ISB: Optics Division

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December 2nd, 2020

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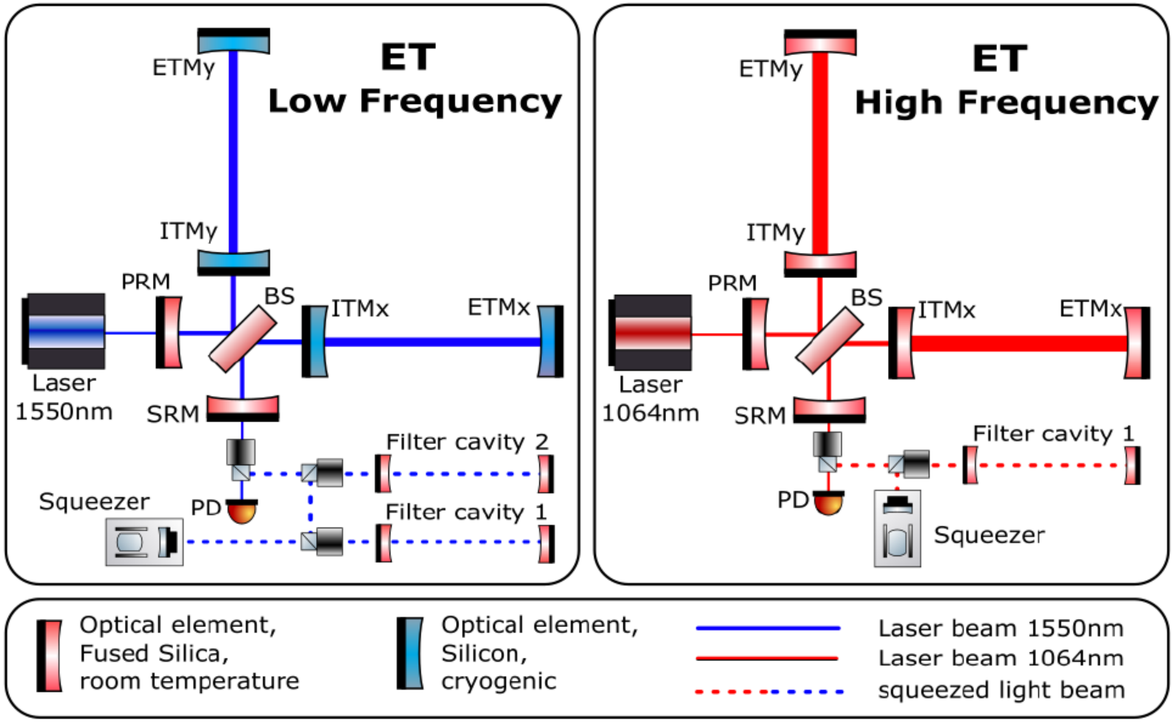
LAPP
Laboratoire d'Annecy de Physique des Particules

University of Strathclyde Glasgow

The Optics division

- Core optics
- Laser sources
- Input and output optics
- Squeezed light sources
- Wavefront sensing and control
- Scattered light mitigation

	High power / thermal effects
Very low loss	Very low loss
Very low noise	Low noise



ET-HF optics specifications/boundary conditions

- 3 MW circulating power @1064nm
- 12 cm beam radius (LG33/TEM00)
- Room temperature

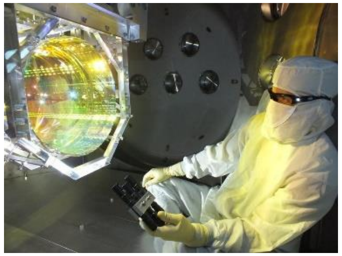
ET-HF substrates

- Fused silica, 200 kg (5 × Adv. LIGO/Virgo)
  (2 × Virgo+)

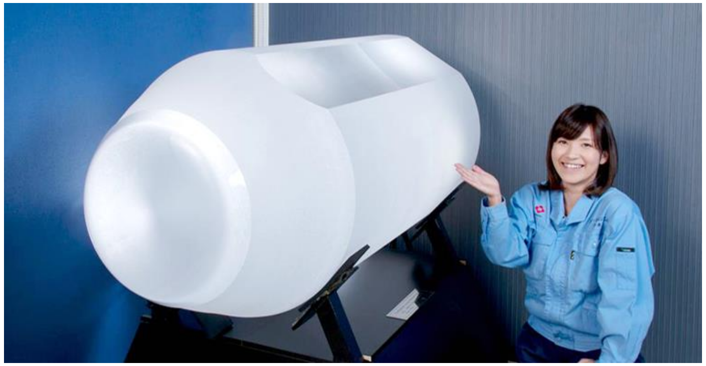
Manufacture complete at Heraeus, arriving end 2020 (now!)

ET-HF coatings

- With typical considerations, require 4 × reduction in coating loss compared to SiO_2 and TiO_2:Ta_2O_5 in Adv. LIGO/Virgo (for 12 cm beam)
- 0.5 ppm absorption target due to thermal compensation system (TCS).
- 10-20 ppm scattering limit per mirror (needs further review following 2G scatter challenges).

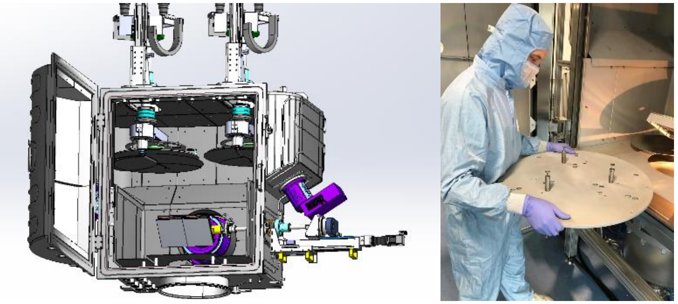


Advanced LIGO – 40 kg



Heraeus/Corning - 100s-kg scale SiO_2

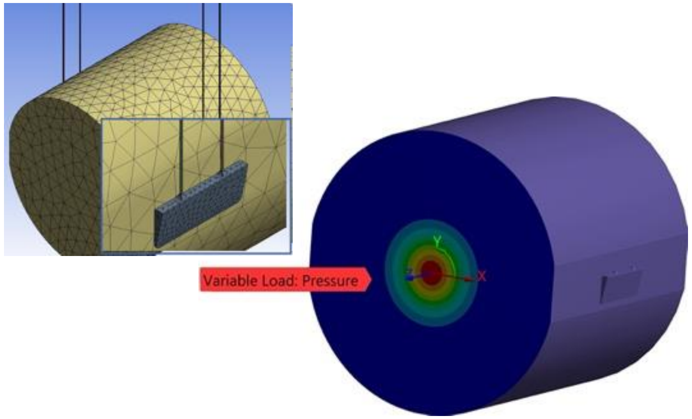
https://www.nikon.com/about/technology/stories/2003_synthetic_silica_glass/



CEC/Strathclyde/Glasgow/UWS amorphous coatings for 620 mm / 200 kg

ET-LF optics specifications/boundary conditions

- 18 kW circulating power @1550nm
- 12 cm beam radius (TEM00)
- 10K (see cryogenics for status)



Computational simulations of thermal noise and radiative/conductive cooling

Masso Herrera, Thesis, Glasgow 2019:
http://dx.doi.org/10.5525/gla.thesis.41177

ET-LF substrates

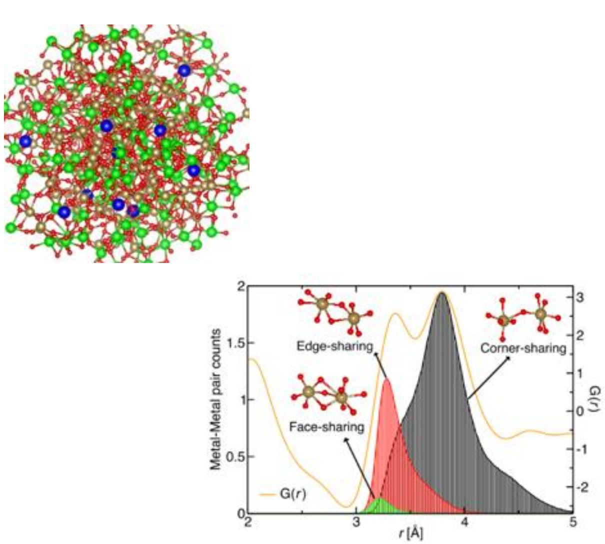
- Silicon, 211 kg
  (sapphire may be considered - birefringence a challenge)

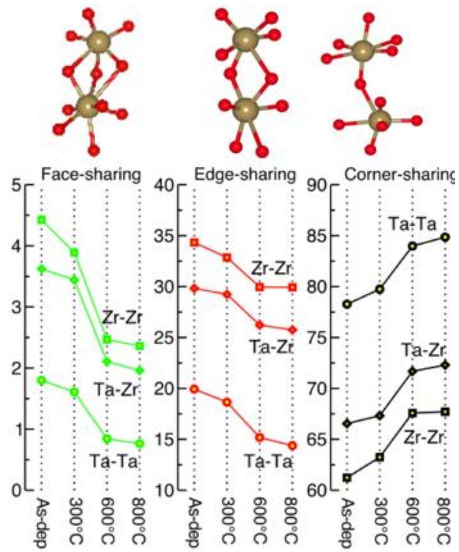
450 mm diameter Si ingot

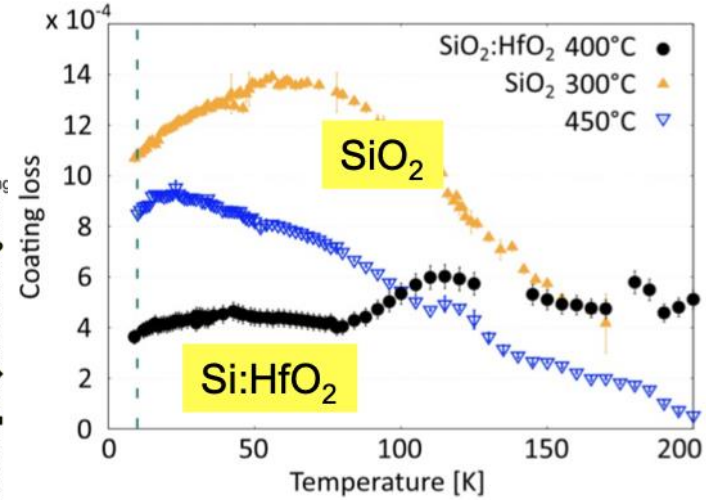
ET-LF coatings

- With typical considerations, require 3.8× reduction in coating loss compared to the loss of $SiO_2/TiO_2:Ta_2O_5$ at 10 K.
- < 5 ppm absorption (ideally sub-ppm to minimise heat load on test mass)

Example progress - optical coatings







Prasai *et al.*, Phys. Rev. Lett. **123**, 045501 (2019)
Craig *et al.*, Phys. Rev. Lett. **122**, 231102 (2019)

Corner-sharing polyhedral fraction:

- $Si{:}HfO_2 < Ta_2O_5 < SiO_2$
- Cryo loss follows same trend
- Room temp loss opposite trend

Crucially important for developing improved amorphous oxides – different materials expected for HF and LF.

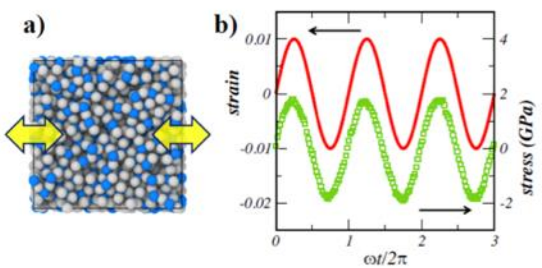
Example progress - optical coatings (contd.)

Molecular Dynamics Mechanical Spectroscopy

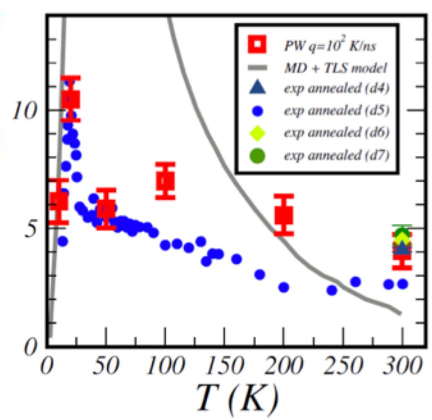
(Puosi VIR-0854A-19 LIGO-G1901646

- apply stress and compute strain
- phase shift ∝ mech. Loss

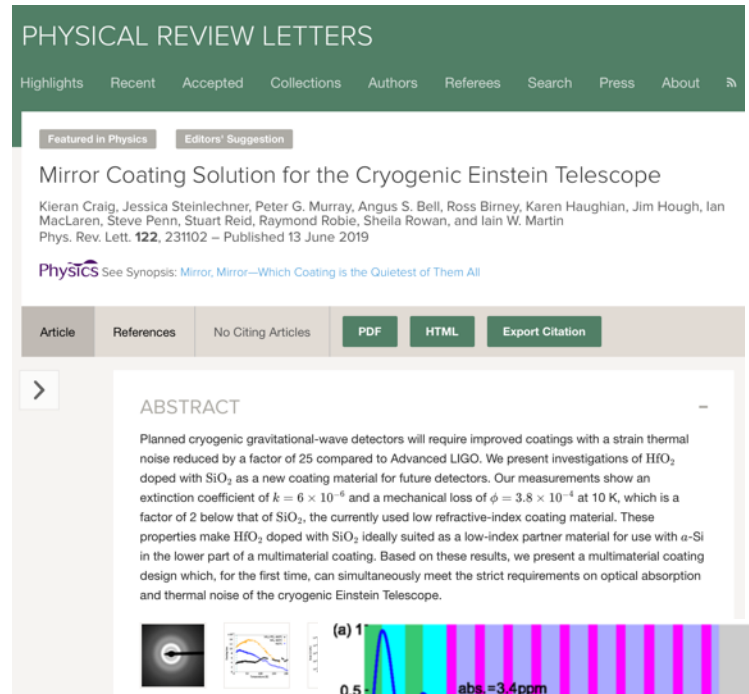
Good agreement with Ta_2O_5 loss



Dissipation $$Q^{-1} = \tan\delta = \frac{E''}{E'}$$



ET-LF proposed solution: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Mirror Coating Solution for the Cryogenic Einstein Telescope

Kieran Craig, Jessica Steinlechner, Peter G. Murray, Angus S. Bell, Ross Birney, Karen Haughian, Jim Hough, Iain MacLaren, Steve Penn, Stuart Reid, Raymond Robie, Sheila Rowan, and Iain W. Martin

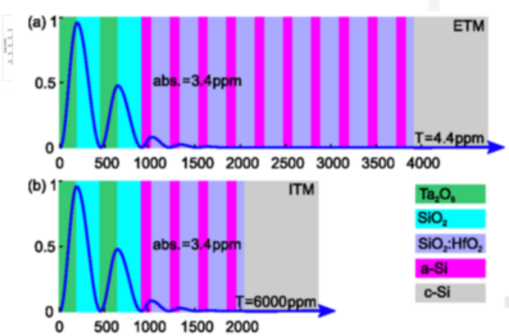
Phys. Rev. Lett. **122**, 231102 – Published 13 June 2019

Physics See Synopsis: Mirror, Mirror—Which Coating is the Quietest of Them All

Article | References | No Citing Articles | PDF | HTML | Export Citation

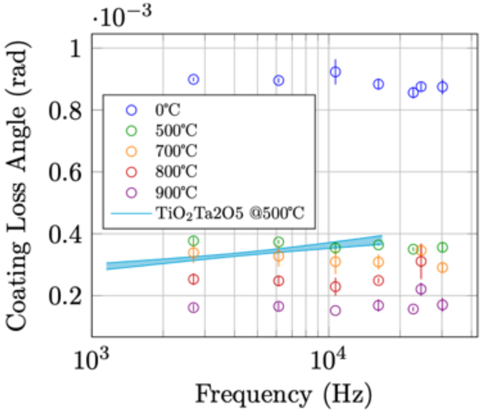
ABSTRACT

Planned cryogenic gravitational-wave detectors will require improved coatings with a strain thermal noise reduced by a factor of 25 compared to Advanced LIGO. We present investigations of HfO_2 doped with SiO_2 as a new coating material for future detectors. Our measurements show an extinction coefficient of $k = 6 \times 10^{-6}$ and a mechanical loss of $\phi = 3.8 \times 10^{-4}$ at 10 K, which is a factor of 2 below that of SiO_2, the currently used low refractive-index coating material. These properties make HfO_2 doped with SiO_2 ideally suited as a low-index partner material for use with a-Si in the lower part of a multimaterial coating. Based on these results, we present a multimaterial coating design which, for the first time, can simultaneously meet the strict requirements on optical absorption and thermal noise of the cryogenic Einstein Telescope.



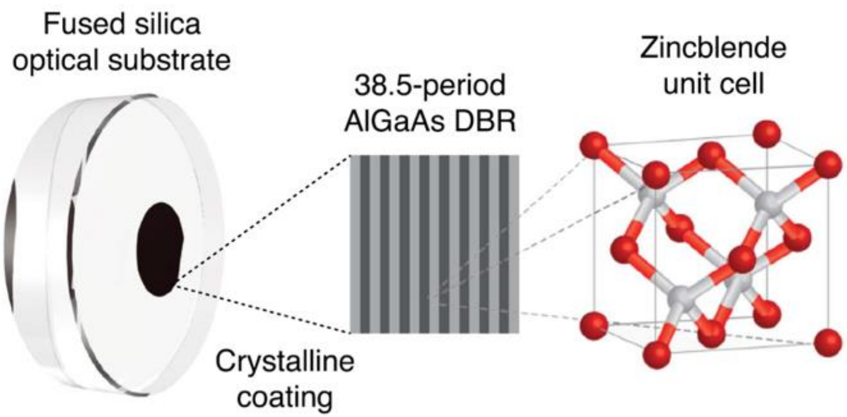
Example progress - optical coatings (contd.)

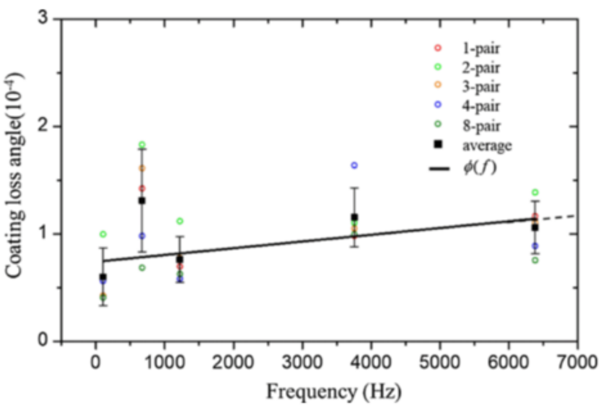
Other materials/technologies *e.g.* SiN_x



Alex Amato *et al.*, J. Phys.: Conf. Ser. **957** 012006 (2018)

AlGaAs crystalline (requires transfer/scaled-up)





Pan *et al.*, Phys. Rev. D 98, 102001 (2018)

AlGaP crystalline? Lattice-matched c-Si / early dev.

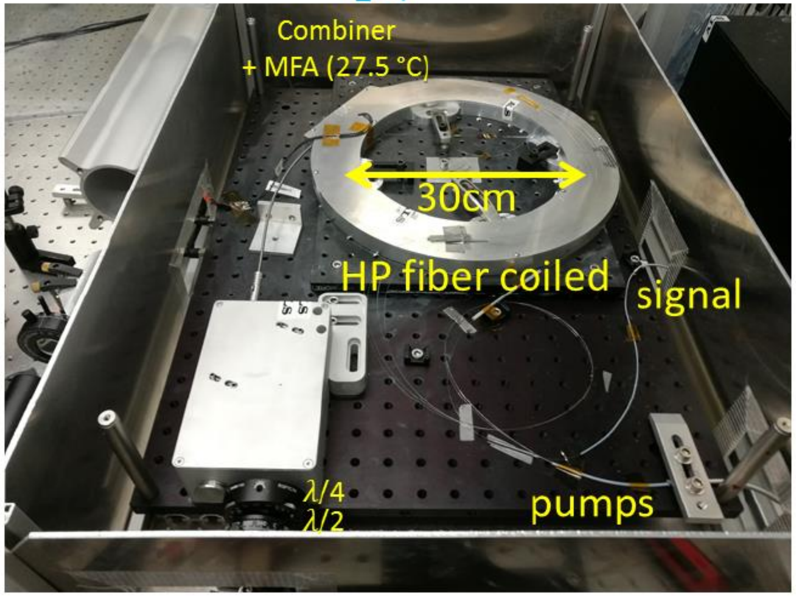
a-Si amorphous? Absorption still challenge so sole use

GaN? Promising but undeveloped

TiO_2:GeO_2? Proposed A+/V+ soln (ET ✓?)

TeO_2:GeO_2? Atomic structure could be highly promising / control of structure/stoch. challenging

Laser sources



Requirements:

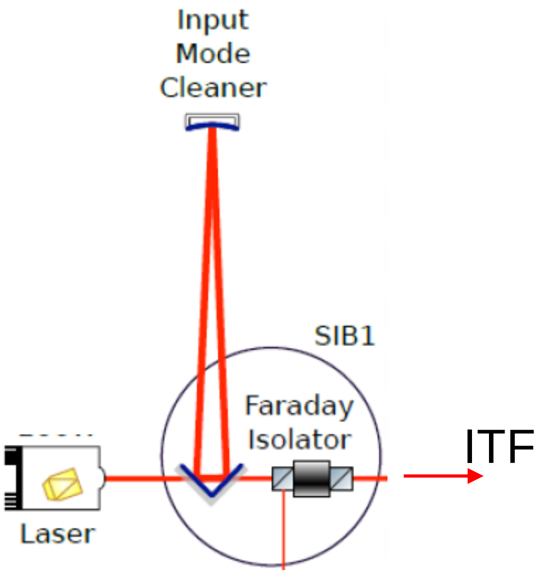
- ET-HF: High power (700W)
- Beam quality (TEM00)
- Low beam pointing noise
- Low intensity noise (~AdV+/10)
- Low phase noise
- High reliability
- ET-LF: low power (5W) but very low noise at LF – beam jitter, scattered light

Present technology:

- Fiber amplifier: AdV+ ~100W

⇒ Improve and combine coherently several sources ?

- Pre-mode cleaner (mode filtering + beam pointing)



Interface between laser source and ITF, provides:

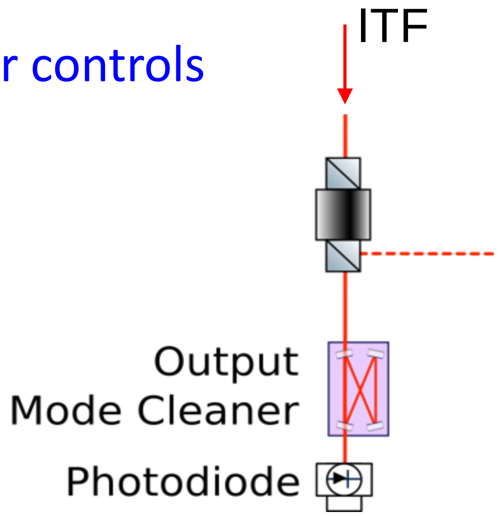
- Pure TEM00 beam
- Very stable in frequency, power and pointing
- Phase modulation for longitudinal and angular controls

Components:

- EOMs
- Faraday isolators (high vacuum compatible)
  - Technology to be developed at ET-LF wavelength

⚠ Thermal effects (ET_HF)

- Mode cleaner cavities ⚠ Radiation pressure and thermal effects
  (beam filtering & frequency stabilisation)
- Mode matching telescopes (tunable)

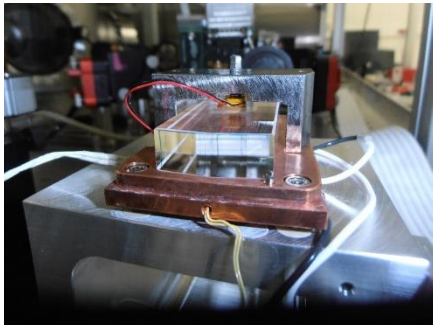


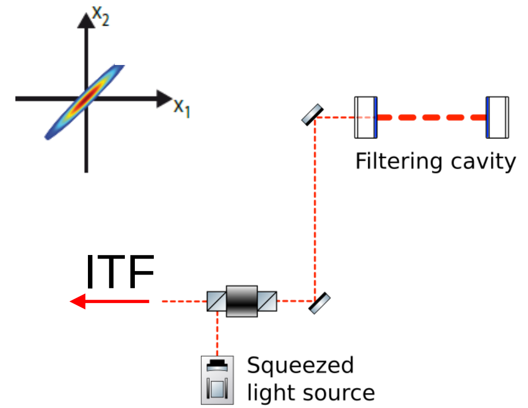
Readout of the dark fringe beam and auxiliary beams for controls

- Mode filtering of the dark fringe
- Squeezing injection
- Photodetection of the beams

Components:

- Mode matching telescopes (tunable)
- Faraday isolator (low optical loss)
- Output mode cleaners (low optical loss) ⚠ Thermal effects and cavity noise
  - Presently 2 types of cavities: monolithic / tombstone
- Photodiodes (high QE, very low noise electronics)

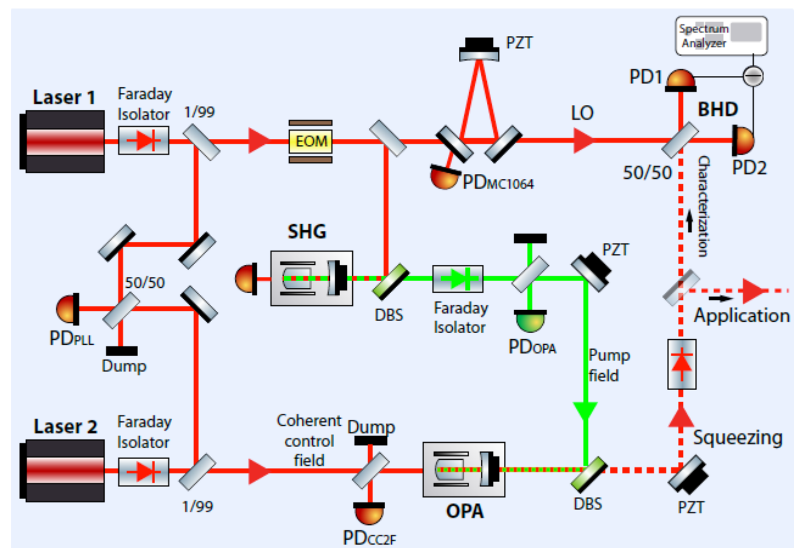




Provides the squeezed light at the required angle

- Squeezed light source
- Faraday isolators (high isolation)
- Filter cavities (low phase noise)
- Mode matching

All components with very low optical loss



Existing technology at 1064nm

- Frequency dependant squeezing being prepared for AdV+ and A+
- Losses to be reduced to reach 9 dB

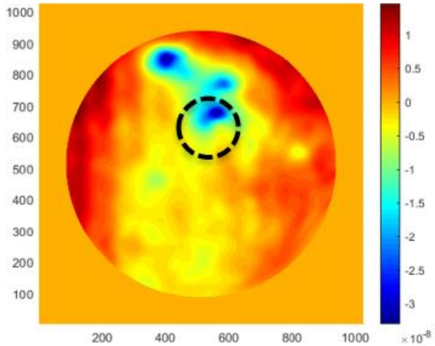
To be developed at 1550nm

Reduction of optical losses due to beam mismatch

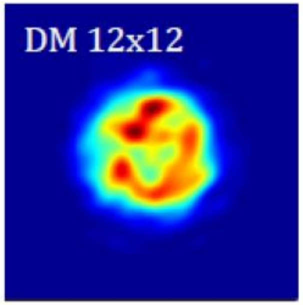
- Sense the core optics deformation (global thermal effects, point absorbers)
- Correct those deformations
- Ease ITF controls during transients

Components:

- Wavefront sensors
- Ring heaters, Co2 lasers (low noise)
- Mode matching optics



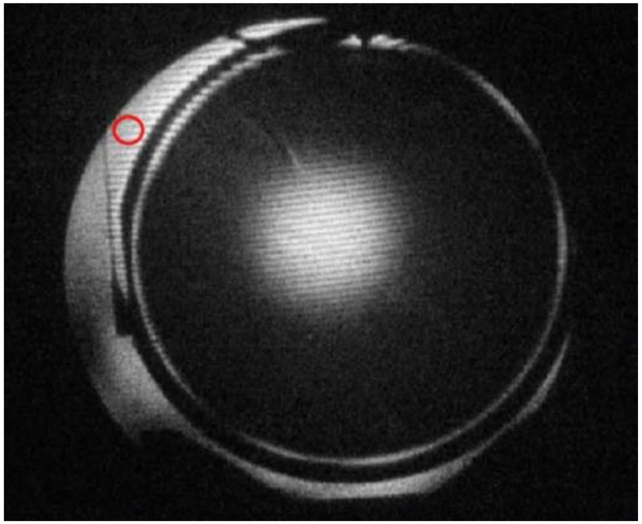
Wavefront map



Heating profile

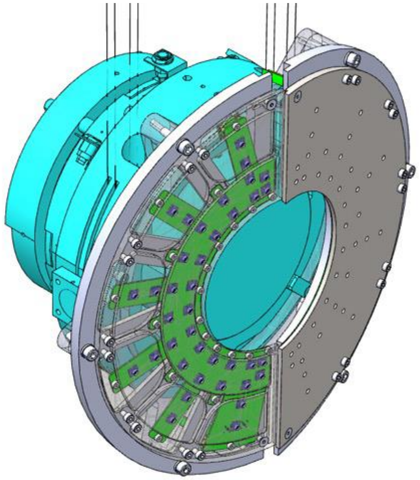
Prevent parasitic noise from scattered light into ITF beam:

- Modeling of scattered light coupling to ITF beam
- Reduction of parasitic light scattered by all optical elements



Components:

- Simulation software
- Guidelines for the design of optical benches
- Monitoring systems (ex: instrumented baffle in AdV+)
- Reduction of scattered light (high quality baffles and beam dumps, …)
- Reduction of mechanical motion of scattering elements(high quality mechanical mounts)



Many challenges ahead of us …

- Improve the present technology at 1064nm for ET-HF
  - High power
  - Reduce and control thermal effects
  - Minimise optical and mechanical losses (core substrates, coatings, all optics)
  - Lower the noises (scattered light, photodetectors,…)
- Develop the technology at 1550nm for ET-LF
  - Squeezed light, Faraday isolators,…
  - Low noise at low frequency (scattered light, beam jitter,…)
  - Minimise optical and mechanical losses (core substrates, coatings, all optics)

… do not hesitate to join the effort !

Related R&D talks in tomorrow's session:

- Higher-order Hermite-Gauss modes for gravitational waves detection by Walid Chaibi
- R&D on coatings by Jessica Steinleichner