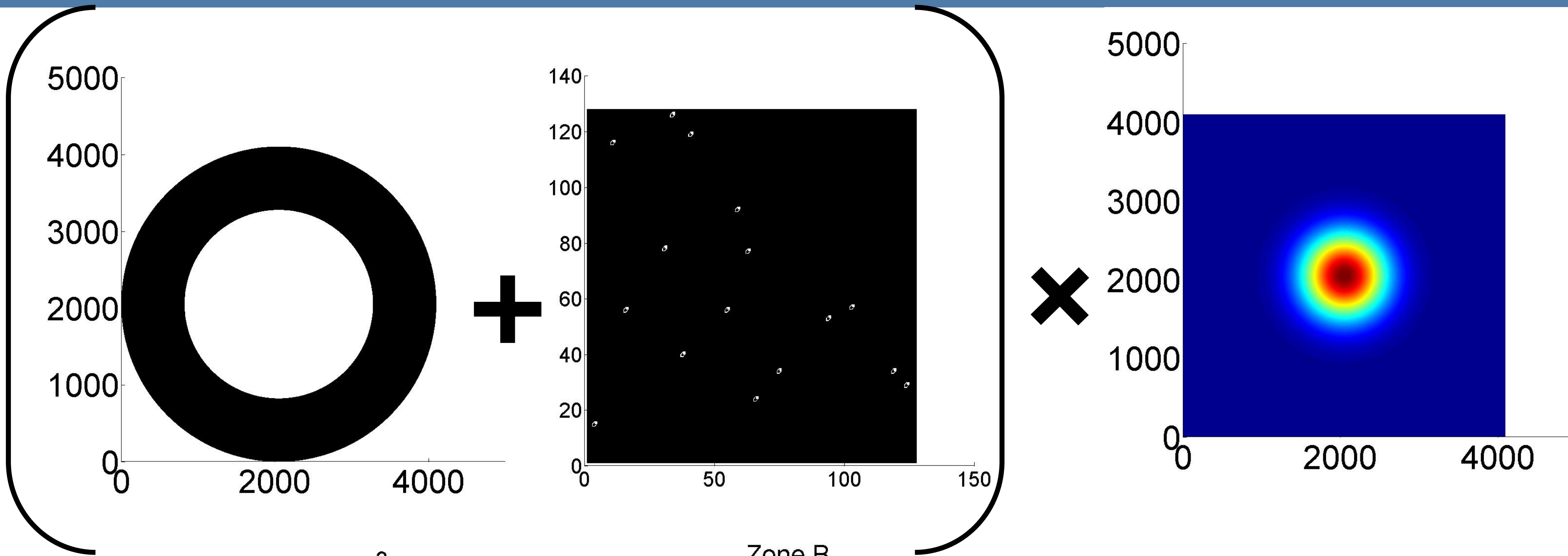
Error	Requirements	SSM estimated Loss	Ligo estimated Loss*
Radius of curvature	7.91m ± 0.02m	$2e^{-4}$ ppm	
Astigmatism	<8nm	$2e^{-3}$ ppm	
Flatness (spatial frequencies: $0.3 - 1\ mm^{-1}$)	Zone A: < 2nm rms	$4e^{-7}$ ppm	20.5 ppm
HSF surface error (spatial frequencies: $1 - 750\ mm^{-1}$)	Zone A: < 0.2nm rms	2 ppm	
Surface defects (digs)	Zone A: size < 1µm , total area < 100µm^2	5 ppm	14 ppm

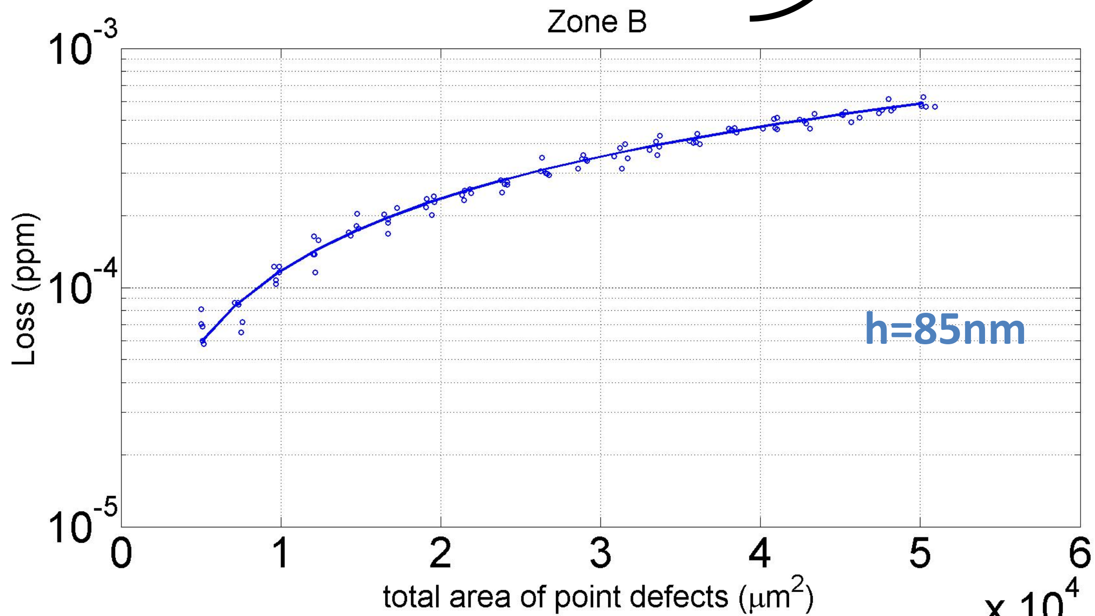
*Source:Yamamoto

Thank you!

Backup slides

Point defects for Zone B (I)





Point defects for Zone B (II)