TEOPS: "Groups, Commonality, Activity, Capabilities & Silicate bonding"

(TEOPS) Technology for Experimental and Observational Physics in Scotland

- **What is TEOPS?**
- **T**echnology for **E**xperimental and **O**bservational **P**hysics in **S**cotland
- **Initiative** in SUPA Astrophysics and Space Research **theme**
- "Spans the areas of particle physics, astrophysics and astronomy with a common theme of leading edge technology"
- Collaboration between UK ATC and Glasgow University Institute for Gravitational Research and Experimental Particle Physics groups

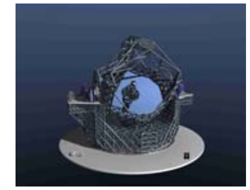
Institute for Gravitational Research (IGR)

- *The work of the Institute is focused on*
  - *the development of detectors to search for gravitational waves from astrophysical sources*
  - *data analysis activities within the LIGO Scientific Collaboration.*
- *The main areas of experimental research are*
  - *development of precision novel interferometric techniques*
  - *development of systems of ultra low mechanical loss for the suspensions of mirror test masses along with research towards the space-based LISA mission*
    - Development of multiple pendulum systems using silica fibres to support the test masses
    - New bonding technology (hydroxide-catalysis bonding), which exibits very low mechanical loss and is compatible with ultra-high vacuum
- *The technology developments within the IGR are of broader relevance to a number of areas of current PPARC interest and extensions of the bonding technology are being pursued with general application to precision optical systems on the ground and in space.*

PPE

- Experimental Particle Physics - Detector Development group
  - involved in a wide range of projects related to imaging, radiation detection and detector development, within particle physics, medicine, biology
- *Examples of current/recent projects include:*
  - CERN ATLAS - Production and testing of modules for the LHC/ATLAS
  - CERN Medipix - High sensitivity X-ray imaging for medical and synchrotron applications
  - Retinal imaging - Measuring the electrical activity of retinal tissues

ATC



- UK Astronomy Technology Centre, Edinburgh
  - **MIRI** – hosting the European PI and opto-mechanical design leads for this key instrument on the JWST, successor to the Hubble Space Telescope
  - Involved in building instrumentation for the most exciting international ground-based and space-borne astronomy projects
    - **WFCAM** – the largest infrared camera ever built, a cryogenic instrument now undertaking unique surveys in the Northern Hemisphere skies
    - **SCUBA2** – the successor to SCUBA, one of the most successful ground-based instruments ever built, utilising a new generation of sub-millimetre CCD-like detectors
    - **European Extremely large telescope (E-ELT) –** The UK ATC is leading the UK's work towards an optical and infrared telescope of up to 42 m in diameter, recently approved into the design phase by ESO CouncilThe UK
- ATC is also involved in several UK and European network and technology development initiatives
- Technology and research strengths complementary to and highly relevant to IGR and PPE groups in Glasgow

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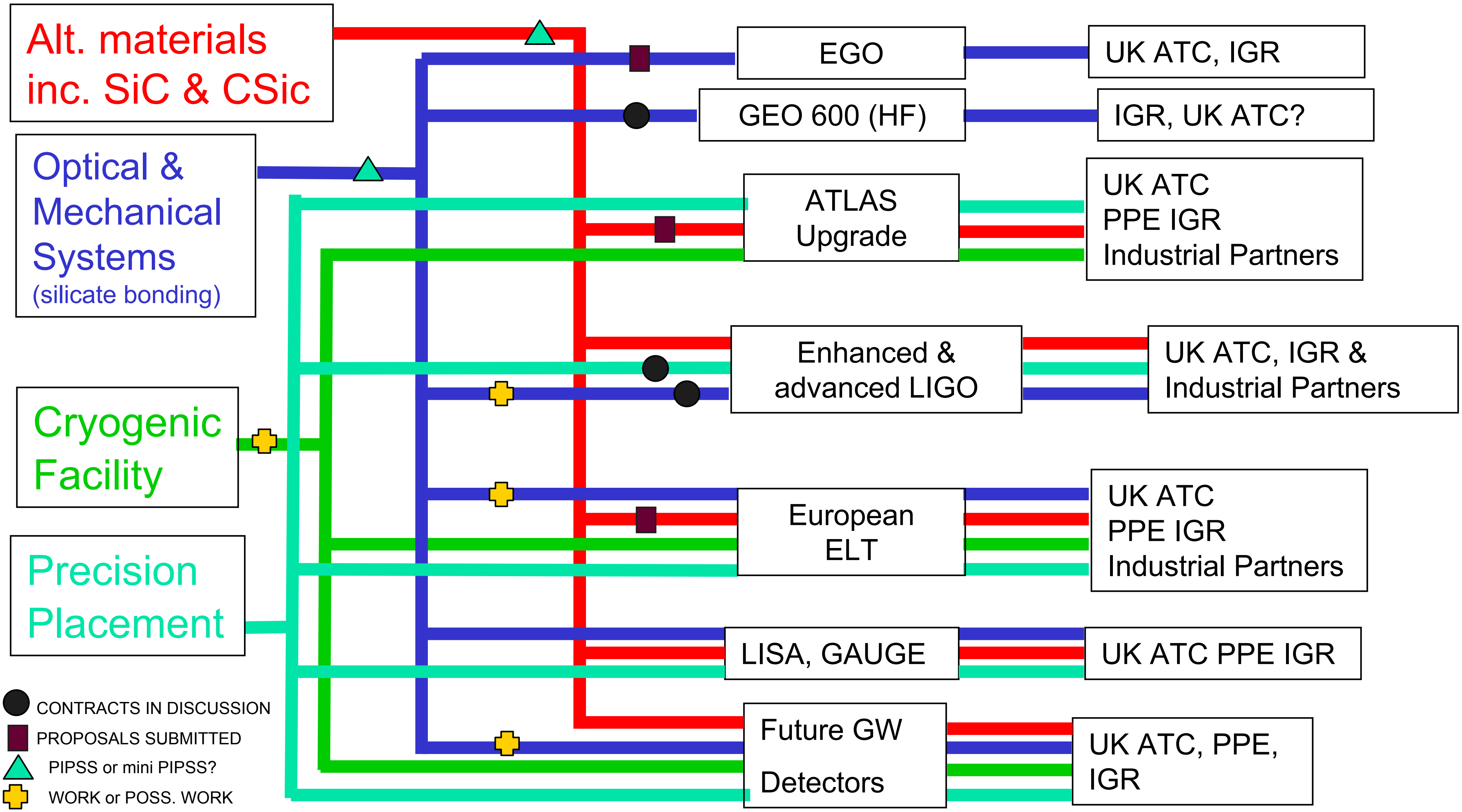
AREAS OF COMMONALITY / INTEREST



TEOPS: Capabilities #1

- VMC (HAAS)
  - 5 axis

- LISA Pathfinder lab
  - precision assembly

- SRDG – Optical Characterisation Suite
- Detector Characterisation Suite (PPE)

Optical Characterisation Suite

- Zygo interferometer
  - Suitable for surface flatness and curvature measurements on mirrors
  - Flatness measurements of <1 nm are possible over a 4 or 6 inch wafer
- Wyko NT1100 optical surface profiler
  - Field of view from 3.5x 4 mm to 50x 50 μm
  - Step heights up to several mm
  - Surface roughness measurements down to 0.5 nı
- TM1000 tabletop SEM
  - ~30 nm resolution on insulating substrates as well as conductive (reduced charging)
  - Totally self contained no additional pumps
  - ~2 min pump down

Detector Development Lab (PPE)

- Automatic wire-bonding system
  - used for high precision, high density connections between detectors and readout electronics
  - used for the wire-bonding of SCT modules for the ATLAS project at CERN (~1.5 Mbonds)

- Cascade Microtech S300 probe station
  - sets the measurement standard for 300mm on-wafer test
  - applications
    - device characterization and modeling
    - wafer-level reliability
    - design de-bug
    - IC failure analysis
  - has the precision and versatility needed for the most advanced semiconductor processes and aggressively scaled devices
  - allows the group to create the perfect on-wafer measurement environment

TEOPS: Capabilities #4

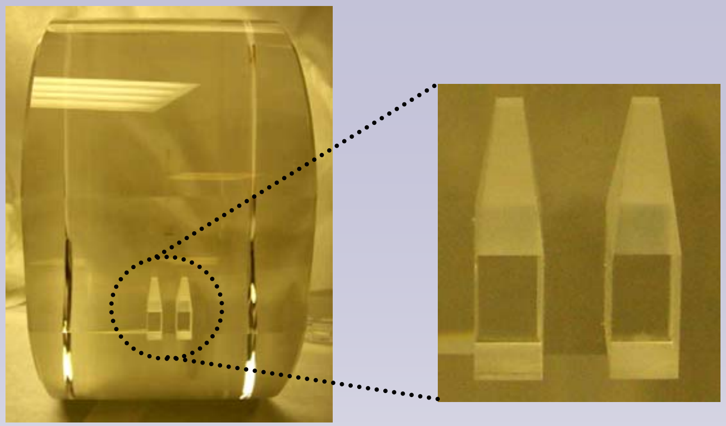
- Cryogenic Material Property Test Bed
  - Based at UK ATC

- Future?

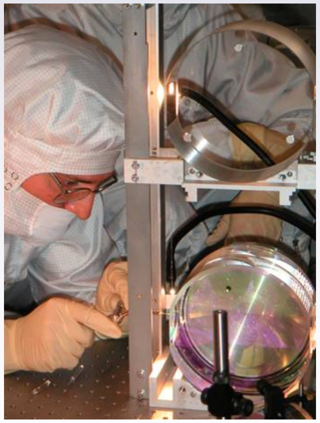
Investigations into hydroxy-catalysis bonding

Current applications

- Originally developed for NASA's Gravity Probe B mission, launched April 2004. (Gwo et al.)
- GEO600 currently operates with quasi-monolithic fused silica suspensions and mirrors. This technology allows improved thermal noise in the suspension systems.
- Construction of the ultra-rigid, ultra-stable optical benches for the LISA Pathfinder mission.



Picture of a GEO600 sized silica test mass in Glasgow with silica ears jointed using hydroxy-catalysis bonding



Silica fibres are welded to the ears in the completion of the lower-stage of the GEO600 mirror suspension.

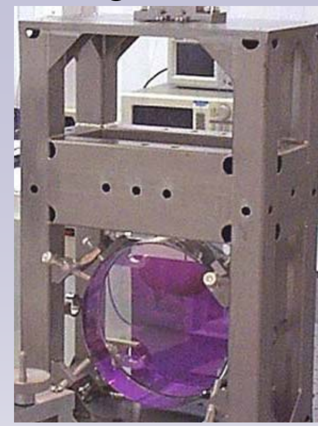
Investigations into hydroxy-catalysis bonding

Planned applications

- The planned upgrades for AdvLIGO and Advanced VIRGO plan to incorporate the GEO600 technology for significantly improved thermal noise performance (in addition to other improvements, e.g higher power lasers).

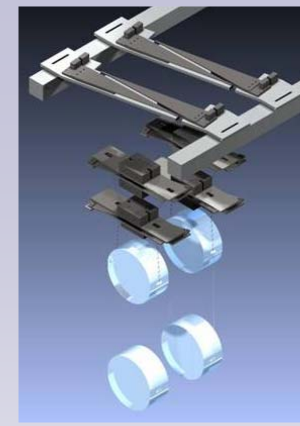
- Construction of the ultra-rigid, ultra-stable optical benches for LISA.

eg. LIGO

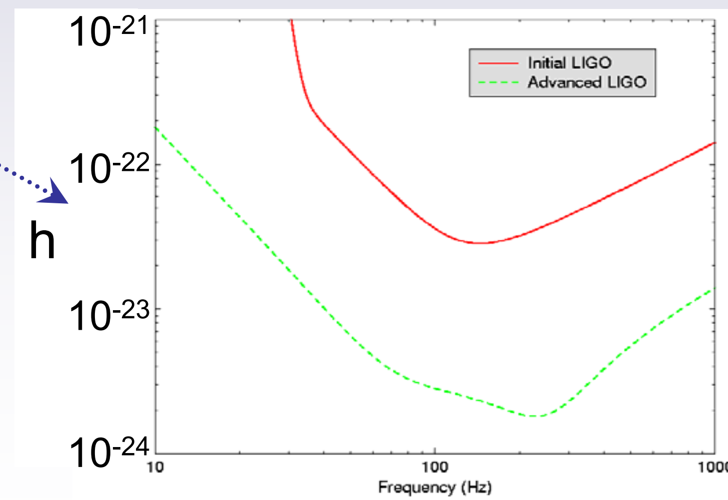


Wire loop
arm length: 4 km

AdvLIGO



Quadruple stage
silica ribbons/fibres

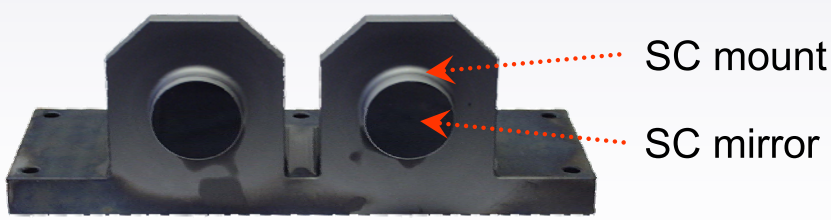


Design sensitivity curves for the LIGO and AdvLIGO detectors.

Catalysis bonding settling time dependence

Motivation

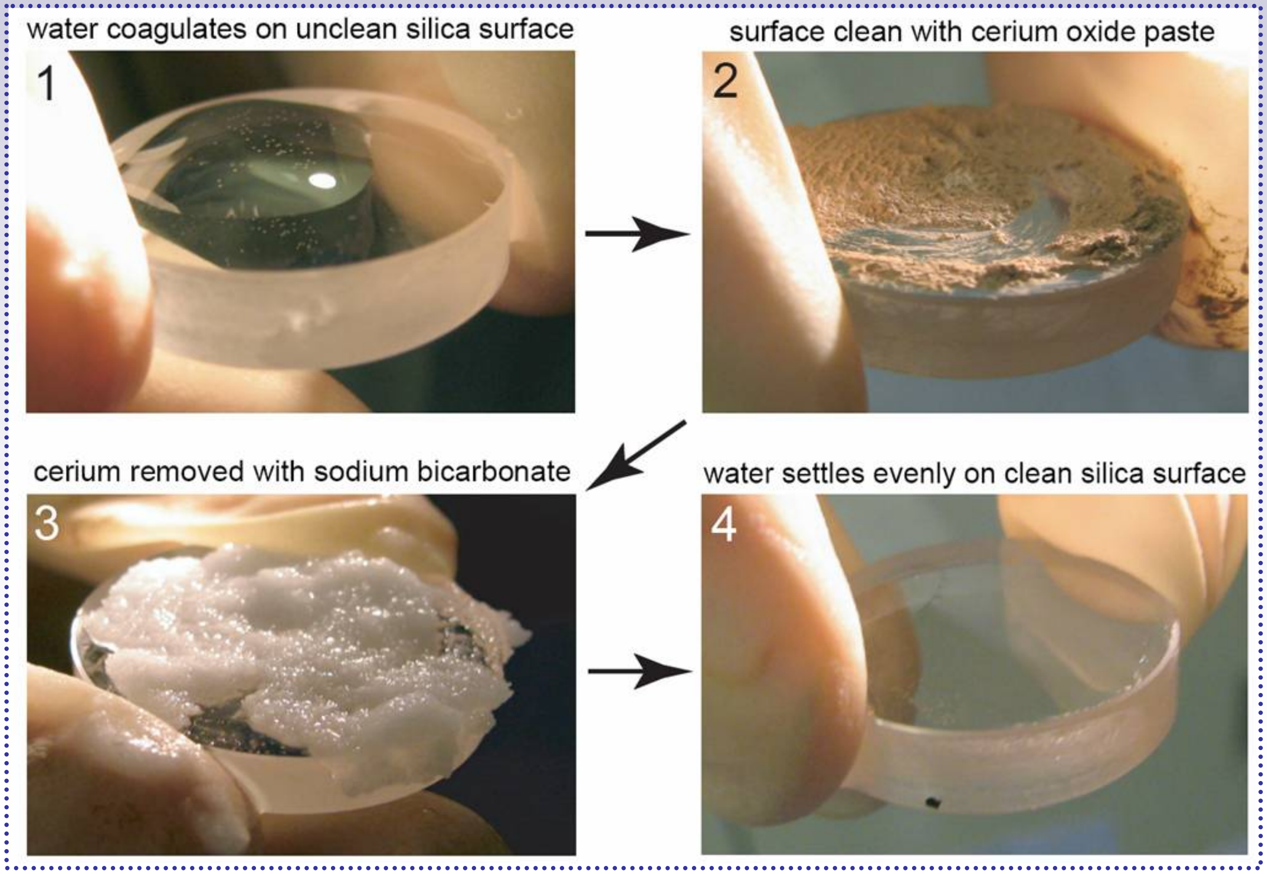
- Many optical systems layouts have stringent requirements for strength, rigidity, stability and alignment.
- Hydroxy-catalysis bonding fulfills all these requirement.
- One possible disadvantage of this technique is that the time taken for a typical bond to "set" at room temperature is in the region of a few tens of seconds. This only allows a short period of time in which to align the various components on the optical bench
  - Glasgow has investigated how to extend the settling time of hydroxy-catalysis bonds through varying the hydroxide concentration and lowering the temperature. (Reid et al, Physics Letter A, 2007)



Picture of silicon carbide mirrors bonded to a silicon carbide base mount for GAIA

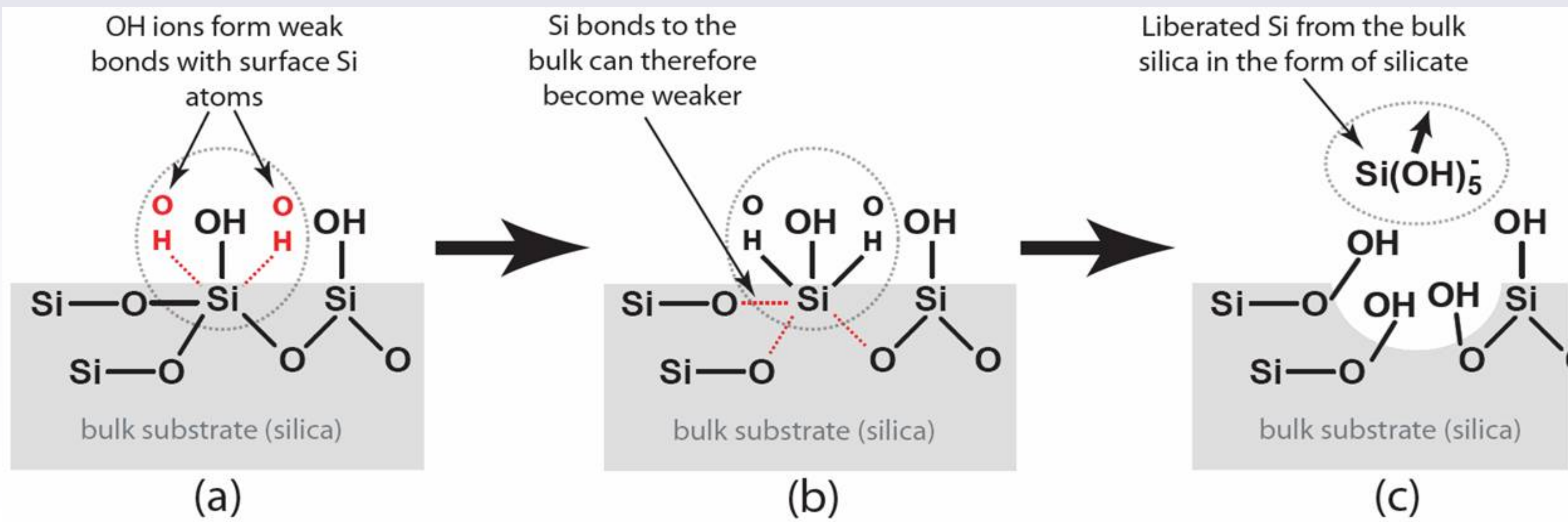
Surface preparation

- Contaminants on the silica surface will likely inhibit hydration. The silica surfaces to be jointed are thus taken through a cleaning process to remove any contaminants and to ensure maximum hydration:



Etching – Etching of the silica surfaces to be bonded

- Placing a solution with a high concentration of OH− ions on the surface of silica causes etching to take place.
- Free OH⁻ ions form weak bonds with silicon atoms on the substrate surface causing the original lattice bonds to weaken
- It becomes possible for the silicate molecule to break away from the bulk structure, producing $Si(OH)^{-}_{5}$ molecules in solution.

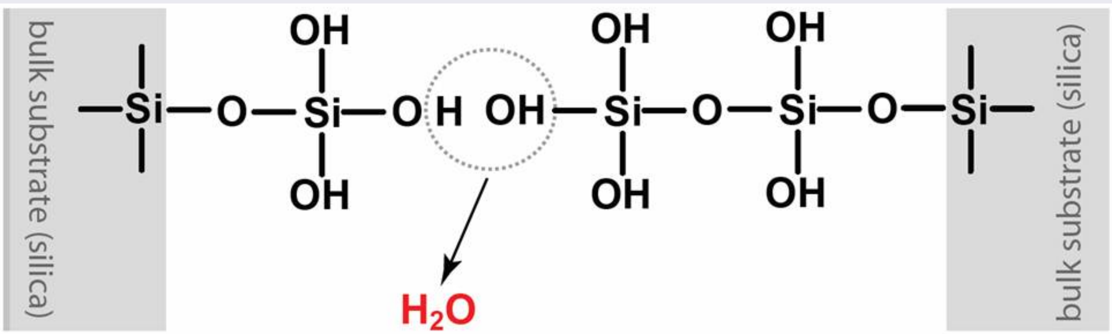


The processes involved in hydroxy-catalysis bonding

Bonding – Polymerisation of silicate in solution

- However, below pH 11, the silicate ion hydrolyses to soluble $Si(OH)_4$ and OH^-. When the concentration of $Si(OH)_4$ molecules reaches 1→2%, the solution polymerises and becomes "rigid" (R.K. Iler, 1979, *The Chemistry of Silica*).
- $Si(OH)_4$ is a monomer which likes to form a polymer arrangement:

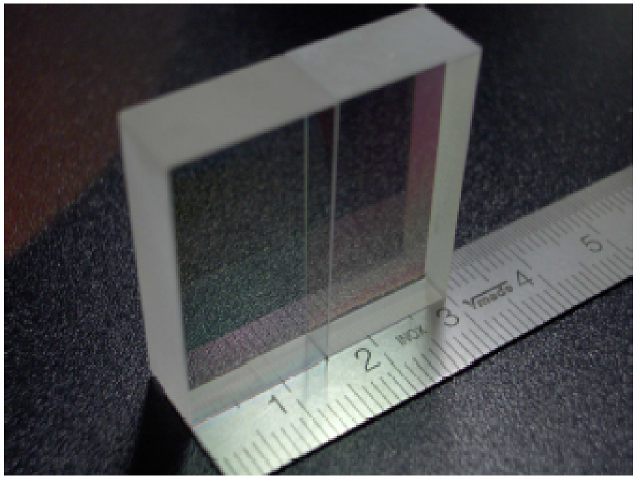
$$Si(OH)_5^- \rightleftharpoons Si(OH)_4 + OH^-$$



- Bonding starts to dry and evaporates H_20
- Bond thickness ~ 100 nm

De-Bonding

- De-bonding is possible within a few hours from bonding, depending on size, shape and quality of the bond
- Using ultra-sonic bath with detergent solution (10% Decon®)
- Each bonding and de-bonding process can slightly damage the surface for bonding



Investigations into hydroxy-catalysis bonding

Ongoing work in Glasgow includes:

- Further investigation of bonding samples with a ground finish.
  - align optics without danger of optical contacting
  - no time constraint on achieving alignment
  - apply bonding solution with pieces in situ

- Bonding other materials

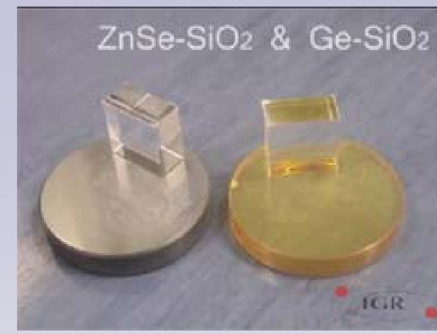
  e.g. Silicon-silicon bonded samples for verifying the feasibilty of monolithic silicon suspensions for 3rd generation gravitational wave detectors:

  - mechanical strength
  - thermal conductivity (at low T)
  - mechanical loss

Silicon-silica hydroxy-catalysis bond

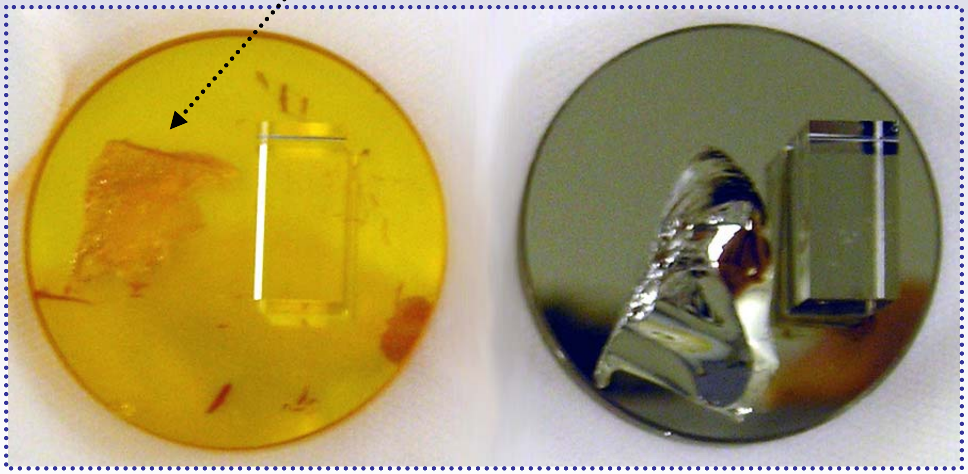
Investigations into hydroxy-catalysis bonding

- Successful test for Astrium D for feasibility of $ZnSe/SiO_2$ and Ge/SiO_2 bonds



Images from video of temperature cycling of SiO_2 bonded to ZnSe down to 77K

Damage due mechanical strength testing.

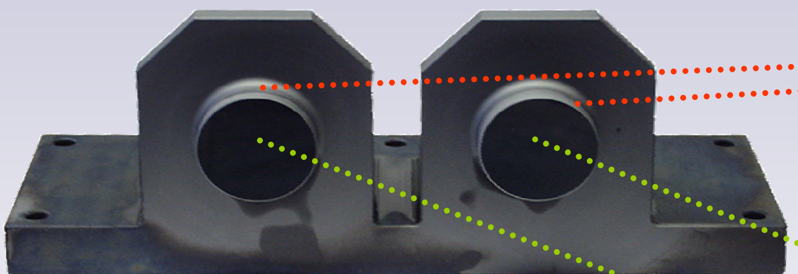


SiO_2 bonded to ZnSe

SiO_2 bonded to Ge

Investigations into hydroxy-catalysis bonding

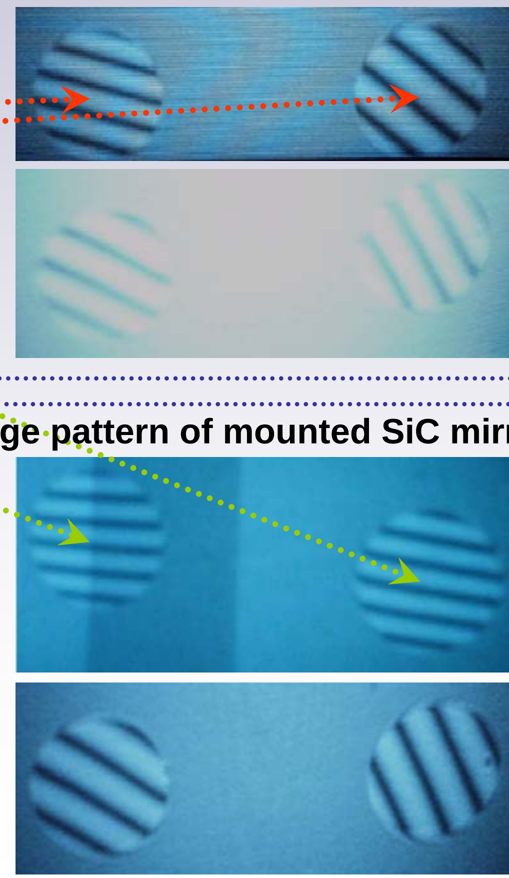
- Astrium France – IGR subcontract – silicon carbide optical assemblies for GAIA – patent application filed
- Current non-disclosure agreement in place with TNO-TPD for further evaluation



Picture of silicon carbide mirrors bonded to a silicon carbide base mount for GAIA

fringe pattern of SiC optical mount

fringe pattern of mounted SiC mirrors



before oxidation

after oxidation

mirrors mounted dry

mirrors hydroxy-catalysis bonded

No relative tilt change between number of fringes within the resolution of the interferometer

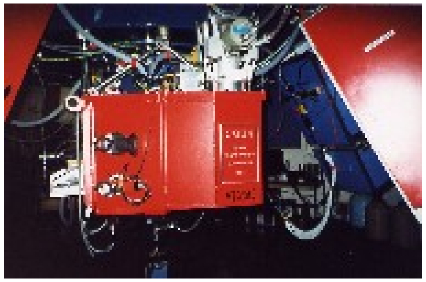
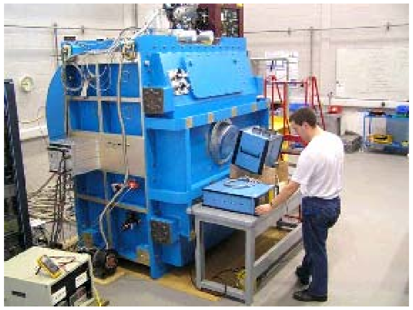
Relative tilt in mirrors before and after bonding < 1arcsec (well within design specification of 3 arcsecs in relative tilt).

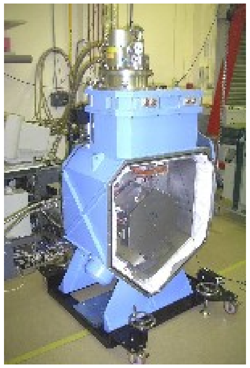
TEOPS Activity

- Submitted (Proposals)
  - European Gravitational Wave Observatory (EGO)
    - silica ribbons for monolithic suspensions – submitted
  - TEOPS Proposal part of larger PPARC proposal for ELT
    - Development of key passive & adaptive mirror technologies using SiC mirrors
  - ATLAS upgrade
    - Development of supermodule structures
- Discussions (Contract)
  - Advanced LIGO
    - Optical and Mechanical Systems
  - GEO 600 and Hannover AEI Prototype
    - Upgrades to existing detector
    - Isolation and Suspension design
- Other
  - Adam Smith Scholarships
    - Mech Eng & Chemistry
  - PIPSS & mini-PIPSS
  - British Consulate LA and Scottish Executive
    - Caltech / Glasgow (SUPA) expansion

Commonality

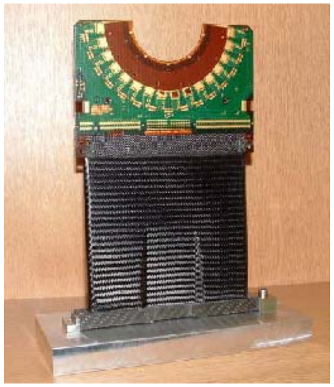
- Significant areas of commonality: some examples:
  - Cryogenics
    - The ATC has decades of experience in constructing reliable and robust instruments operating at cryogenic temperatures (as low as 4 K and even below 100 mK)
  - Cryogenic operation is now of interest for future generations of both gravitational wave detectors and colliders for particle physics




Commonality

- New materials
  - e.g. silicon-carbide being looked for use in astronomical instruments, particle physics detectors and in gravitational wave detectors
  - CSiC trials underway in Glasgow
    - Thermal, mechanical, vacuum & bonding

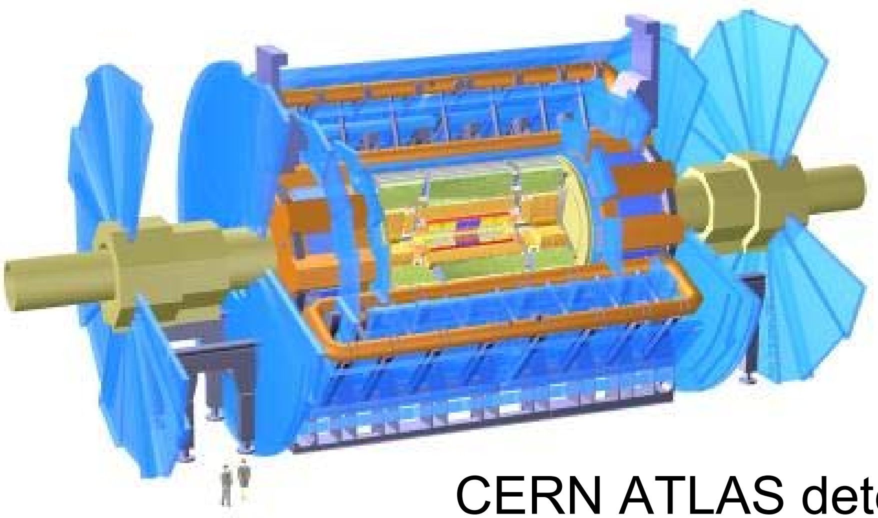


LHC module using carbon fibre mount – Si-C considered as replacement

Si-C lightweighted telescope mirror (courtesy M. Krodel)

Commonality

- Particle physics detector groups have experience in constructing detectors on an “industrial” scale
  - will be required in astronomy as telescopes increase in size (and number of telescopes in the case of arrays)



CERN ATLAS detector