Coatings for the Einstein Telescope

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Highly-reflective coatings

- stack of many layers; usually two materials with different refractive index $n$
- optical layer thickness: quarter of a wavelength (= higher $n$ → thinner layer)

Example: SiO$_2$ (blue, $n=1.45$) and Ta$_2$O$_5$ (green, $n=2.05$)

- ~38 layers needed for highly reflective ETMs of $R = 99.9995\%$
- light intensity reduces with every layer pair
- ITMs, lower reflectivity → fewer layers (about half of ETM)

Requirements:

- Low coating thermal noise (CTN):  
  ○ limiting noise source → needs to get reduced

- Low optical absorption: few parts per million ($10^{-6}$)  
  ○ to avoid heating  
  ○ to avoid thermal deformations

- Low scattering (from e.g. defects or micro crystals)  
  ○ only purely amorphous or single-crystalline materials suitable
Coating thermal noise

- **Coating thermal noise**
  - frequency dependent
  - lower for larger beams
  - temperature dependent
  - determined by material properties (coating and substrate)

→ Cooling at low $f$ where CTN is high!

1. ET low-frequency (LF) detector
   a. low temperature (10K, 20K or 120K?)
   b. low laser power (to minimize heating from absorption)
   c. fused silica unsuitable at low temp. due to high thermal noise: change to crystalline silicon (or sapphire)
   d. silicon requires longer wavelength (1550nm or ~2000nm?)

2. ET high-frequency (HF) detector
   a. same substrate material, temperature and laser wavelength as LIGO and Virgo detectors
   b. can tolerate high laser power to reduce quantum noise

→ both LF and HF require new coating solutions!
ET HF (same wavelength, substrate material and temperature as LIGO and Virgo detectors)

- **Orange line:** Using aLIGO/AdvVirgo coatings in ET-HF
  - Reduction from longer arms and larger beams
- **Red dashed line:** ET-HF design

- Planned A+ coatings will meet ET-HF design
  - Likely candidates to achieve this goal: TiO$_2$:GeO$_2$ or TiO$_2$:SiO$_2$, to replace TiO$_2$:Ta$_2$O$_5$ as high-n material, (currently ~20% above ET-HF goal)
  - Still to be confirmed: low absorption and mechanical loss of multilayers
- **AdV+ looking into SiN** as a high-n material
  - Similar mechanical loss to TiO$_2$:GeO$_2$, but thinner coatings from higher n → meets ET-HF goal
  - SiN R&D in Taiwan, Virgo groups working on absorption reduction of IBS SiN

- R&D and implementation for A+/AdvV+: Best test!

Remaining challenges: Upscaling coating diameter by almost a factor of two (bubble- and defect-free)
ET-LF (using 1550nm and 20K for calculations)

- **Orange line:** Current LIGO/Virgo coatings cooled:
  - mechanical loss of SiO$_2$ and TiO$_2$:Ta$_2$O$_5$ increases
  - → less improvement than expected from low temp.
  - (note different x range)

- **Pink line:** (undoped) GeO$_2$ and SiO$_2$:
  - increasing loss
  - → CTN increase

- **Green line:** SiN and SiO$_2$
  - ○ limited by SiO$_2$ loss
  - → less CTN improvement than at room temp.

Low temperatures: We need a factor of two CTN reduction.
Different low-n material needed (or fewer SiO$_2$ layers)!
ET-LF (using 1550nm and 20K for calculations)

- Orange line: Current LIGO/Virgo coatings cooled (for comparison)

- Blue: SiO$_2$/aSi coatings - few layers due to high n of aSi

  ~8ppm coating absorption → too high + further R&D needed for reproducibility

  absorption lower at 2um (slight CTN increase from thicker layers)
ET-LF (using 1550nm and 20K for calculations)

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- Blue: SiO$_2$/aSi coatings - few layers due to high n of aSi ~8ppm coating absorption → too high + further R&D needed for reproducibility absorption lower at 2um (slight CTN increase from thicker layers)

- 10K: CTN reduces further, but we can tolerate even less absorption

Other options:

- Nanolayers: Can suppress cryogenic loss peaks (suppressing structural changes with annealing? Layers thinner than structural units responsible for loss?)

- Other materials: Structural predictions

- Multimaterial coatings
Multimaterial Coatings - a trade-off of absorption and CTN

Due to high $n$, replacing one $\text{Ta}_2\text{O}_5$ layer by aSi, allows to remove additional $\text{SiO}_2/\text{Ta}_2\text{O}_5$ for $R = \text{const.}$

- Use some low-absorbing $\text{SiO}_2/\text{TiO}_2:\text{Ta}_2\text{O}_5$ at the top to reduce laser power, high-absorbing aSi only used further down
- each point represents one aSi layer added
- trade-off between CTN decrease and absorption increase

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Coating Solution for ET-LF

You might have seen [this picture](#) in some talks this week...
Coating Solution for ET-LF?

- meets CTN design of ET-LF at 10K
- uses $2 \times \text{SiO}_2/\text{TiO}_2: \text{Ta}_2\text{O}_5$ on top of aSi and $\text{SiO}_2: \text{HfO}_2$
- absorption = 3.4 ppm per mirror
  - < 5ppm: target in initial (2011) ET design study
  - more recently: absorption ideally lower

- but how low?
Crystalline Coatings an alternative concept

- **Orange line:** Current LIGO/Virgo coatings cooled (for comparison)
- **Blue area:** Crystalline coatings show low CTN
  - Upper boundary: AlGaP/GaP
    → can be grown directly on silicon (matching lattice structure required for growth), absorption needs reduced
  - Lower boundary: GaAs/AlGaAs
    → low absorption, needs to be grown on GaAs wafers: too small

- Crystalline coatings: Promising
  - Variety of materials can be grown on silicon (or also on other materials + transfer)
  - Within ETPF: J.P. Locquet, Uni Leuven

Other ideas: amorphous and crystalline hybrids
- Hamburg: amorphous coatings with crystalline toplayer
Crystalline Coatings: an alternative concept

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Other ideas: amorphous and crystalline hybrids
- Hamburg: amorphous coatings with crystalline top layer
- Glasgow: SiO$_2$ implantation into silicon substrate

ET-LF design (2020 update)

The End!