University of Glasgow | Faculty of Physical Sciences

The ET optical layout

Stefan Hild
for the ET-WP3 working group

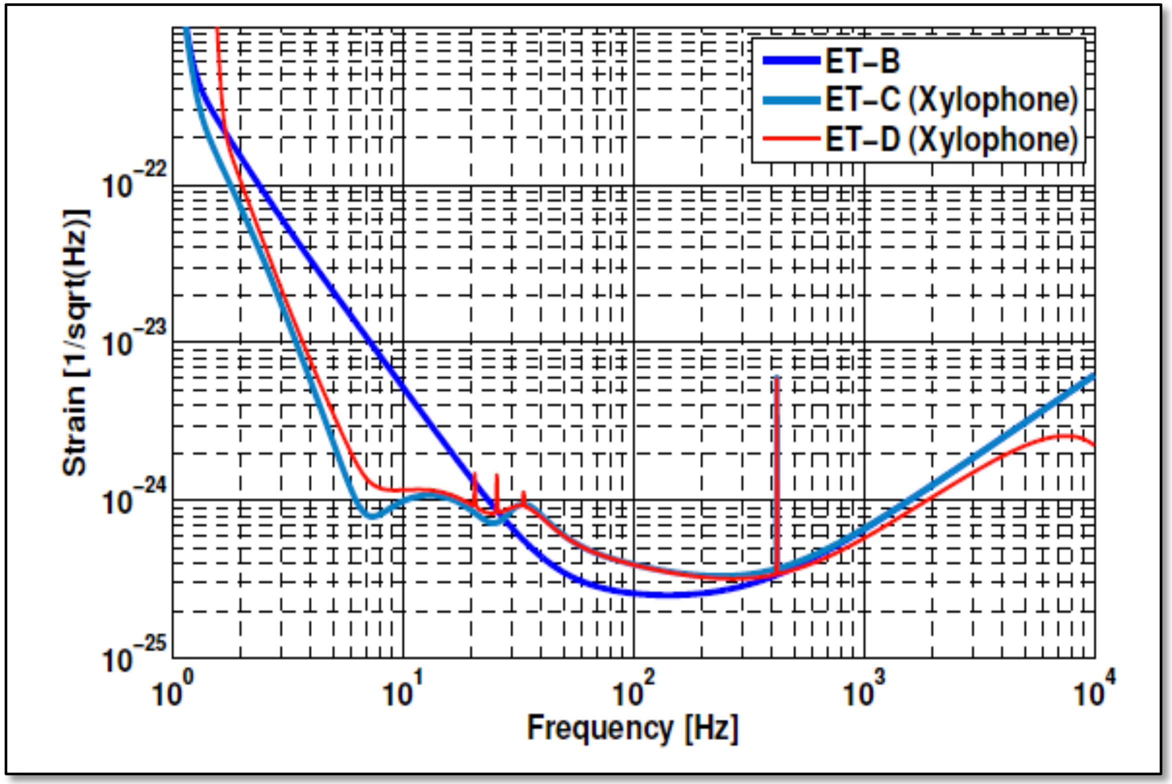
3rd ET General meeting,
Budapest, November 2010

Overview

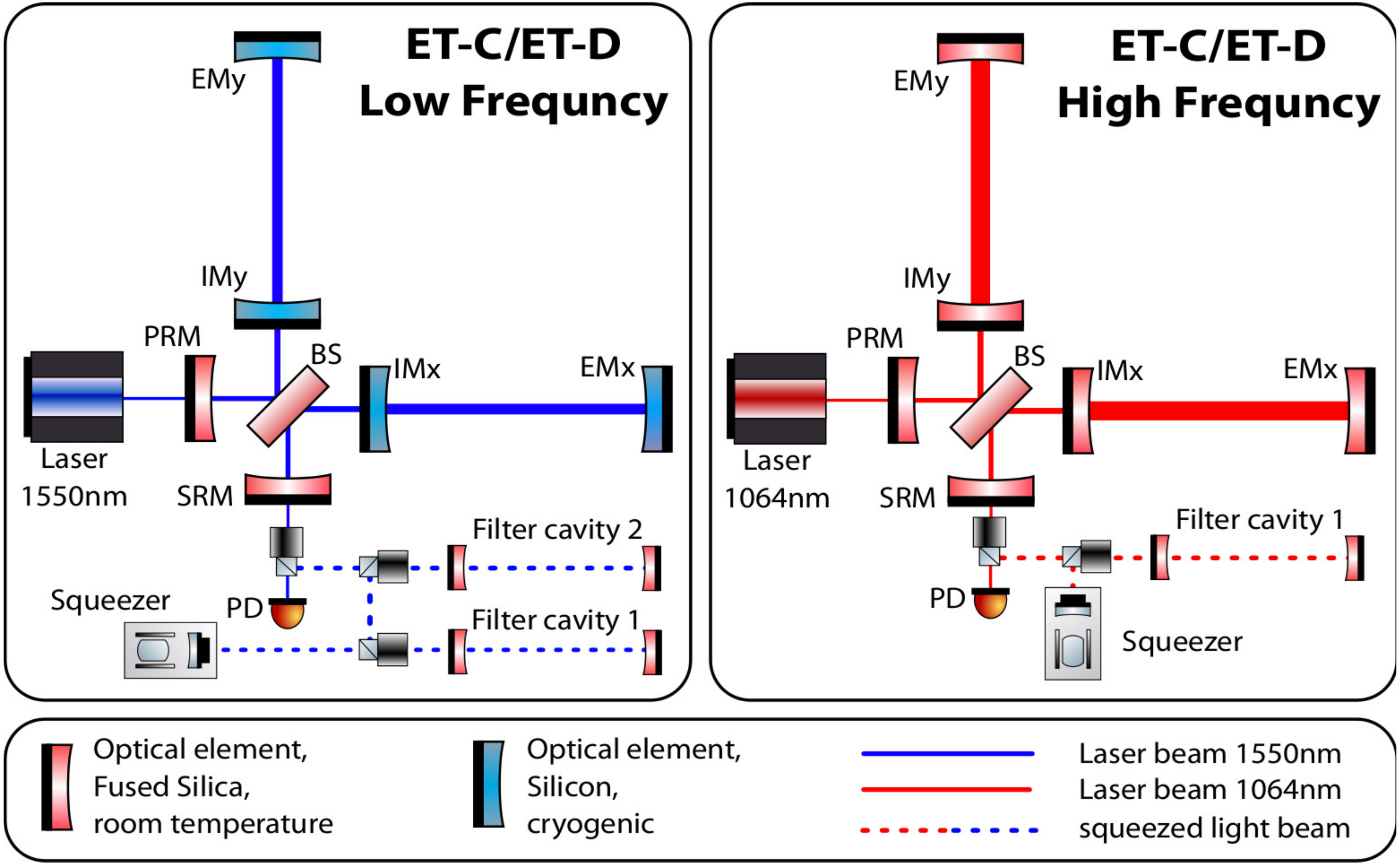
- **Where it all starts: … the sensitivity target.**
- **ET-D quickly explained**
- **From ET-D to the full ET observatory**
- **ET optical layout:**
  - ➢ Arm cavity design
  - ➢ Central interferometer design

The starting point for *'everything'* …

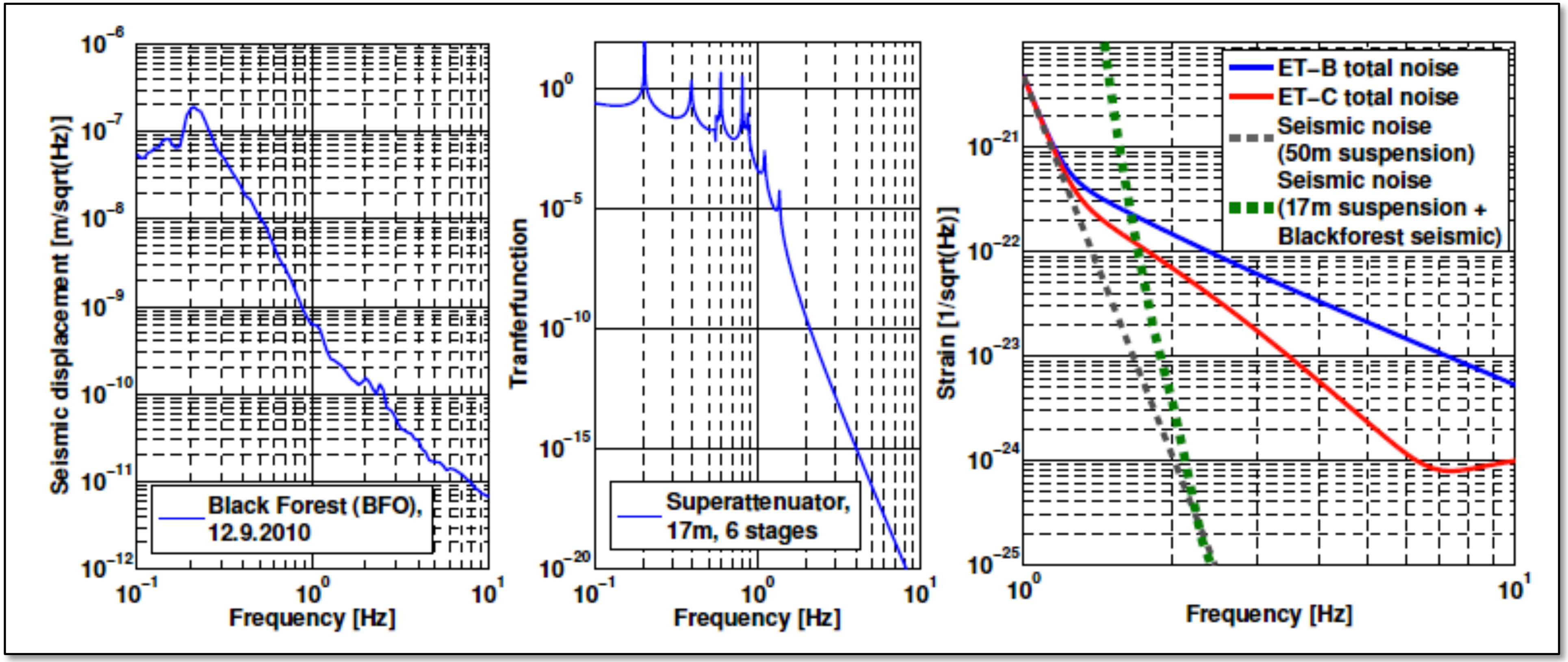
- **At the current stage of the design nearly everything is done for sensitivity reasons.**
- **Evolution of ET sensitivity curves:**
  - ET-B: Single broadband detector
    arXiv:0810.0604v2 [gr-qc] (2008)
  - ET-C: first Xylophone approach
    CQG 27 (2010) 015003
  - ET-D: refined Xylophone approach.



ET-C/ET-D Core interferometers



Seismic noise



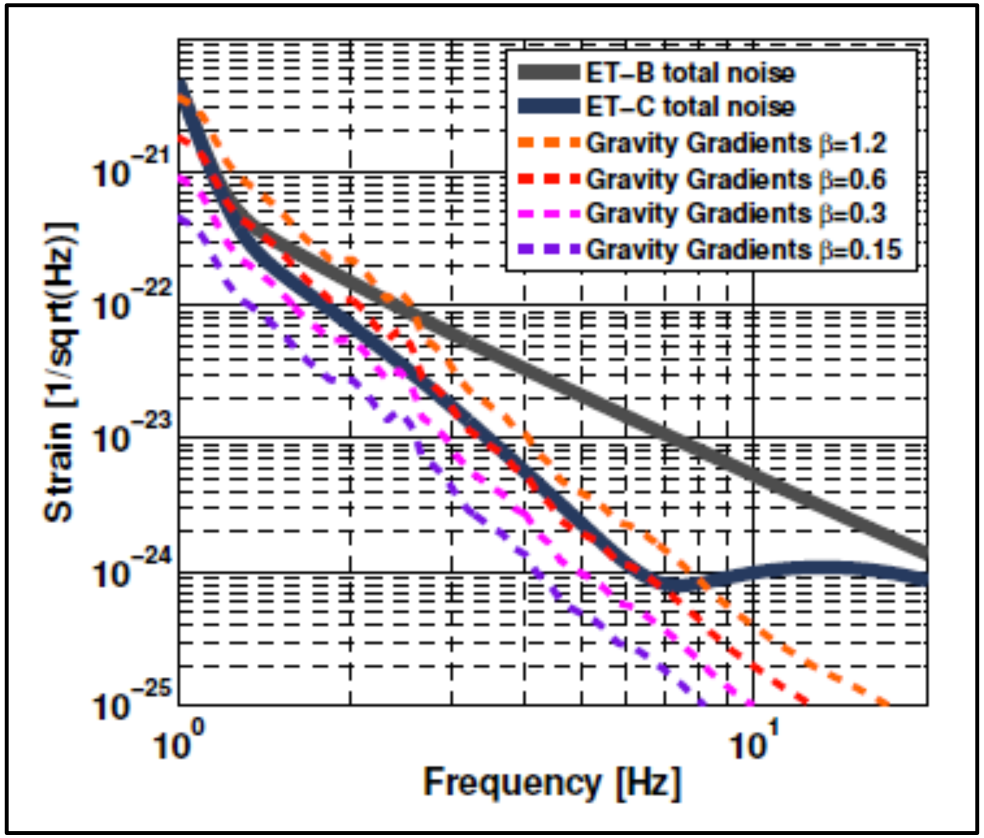
Seismic excitation x **17m SA Transfer function** = **Seismic noise contribution**

S.Braccini et al: presentation at GWADW 2010, Kyoto.

Gravity Gradient Noise

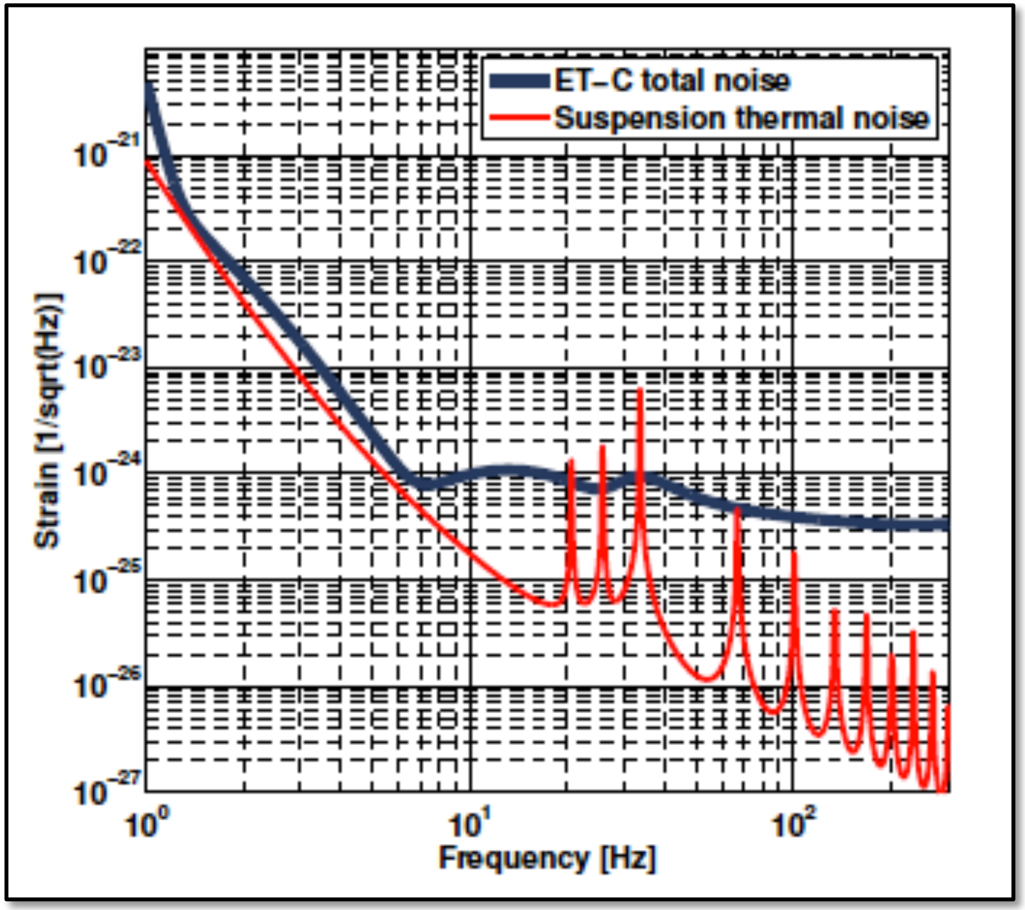
- **ET-B and ET-C assume a medium quiet site + factor 50 GGN subtraction.**
- **ET-D considers very quiet underground site (about 5e-10/f2*m/sqrt(Hz)) at Black Forest.**
- **Please note:**
  - ET measurement campaign showed several sites on the same level or even better than the BFO site (see talk by M.Beker).
  - Biggest uncertainty in beta

$$N_{GG}(f)^2 = \frac{4 \cdot \beta^2 \cdot G^2 \cdot \rho_r^2}{L^2 \cdot f^4} \cdot X_{\mathrm{seis}}^2,$$



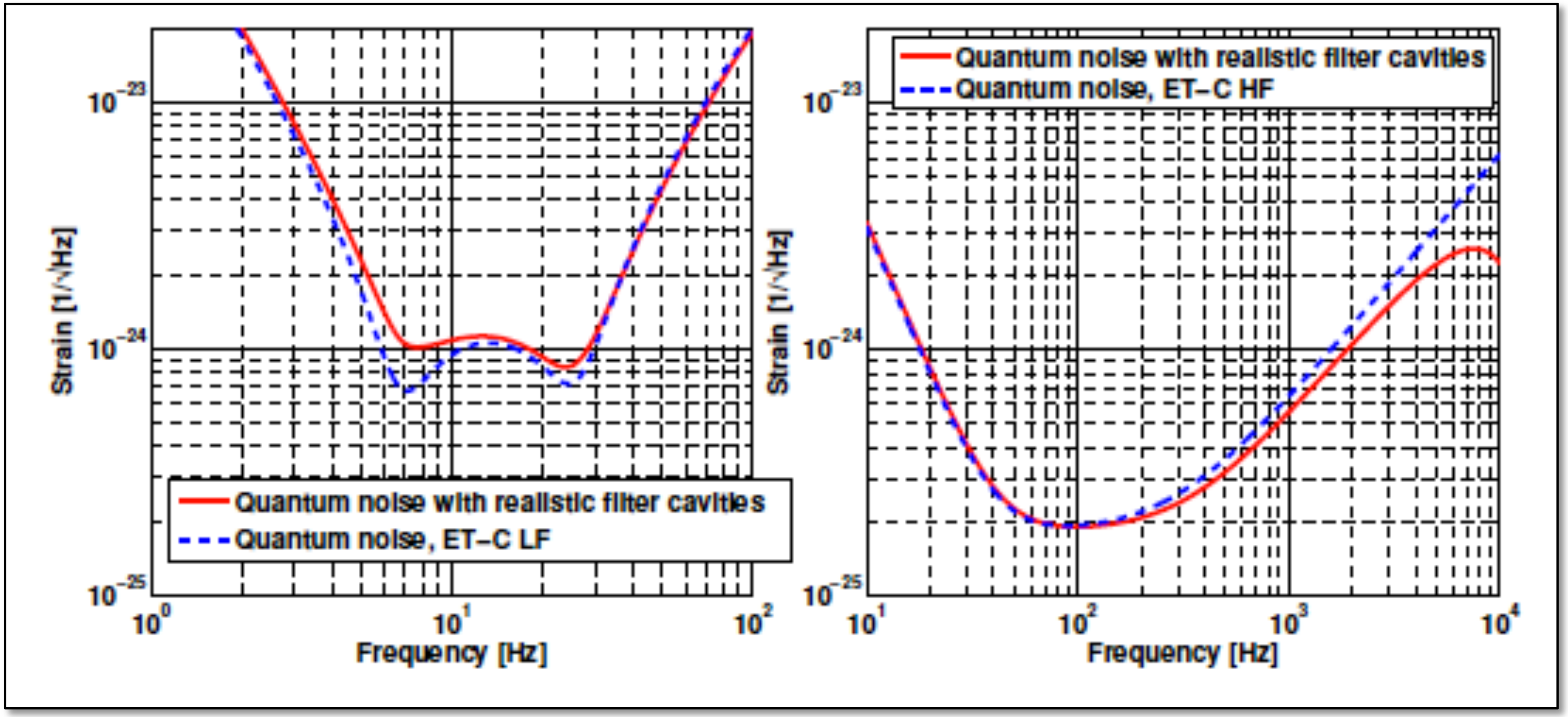
Suspension Thermal Noise

- **Silicon fibers of 3mm diameter and 2m length.**
- **Test mass temperature = 10K**
- **Penulitmate mass temperature = 2K**



- P. Puppo, Journal of Physics: Conference Series 228, (2010) 012031
- P. Puppo and F. Ricci, General Relativity and Gravitation, Springer Netherlands, 2010, 1-13
- F.Ricci, presentation at GWADW 2010,Kyoto. Available at:http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Ricci.pdf

Squeezing losses in filter cavities



See talk by Andre Thuering

Summary of ET-D parameters

Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	Fused Silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ TBD
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×10 km	2×10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	none

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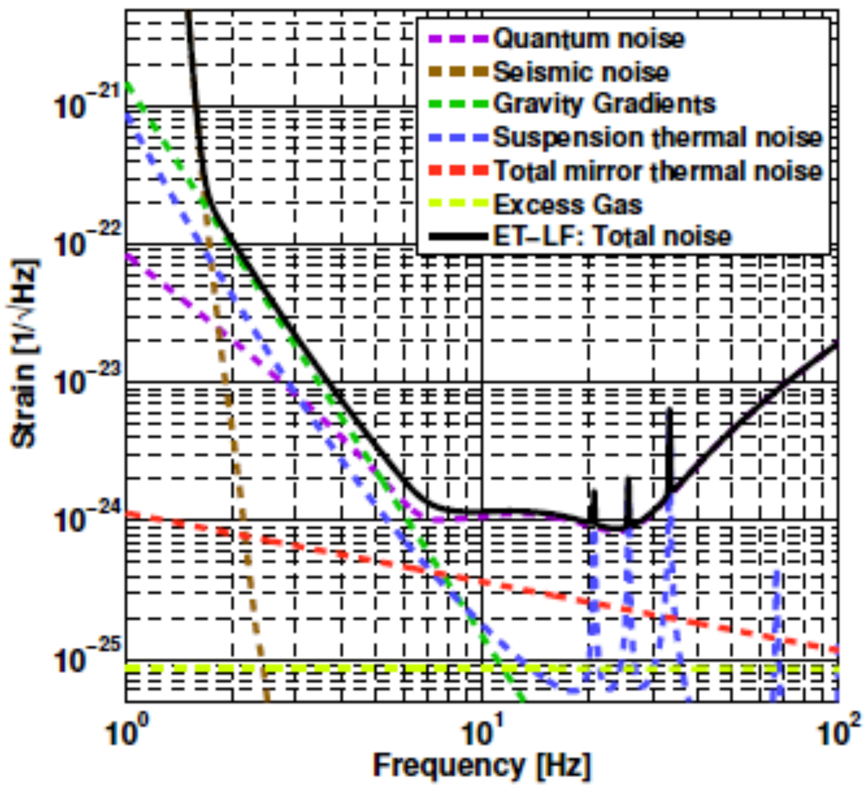
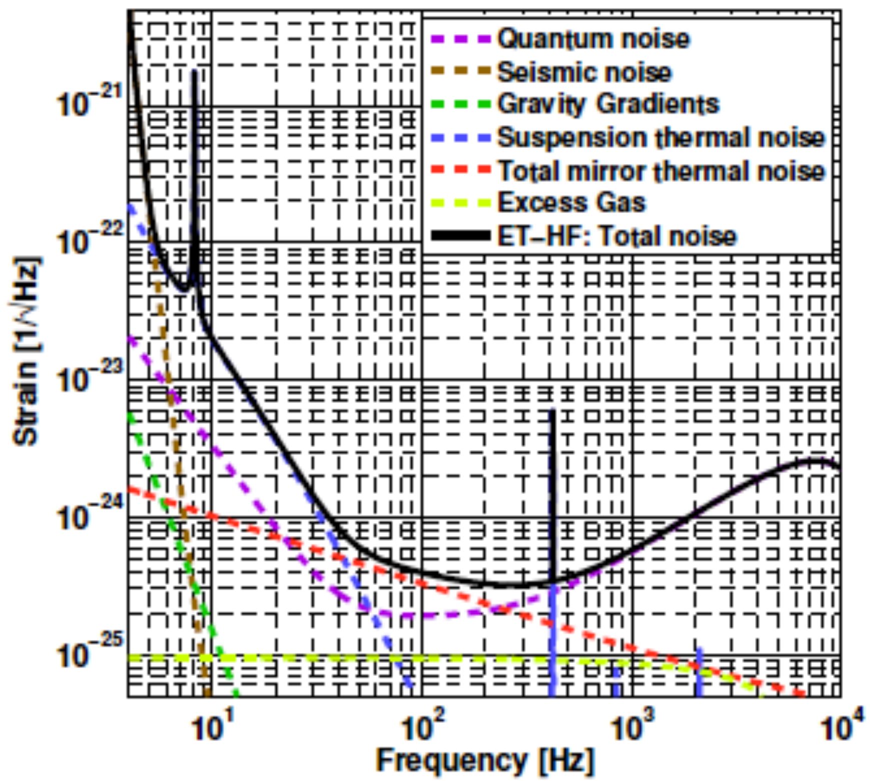
Important for the later
Part of this talk

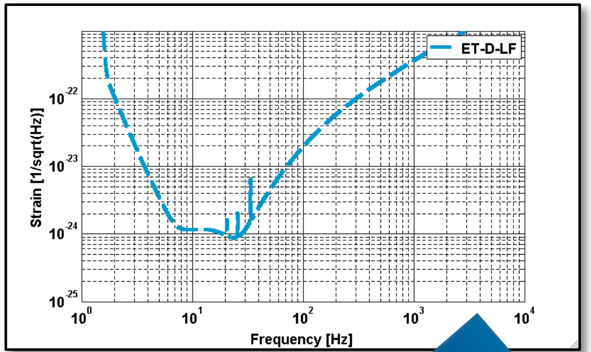
ET-D Noise budgets

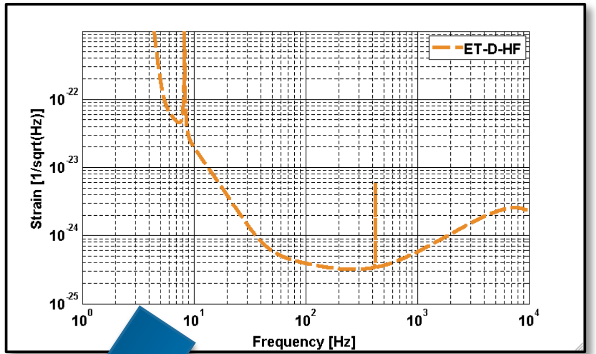




ET-D-LF **ET-D-HF**

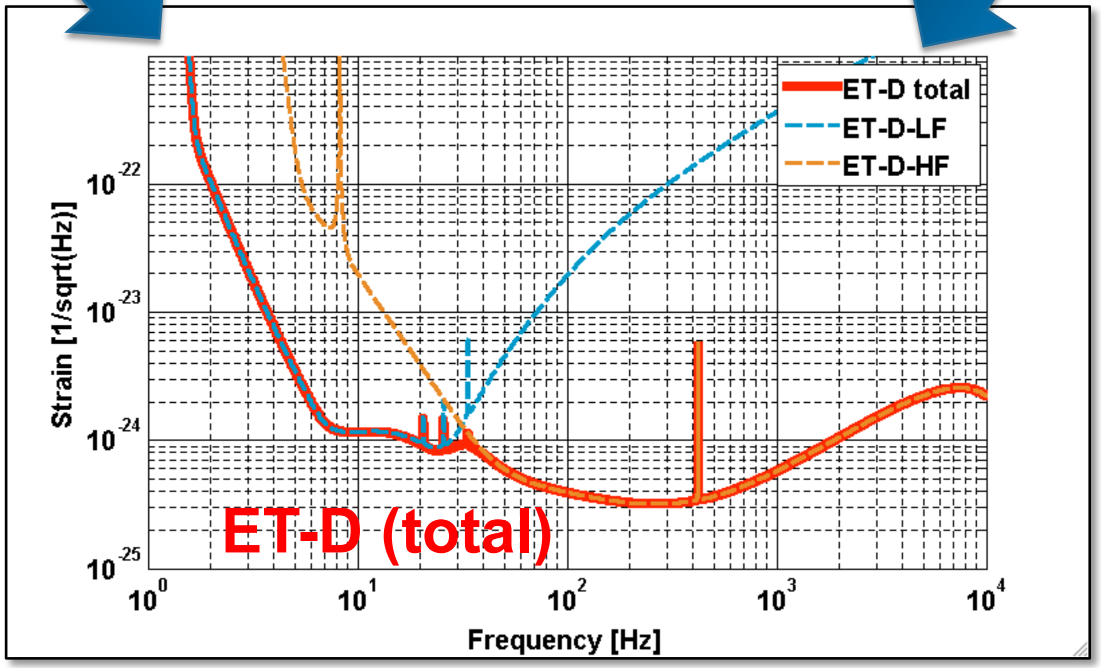
Combining the two interferometers





ET-D-LF

ET-D-HF



Overview

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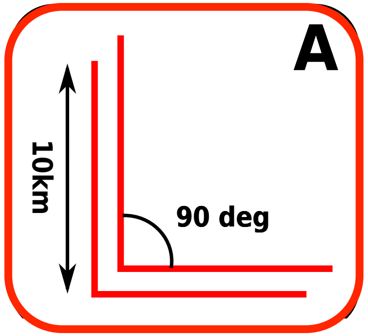
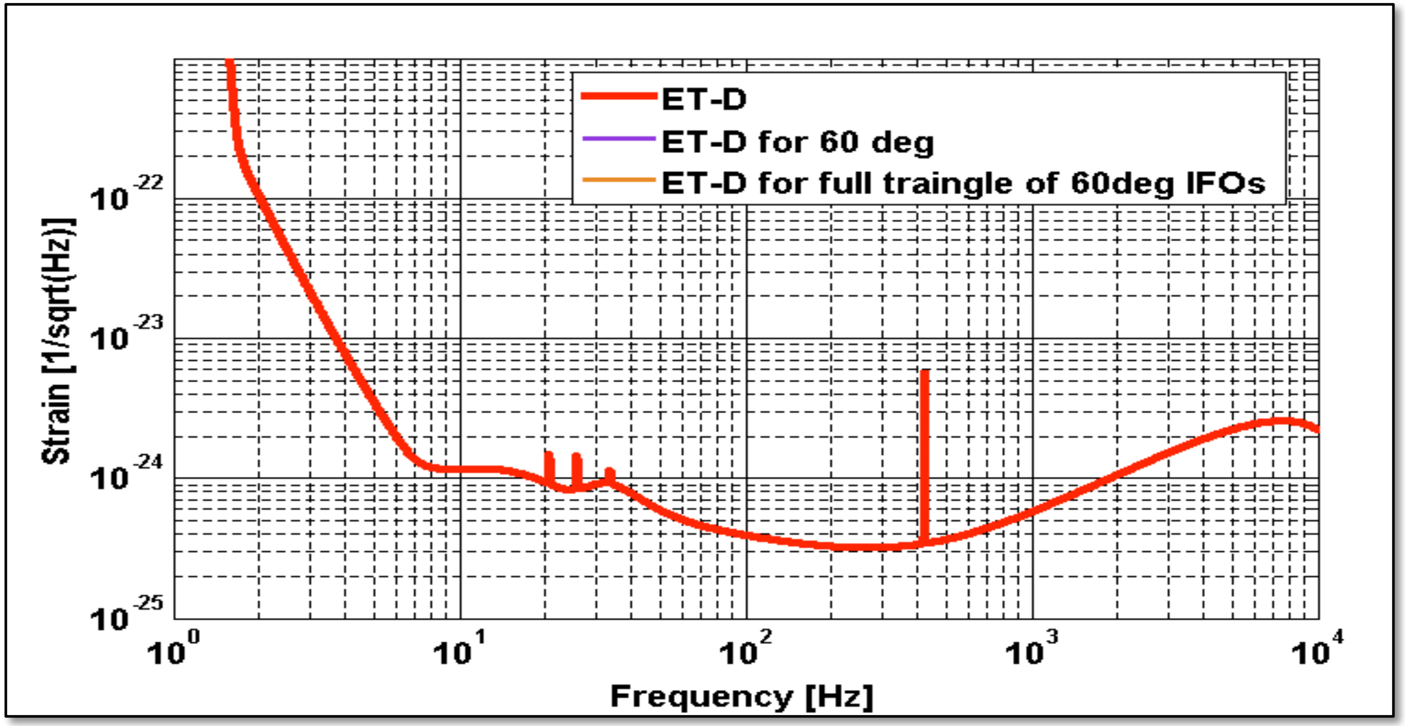
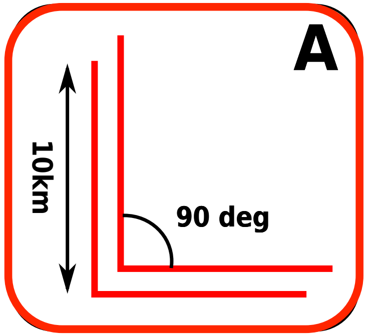
- **ET-D quickly explained**
- **From ET-D to the full ET observatory**
- **ET optical layout:**
  - ➢ Arm cavity design
  - ➢ Central interferometer design

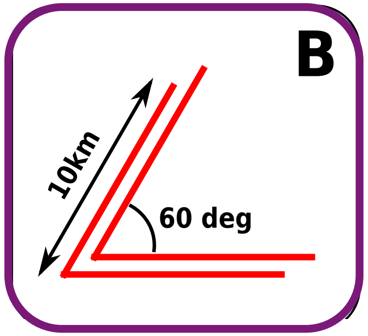
The full ET Observatory

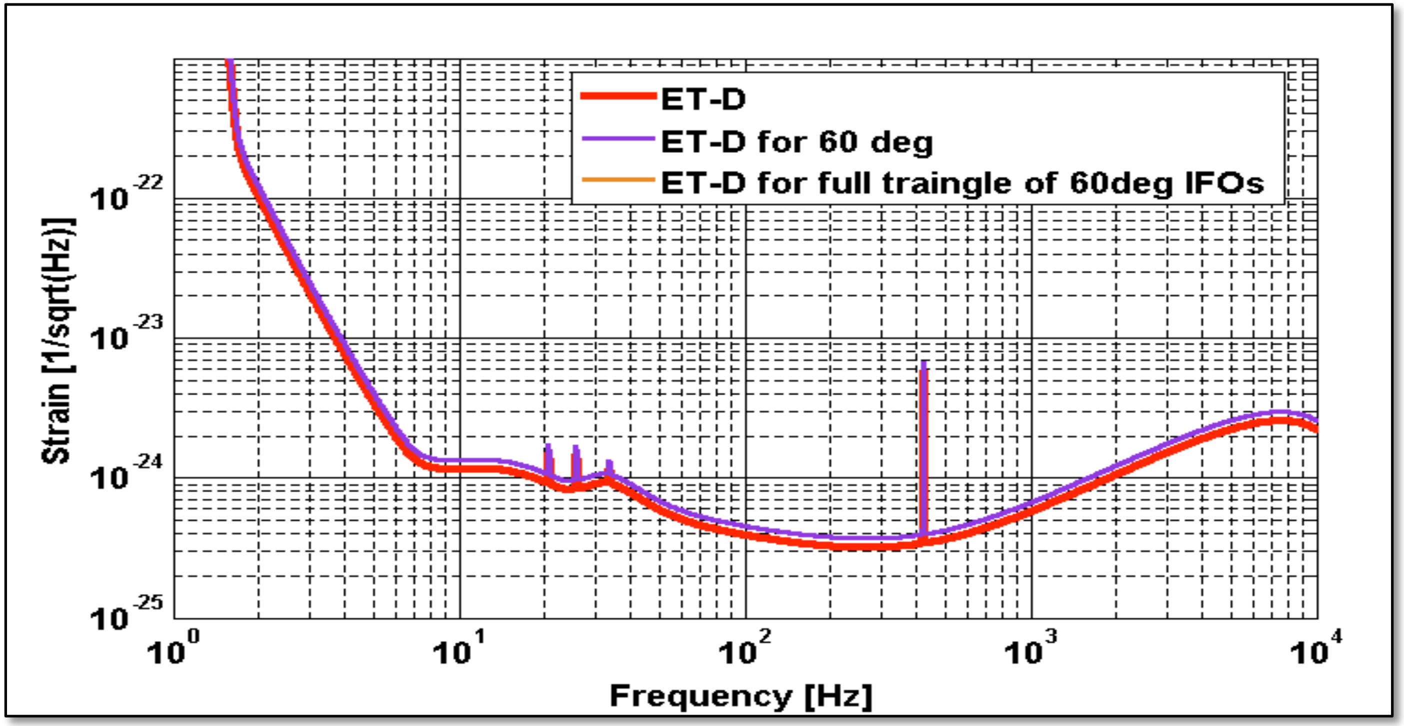




The full ET Observatory

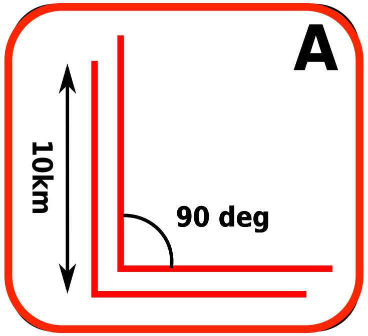


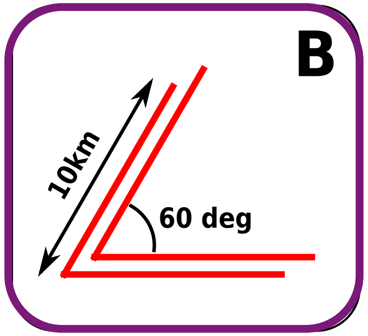


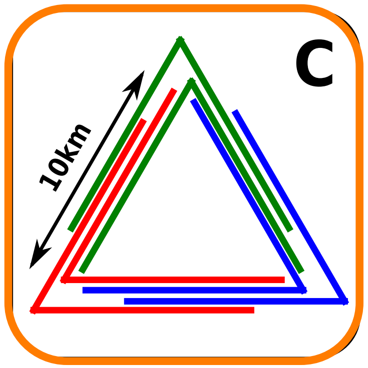


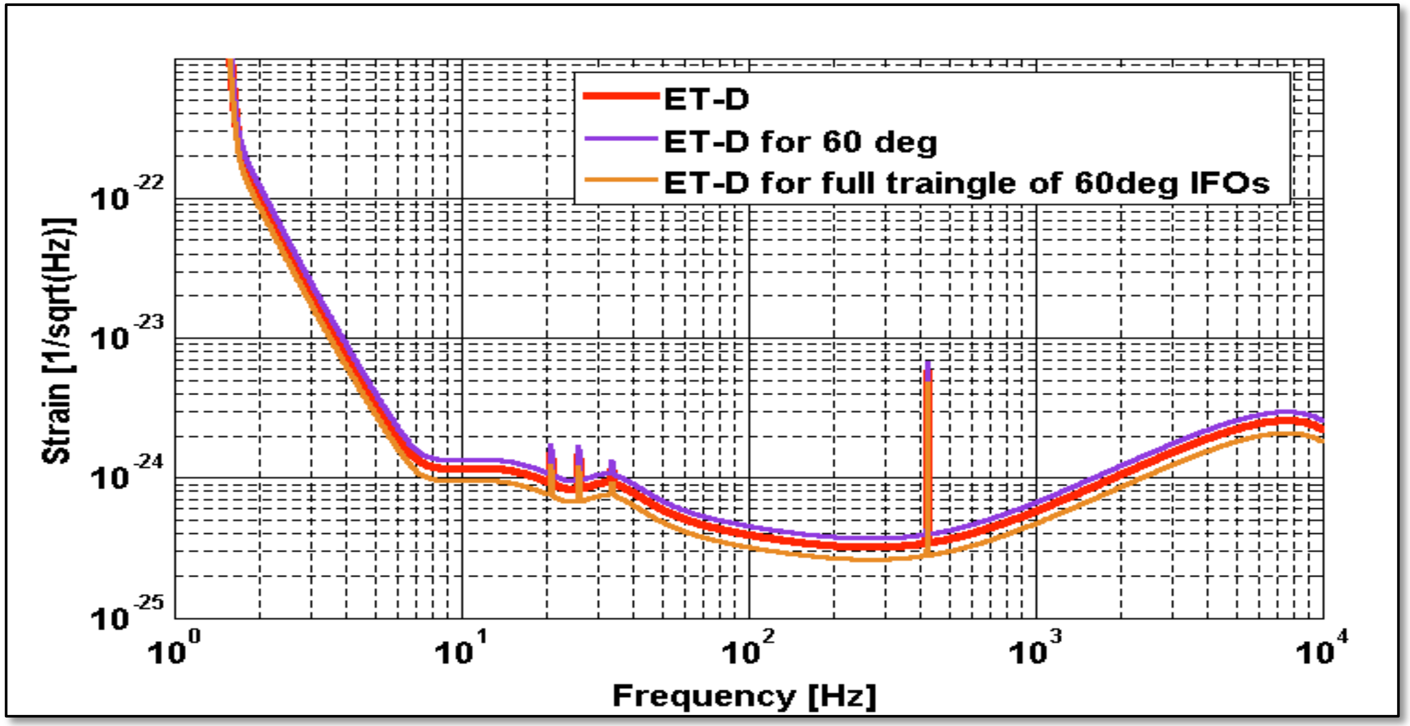
$$h(f)_{60} = \frac{1}{\sin(60^\circ)} \times h(f)_{90} = 1.155 \times h(f)_{90},$$

The full ET Observatory





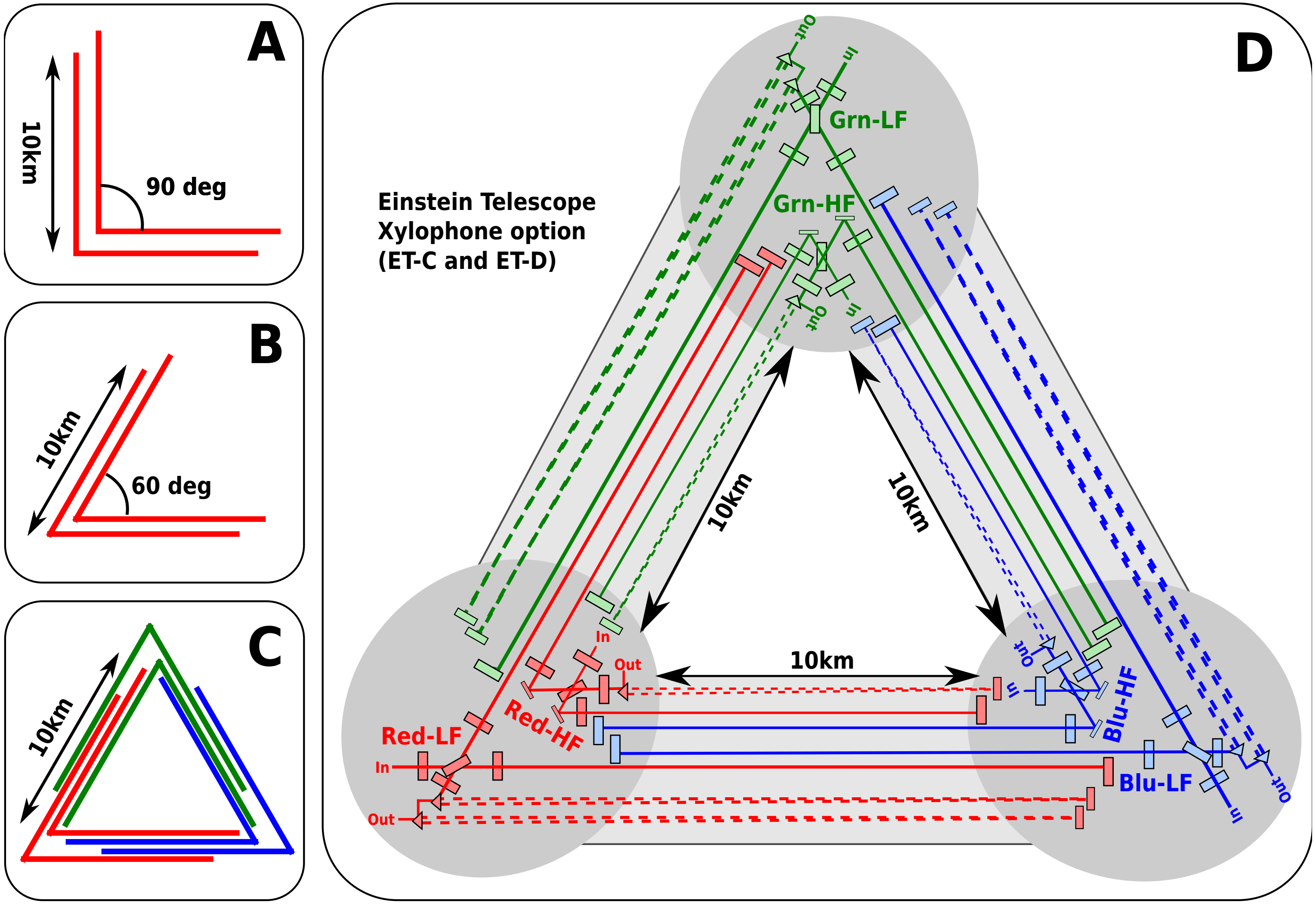




$$h(f)_{60} = \frac{1}{\sin(60^\circ)} \times h(f)_{90} = 1.155 \times h(f)_{90},$$

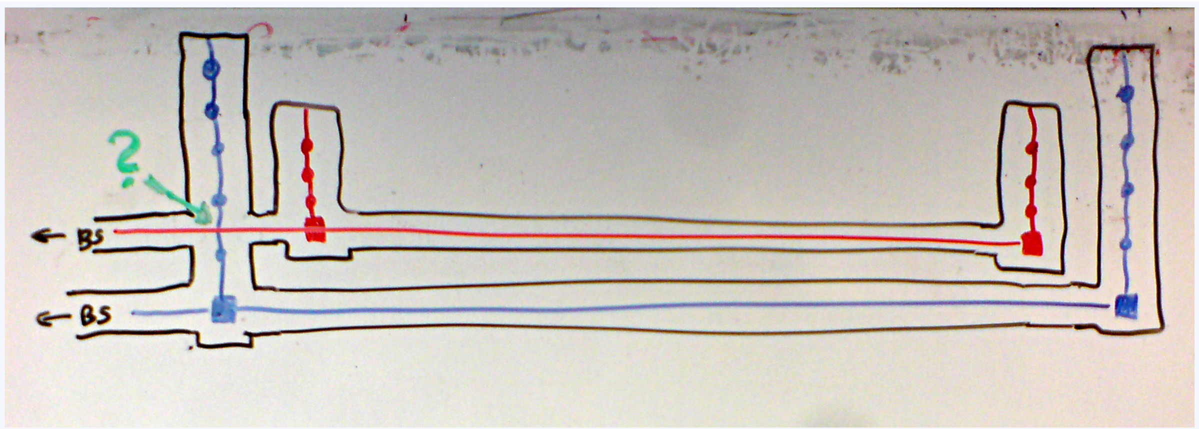
$$h(f)_{\Delta} = \frac{1}{\sqrt{(\sin(60^\circ))^2 + (\sin(60^\circ))^2}} \times h(f)_{90} = 0.816 \times h(f)_{90},$$

The full ET Observatory

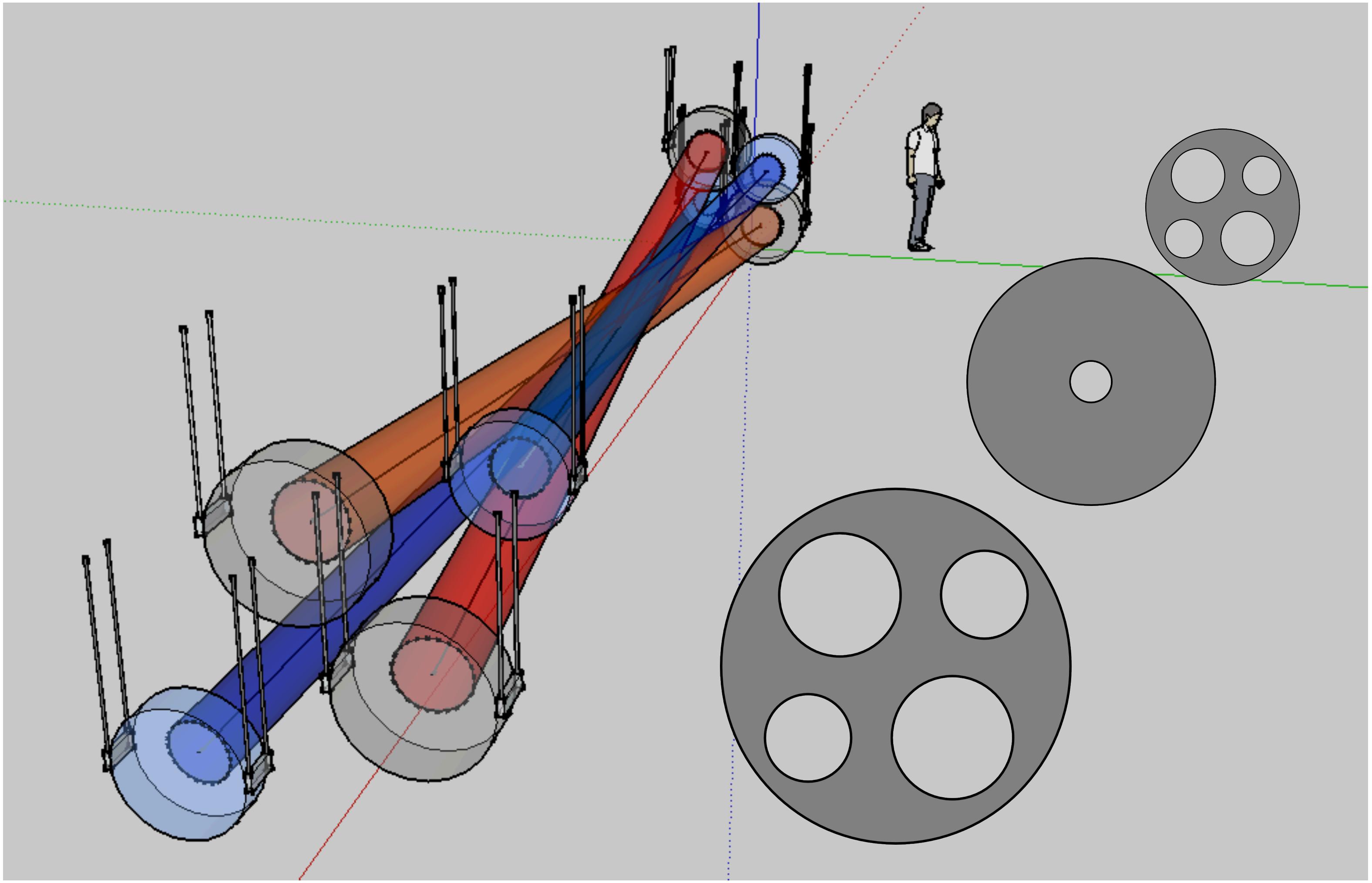


Can Laser Beams pass a suspension?

- **Can we pass one ifo beam through suspension of another ifo?**
- **In principle that does not sound impossible, perhaps rather an engineering task.**
- **If you do not want to cross the main arm cavities there is no way to avoid one input beam passing suspension of another ifo.**



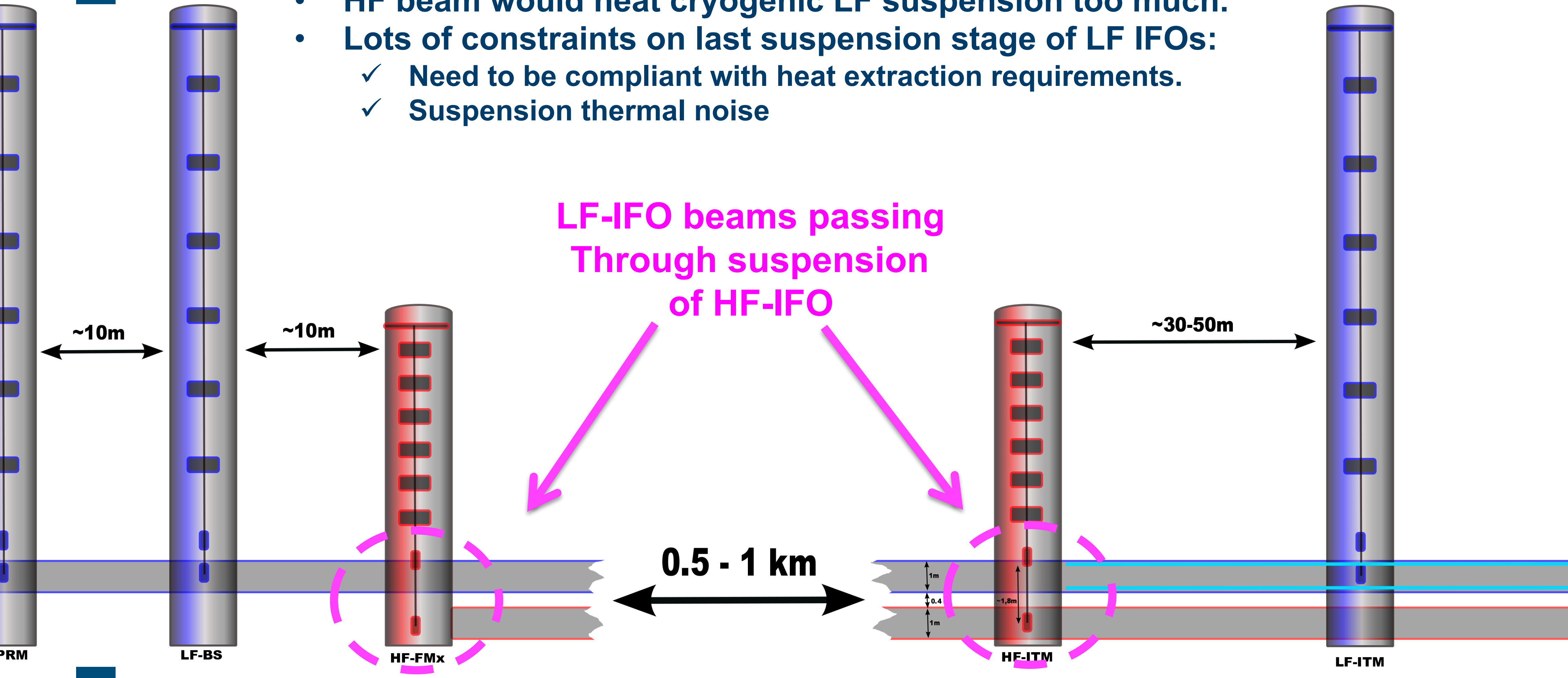
Crossed beams in a single 2m-tube?



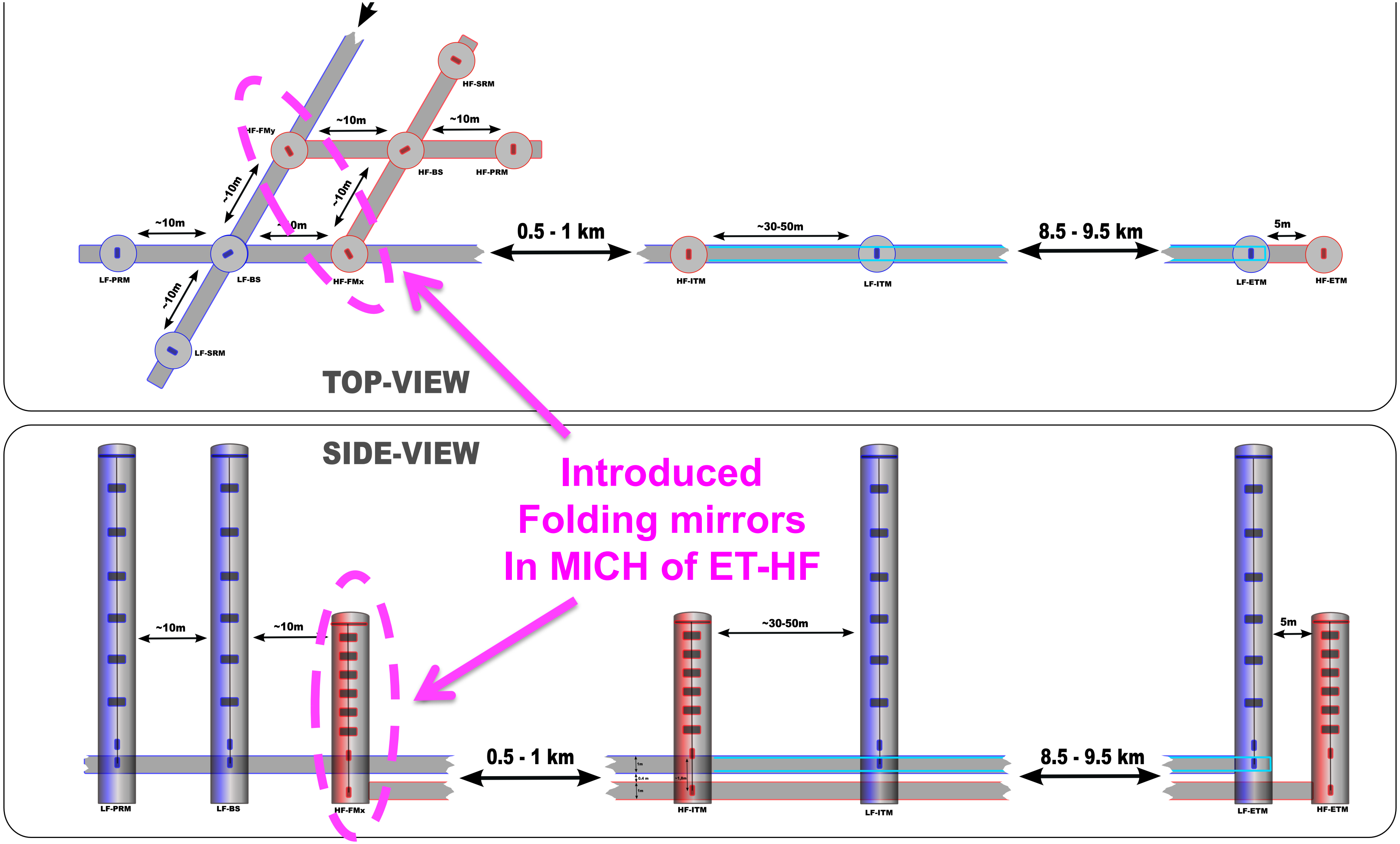
For details please see: http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Freise.pptx
http://gw.icrr.u-tokyo.ac.jp/gwadw2010/program/2010_GWADW_Hild_v2.pdf

IFO beams passing through suspensions

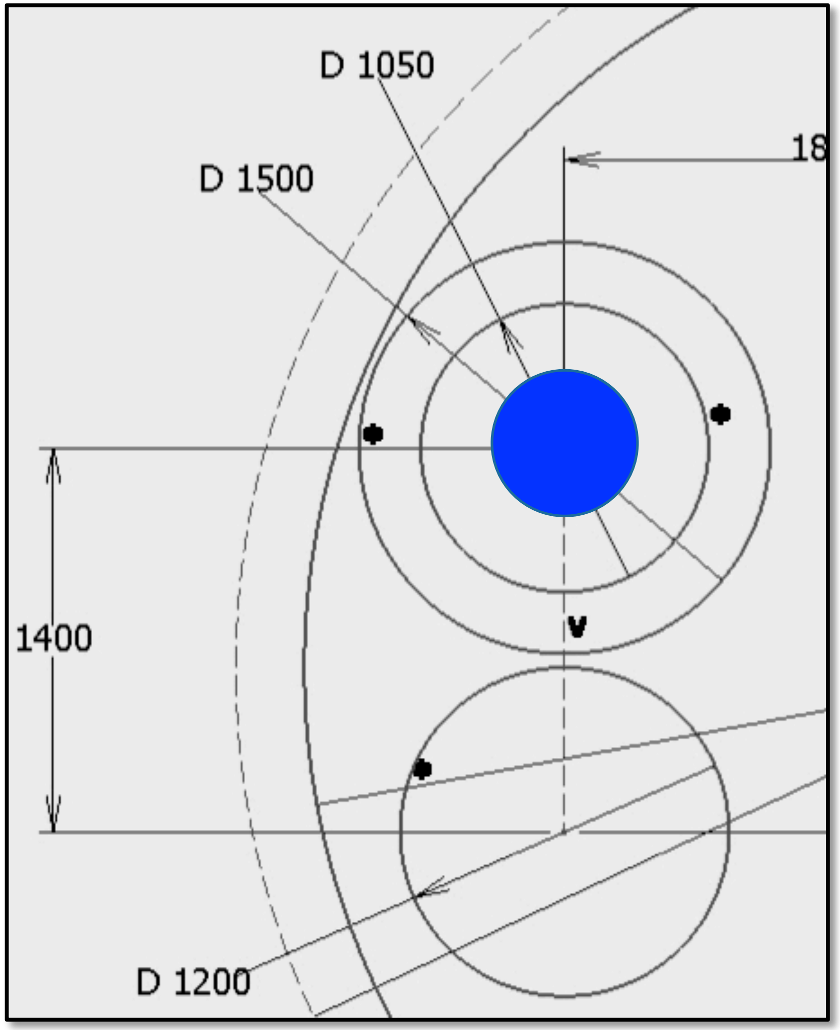
- **HF through LF suspension or vice versa?**
- **HF beam would heat cryogenic LF suspension too much.**
- **Lots of constraints on last suspension stage of LF IFOs:**
  - ✓ **Need to be compliant with heat extraction requirements.**
  - ✓ **Suspension thermal noise**



2 detectors on top of each other

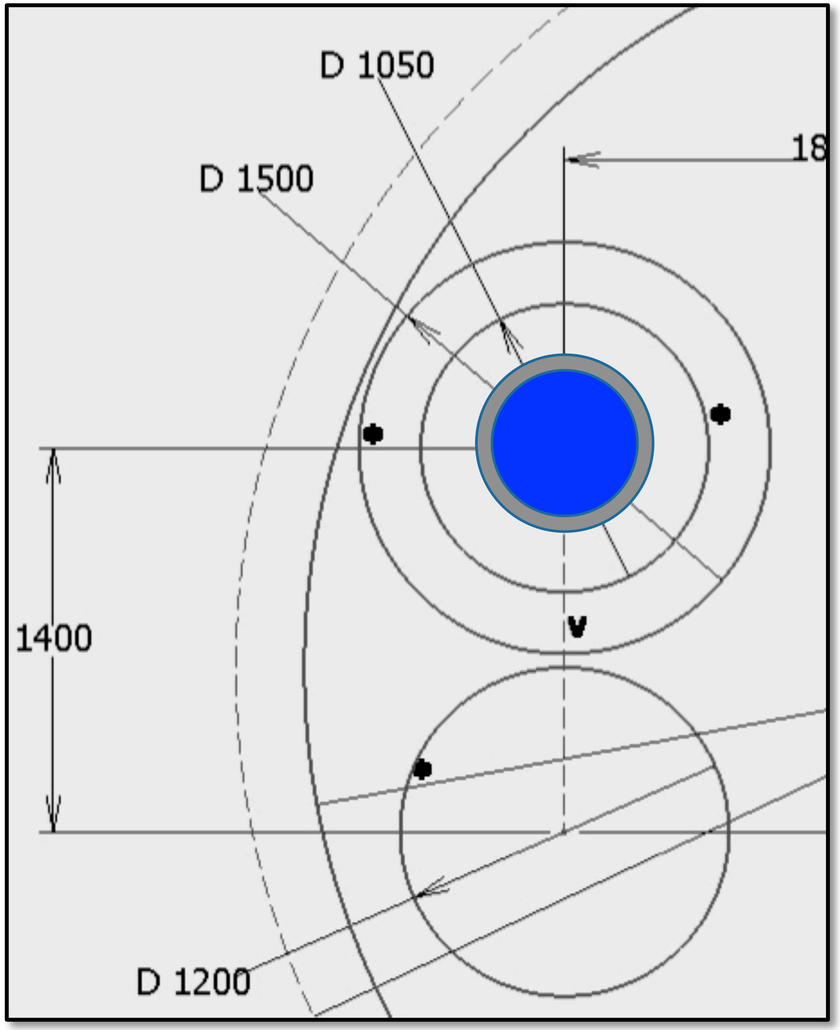


Required space for individual IFOs



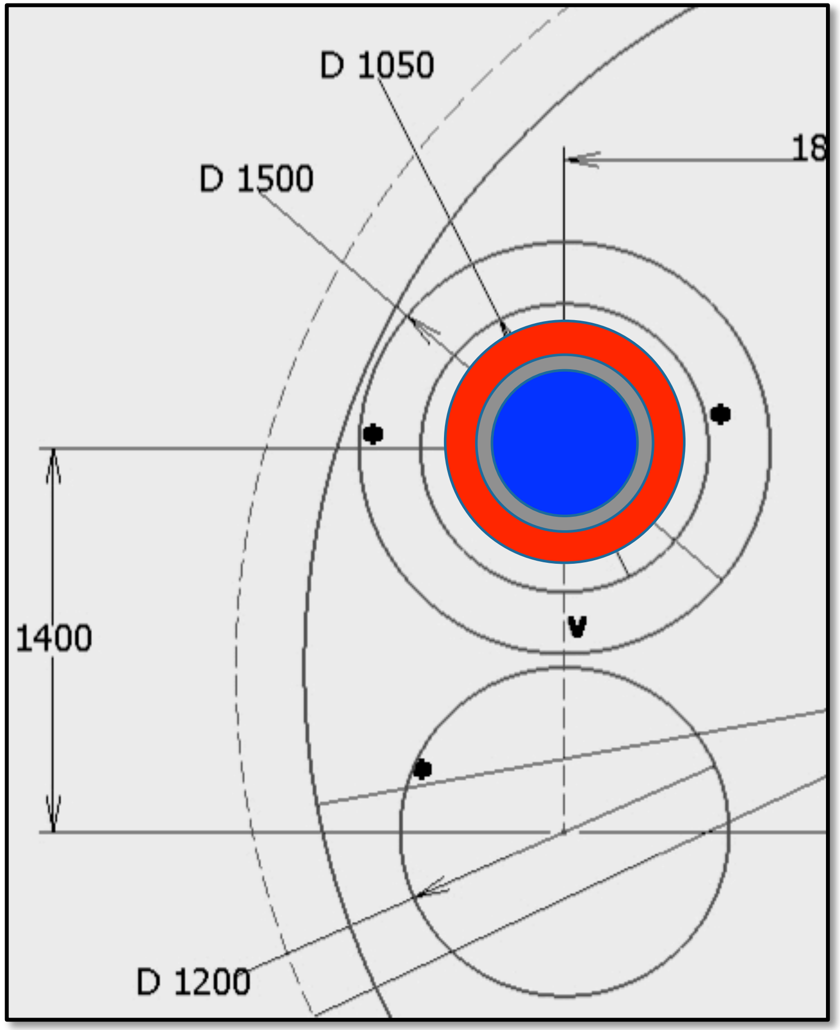
- **ET-LF:**
  - 45cm free aperture

Required space for individual IFOs



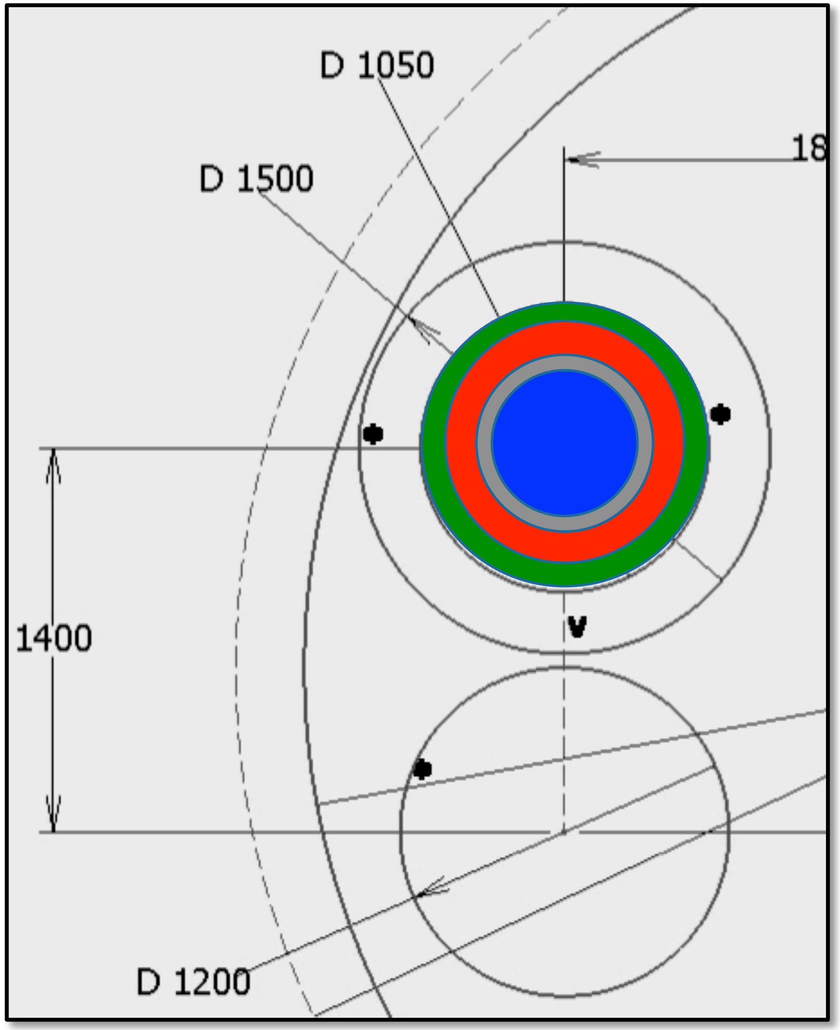
- **ET-LF:**
  - 45cm free aperture
  - 2x5cm free space

Required space for individual IFOs



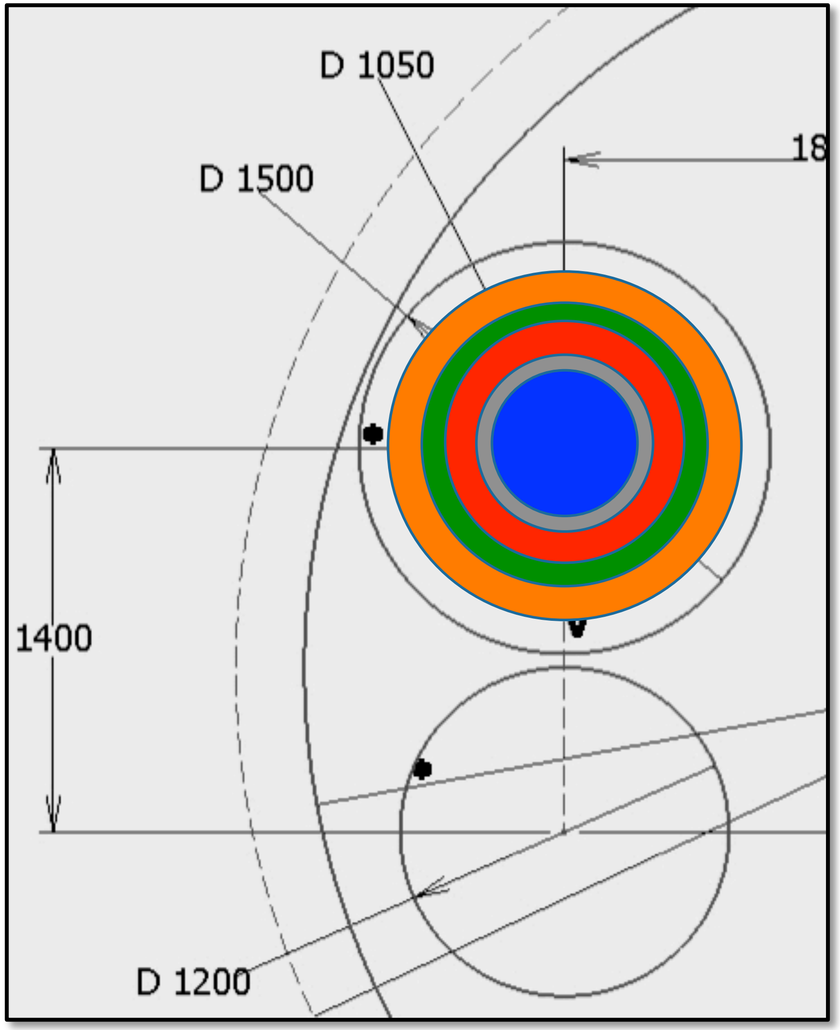
- **ET-LF:**
  - 45cm free aperture
  - 2x5cm free space
  - 2x10cm baffles

Required space for individual IFOs



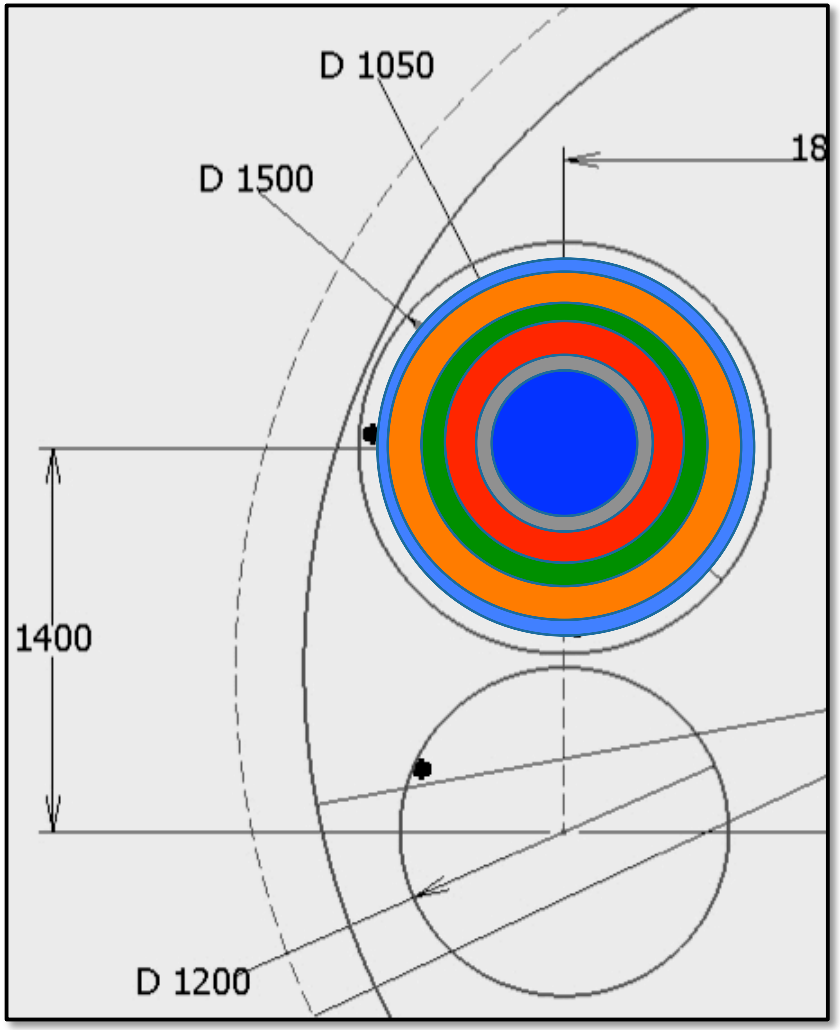
- **ET-LF:**
  - 45cm free aperture
  - 2x5cm free space
  - 2x10cm baffles
  - 2x10cm liquid helium reservoir

Required space for individual IFOs



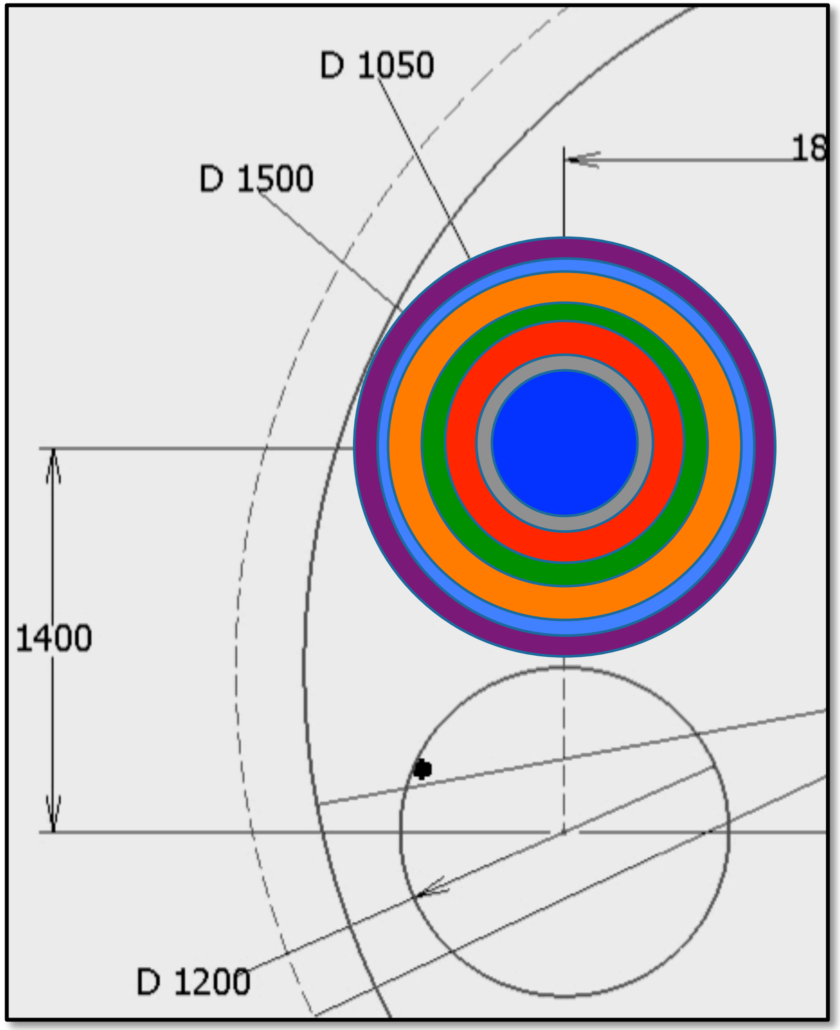
- **ET-LF:**
  - 45cm free aperture
  - 2x5cm free space
  - 2x10cm baffles
  - 2x10cm liquid helium reservoir
  - 2x10cm liquid nitrogen reservoir

Required space for individual IFOs



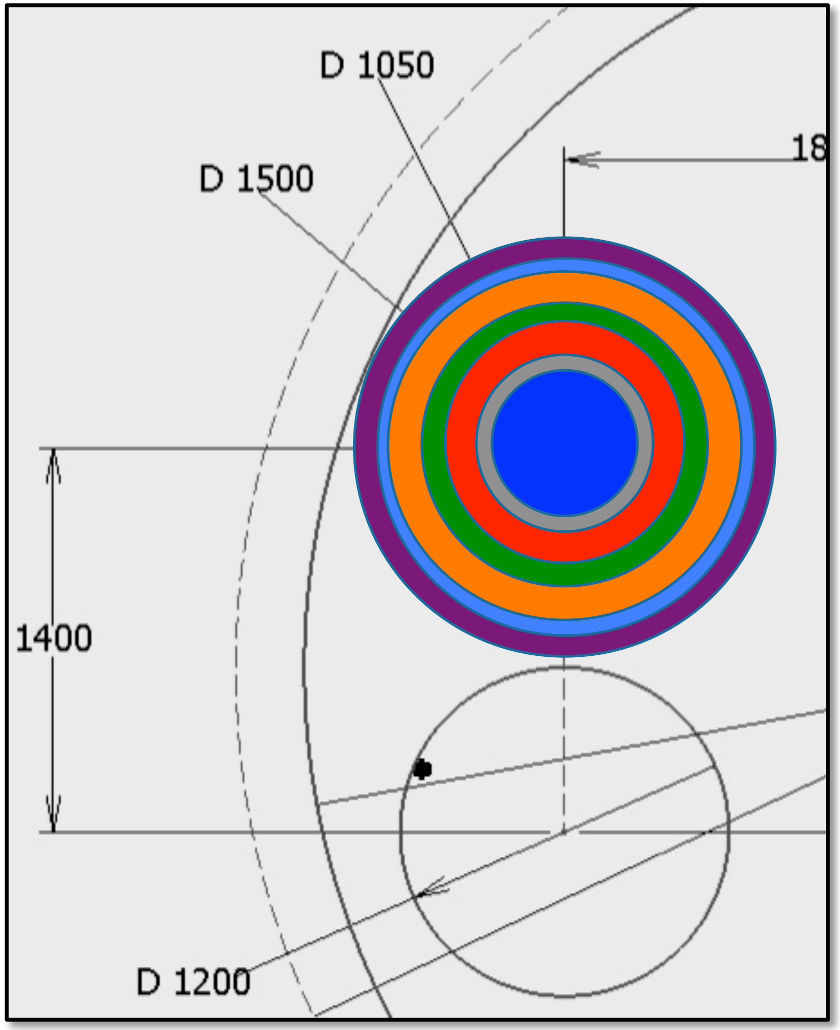
- **ET-LF:**
  - 45cm free aperture
  - 2x5cm free space
  - 2x10cm baffles
  - 2x10cm liquid helium reservoir
  - 2x10cm liquid nitrogen reservoir
  - 2x8cm tube wall + reinforcement ribs

Required space for individual IFOs



- **ET-LF:**
  - 45cm free aperture
  - 2x5cm free space
  - 2x10cm baffles
  - 2x10cm liquid helium reservoir
  - 2x10cm liquid nitrogen reservoir
  - 2x8cm tube wall + reinforcement ribs
  - 2x10cm baking insulation

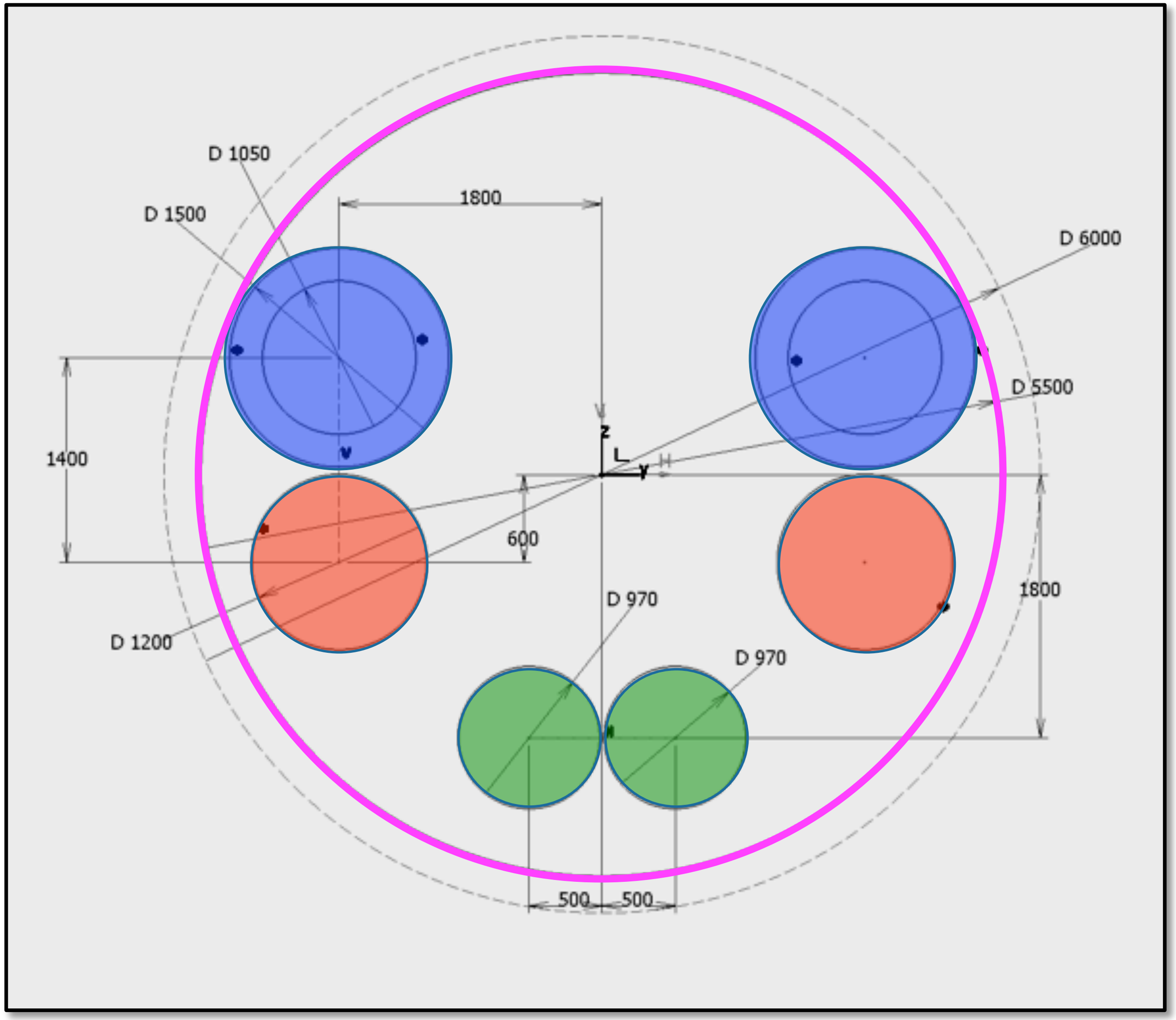
Required space for individual IFOs



- **ET-low frequency IFO:**
  - 45cm free aperture
  - 2x5cm free space
  - 2x10cm baffles
  - 2x10cm liquid helium reservoir
  - 2x10cm liquid nitrogen reservoir
  - 2x8cm tube wall + reinforcement ribs
  - 2x10cm baking insulation
- **Total diameter required = 151cm**

Tunnel Cross Section

- **LF IFOs = 150cm**
- **HF IFOs = 120cm**
- **Filter cavity = 97cm**
- **Tunnel inside = 550cm**



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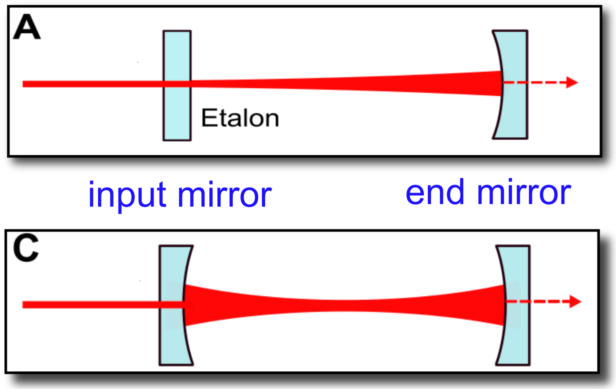
Arm cavity design

- **Arm cavities are hearts of ET => most important part of ET.**
- **To reduce coating thermal noise we have to make the beams on the test masses large.**



$$S_x(f) = \frac{4k_B T}{\pi^2 f Y} \frac{d}{r_0^2} \left(\frac{Y'}{Y} \phi_{||} + \frac{Y}{Y'} \phi_{\perp} \right)$$

Temperature
Boltzmann constant
Geometrical coating thickness
Loss angle of coating
Young's modulus of mirror substrate
laser beam radius
Young's modulus of coating

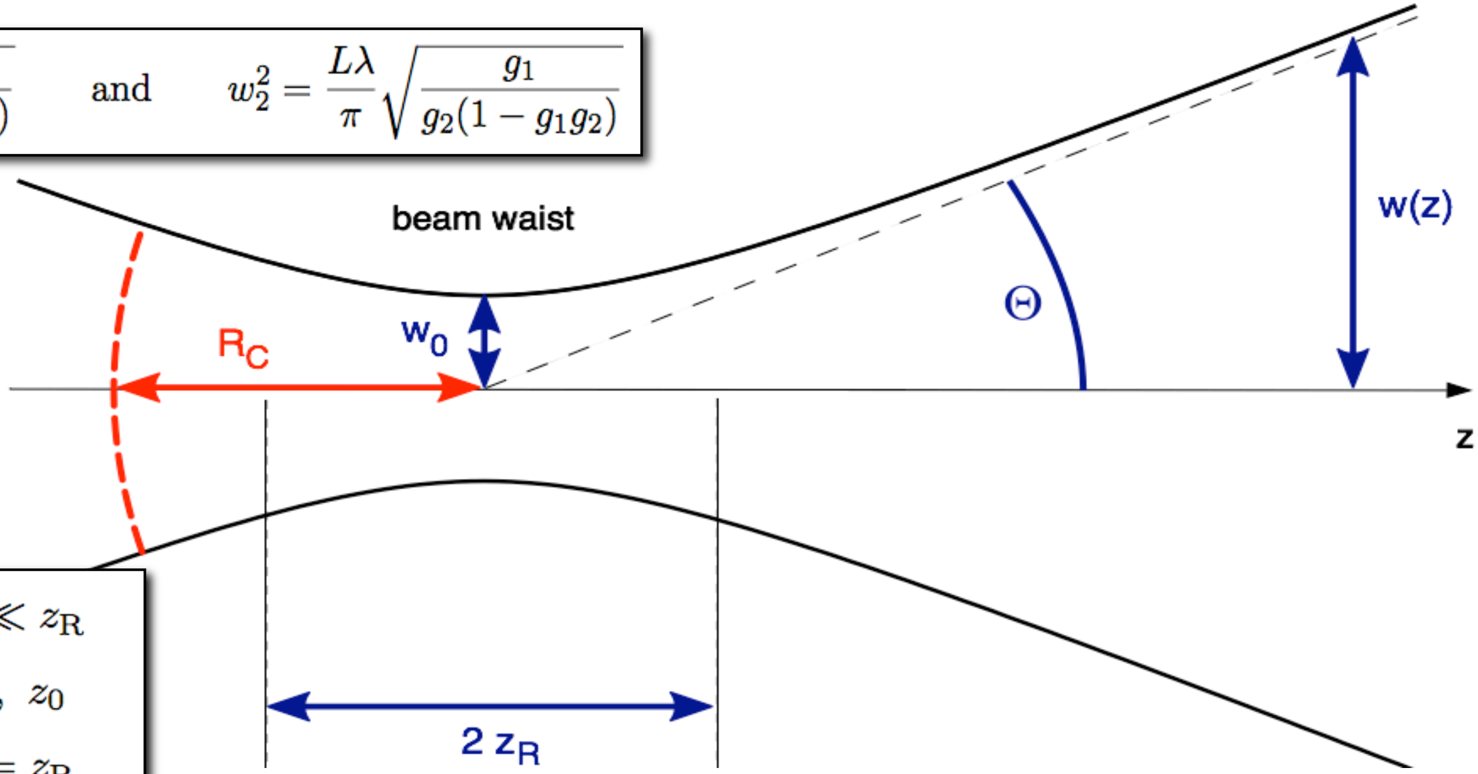
- **There is a minimal beam size possible (limited by divergence of beam).**
- **There are upper limits of the beam size:**
  - Available substrate size
  - Cavity stability

Gauss Beams in General

Slide stolen from A.Freise

$$g_1 = 1 - \frac{L}{R_{C1}} \quad \text{and} \quad g_2 = 1 - \frac{L}{R_{C2}}$$

$$w_1^2 = \frac{L\lambda}{\pi}\sqrt{\frac{g_2}{g_1(1-g_1 g_2)}} \quad \text{and} \quad w_2^2 = \frac{L\lambda}{\pi}\sqrt{\frac{g_1}{g_2(1-g_1 g_2)}}$$

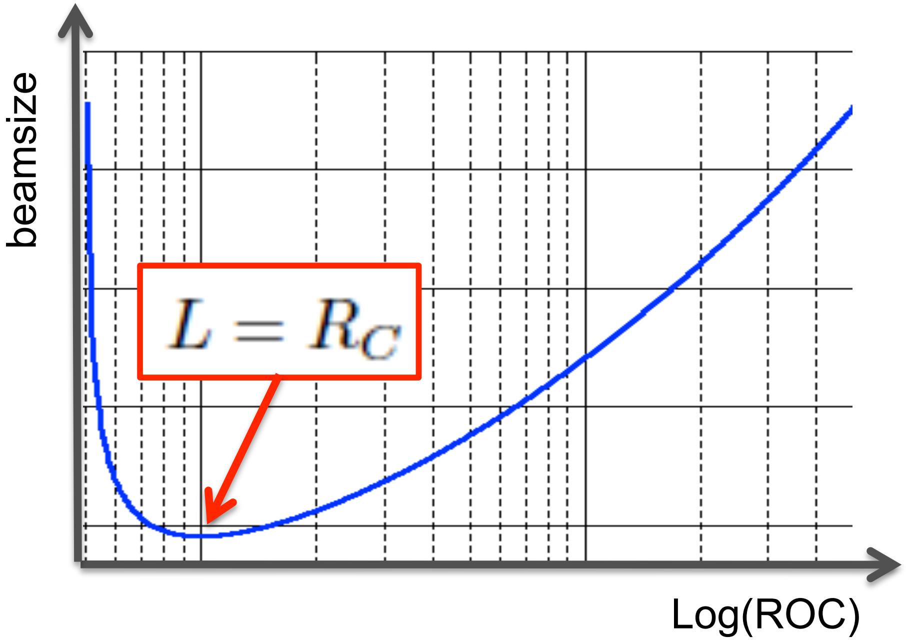


$$R_C \approx \infty, \quad z - z_0 \ll z_R$$

$$R_C \approx z, \quad z \gg z_R,\ z_0$$

$$R_C = 2z_R, \quad z - z_0 = z_R$$

Mininal Beam and Mirror Sizes



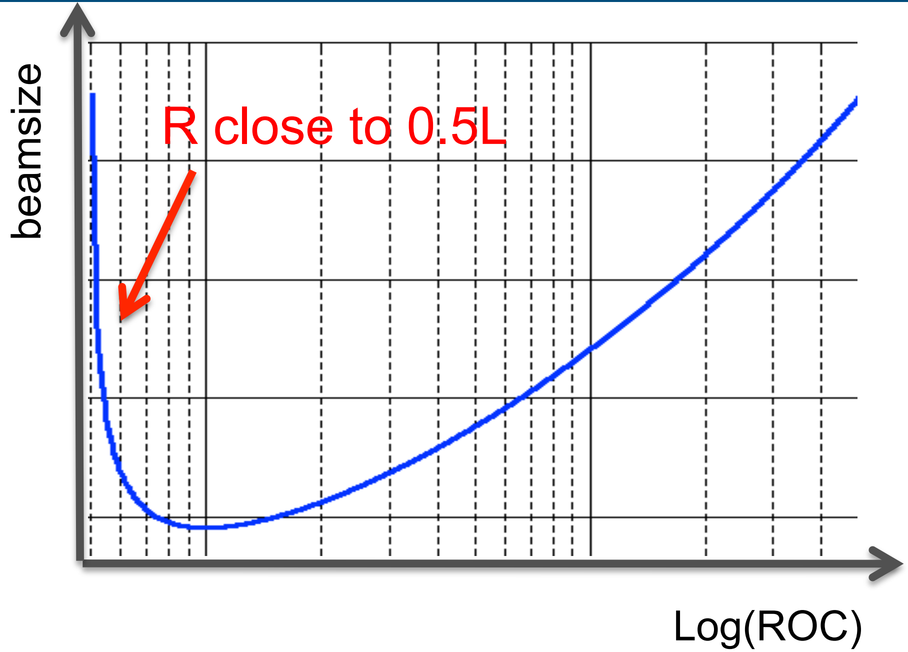
$$w_{\text{min}} = \sqrt{\frac{L\lambda}{\pi}}.$$

setup	min beam radius [cm]	min mirror diameter [cm]
LG33, 1064nm	5.8	50.2
LG00, 1550nm	7.0	37.0

For more details:
ET-0103B-10

Realistic beam sizes

- **Realistic beam and mirror sizes:**
  - Pushing to towards maximum available substrate size
  - Pushing to cavity instability

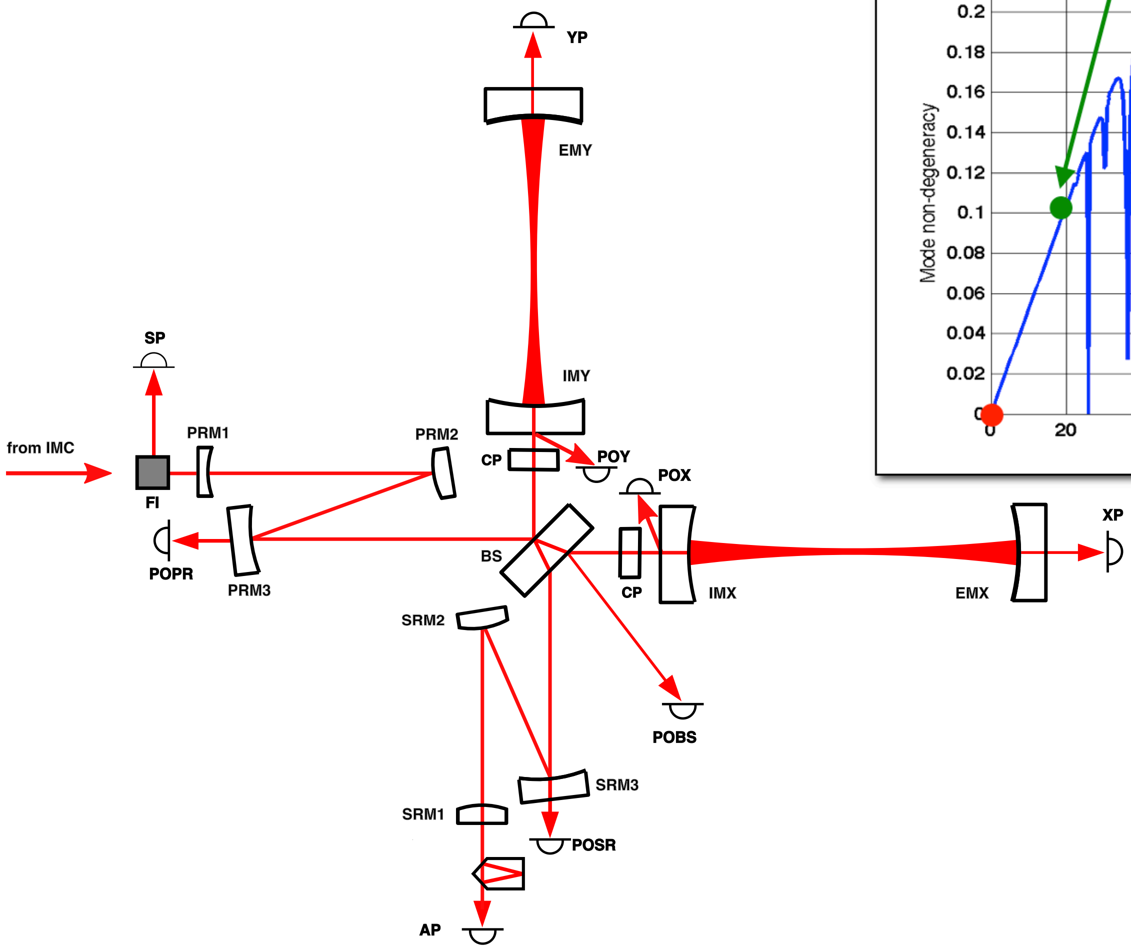


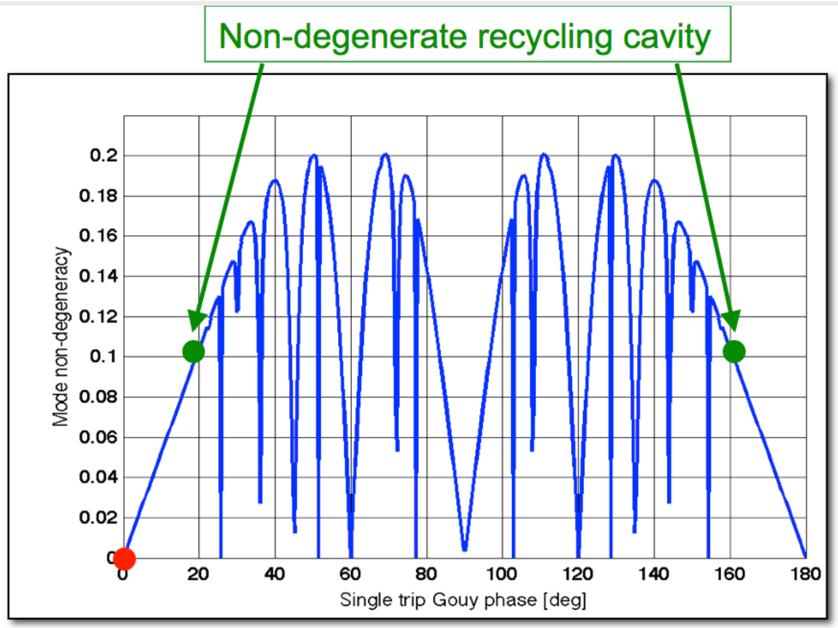
IFO	λ	beam shape	mirror diameter
ET-HF	1064 nm	LG_{33}	62 cm
ET-LF	1550 nm	TEM_{00}	45 cm

For more details:
ET-0103B-10

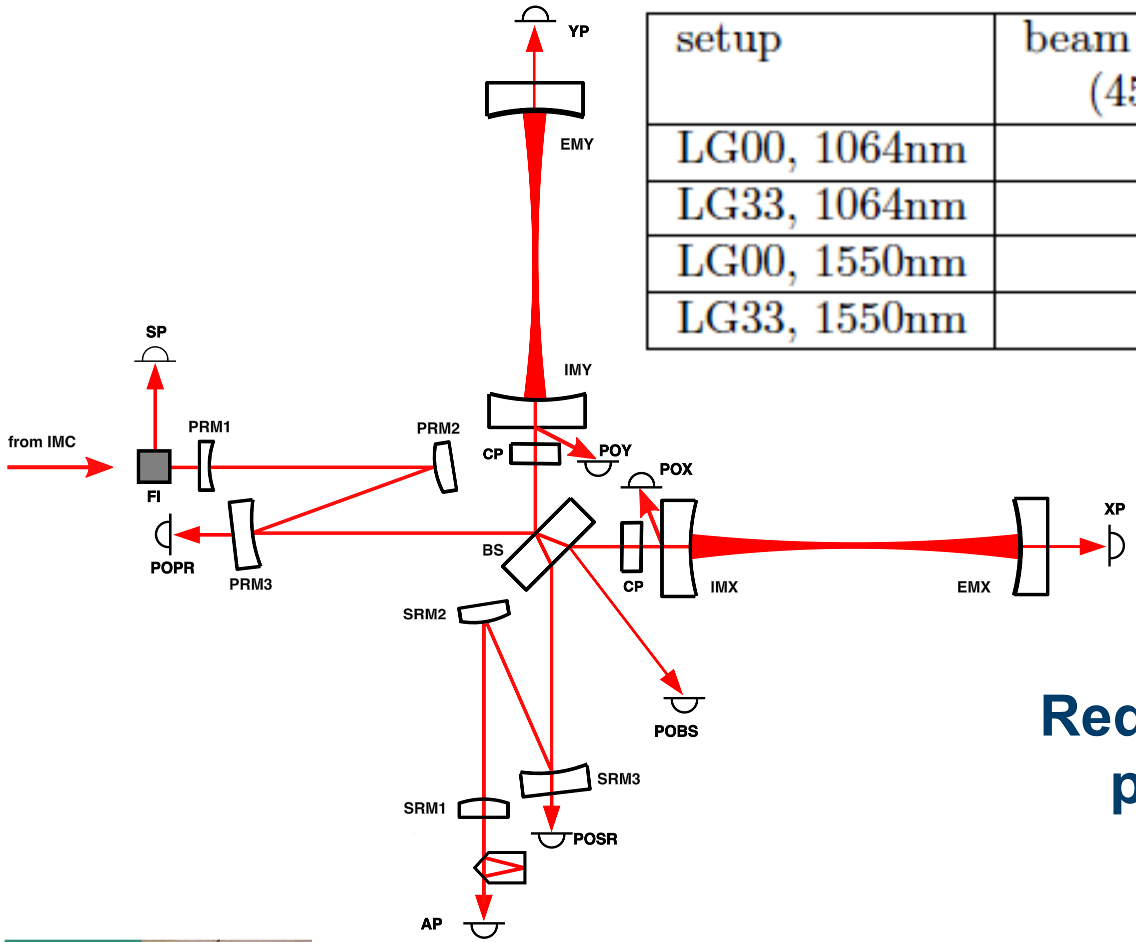
IFO	R_C	w_0	z_0	w	z_R
ET-HF	5147.7 m	2.27 cm	4650 m	7.25 cm	1521.3 m
ET-LF	5489 m	3.11 cm	4650 m	8.0 cm	1964 m

Non-degenerate Recycling cavities al a 2G





Why do 2G NDRC do not work for ET?

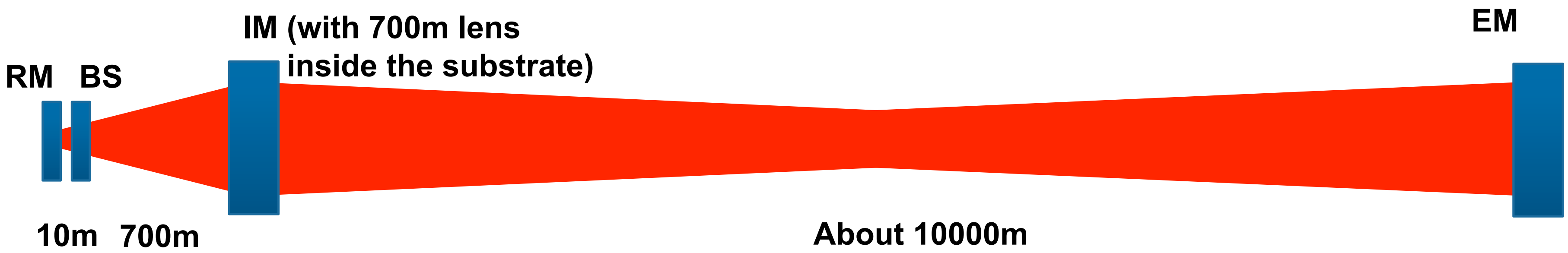


setup	beam splitter diam. (45 deg) [cm]	beam splitter diam. (60 deg) [cm]
LG00, 1064nm	50	70
LG33, 1064nm	80	115
LG00, 1550nm	60	84
LG33, 1550nm	97	136

Required substrate seizes probably not available

Small beams in the central interferometer?

- For various reasons it would be nice to have small beams (few cm) rather than 60cm beams in the central interferometer.
- Could be achieved by focusing the beam down between IM and BS?



- In order to reduce problems from imperfect optics, the focusing should be rather gentle.
- For current dummy design we assume 700m to focus from 60cm down to 5cm.
- Thermal noise in central interferometer?

Potential way to get NDRC for ET?

ET-LF: LG00, 1550nm

- focussing element in or near the ITM with a focal length of $f = 685\,\mathrm{m}$
- distance ITM-BS: 700 m
- distance BS-MPR: 10 m
- beam size on BS: 0.95 cm
- beam size on MPR: 0.86 cm
- Rayleigh range in central interferometer: 47.0 m

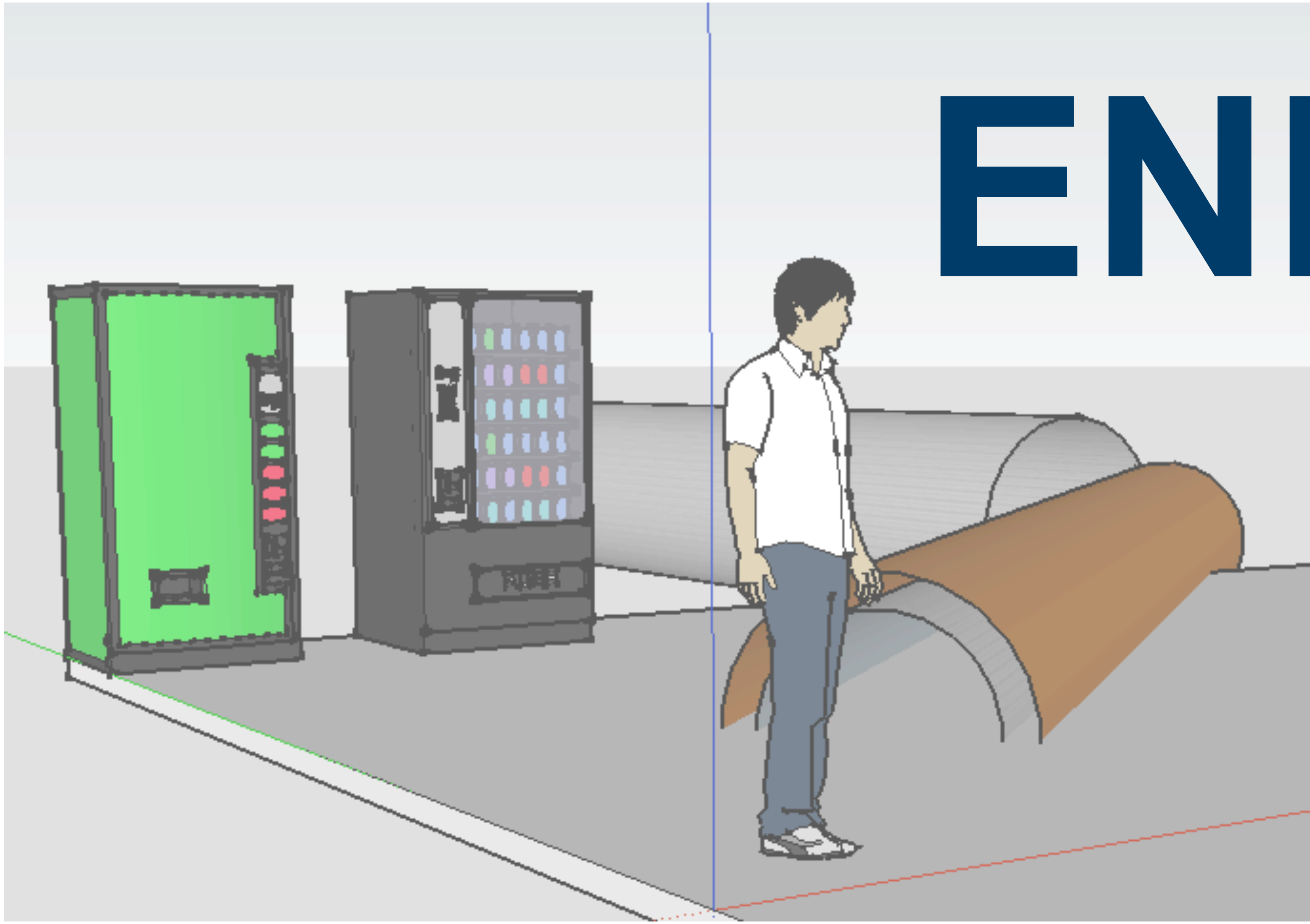
ET-HF: LG33, 1064nm

- beam size on BS: 0.89 cm
- beam size on MPR: 0.81 cm
- Rayleigh range in central interferometer: 40 m
- Gouy phase: 7.6 deg
- mode separation frequency: 9 kHz

For more details: ET-0103B-10

Summary and Outlook

- **Sensitivity studies are converging.**
- **Optical design Hierarchy**
  - Sensitivity => Arm cavity => Central interferometer => all the rest.
- **Space for further action on Central interferometer:**
  - Mirror materials
  - Thermal noise / beam sizes
  - Thermal compensation for ET-HF
  - Astigmatism
  - Scattered light
  - ….



END