Precision Measurement Sensing for Spaceborne Gravitational Wave Detectors

Christian Killow for the LISA Team

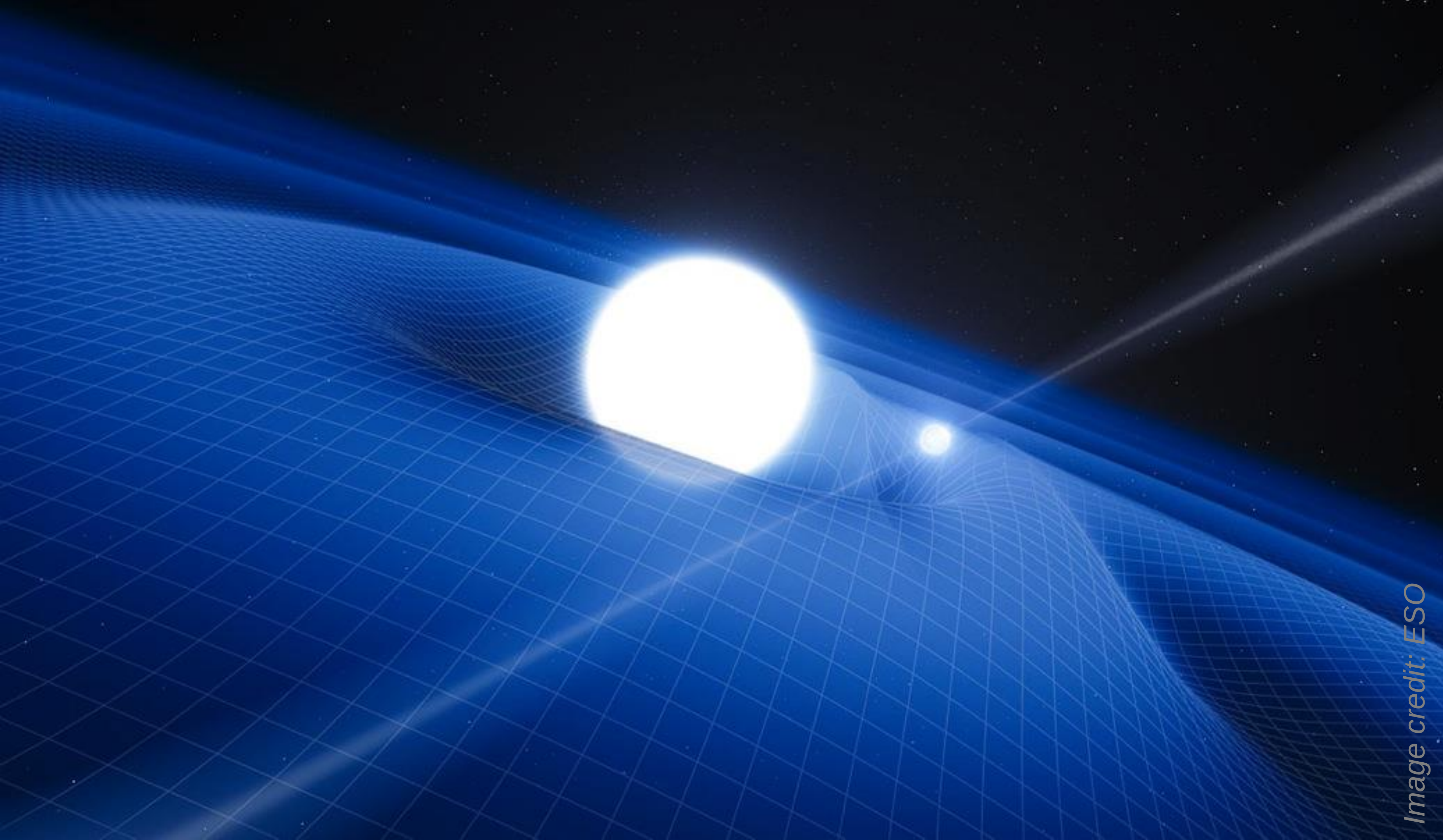


Image credit: ESO

Overview

Gravitational Wave Detection

- What and Why

Space observatory: eLISA

- Gigametres and picometres

LISA Pathfinder

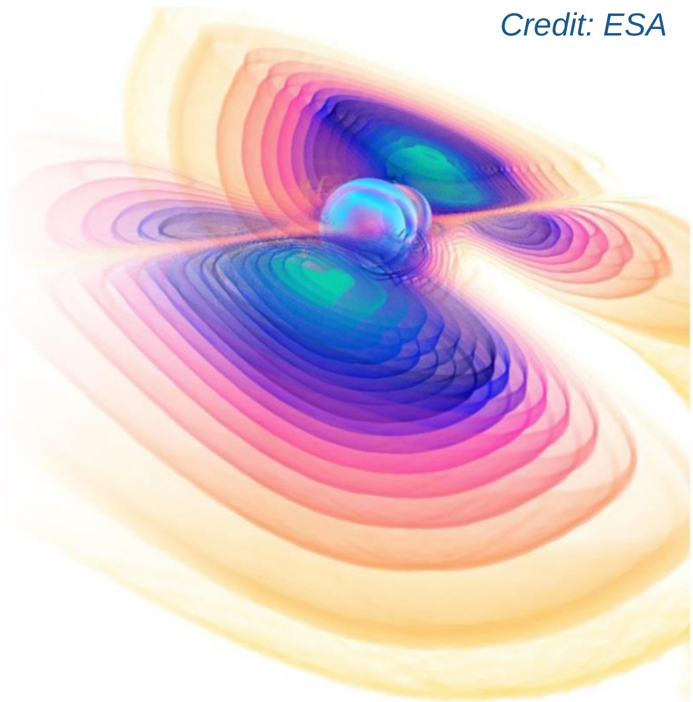
- Technology demonstration

Optical sensing for spaceborne precision measurement missions

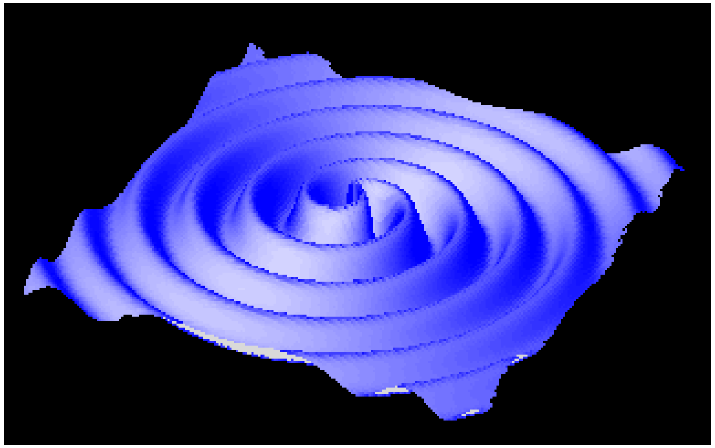
Gravitational Wave Astronomy

- Gravitational waves are a prediction of Einstein's theory of relativity
- They are *ripples in spacetime*
  - Not EM radiation
  - Akin to *listening* to the Universe

- When we observe them they will provide a new observational window on the universe
- They are the only known way of observing some of the most exotic processes that take place in the universe, e.g.
  - Super Massive Black Hole collisions
  - Extreme mass-ratio inspirals



Credit: ESA



Gravitational Wave Detectors

- The best way we have to build gravitational wave detectors is to isolate 'test masses' from local disturbances and measure their separation as gravitational waves pass through the system
  - We use laser interferometry as the 'ruler' as high precision is needed

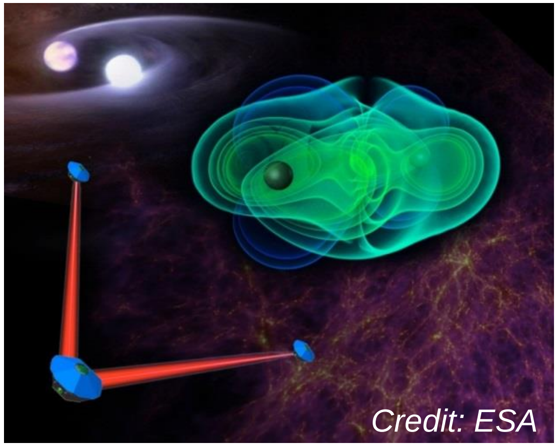
The 4 km arm length LIGO gravitational wave observatory in Louisiana, part of the world-wide effort to detect gravitational waves

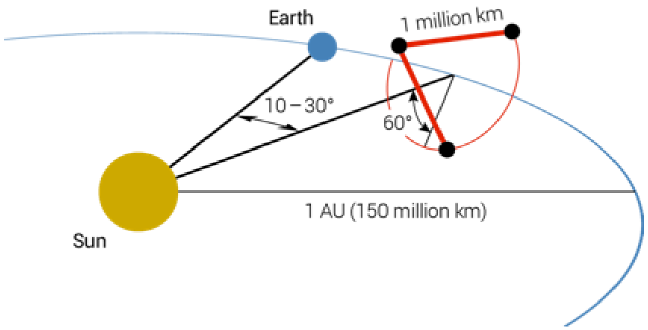
$$h = \frac{\Delta L}{L} \sim 10^{-20}$$

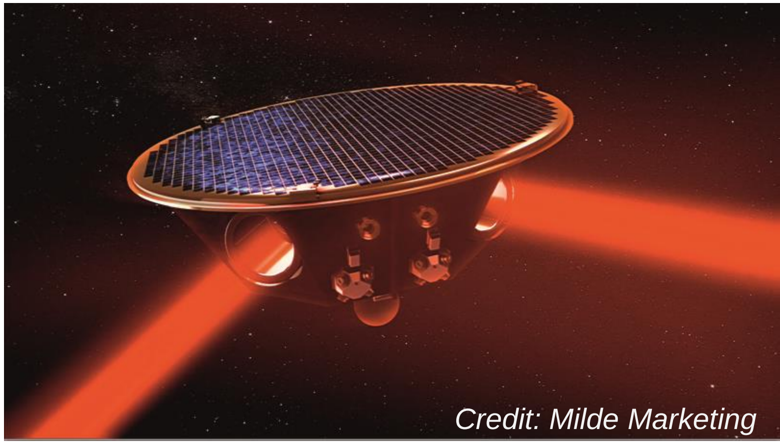
- LIGO extends one ten thousandth of the way around the earth!
- You could use ~530 calories if you ran it

A problem and a solution

- Changes in local mass distribution – even clouds passing – cause a variation of the forces acting on the test masses
  - This is a problem if the mass distribution changes in the band you want to measure
- We need to go to a gravitationally quiet environment: space
  - Added benefit that we can have very long armlengths
- eLISA is a proposed spaceborne gravitational wave detector







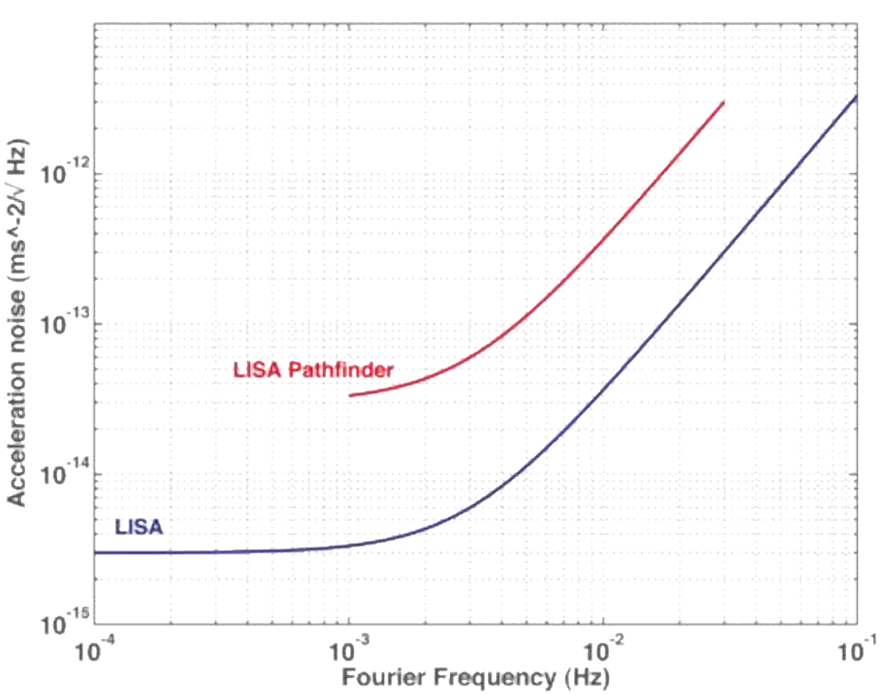
- Similar detection principles as ground-based detectors: monitor separation of inertially free masses using interferometry
- With gigametre armlengths and requiring picometre test mass monitoring at milliHertz
  - A demonstrator mission – LISA Pathfinder – is being flown to retire technological risks

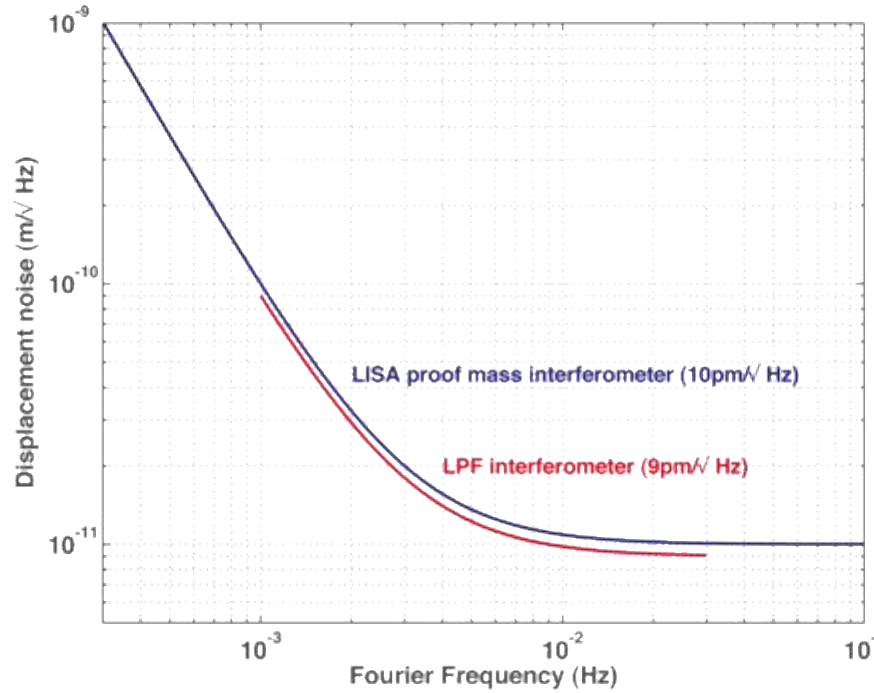
LISA Pathfinder

- We can verify many aspects of eLISA on ground, but not all
- The aim of LISA Pathfinder is to verify technology for future spaceborne gravitational wave detectors
  - It will effectively demonstrate the ‘short-arm’ interferometry for eLISA
- Fly two test masses and measure the purity of their freefall
  - Experiment in micro-gravity at L1
- European Space Agency mission due for launch in 2015

LISA Pathfinder
(courtesy Astrium UK)

LISA Pathfinder in two graphs





Differential acceleration noise:

Can we keep the test masses still?

Displacement sensing noise:

Can we measure the stillness?

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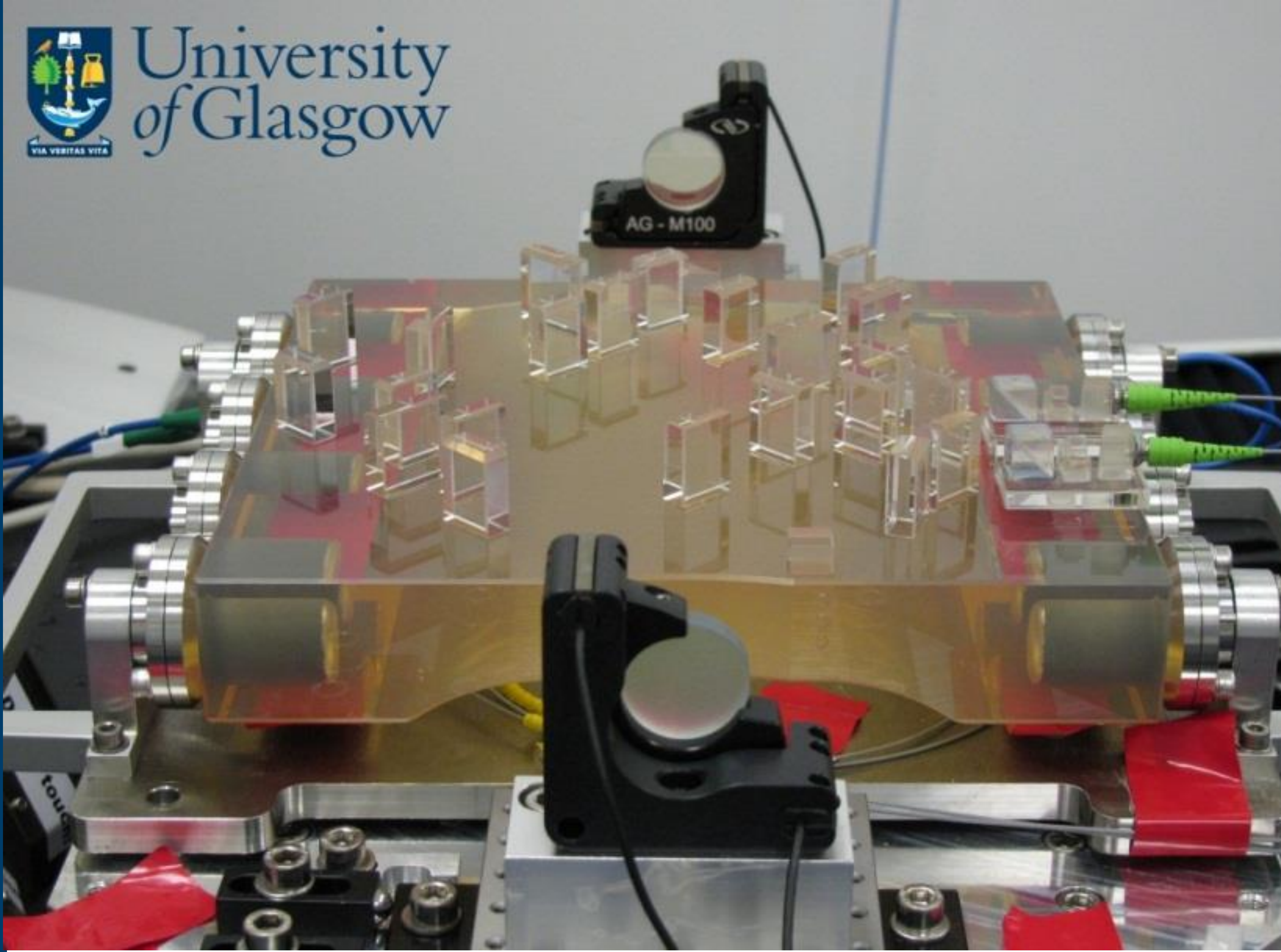
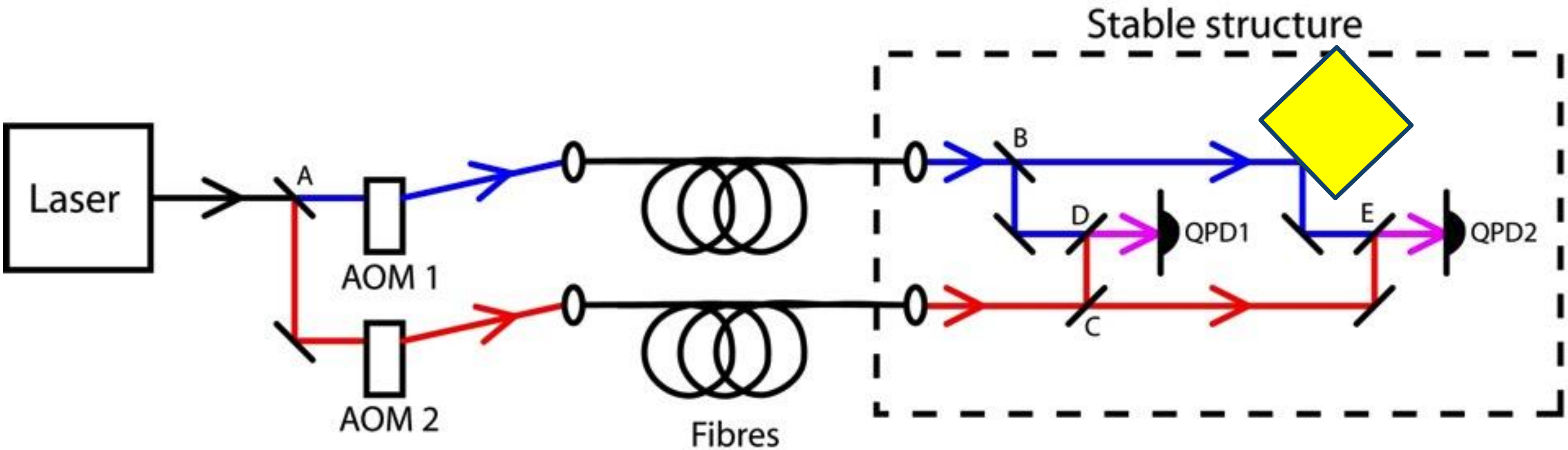


Design from first principles

- The Optical Bench Interferometer (OBI)
  - Has to physically fit into the space available
  - Plays a structural role
  - Has to survive launch and radiation environment
  - Measure 10 picometre longitudinal variations and 20 nanorad angular beam motion (in band) in milliHertz regime
  - Be non-magnetic
  - Beams have to hit the Test Masses (TMs) within 25 μm of absolute nominal
- This leads to a lot of derived requirements
  - And a lot of paperwork

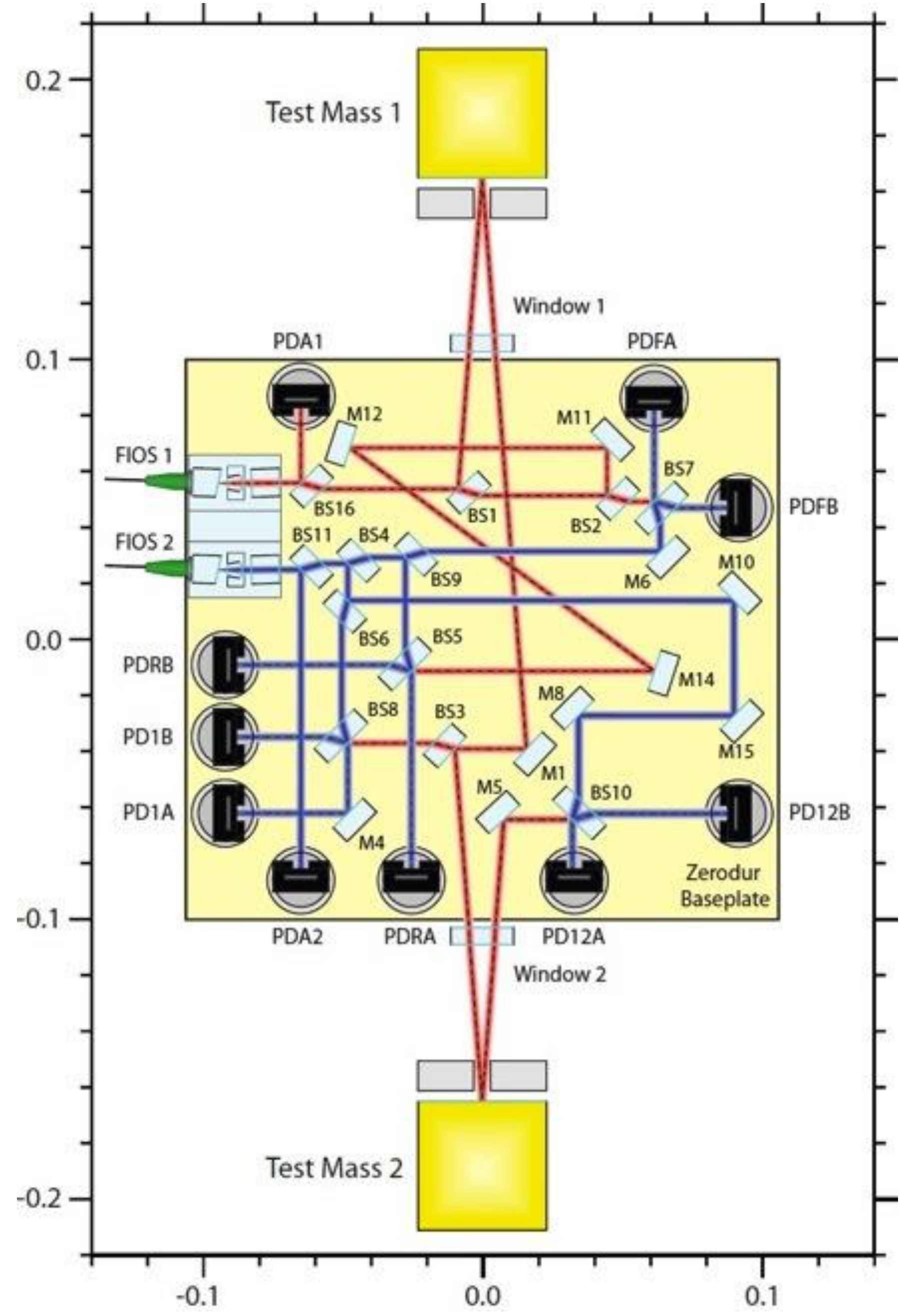
Heterodyne interferometry for LTP



- Compare phase of beatnote between red and blue beams at QPD1 and QPD2
- Should be stable if the paths DBE and DCE are stable
- For LTP we replace a mirror on the stable structure with a test mass

Optical layout

- The optical layout was originally designed by the AEI, Hannover
- The design incorporates:
  - Four Mach-Zender interferometers
  - Path length matching of all interferometers
  - Equal transmission through beamsplitters for all interferometers
- Enabling technology: hydroxide-catalysis bonding



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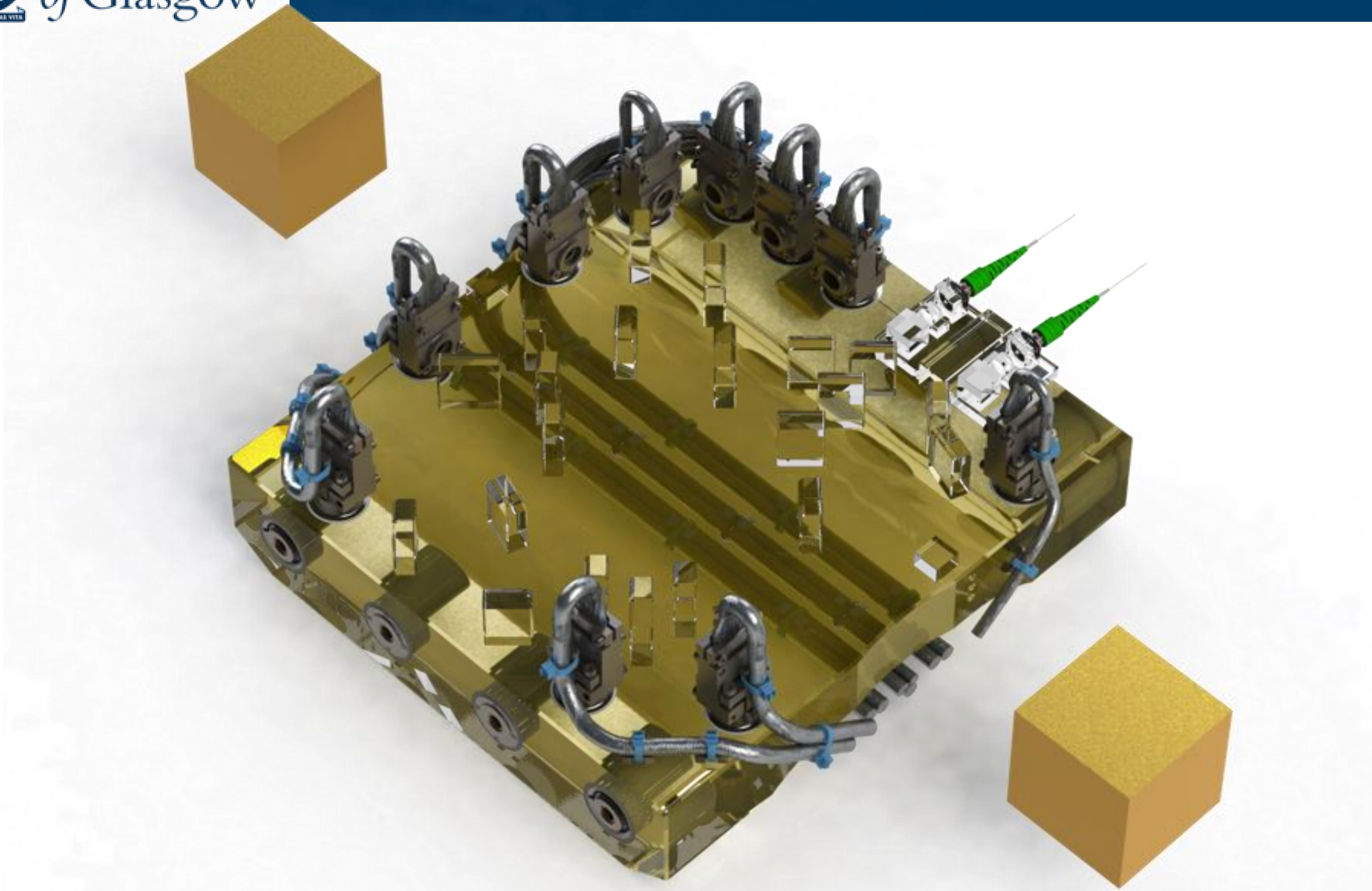

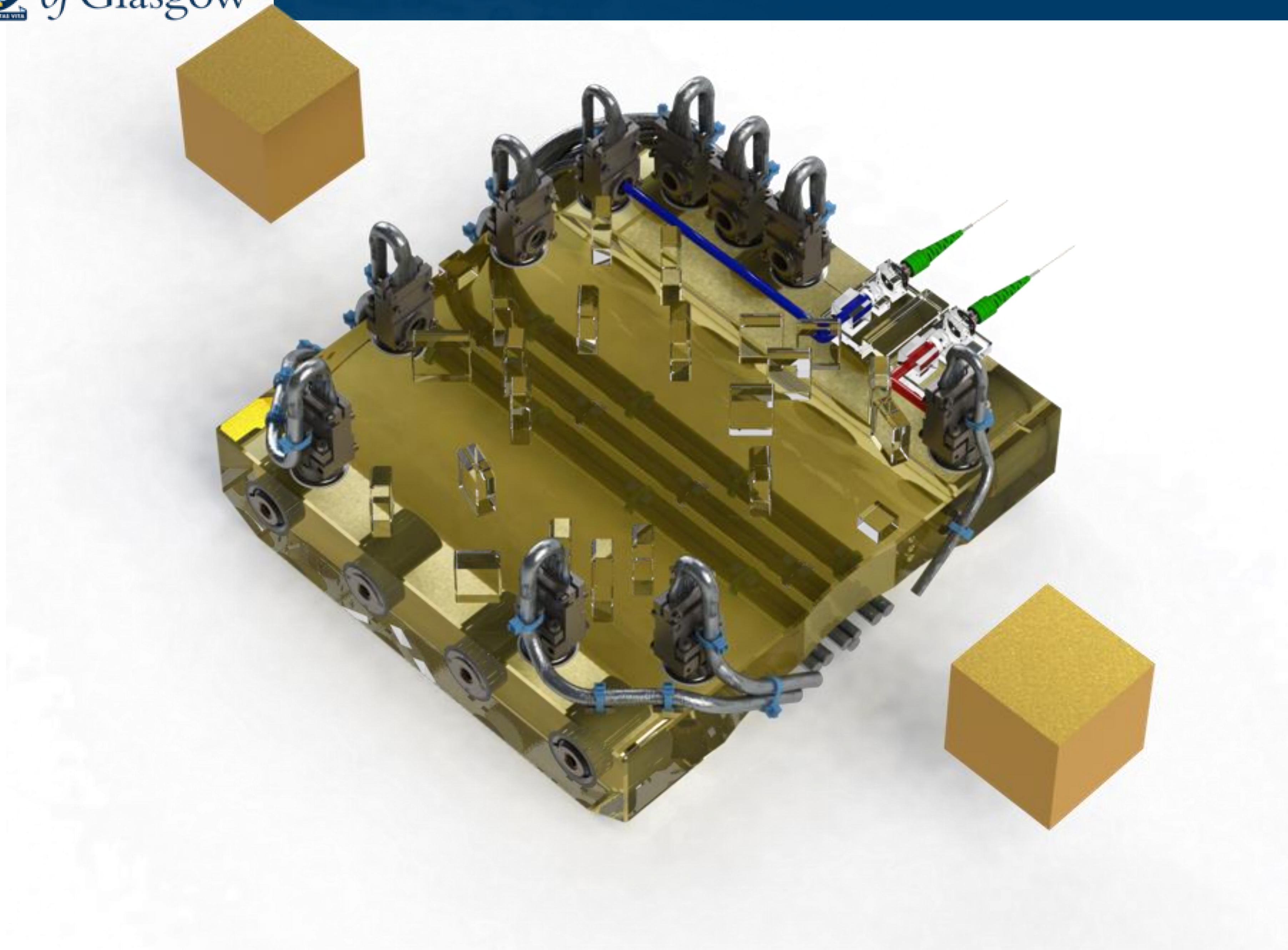

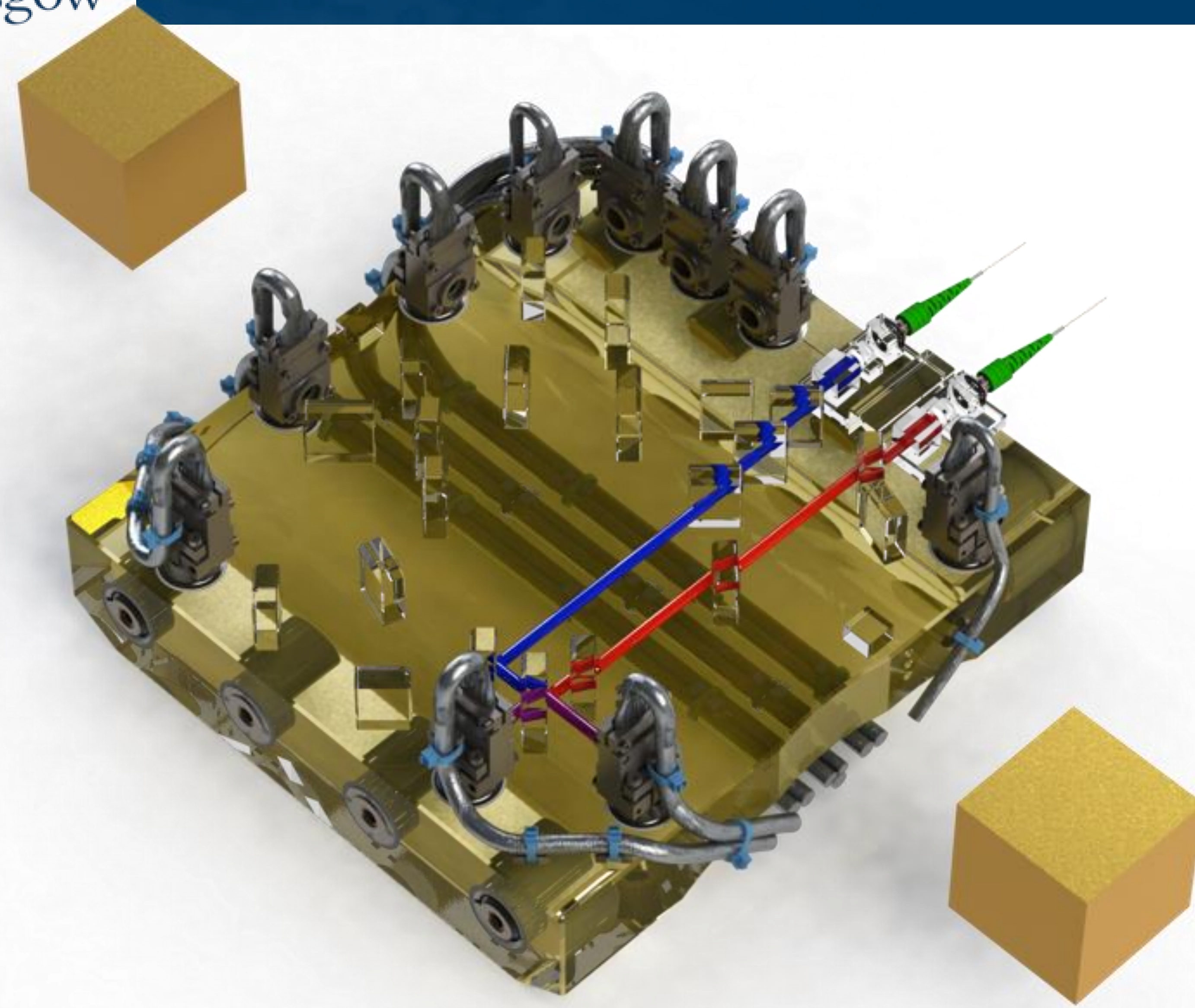

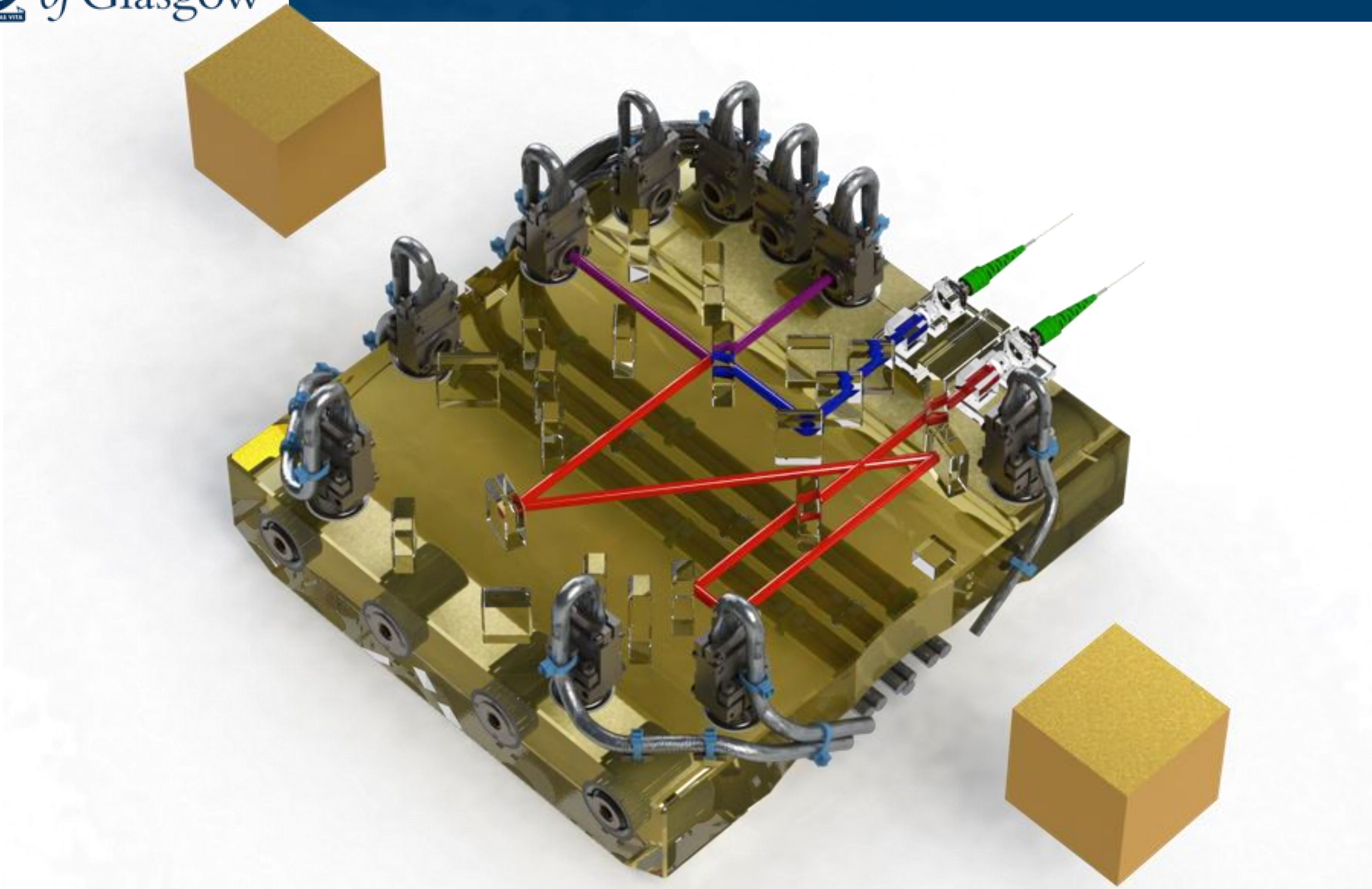

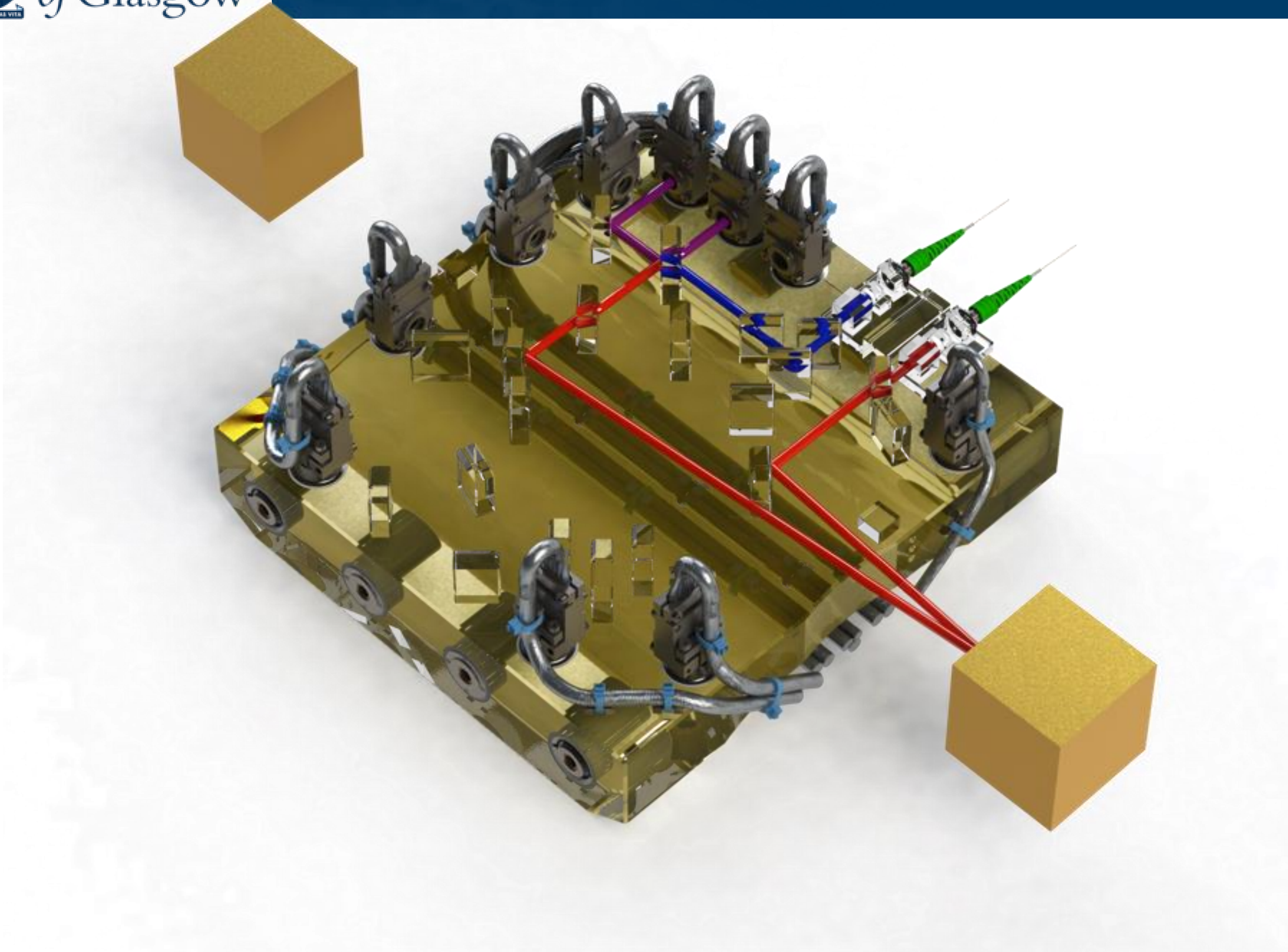

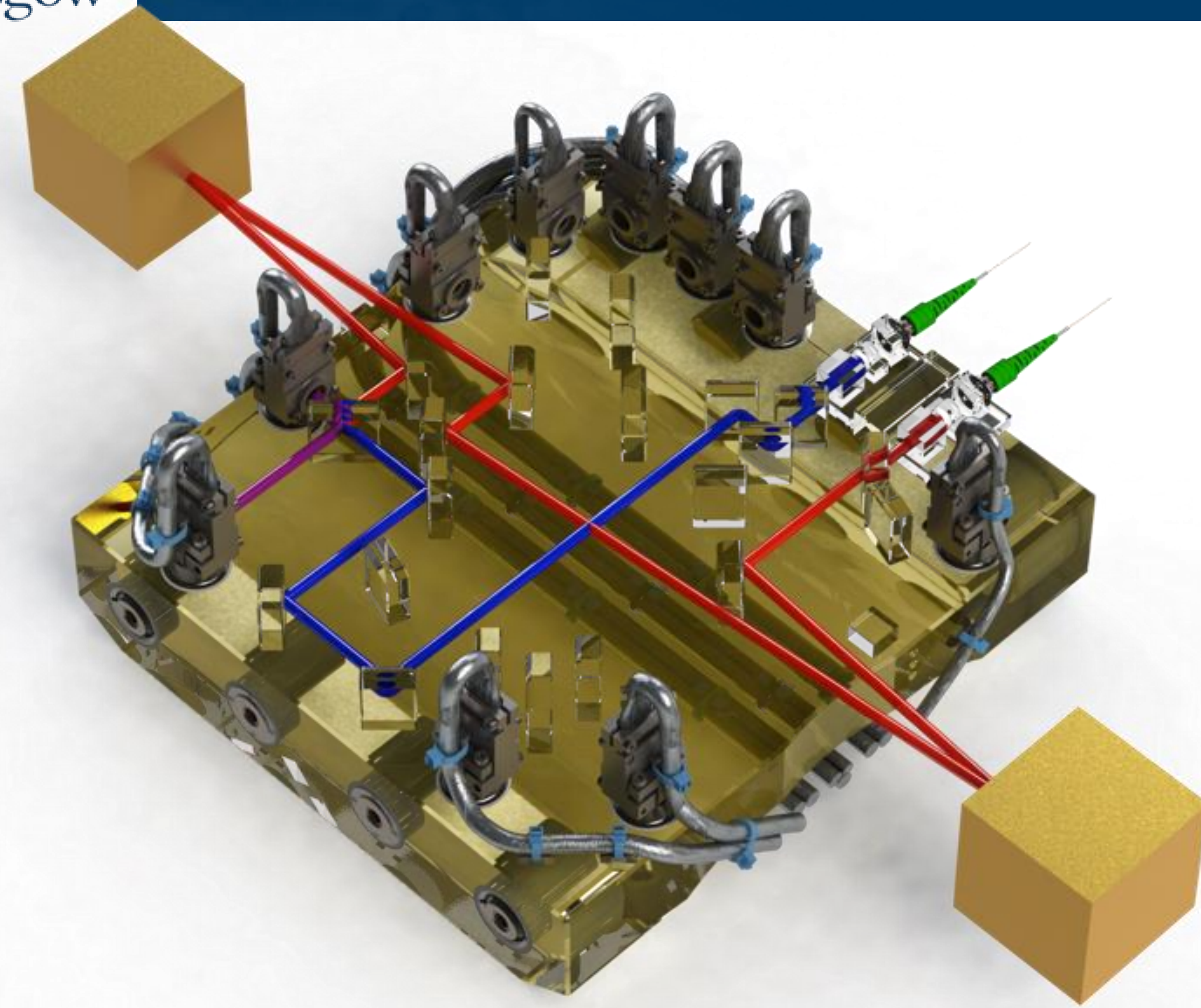

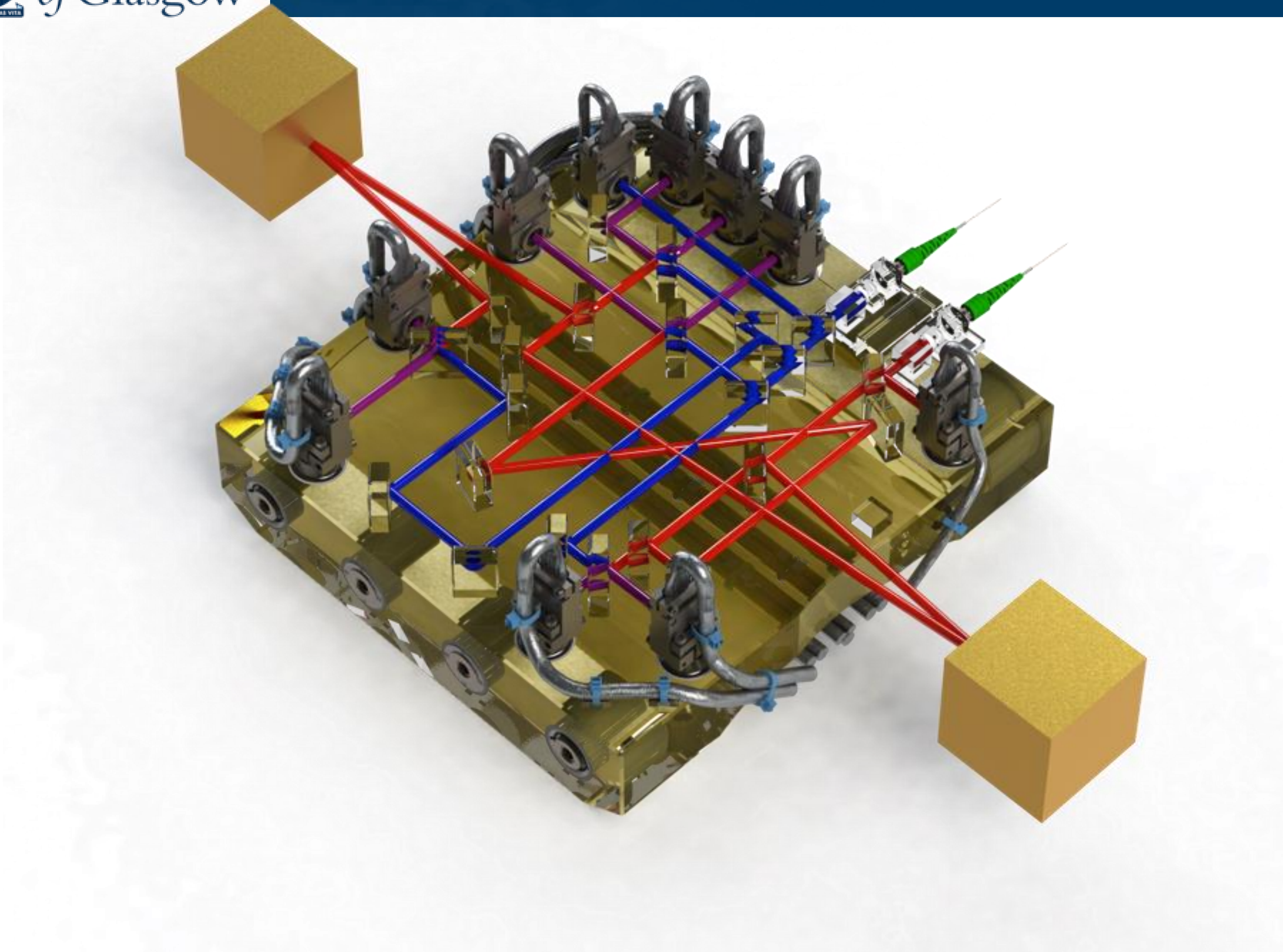

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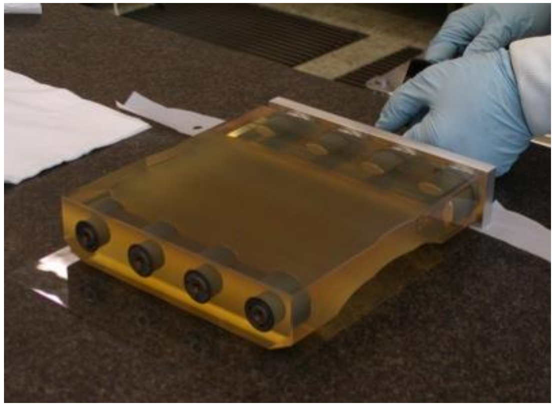
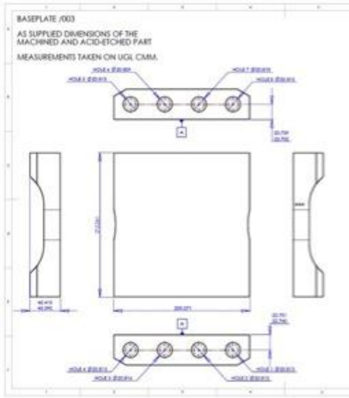
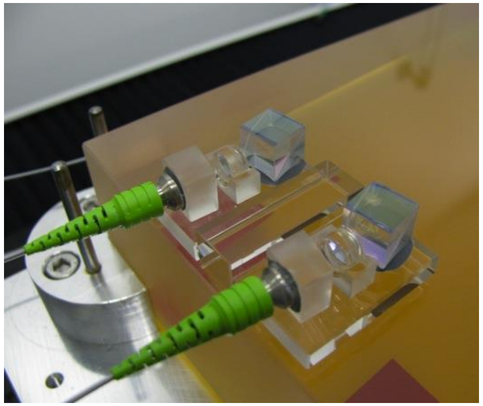
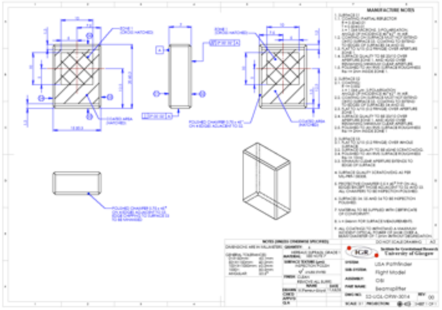
Flight hardware

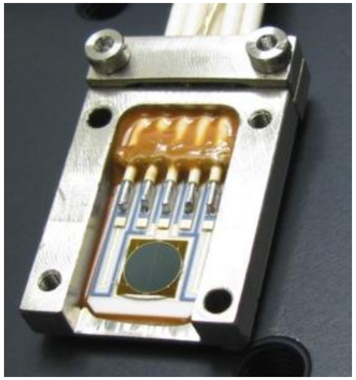


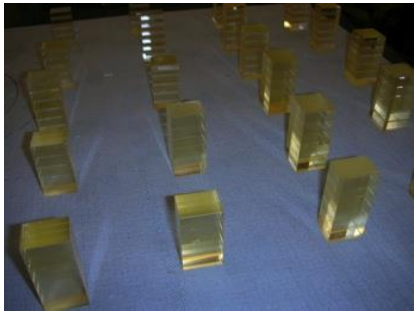


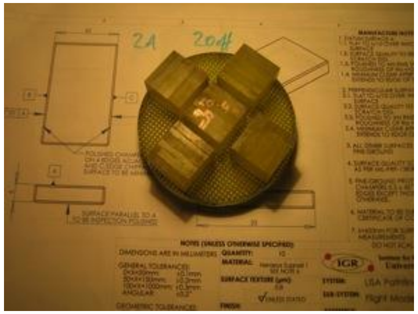


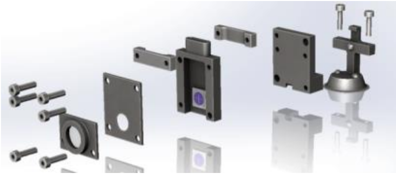


- Lots of detailed work went in to what is a very complicated assembly
  - There’s no time for details here!









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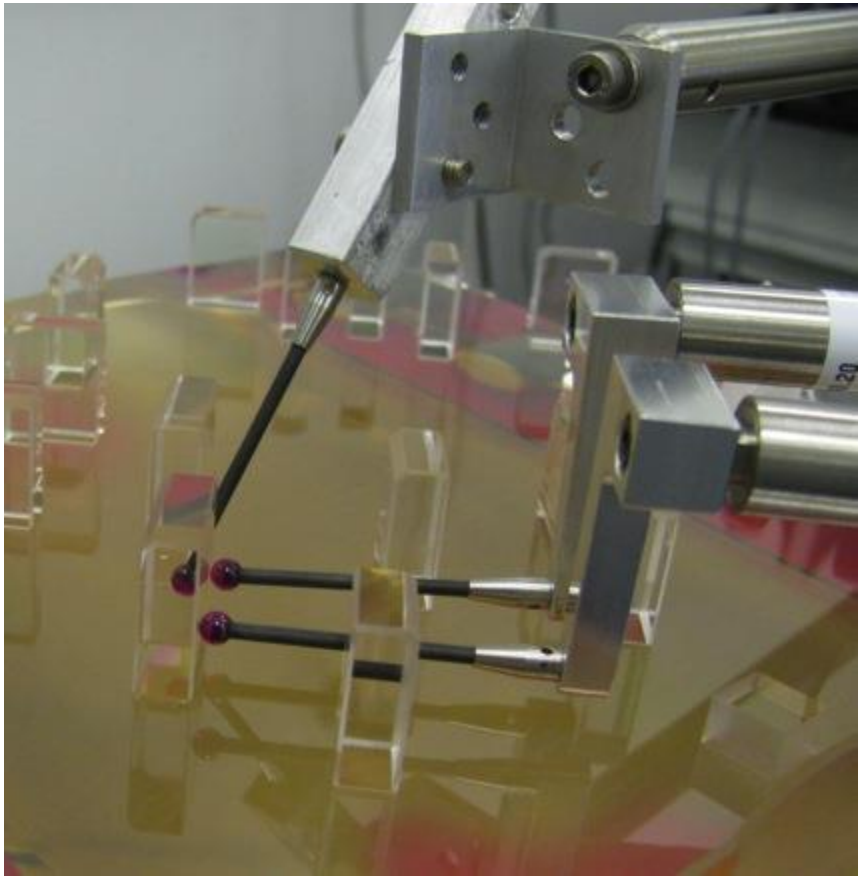
Precision alignment

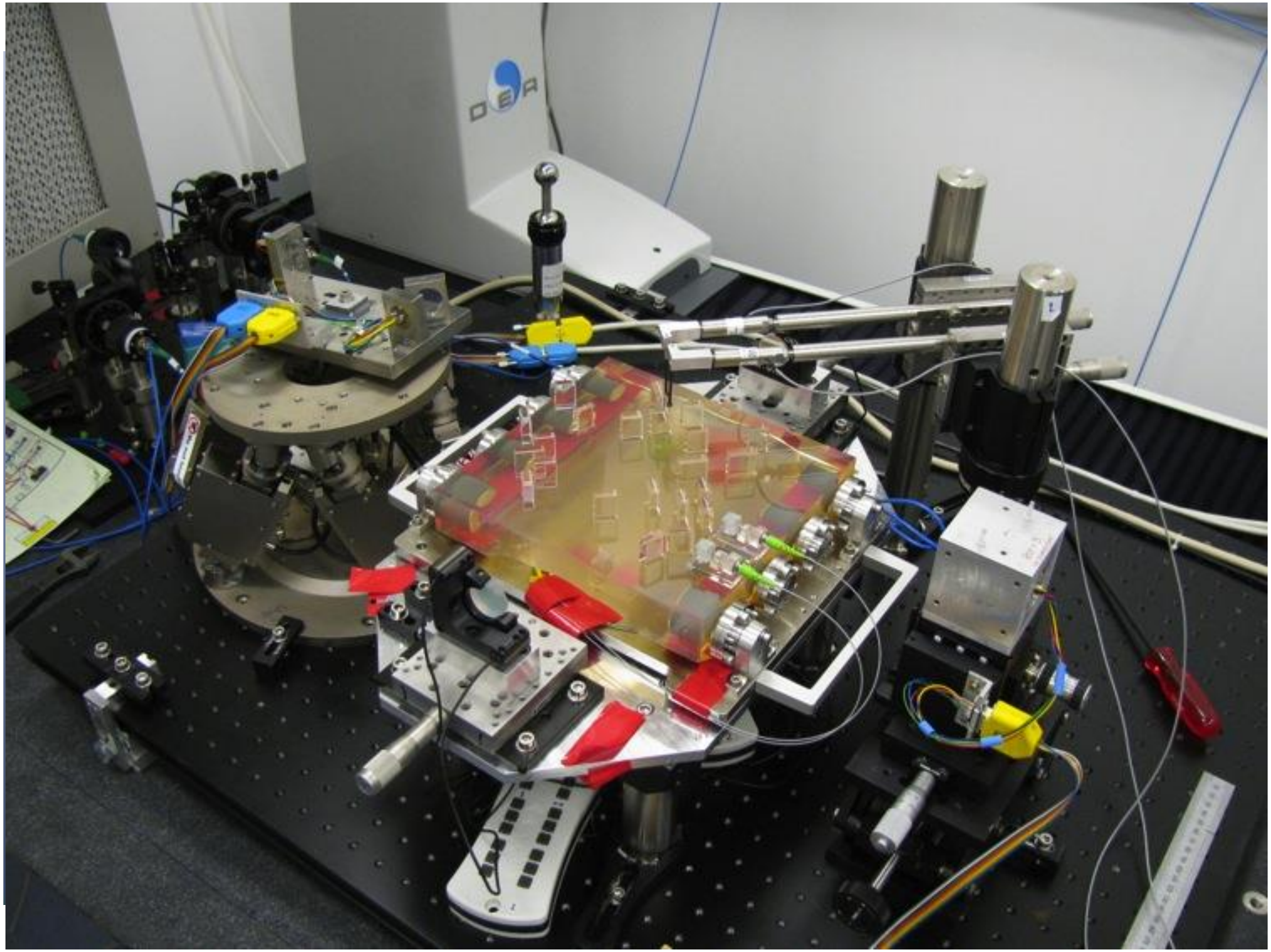
- We developed the technique to precision locate a component and then bond it in place
  - This uses hydroxide-catalysis bonding to form quasi-monolithic assemblies
  - Once built the assembly is permanently aligned
  - Demonstrated picometre stability
- Component placement at the sub-μm and 20 μrad level
  - Killow *et al.* Applied Optics, Vol. 52, Issue 2, pp. 177-181 (2013)



Photograph of active alignment of an optical component to be bonded

Precision alignment

- Each alignment stage was carefully planned



Testing

- The flight OBI underwent considerable testing
  - More details in Robertson *et al*. Class. Quantum Grav. 30 (2013) 085006

- Properties of the optical chain
  - Transmission efficiency
  - Photodiode responsivity
- Alignment to the IAF Frames
- Beam DC positions and scaling
- DWS Calibration
  - Operating point
  - k-coefficients
- Other Optical Properties
  - Interference contrast
  - Path length matching
- Thermal Vacuum cycling
- Vibration and shock

Delivered!

The LISA Pathfinder Optical Bench Interferometer - a fine vintage!

Finishing thoughts

- The University of Glasgow has provided the ‘jewel in the crown’ flight Optical Bench Interferometer for LISA Pathfinder of LISA Pathfinder
  - We are now using our experience to further the readiness of eLISA
  - As well as performing knowledge transfer activities to multiple new areas

- And a lateral thought…
  - Delivering flight hardware is more than ‘just’ hardware
  - >45 GB SVN file repository
    - >10000 updates!
    - Plus 10 GB of lab photos (N~7000)

Further information

- https://www.elisascience.org/whitepaper/
- Robertson *et al*. Class. Quantum Grav. 30 085006 (2013)
- Fitzsimons *et al*. Applied Optics, 52 (12). pp. 2527-2530 (2013)
- Killow *et al.* Applied Optics, Vol. 52, Issue 2, pp. 177-181 (2013)
- Killow *et al.* fibre coupler paper in preparation for Optics Express

- Search ‘LISA Pathfinder’ on YouTube

- This work was funded by: