Laboratoire d'Annecy de Physique des Particules

# Broadband quantum noise reduction in Virgo using frequency dependent squeezing

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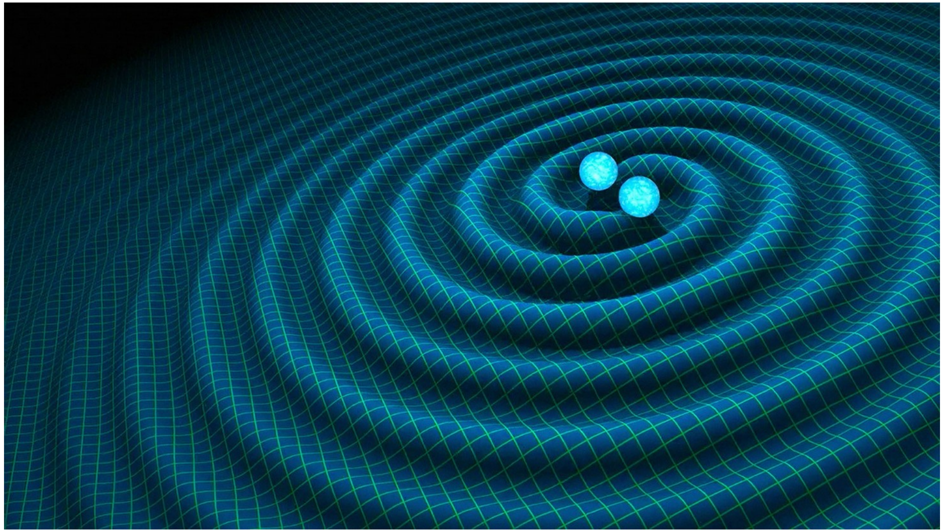
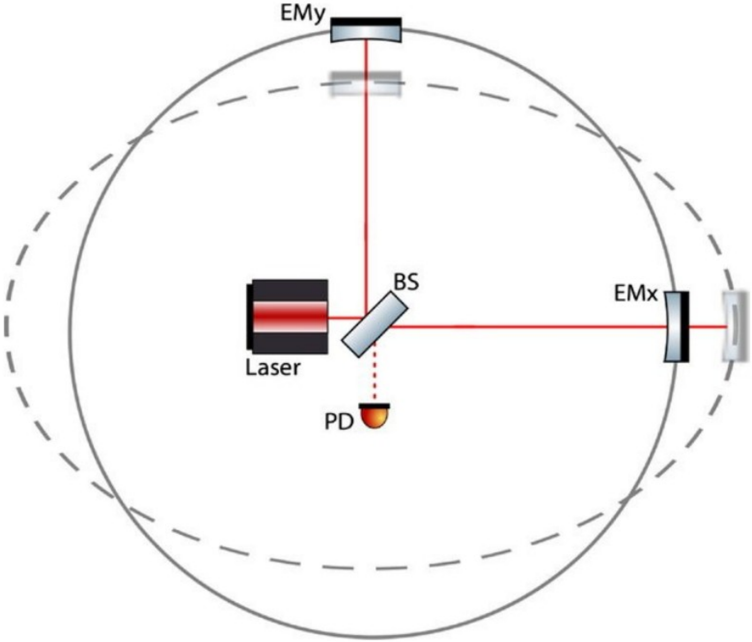
# Detection of gravitational waves (GWs)

- **Gravitational waves** are 'ripples' in the fabric of space-time caused by some of the most violent and energetic processes in the Universe.

$$g_{\mu\nu} = \eta_{\mu\nu} + \boxed{h_{\mu\nu}} \longrightarrow$$

small perturbation of the metric tensor





- **Detection principle:** Michelson interferometer measures the difference in phase associated to the passing gravitational wave (GW)

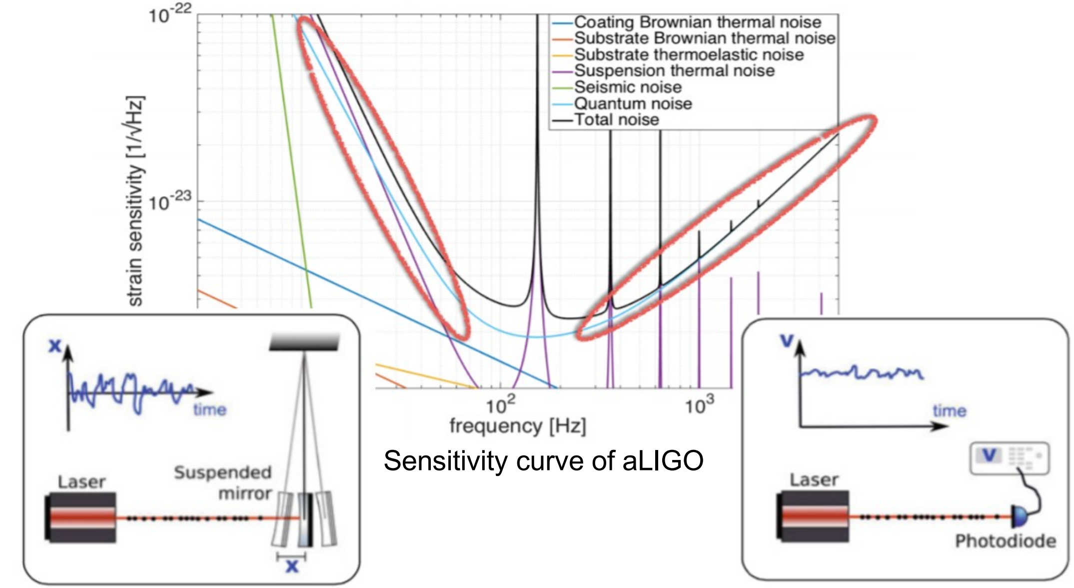
$$\delta\phi_{\mathrm{GW}} = \frac{4\pi}{\lambda}\delta L_{\mathrm{GW}} \longrightarrow h = \frac{2\,\delta L_{\mathrm{GW}}}{L}$$

# Quantum noise in GW detectors

- **Introduction:**

✓ *Quantum noise (QN)* limits the sensitivity of GW detectors

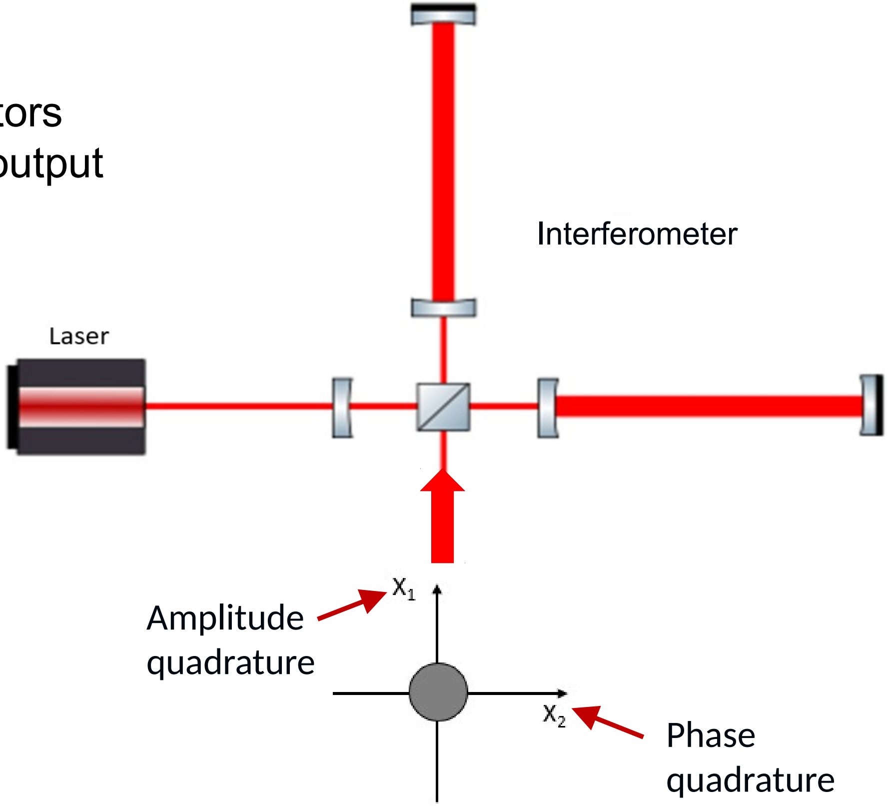
✓ *QN are vacuum fluctuations* entering interferometer's output port



Sensitivity curve of aLIGO

Radiation pressure noise

Shot noise



Amplitude quadrature

Phase quadrature

$$\hat{\mathcal{H}} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) \longrightarrow \hat{\mathcal{H}} = \hbar\omega\left(\hat{X}_1^2 + \hat{X}_2^2\right)$$

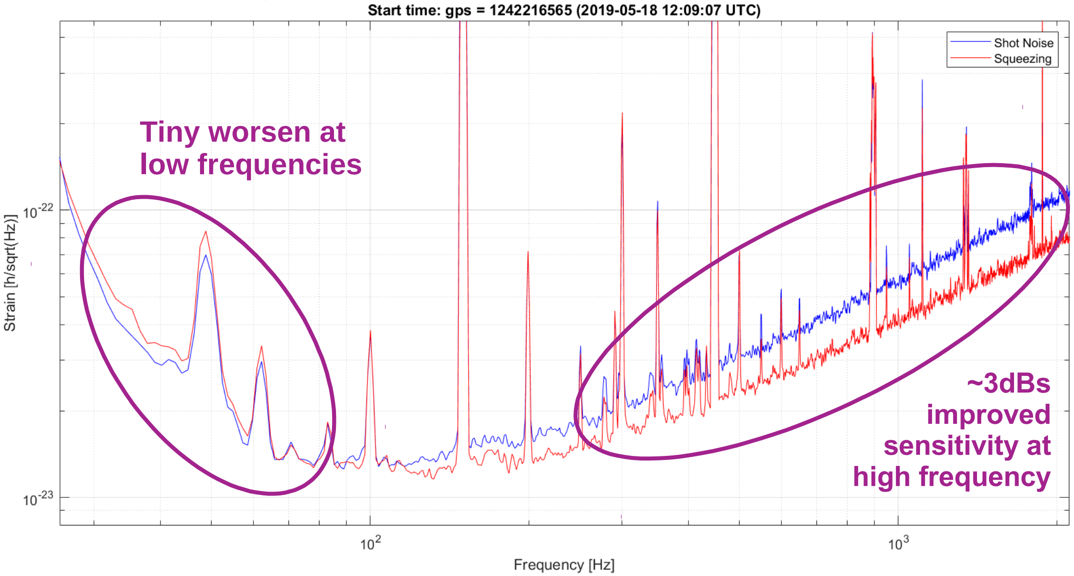
# Quantum noise reduction

- **First step:**

✓ Injecting squeezed vacuum states from the output port to improve sensitivity, run O3

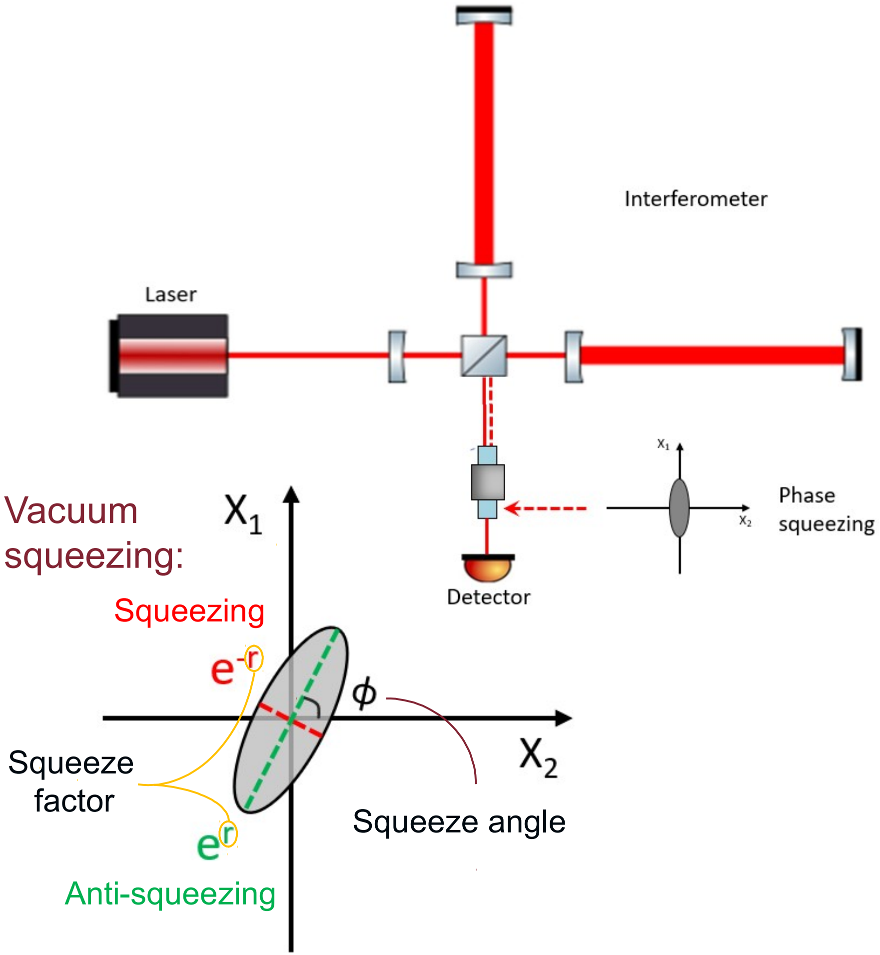
✓ Implemented in AdVirgo and aLIGO

Advanced Virgo



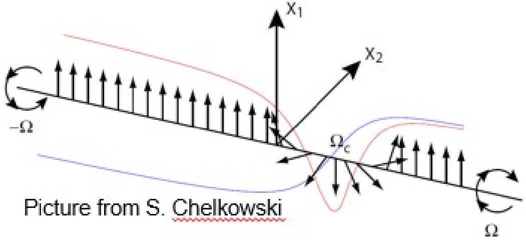
Plot from M. Vardaro

Vacuum squeezing:

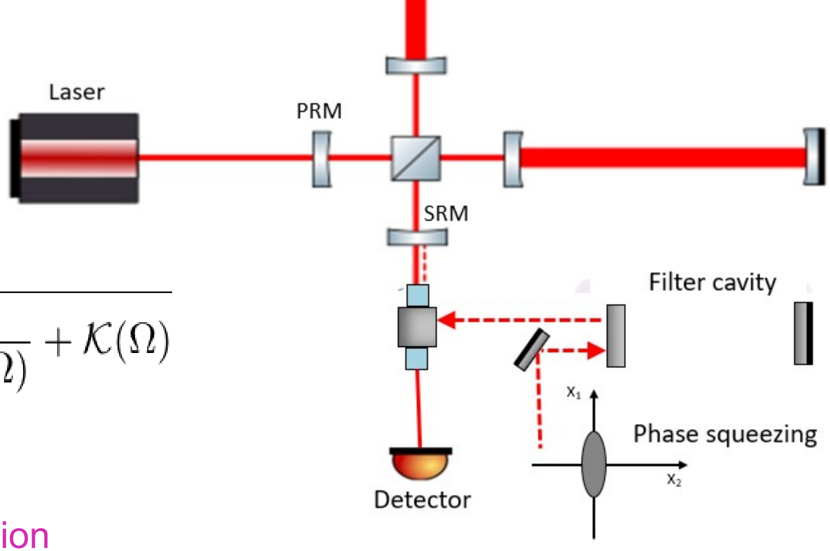


# Quantum noise reduction

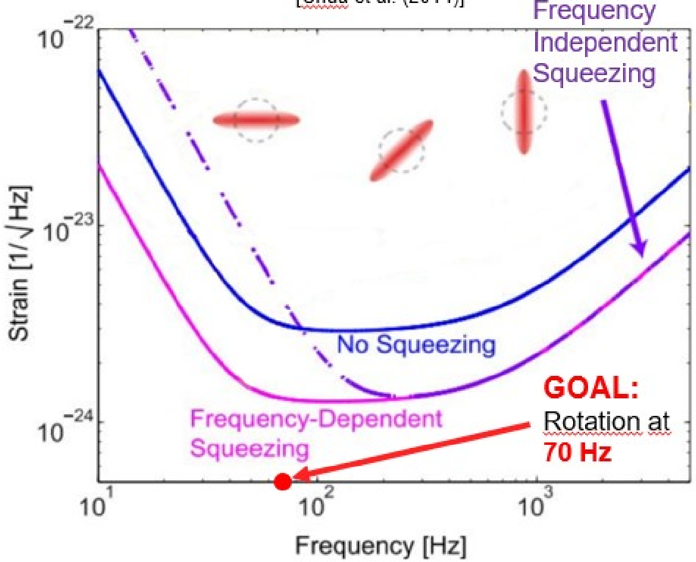
- **Next step:**
- ✓ Vacuum squeezed state angle become frequency dependent when reflected by a detuned Fabry-Perot filter cavity
- ✓ Implementation in GW detectors in O4



Picture from S. Chelkowski



[Chua et al. (2014)]

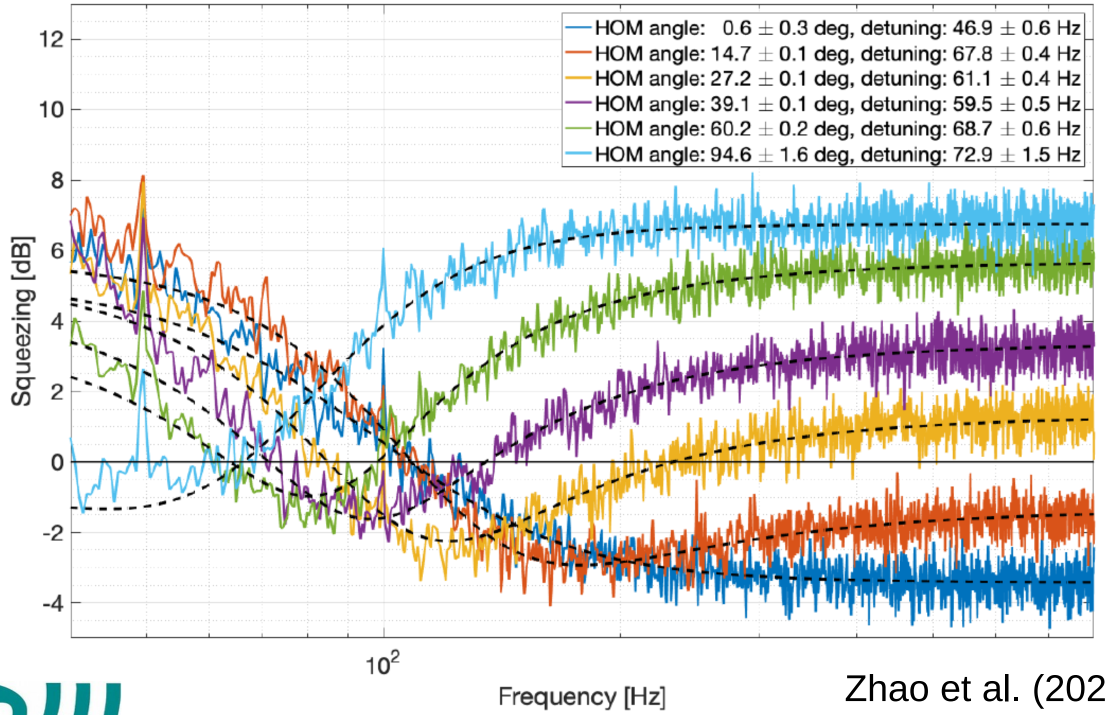


$$h(\Omega) = \frac{h_{SQL}}{\sqrt{2}} e^{-r} \sqrt{\frac{1}{\mathcal{K}(\Omega)} + \mathcal{K}(\Omega)}$$

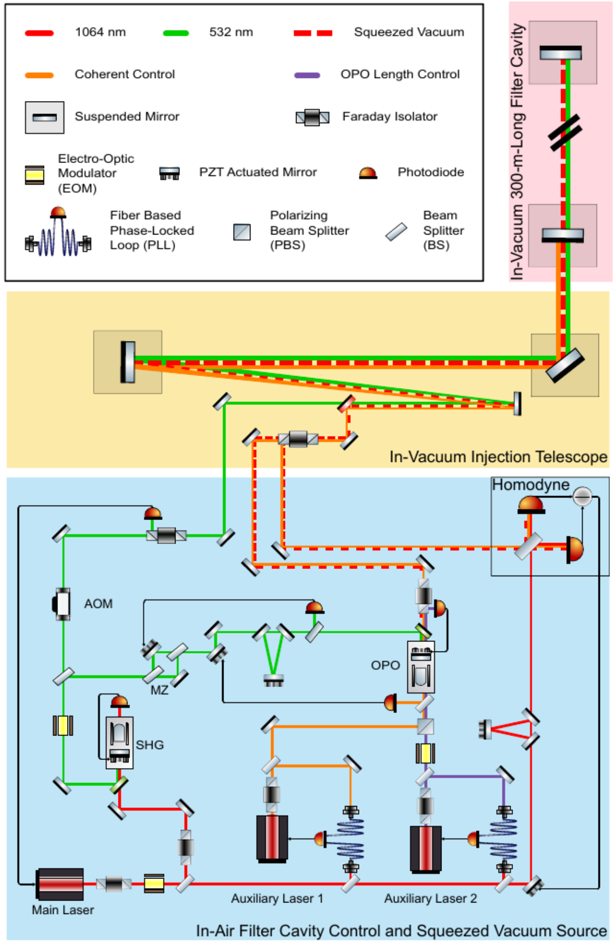
Broadband reduction factor

# Frequency dependent squeezing (FDS) demonstration

R&D experiment at NAOJ, Tokyo, Japan, was the first demonstration (2020) of a frequency dependent squeezed vacuum source, realized with a 300 m suspended filter cavity. The squeezing rotation takes place in the frequency region (~ 100 Hz) needed to reduce the quantum noise in the whole spectrum of advanced GW detectors.

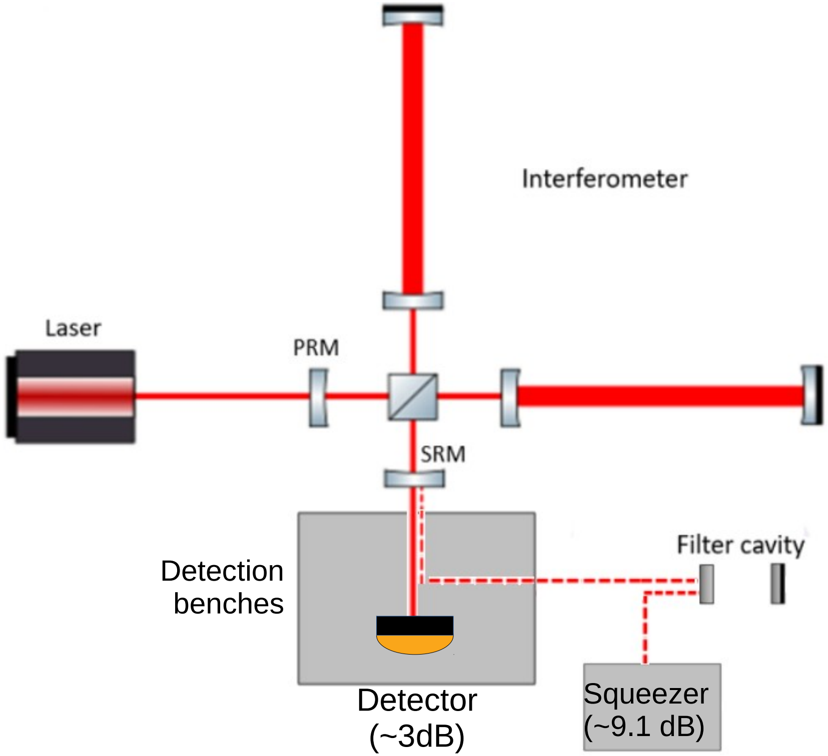


Zhao et al. (2020)



# Decoherence and degradation of FDS

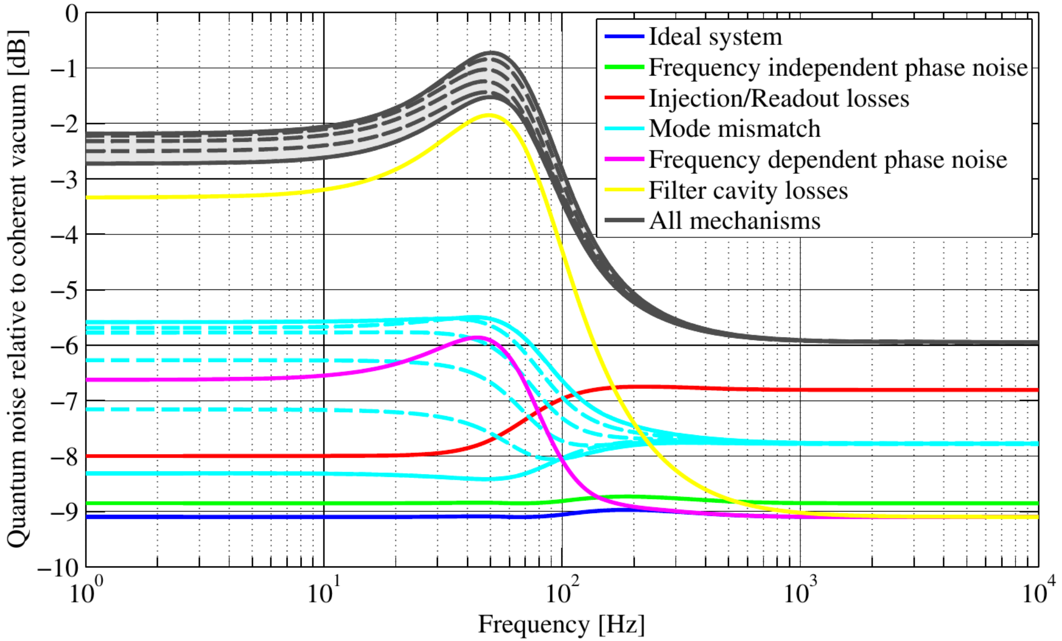
Decoherence (**optical losses + mode mismatch**) and degradation (phase noise due to phase lock errors + **stray light** + cavity length fluctuations) mechanisms limit the experimentally achievable QN reduction.



Detection benches

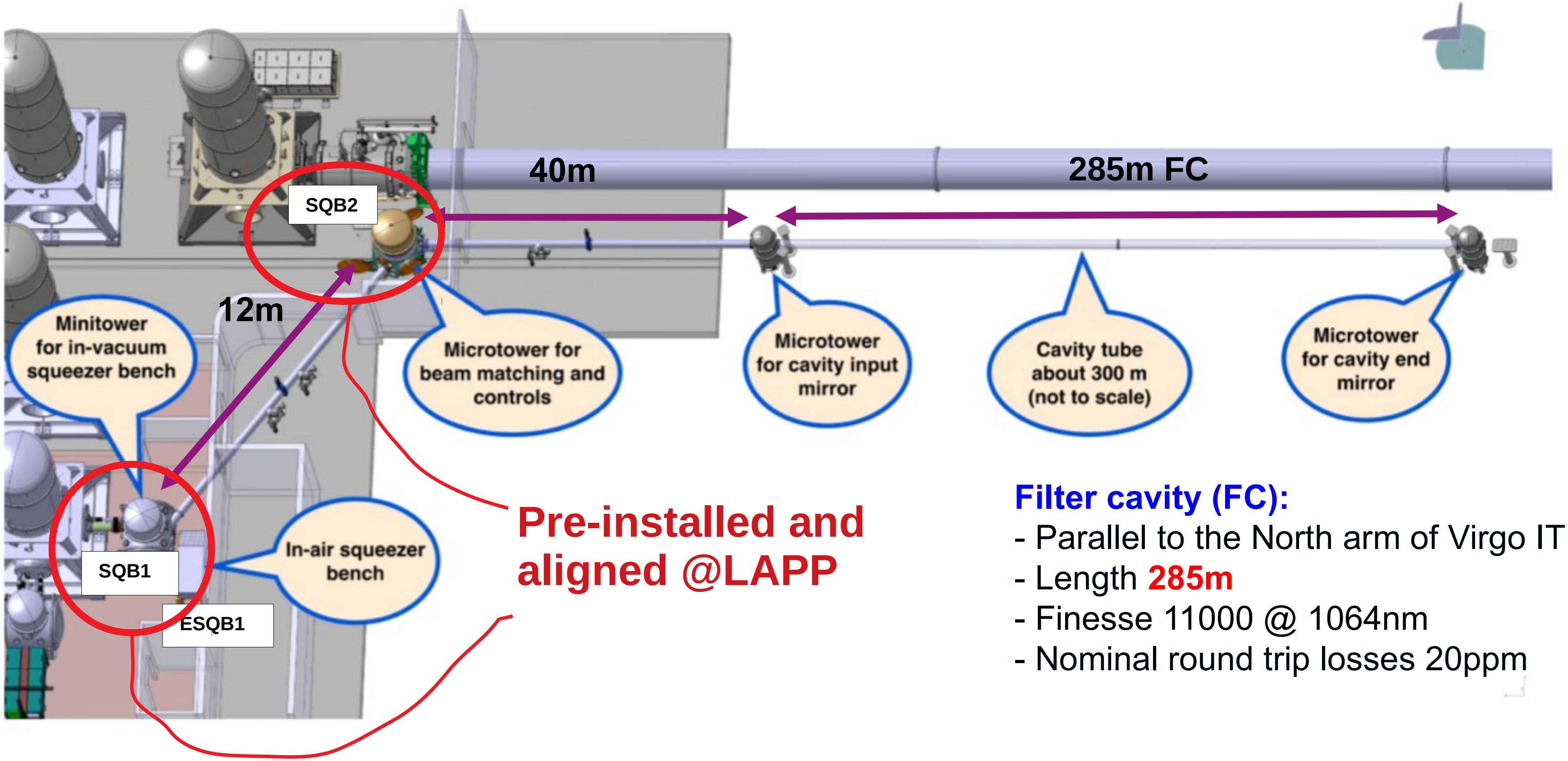
Detector (~3dB)

Squeezer (~9.1 dB)



Kwee et al. (2014)

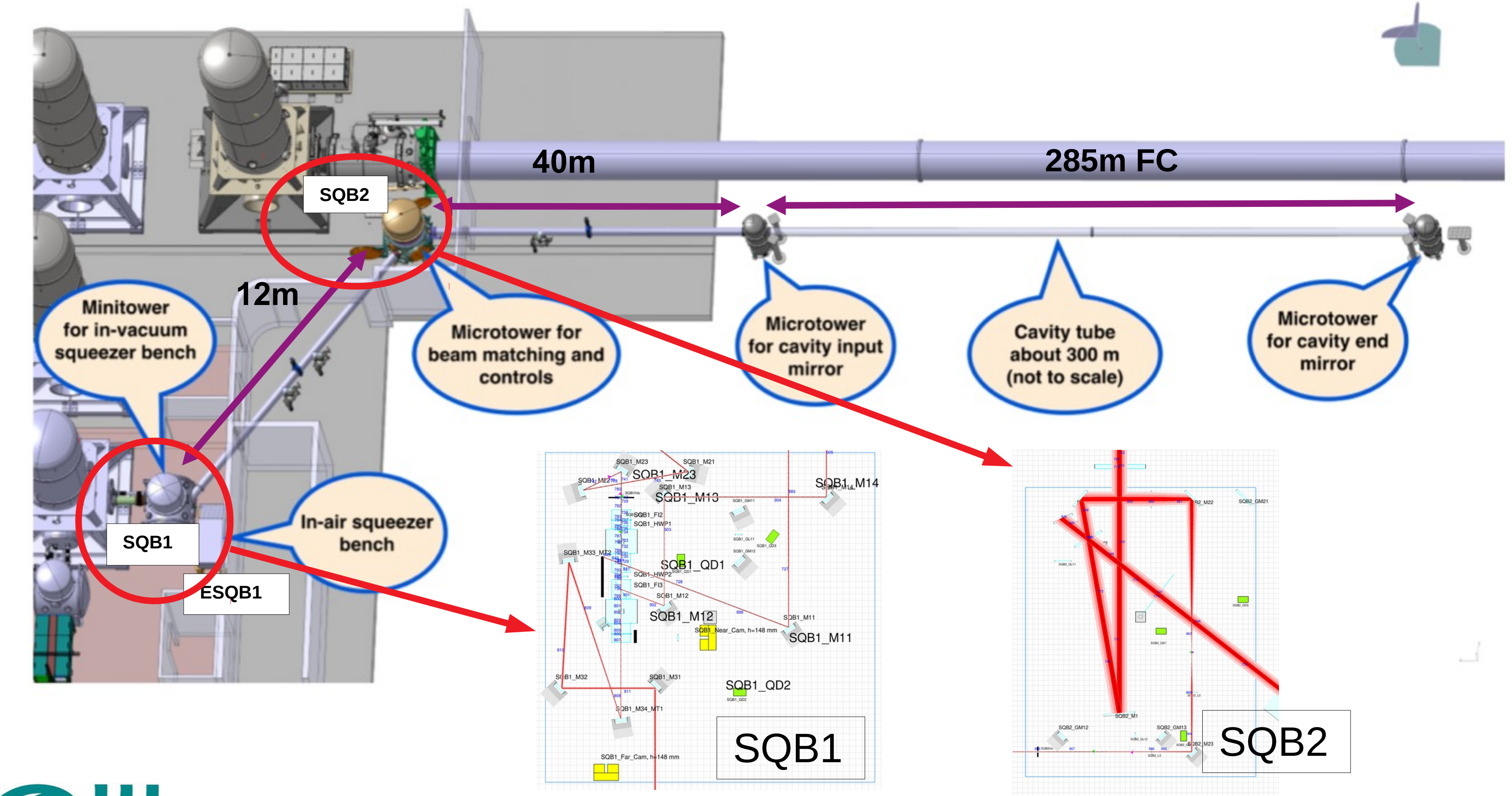
# FDS implementation in AdV+



**Pre-installed and aligned @LAPP**

**Filter cavity (FC):**
- Parallel to the North arm of Virgo ITF
- Length **285m**
- Finesse 11000 @ 1064nm
- Nominal round trip losses 20ppm

# FDS implementation in AdV+

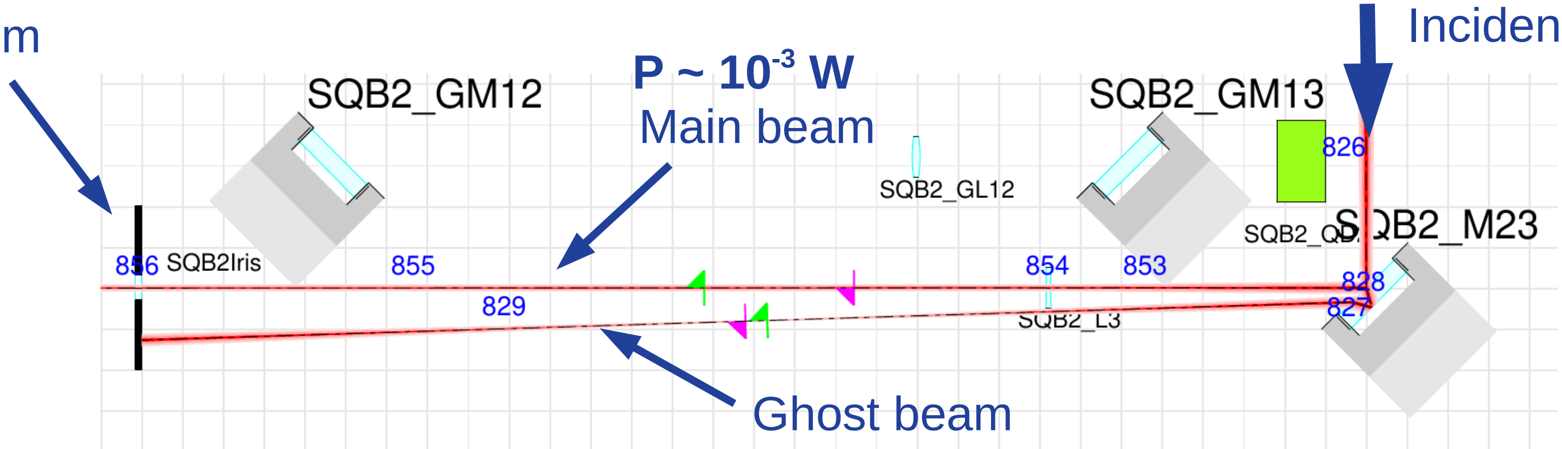


# Stray light and Ghost beams study on FDS system

***Ghost beams:*** *secondary beams generated by not perfect mirror coatings:*

1) we want to dump these beams to **avoid scattered light** on squeezing benches (it has been proved that the squeezing sensitivity enhancement is affected by stray light: Virgo Logbook #48337, #44990);

Ghost beam tracing using *Optocad*: beam transmitted by the first mirror surface and reflected by the second one.



Diaphragm

**P ~ $10^{-3}$ W**

Main beam

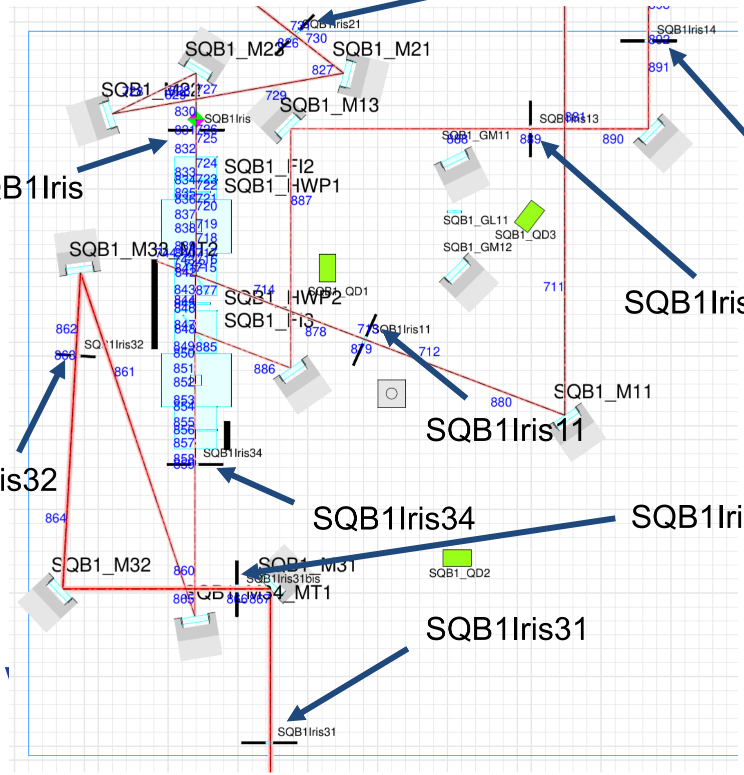
Incident beam

Ghost beam

**P ~ $10^{-12}$ - $10^{-15}$ W**

# Diaphragms on SQB1 and SQB2

## Dumping diaphragms on SQB1:



SQB1Iris21

SQB1Iris

SQB1Iris14

SQB1Iris13

SQB1Iris11

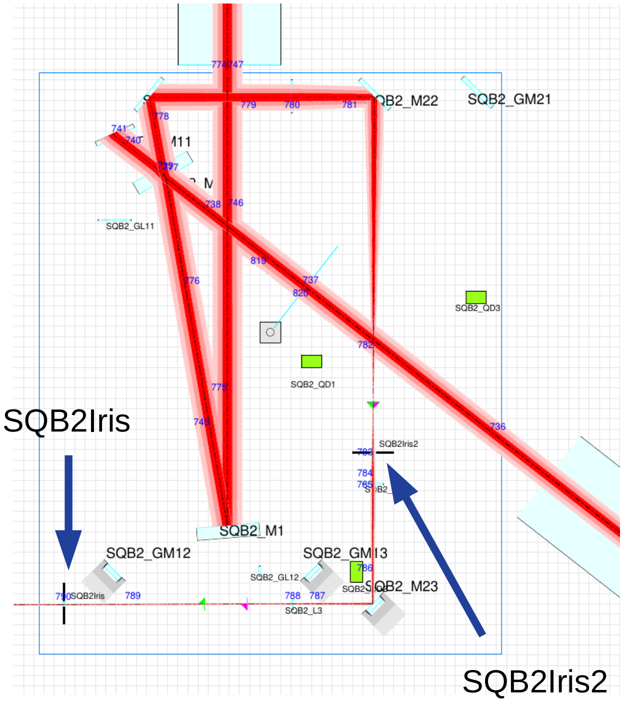
SQB1Iris32

SQB1Iris34

SQB1Iris31bis

SQB1Iris31

## Dumping diaphragms on SQB2:

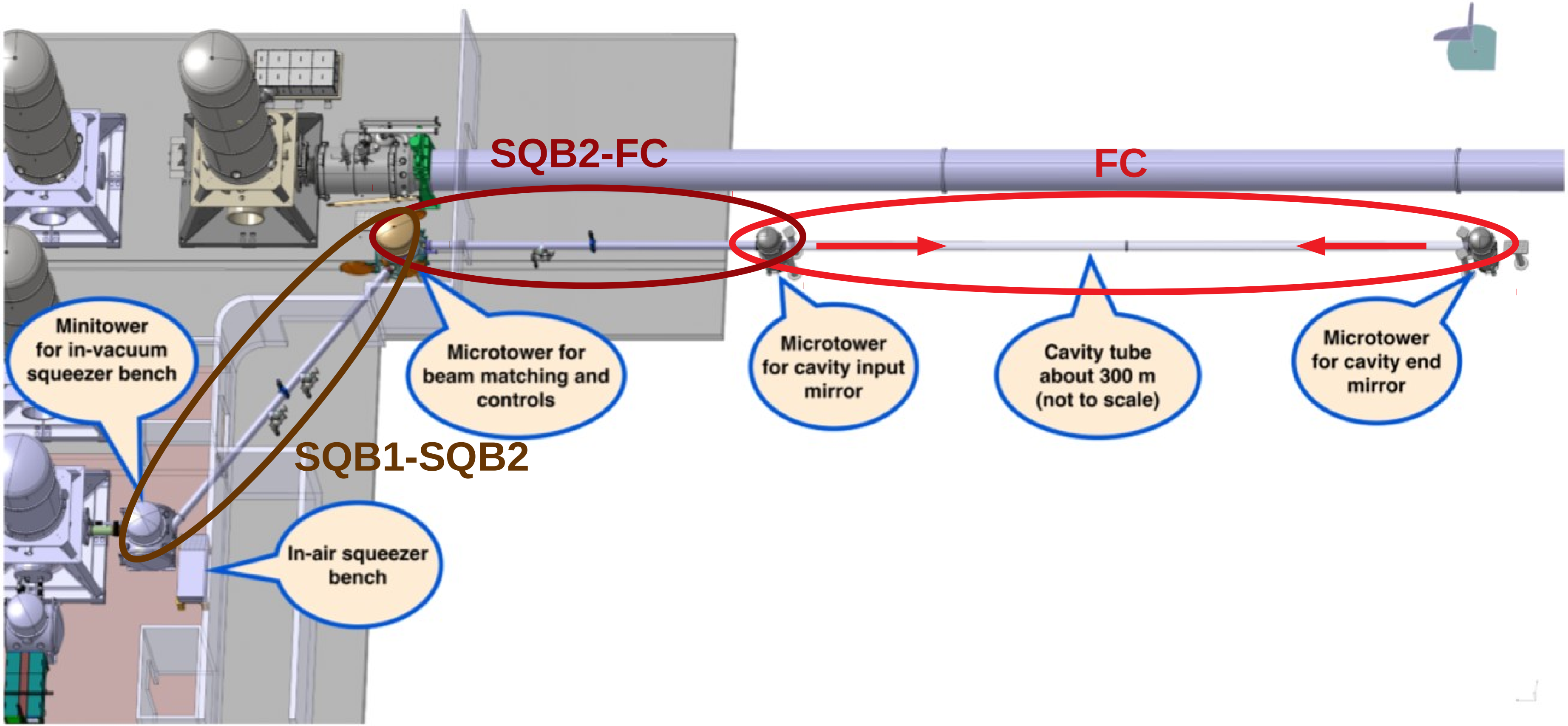


SQB2Iris

SQB2Iris2

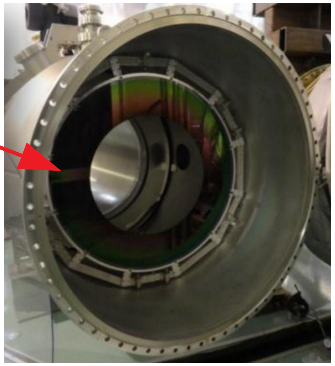
AdV TDS: VIR-0549B-20

# Ghost beams propagation inside the tubes

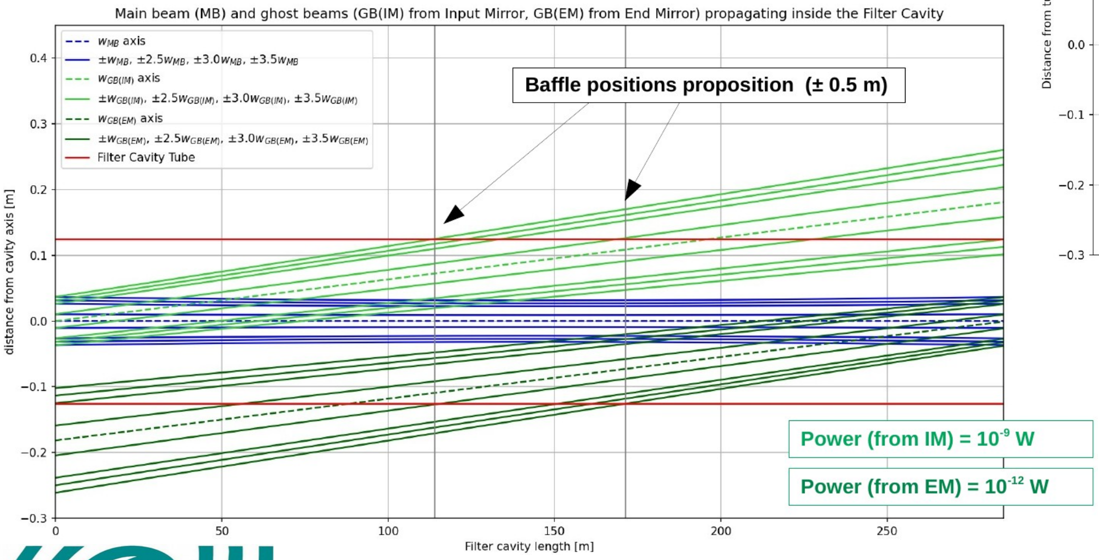


# Baffles inside FC and linking tubes

Baffle



## Baffles inside FC:

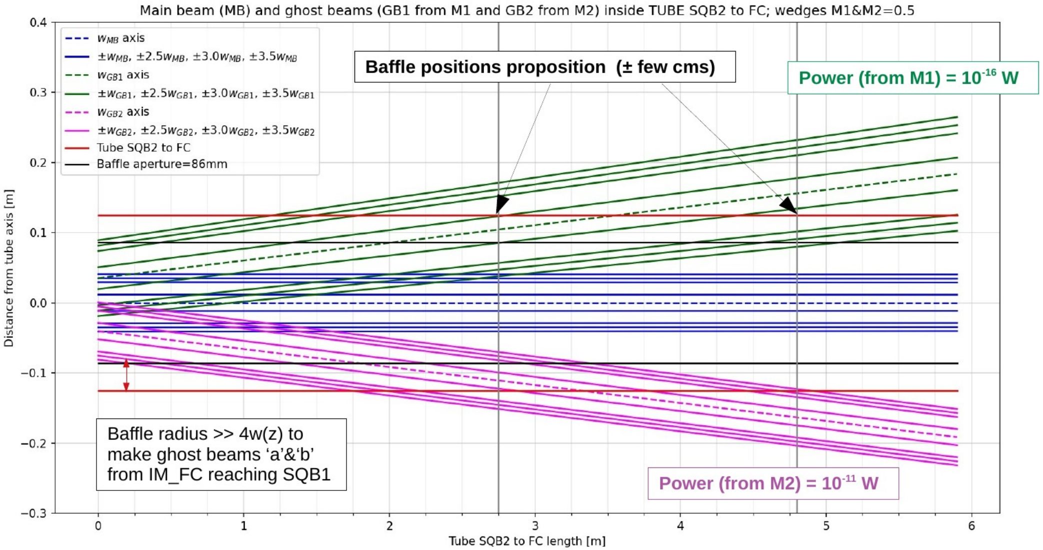


**Baffle positions proposition (± 0.5 m)**

**Power (from IM) = $10^{-9}$ W**

**Power (from EM) = $10^{-12}$ W**

## Baffles inside linking tube SQB2-FC:



**Baffle positions proposition (± few cms)**

**Power (from M1) = $10^{-16}$ W**

Baffle radius >> 4w(z) to make ghost beams ‘a’&‘b’ from IM_FC reaching SQB1

**Power (from M2) = $10^{-11}$ W**

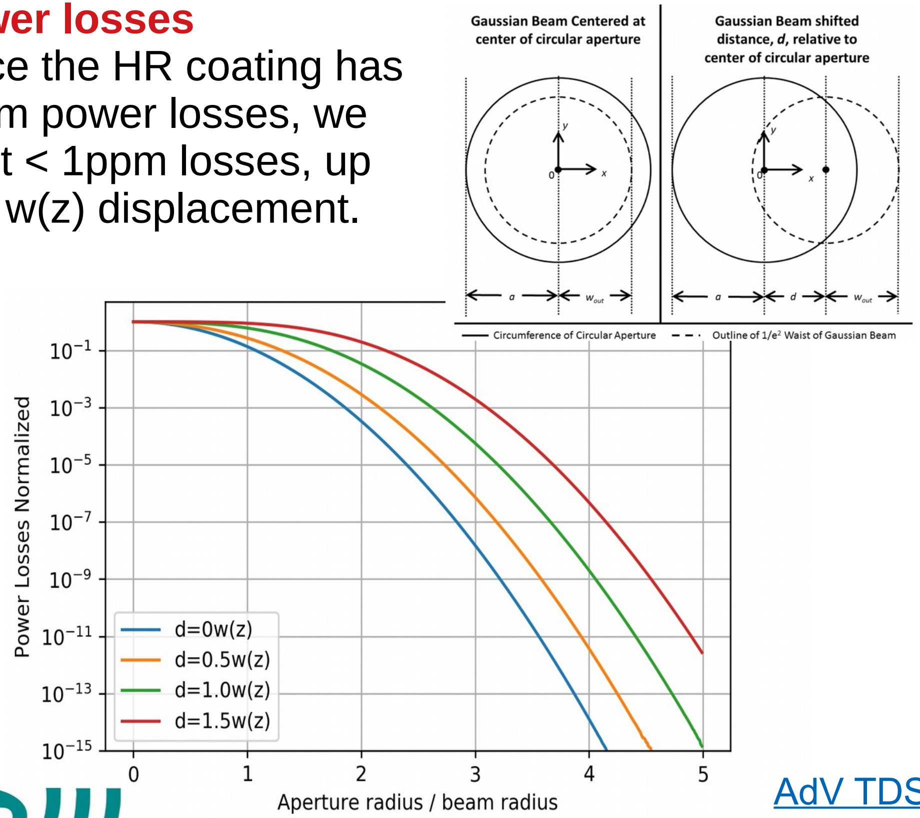
AdV TDS: VIR-0585A-20

# Stray light and Ghost beams study on FDS system

2) we need to chose an <u>optimal size of diaphragm/baffle apertures</u> to **limit losses** on the main beam.

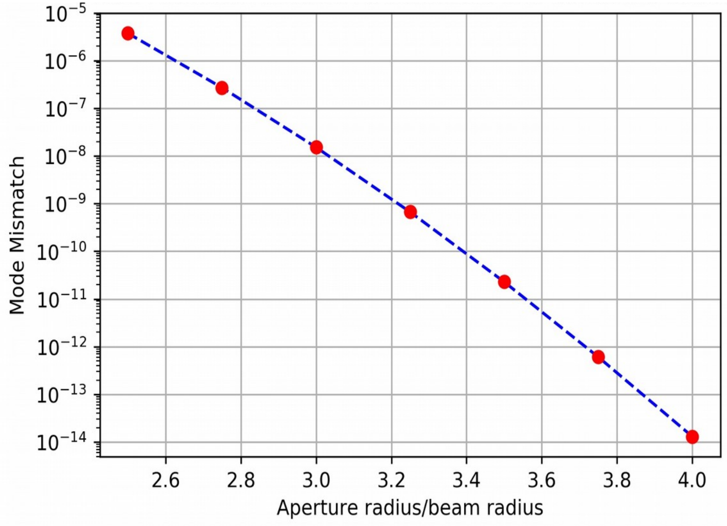
## Power losses

Since the HR coating has 3ppm power losses, we want < 1ppm losses, up to 1 w(z) displacement.



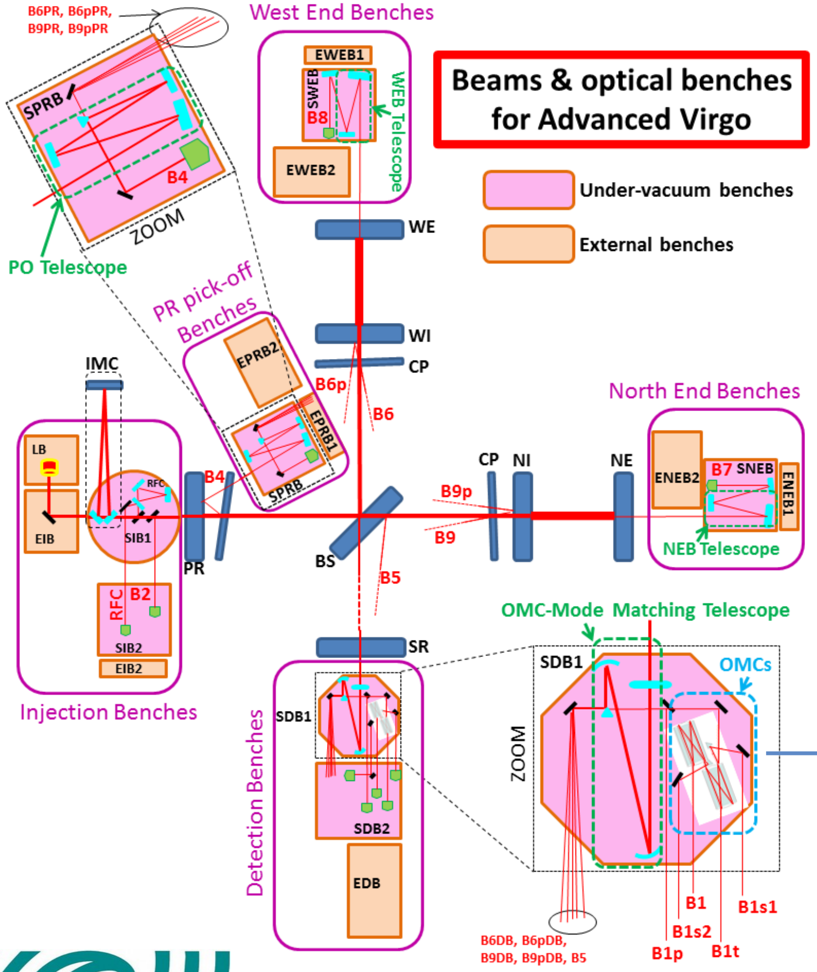
## Mode mismatch losses

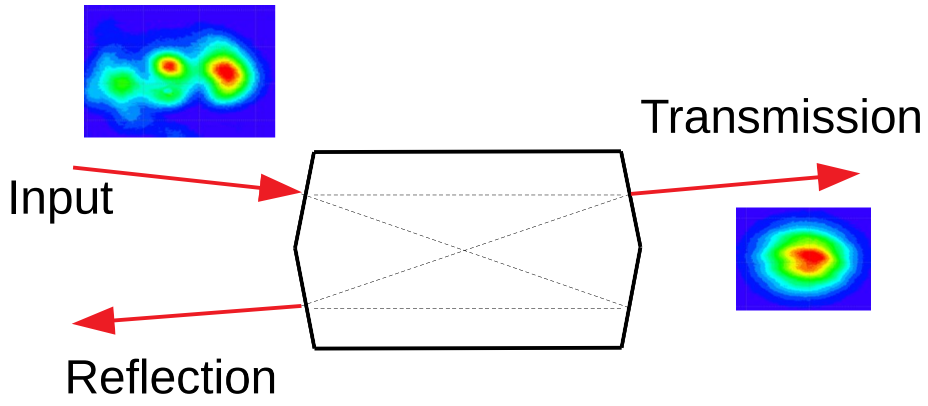
The total MM requirement for FDS is 1%. We can conclude that mode mismatch due to diffraction is **negligible**.



AdV TDS: VIR-0518A-20

# Detection (DET) system

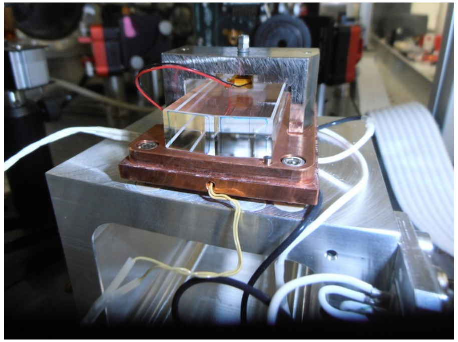




**Characterized @ LAPP**

Two Output Mode Cleaners (OMCs) will be replaced by 1 **High Finesse OMC** in AdV+

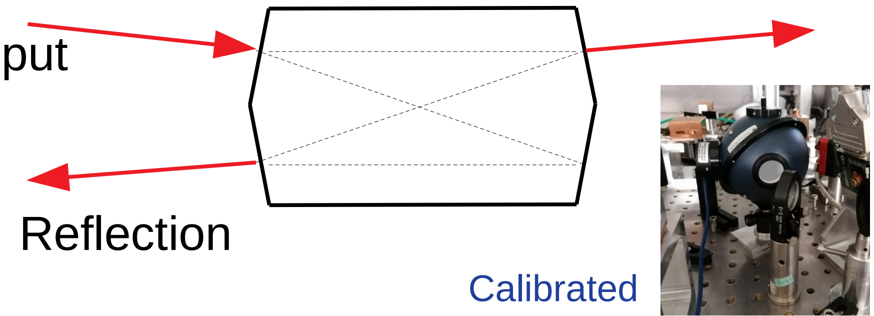
# High Finesse OMC characterization



We are characterizing the OMC at LAPP:

1. **Losses = 3.5% ± 0.3 %** (during O3 Losses = 5%)
   Losses = Input power – Transmitted power – Reflected power
2. Radius of Curvature (ρ) of the spherical surface: ρ ~ 1700 mm
3. High reflective coating residual transmission: few ppm

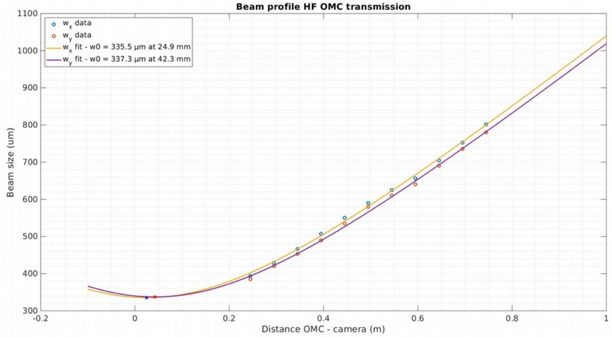
1.



Calibrated integrating sphere

2.

$$w_0 = \sqrt{\frac{\lambda}{n\pi}\sqrt{2L_{geo}(\boxed{\rho} - 2L_{geo})}}$$



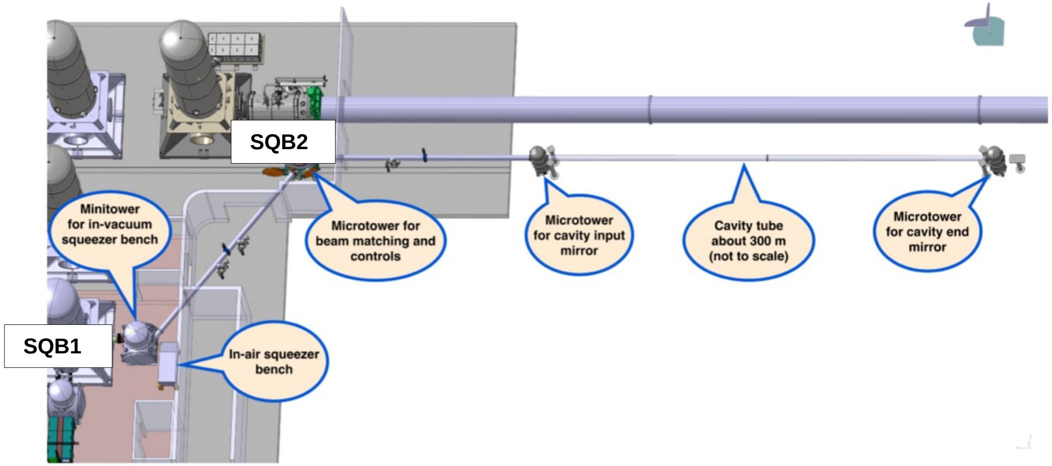
# Conclusions and future plans

Conclusions:

- ✓ Ghost beams study on Frequency Dependent Squeezing system
- ✓ Design of diaphragms and baffles
- ⚙ Construction of diaphragms and baffles
- ⚙ Mechanical installation of FDS system at Virgo
- ⚙ Characterization of OMC at LAPP

Next steps:

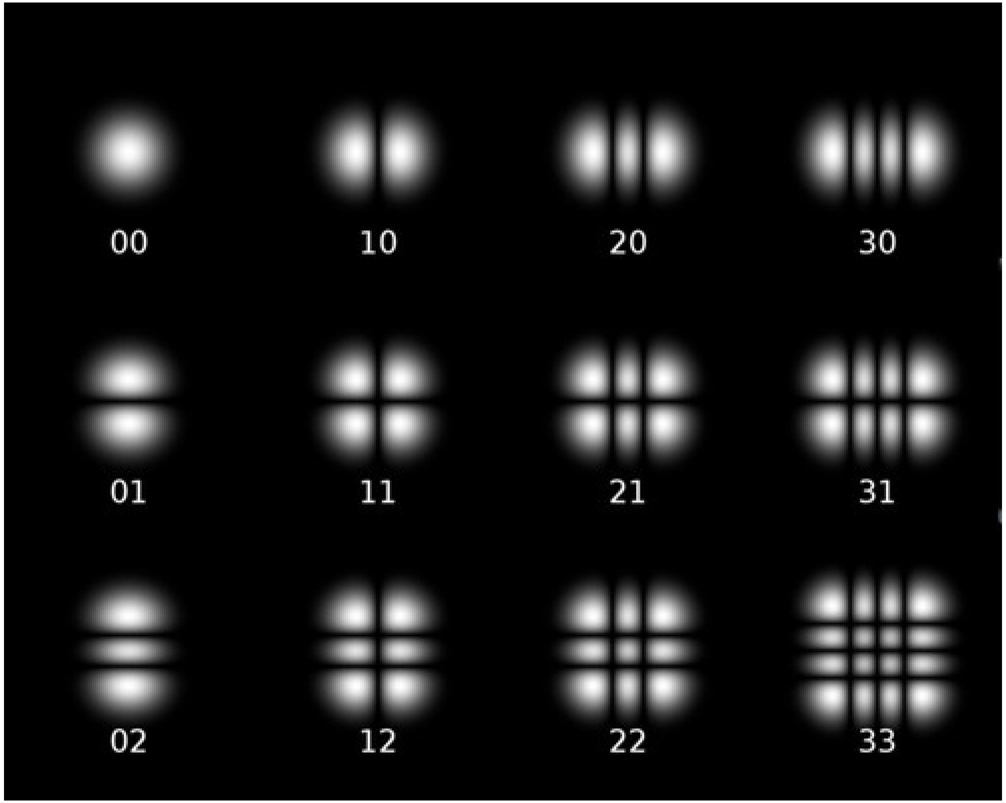
- ✘ Pre-installation of SQB1 and SQB2 at LAPP (December 2020)
- ✘ Commissioning of the whole FDS system on site (beginning 2021)
- ✘ Commissioning of OMC on site (November 2020)
- ✘ Observing run O4 starts in 2022

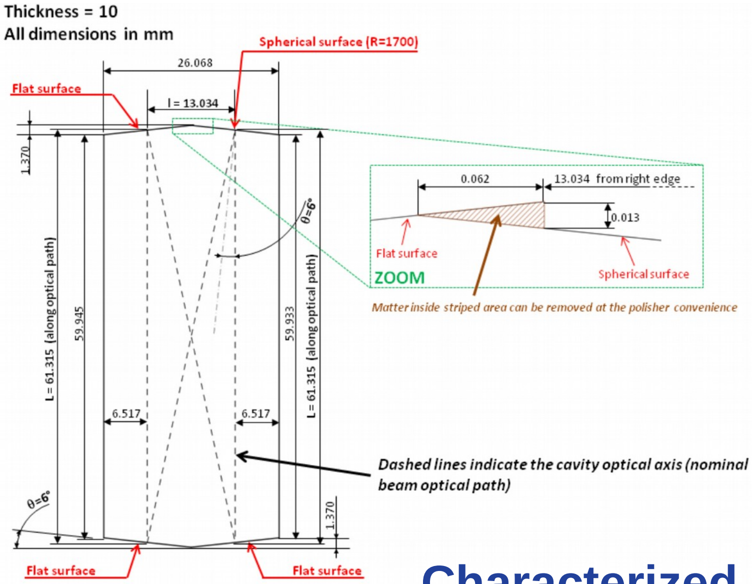


THANK YOU FOR THE ATTENTION

# EXTRA SLIDES

# Detection (DET) system



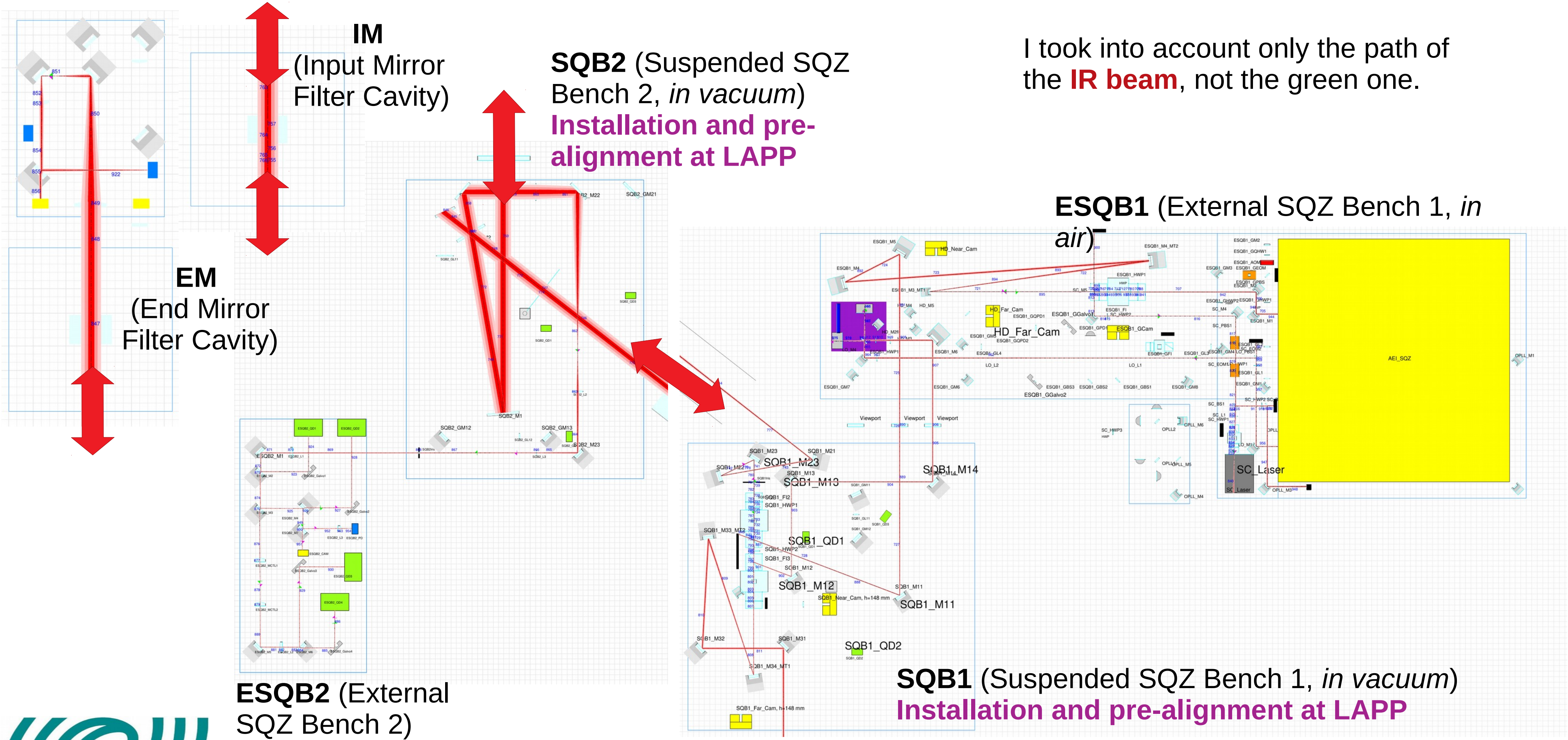


**Characterized @ LAPP**

Two Output Mode Cleaners (OMCs) will be replaced by 1 **High Finesse OMC** in AdV+

# FDS benches on Optocad

I took into account only the path of the **IR beam**, not the green one.



**IM**
(Input Mirror
Filter Cavity)

**EM**
(End Mirror
Filter Cavity)

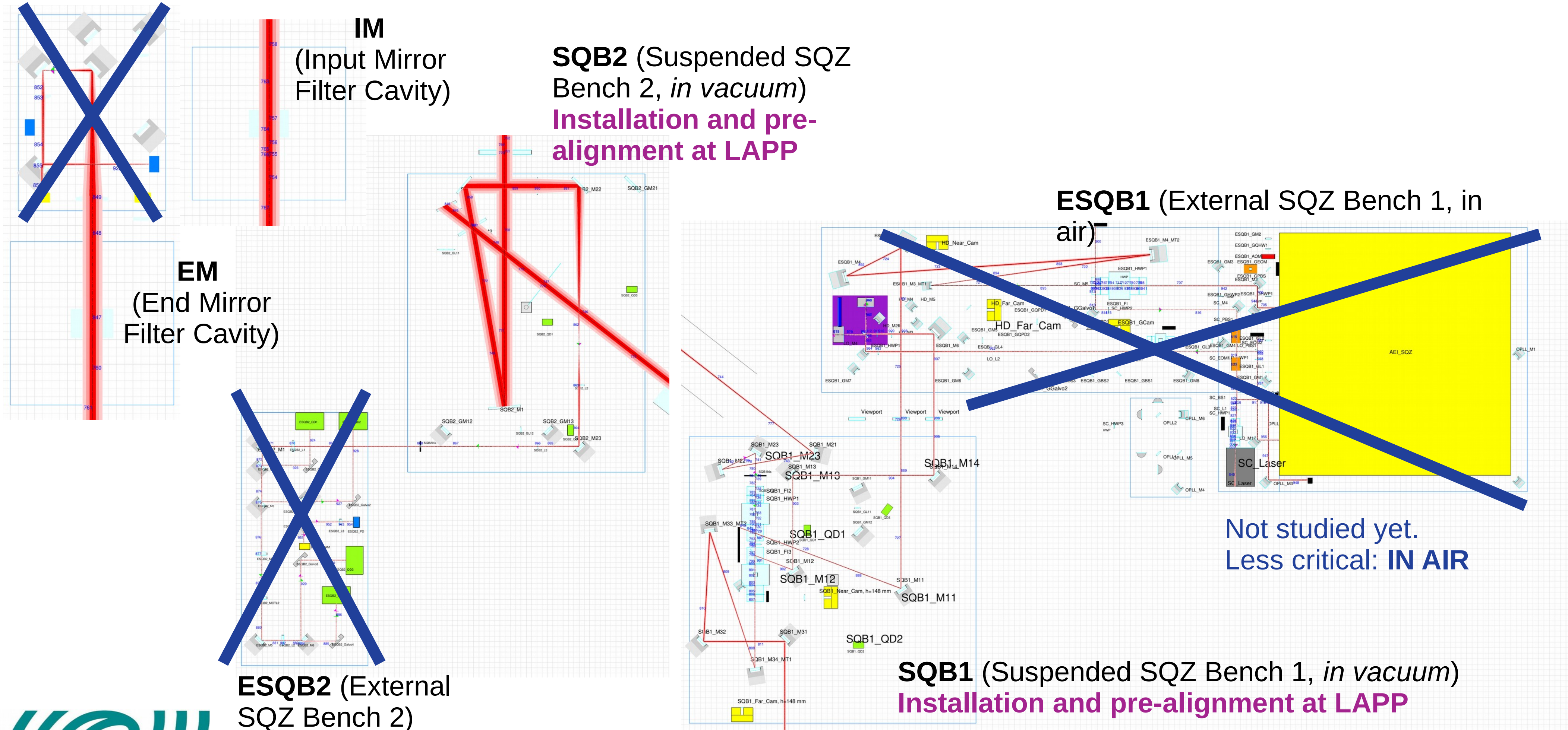
**SQB2** (Suspended SQZ Bench 2, *in vacuum*)
**Installation and pre-alignment at LAPP**

**ESQB1** (External SQZ Bench 1, *in air*)

**ESQB2** (External SQZ Bench 2)

**SQB1** (Suspended SQZ Bench 1, *in vacuum*)
**Installation and pre-alignment at LAPP**

# FDS benches on Optocad



**IM**
(Input Mirror
Filter Cavity)

**SQB2** (Suspended SQZ Bench 2, *in vacuum*)
**Installation and pre-alignment at LAPP**

**ESQB1** (External SQZ Bench 1, in air)

**EM**
(End Mirror
Filter Cavity)

**ESQB2** (External SQZ Bench 2)

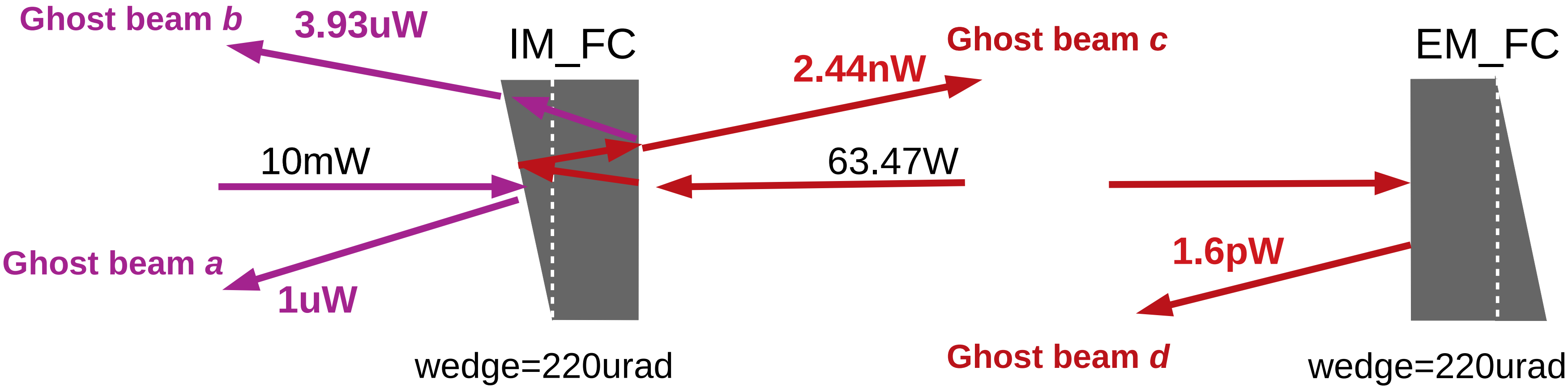
**SQB1** (Suspended SQZ Bench 1, *in vacuum*)
**Installation and pre-alignment at LAPP**

Not studied yet.
Less critical: **IN AIR**

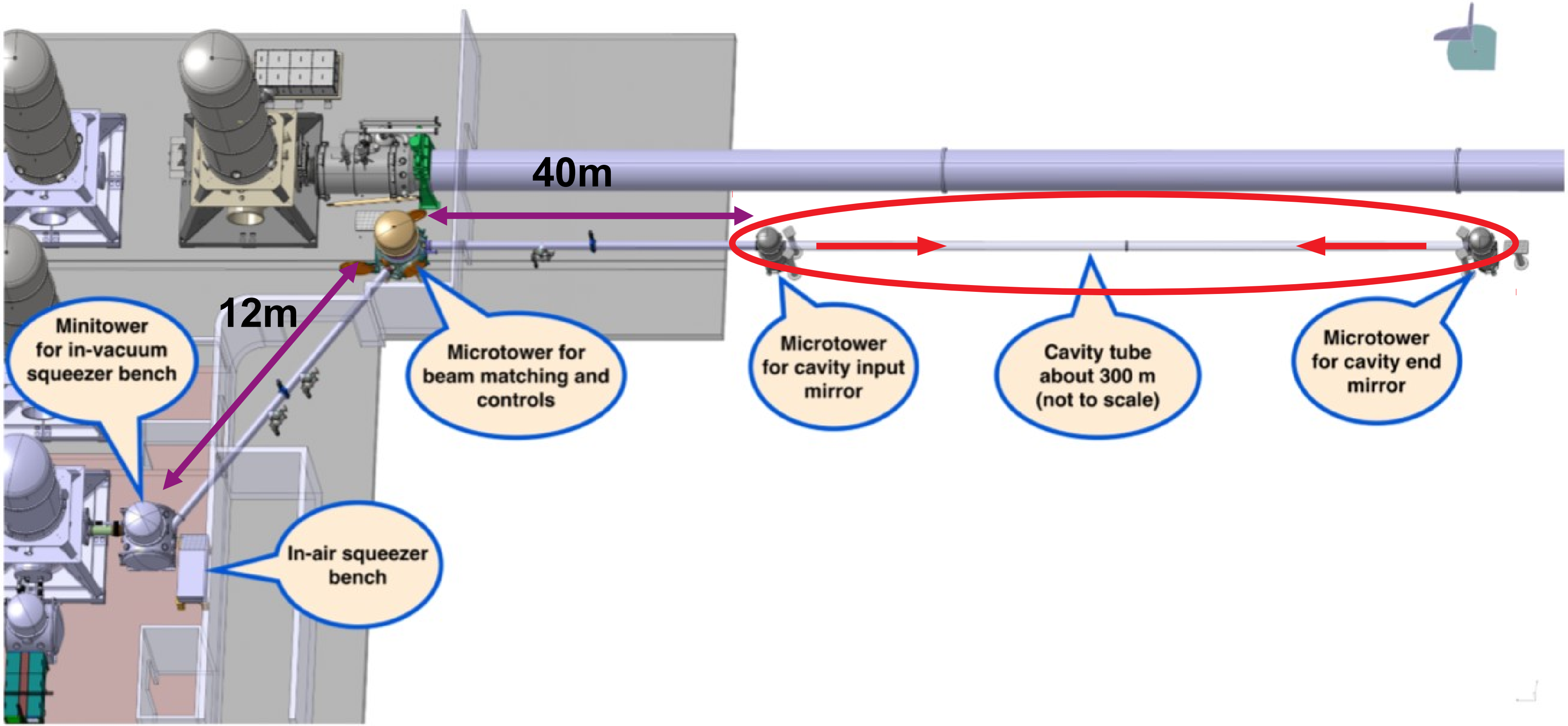
# Ghost beams propagation inside the tubes

I studied the ghost beams propagation inside different tubes (VIR-0585A-20): Filter Cavity (both Input and End Mirrors), Tube between SQB2 and FC, Tube between SQB2 and SQB1. We are designing the **baffles** to install inside these three tubes.

**Filter Cavity** (VIR-0473A-20, VIR-0584A-20)**:**
- These ghost beams are way **more powerful** than the others, so we need to dump them properly;
- *Ghost beams 'a' & 'b'* are dumped on diaphragms on SQB1;
- *Ghost beams 'c' & 'd'* are symmetrical and dumped on baffles inside FC.

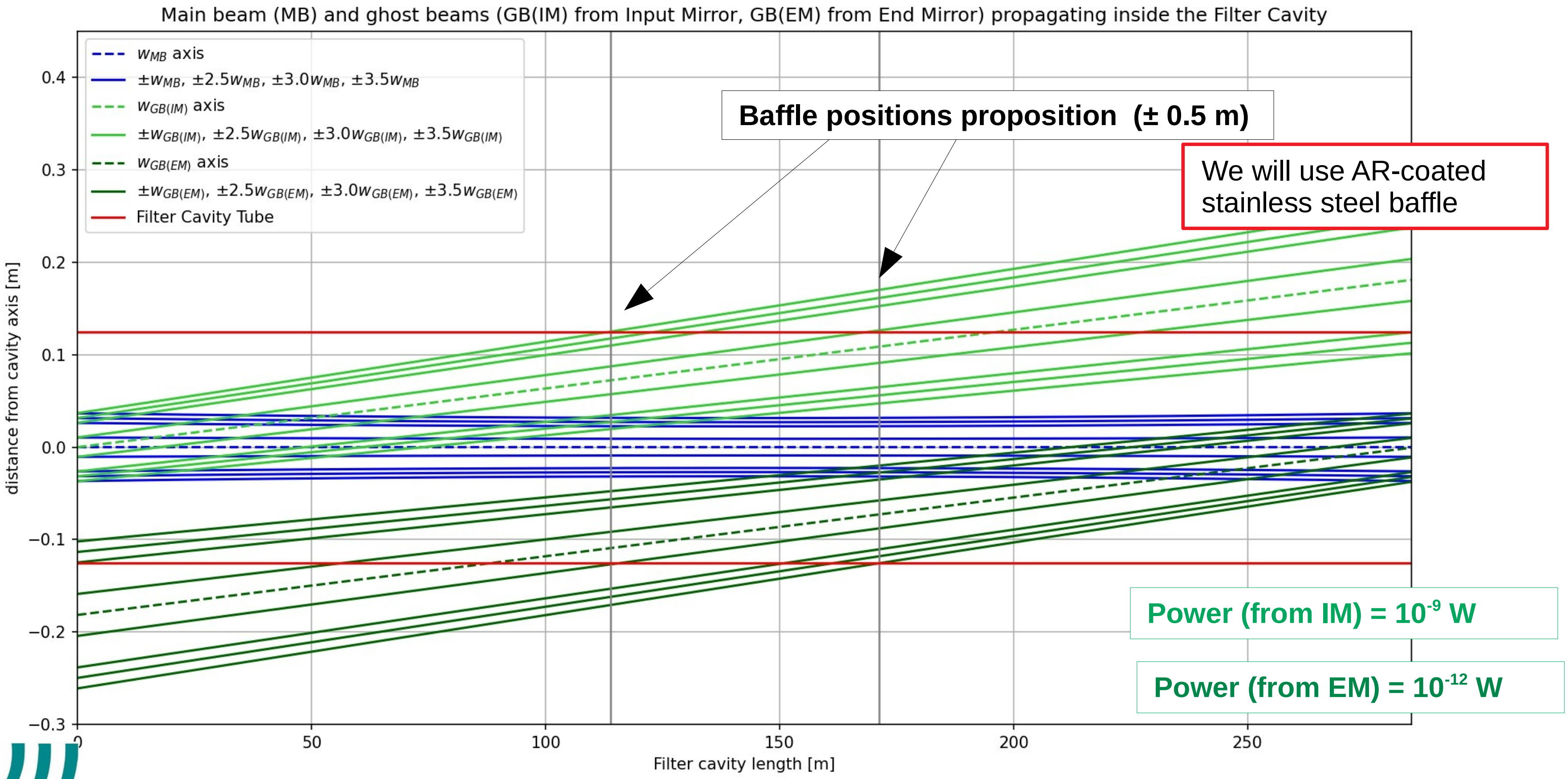


# Propagation inside the tubes : **FC** from **IM** and **EM**



# Propagation inside the tubes : **FC** from **IM** and **EM**

Discussion with FLT to install baffles at different locations inside the tube: **IN PROGRESS**.
Constraints: available mechanical positions inside FC, do not cut the Ghost Beam in two with the baffle, minimize stray light etc.



Main beam (MB) and ghost beams (GB(IM) from Input Mirror, GB(EM) from End Mirror) propagating inside the Filter Cavity

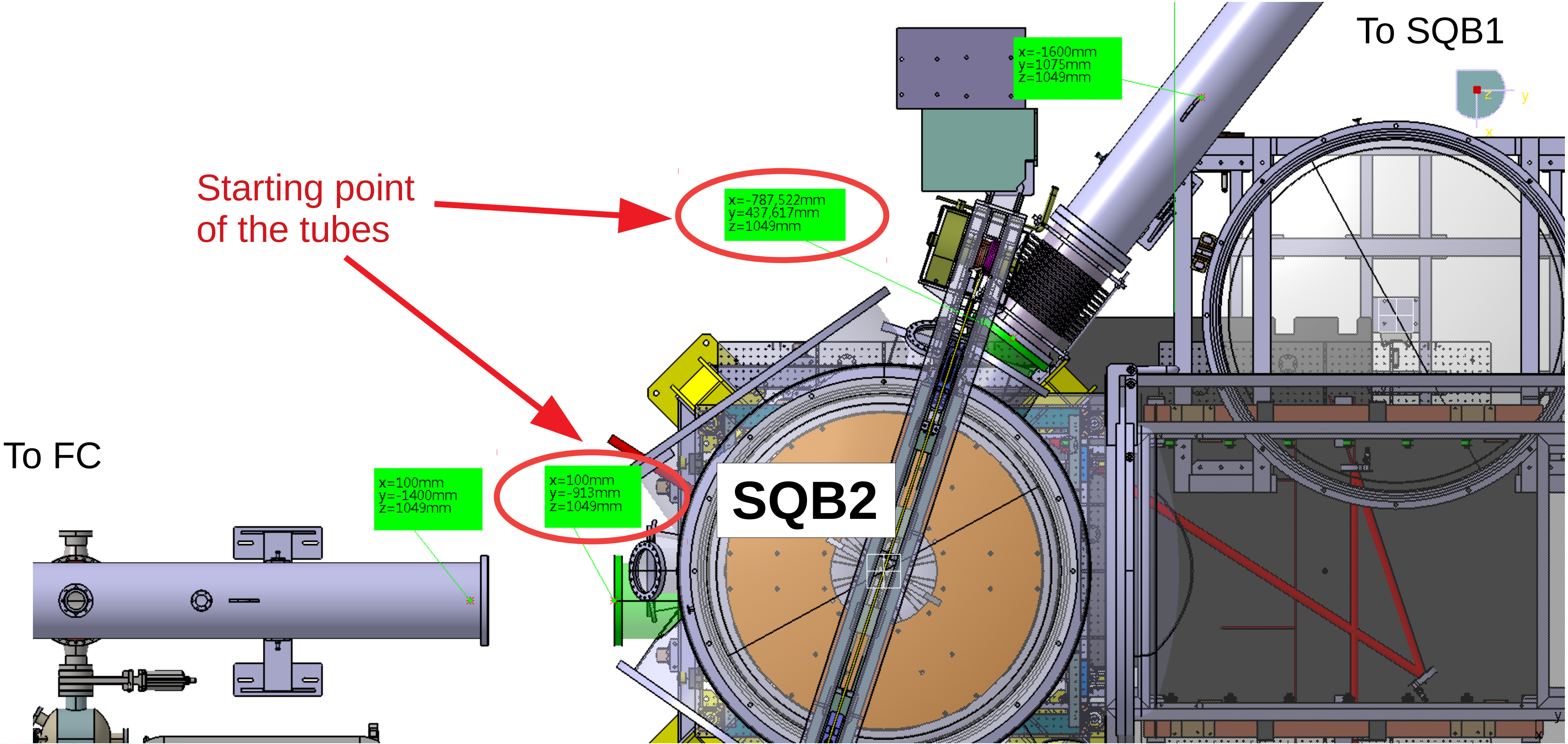
**Baffle positions proposition (± 0.5 m)**

We will use AR-coated stainless steel baffle

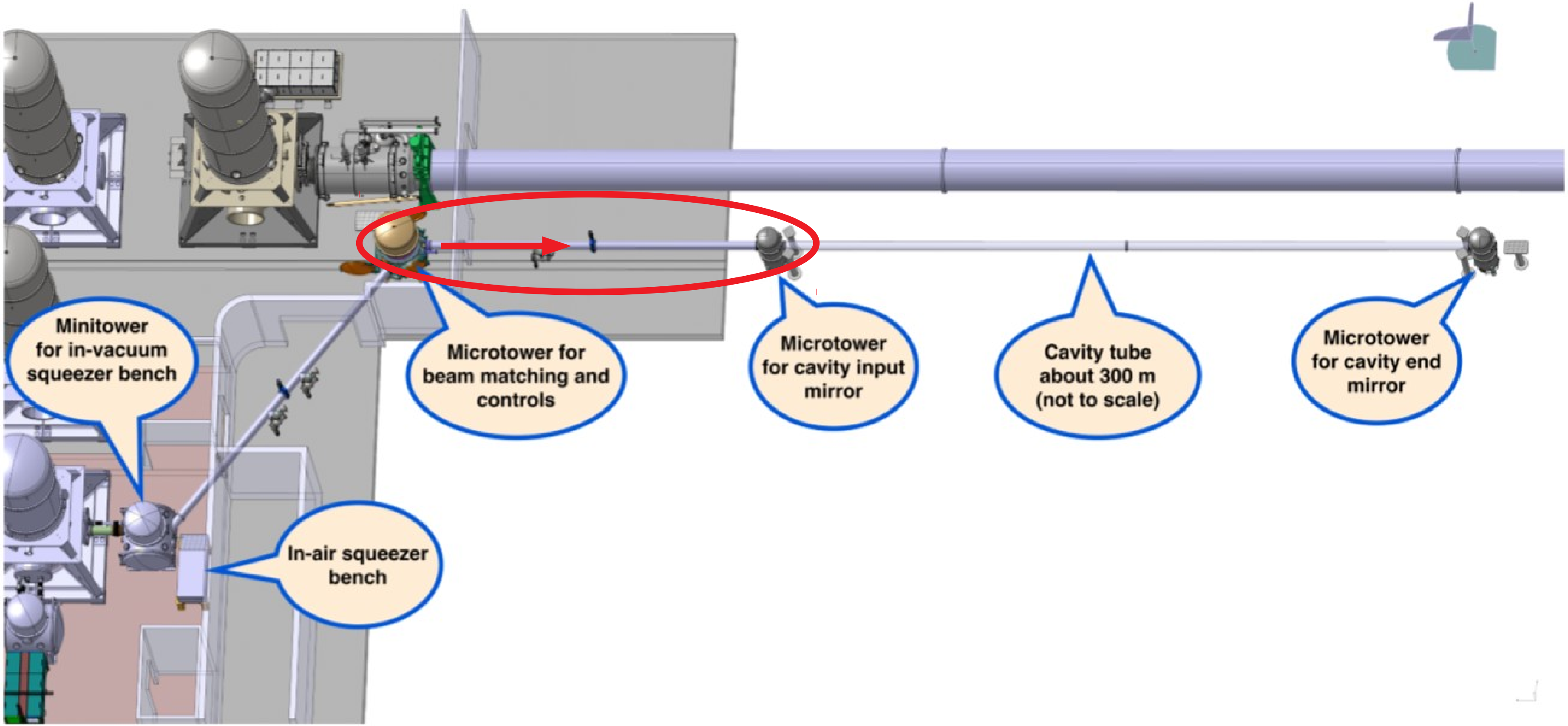
**Power (from IM) = $10^{-9}$ W**

**Power (from EM) = $10^{-12}$ W**

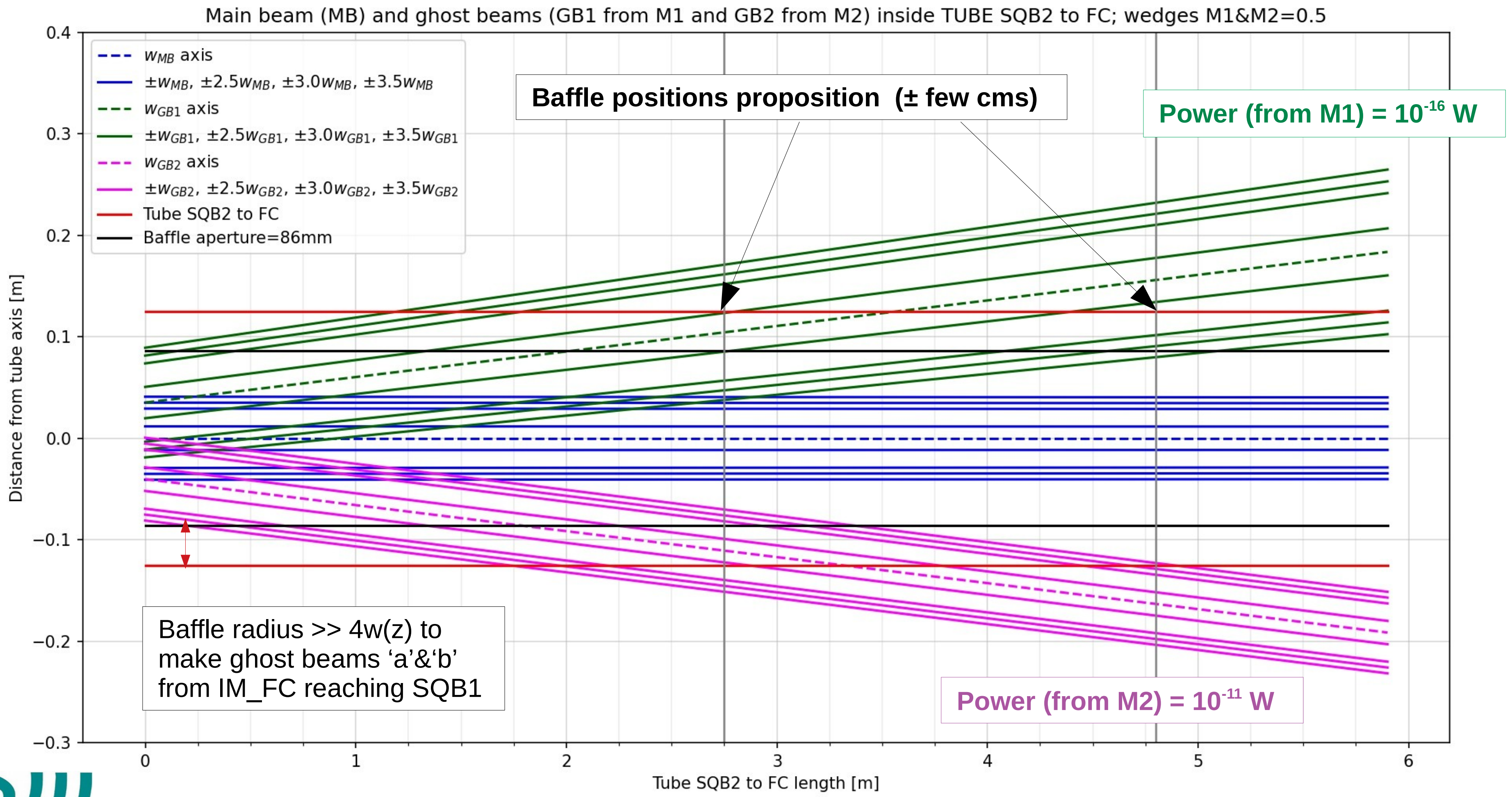
# Mechanical contrains to place baffles



# Propagation inside the tubes : **SQB2 to FC**



# Propagation inside the tubes : SQB2 to FC



Main beam (MB) and ghost beams (GB1 from M1 and GB2 from M2) inside TUBE SQB2 to FC; wedges M1&M2=0.5

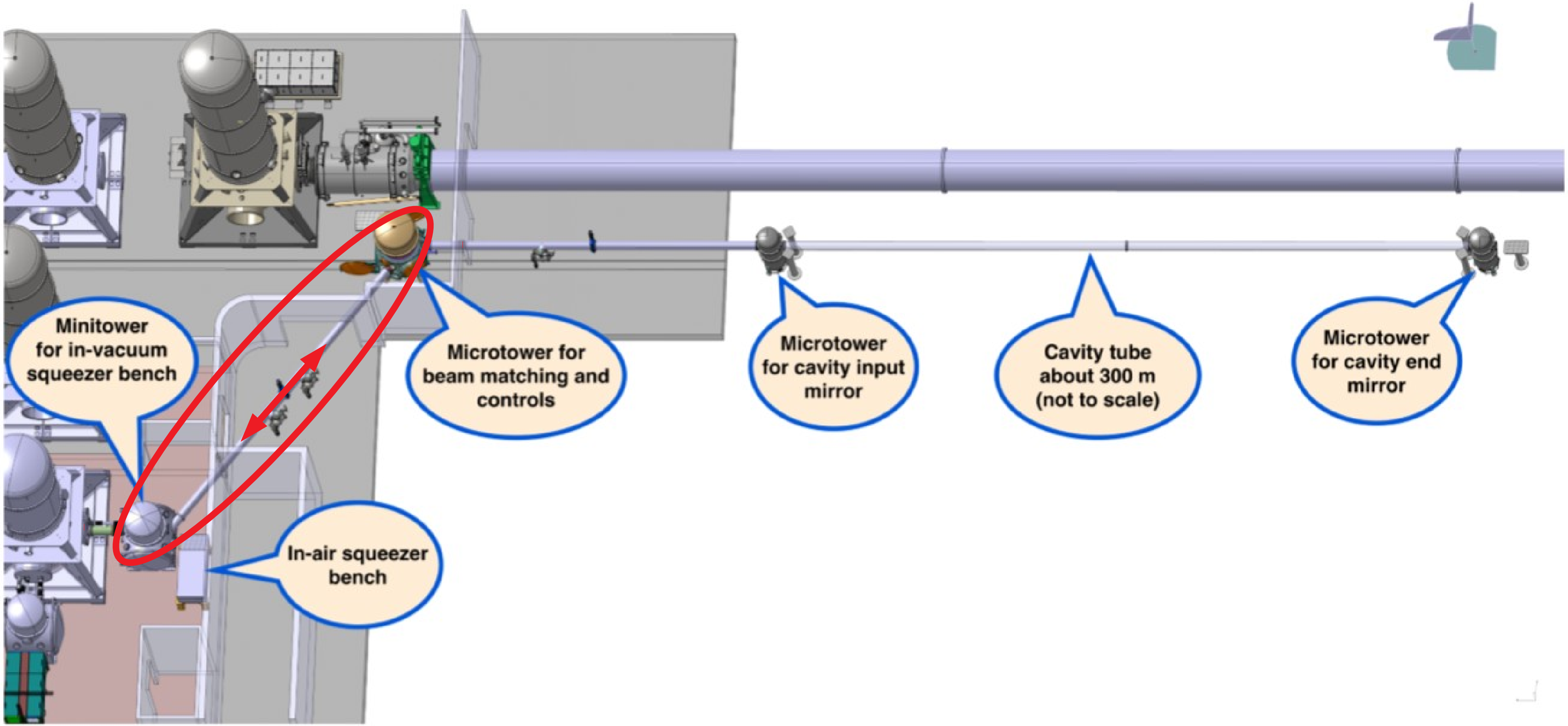
**Baffle positions proposition (± few cms)**

**Power (from M1) = $10^{-16}$ W**

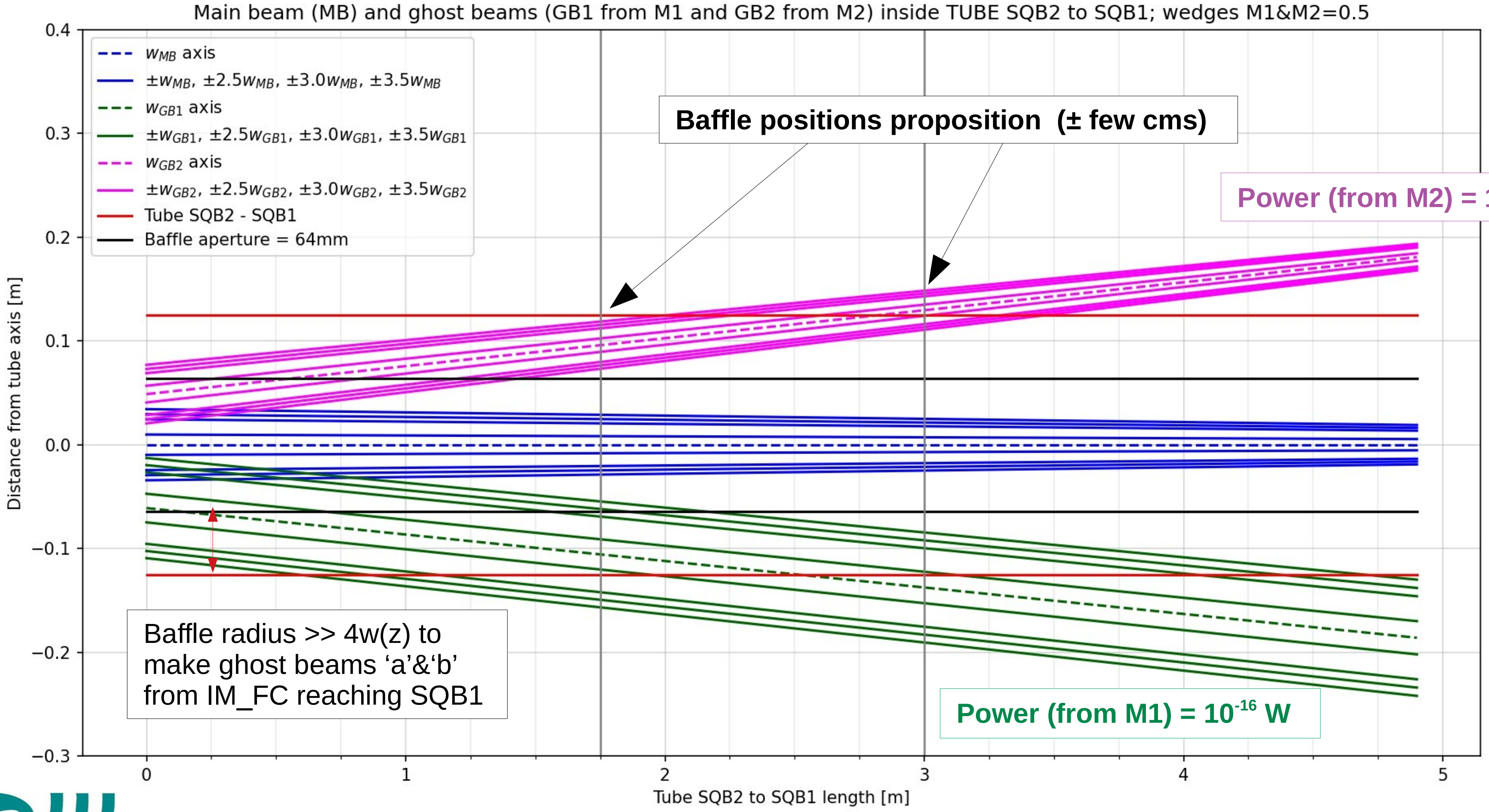
Baffle radius >> 4w(z) to make ghost beams 'a'&'b' from IM_FC reaching SQB1

**Power (from M2) = $10^{-11}$ W**

# Propagation inside the tubes : SQB1 – SQB2



# Propagation inside the tubes : SQB2 to SQB1



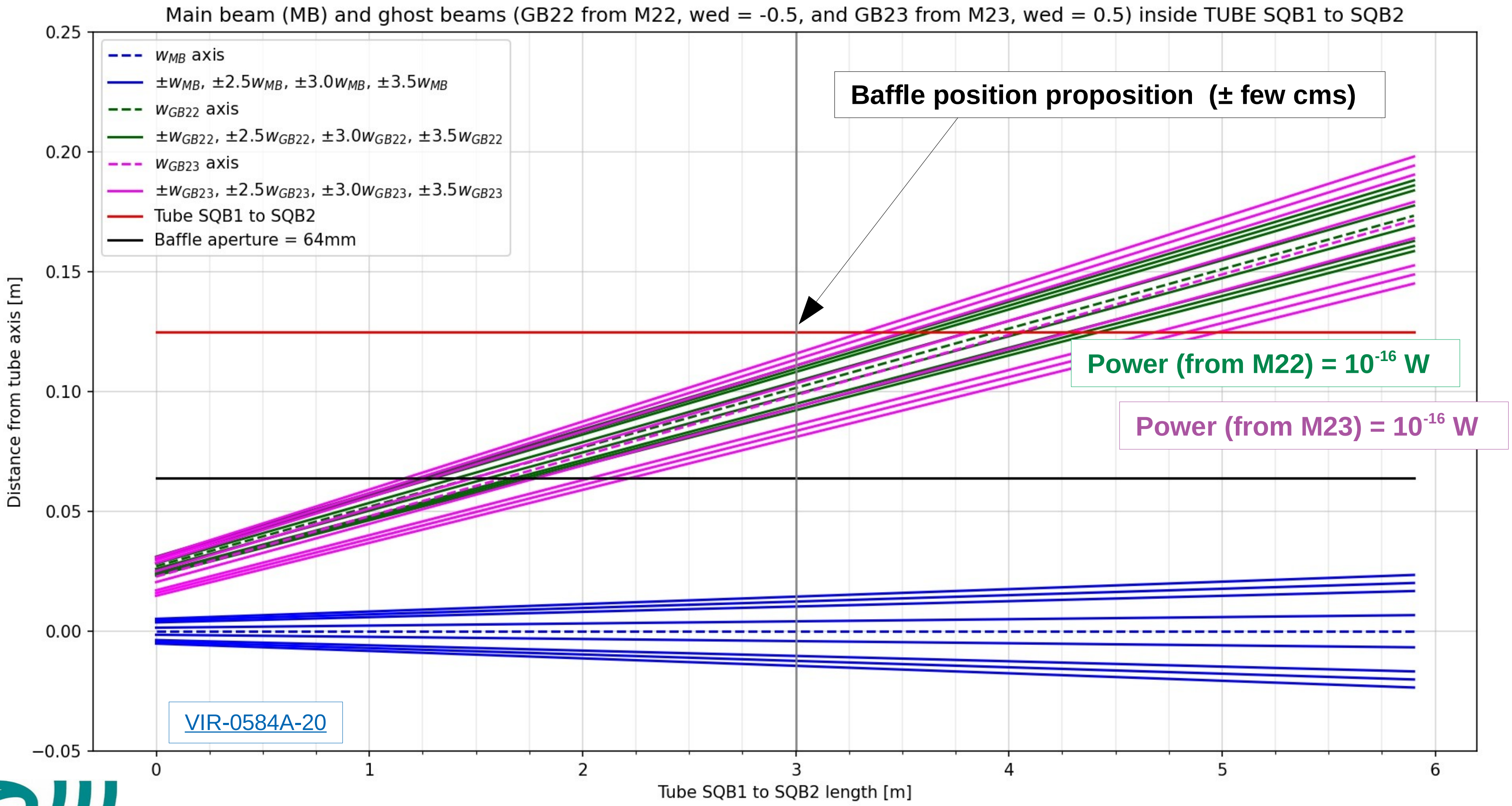
**Baffle positions proposition (± few cms)**

**Power (from M2) = $10^{-11}$ W**

Baffle radius >> 4w(z) to make ghost beams ‘a’&‘b’ from IM_FC reaching SQB1

**Power (from M1) = $10^{-16}$ W**

# Propagation inside the tubes : SQB1 to SQB2



**Baffle position proposition (± few cms)**

**Power (from M22) = $10^{-16}$ W**

**Power (from M23) = $10^{-16}$ W**

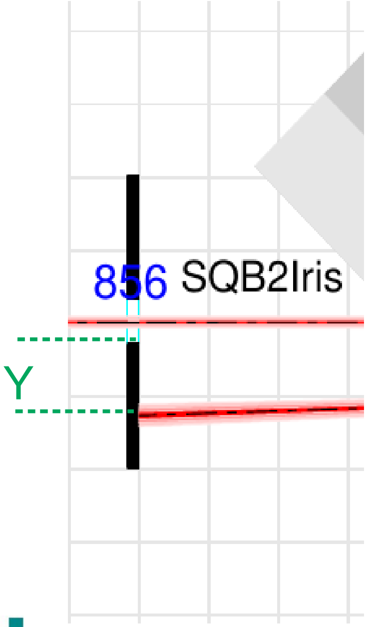
VIR-0584A-20

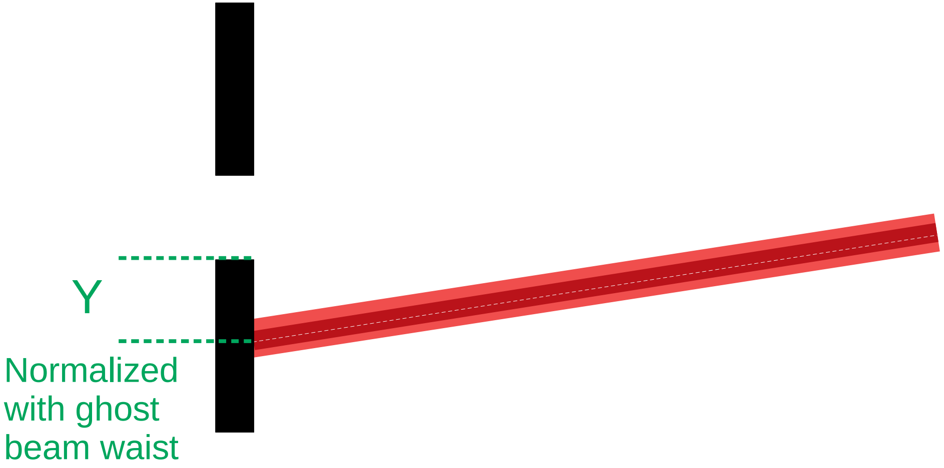
# Are ghost beams dumped properly?

To understand if the ghost beams are stopped by diaphragms and baffles properly, we introduce a quantity Y defined as:

**Y = (distance ghost and main beams – aperture radius)/ghost beam radius**.

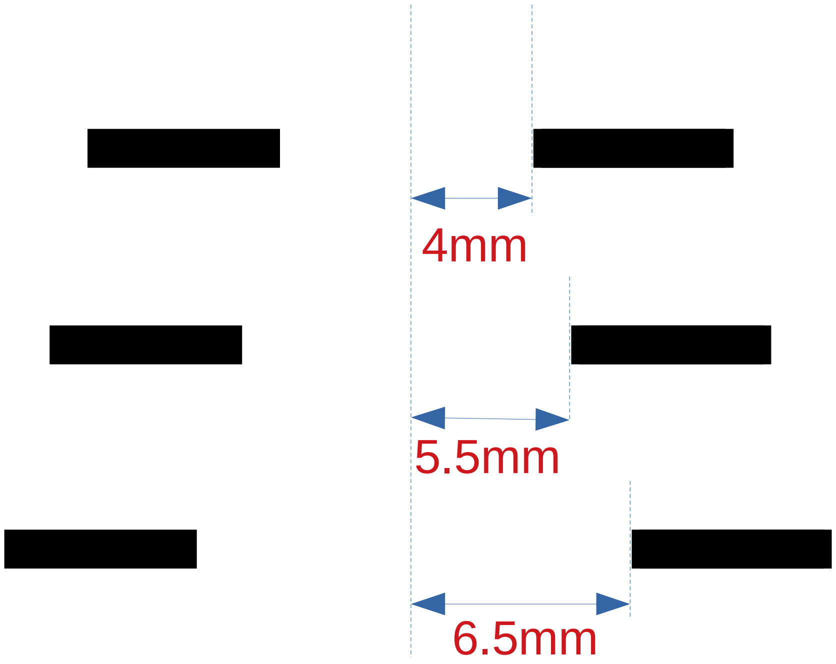
The <u>fraction of ghost beam power</u> passing through the aperture can be computed using the corrected error function **Erfc(Y) = 1 – Erf(Y)**.





# Standard apertures

I took ‘standard apertures’ in order to ease the production and installation processes.
With **a = 4, 5.5, 6.5 mm** we don’t change the performances of diaphragms on benches.
Concerning baffles, we need to consider stray light effect at the aperture edges.



We want a/w(z) = 3.5 for diaphragms.
I report this quantity using standard aperture radius.