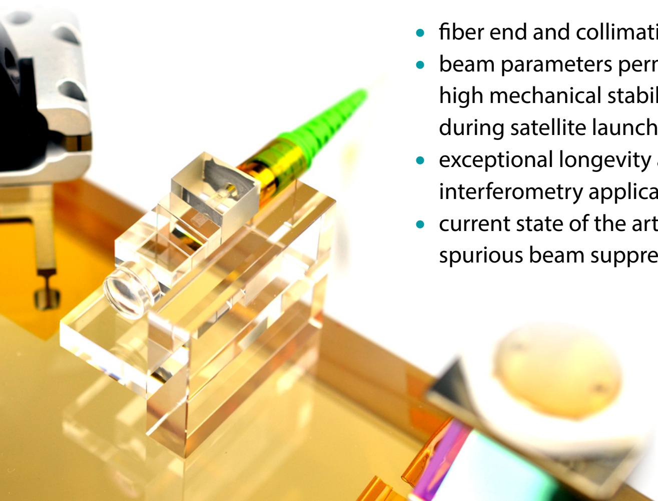
ULTRA-STABLE FIBER INJECTORS FOR RAPID DEVELOPMENT CYCLES

Daniel Penkert[2], Dennis Schmelzer[2], Michael Tröbs[1], Thomas Schwarze[2], Oliver Gerberding[1], Gerhard Heinzel[1,2]
[1] Max Planck Institute for Gravitational Physics (Albert Einstein Institute) [2] Leibniz Universität Hannover • • • Edoardo Amaldi Conference on Gravitational Waves, July 9-14, 2017

Outline of this talk

1. Ultra-stable fiber injectors — a.k.a. FIOSs
2. Current design version 2.0 & the "Hexagon" interferometer
3. Improved future version 2.1 & the Three-Backlink Experiment
4. How to determine a FIOS's thermal stability



Fiber injector optical subassembly (FIOS)

- fiber end and collimating lens in a single quasi-monolithic structure
- beam parameters permanently fixed during initial assembly process $\Rightarrow$ high mechanical stability (e.g. resilience against shock and vibrations during satellite launch)
- exceptional longevity and thermal stability $\Rightarrow$ high precision interferometry applications
- current state of the art in terms of thermal/mechanical stability and spurious beam suppression: University of Glasgow (image: LOB FIOS)

AEI FIOS Design 2.0/2.1 – Objective

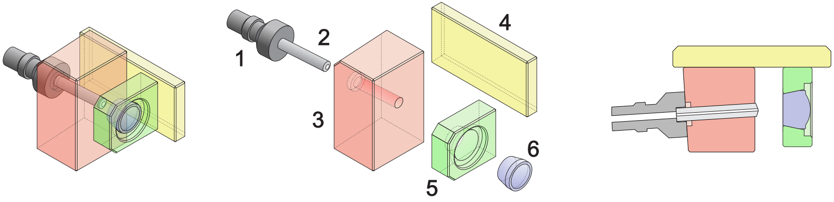
Alternative approach

- optimized for lab use and batch production ⇒ emphasis on cost efficiency and simplicity
- UV-gluing instead of silicate bonding/optical contacting ⇒ streamlined assembly process
- interfaces between materials of different CTEs realized either in a rotationally symmetric arrangement around beam axis or as thermally compensated pairs
- full control over the beam's horizontal and vertical positions and angles

Current development: version 2.1

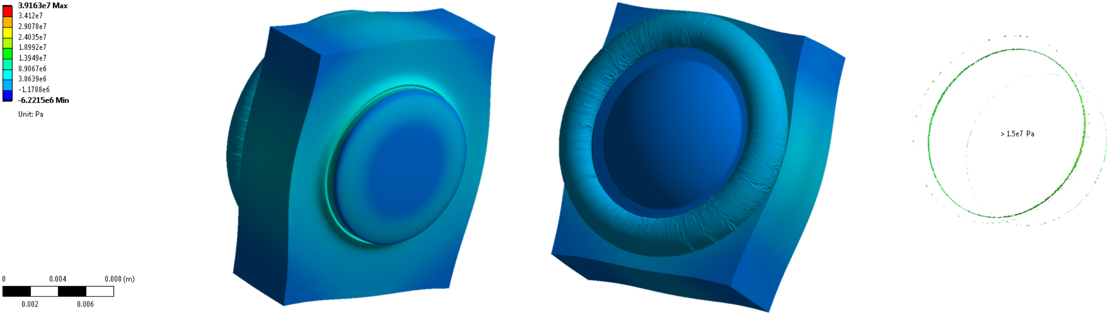
- additional means of ensuring thin, non-wedged adhesive layers of reproducible thickness
- simplified, yet more powerful assembly process

FIOS Design 2.1 – Details



- all components pre-machined ⇒ no intermediary grinding/polishing required
- strain relief (1) holding ferrule (2) with polished 8-degree fiber end
- fiber mount assembly (FMA) (3) with through hole and UV glue trench providing an extremely tight fit for the ferrule ⇒ reduced risk of nonuniform gluing layers
- lens (6) with tapered lateral surface & lens holder (5) with matching conical hole ⇒ guaranteed on-axis fit with an extremely thin adhesive layer
- longitudinal girder (4) bridging FMA and lens holder ⇒ thermally compensated pair of adhesive interfaces

FIOS Design 2.1 – FEM Strain & Stress Analysis

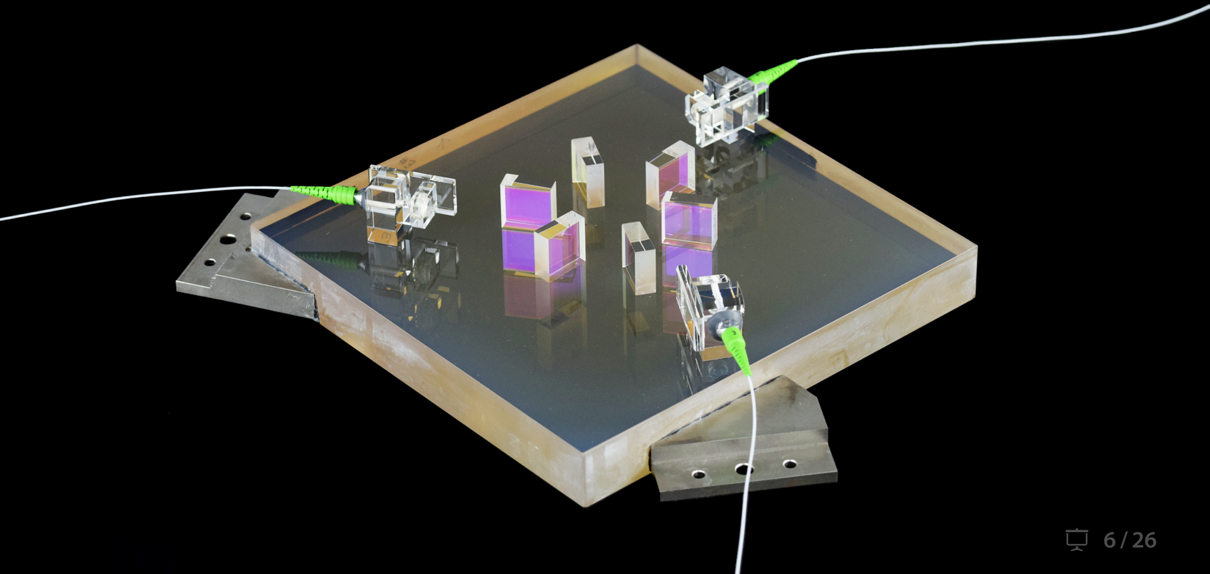


- lens holder: Corning 7980
- lens: CDGM D-ZLaF52LA
- glue: Optocast 3553-LV-UTF

$\Rightarrow$

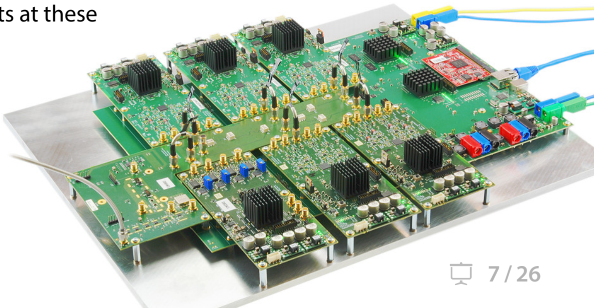
- temperature raise of 20 °C induces a maximum normal stress of 39.2 MPa into lens holder (tensile strength 54 MPa)
- high stress concentrated in sharp spikes (probably mesh artifacts)

FIOSs 2.0 on the “Hexagon” Interferometer

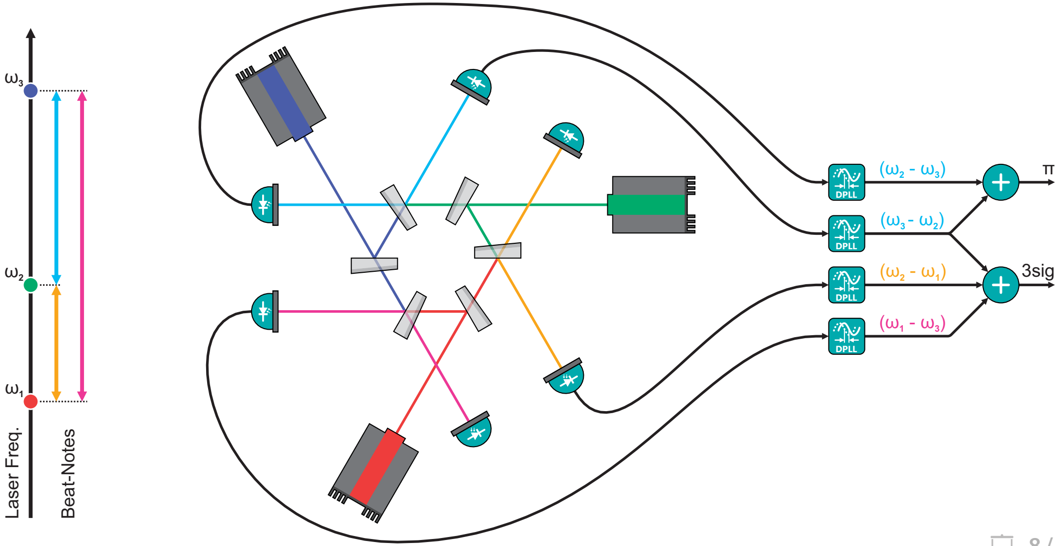


The Hexagon interferometer

- main purpose of Hexagon: test driving our FPGA-based LISA phasemeter prototype (co-developed in the scope of an ESA technology development program by AEI Hannover, Technical University of Denmark, and Axcon ApS)
- more in-depth treatment and results ⇒ LISA phase extraction talk by Thomas Schwarze
- main goal: to reach $\mathrm{pm}/\sqrt{\mathrm{Hz}}$ sensitivity within upper half of LISA's frequency band
- no off-the-shelf equipment available to conduct tests at these extreme sensitivity levels ⇒ use multiple prototype phasemeters to measure against each other in a way that is also sensitive to systematic non-linearities in the measurement process and should ideally be derived from optical source signals ⇒ three-signal test ⇒ Hexagon

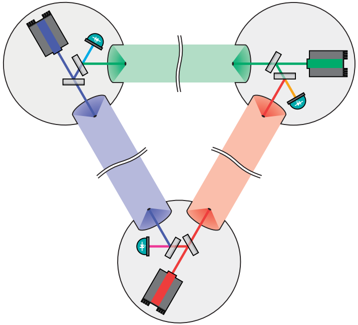


Hexagon – Basic Working Principle

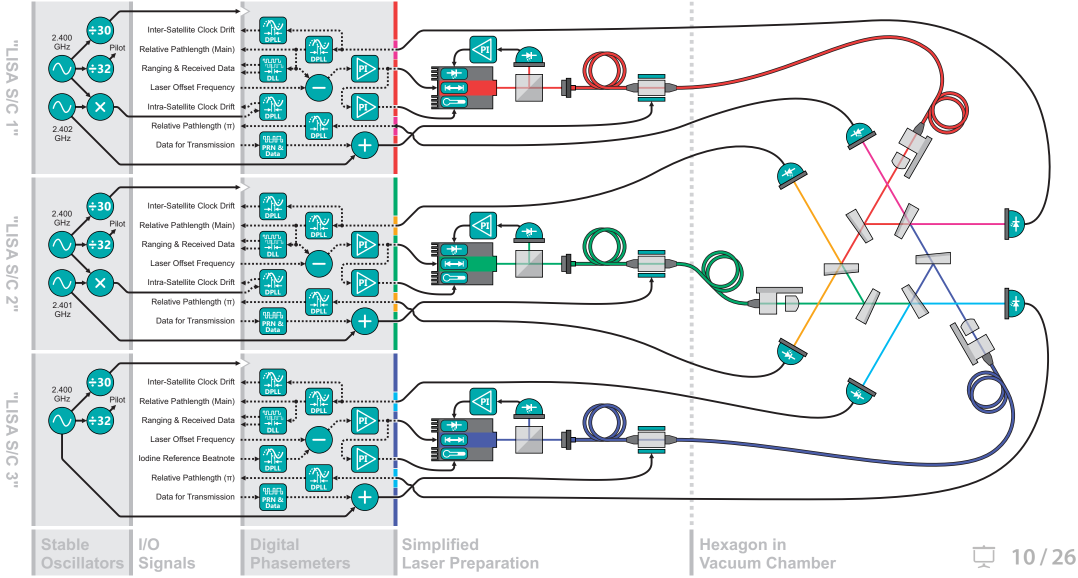


Step-by-step simplification of LISA

- no external forces acting upon the three LISA S/C
- remove test masses along with dedicated readout interferometers
- use only one optical bench and one laser per S/C
- remove all clockwise laser links
- remove telescopes and shrink constellation down to fit on a single ultra-stable optical bench ⇒ Hexagon

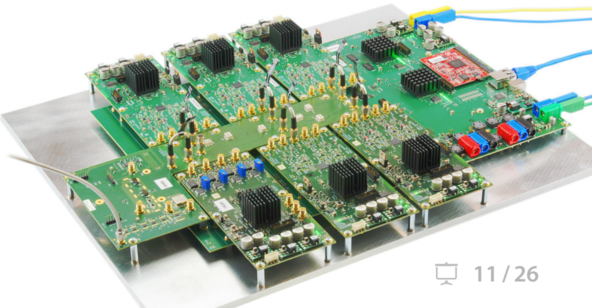


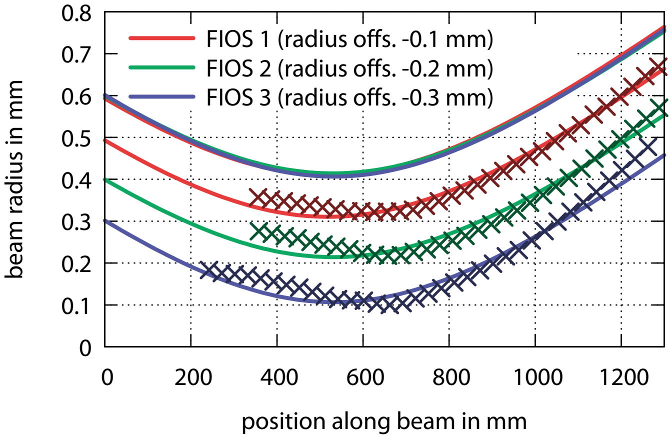
Hexagon – Testing the Full LISA Arm Metrology Chain



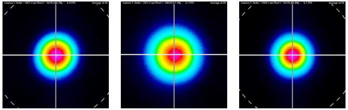
Supplemental and Auxiliary Phasemeter Functionality

- **automatic beatnote acquisition**
  FFT-based search for spectral peaks and initialization of digital phase-locked loops (DPLLs)
- **laser offset locking**
  keep beatnote within phasemeter's bandwidth & beatnote sweeping ($\Rightarrow$ dynamic Doppler shifts)
- **quad phase tracking optimized for differential wavefront sensing on QPDs**
  using sum/differential signals
- **pilot tone injection and tracking**
  measure intra-satellite clock jitter
- **clocktone transfer**
  measure inter-satellite clock drifts
- **sub-meter inter-satellite ranging**
  PRN modulation (TX) & delay locked loop (RX)
- **low bandwidth data communication**
  switching sign of chunks of PRN chips



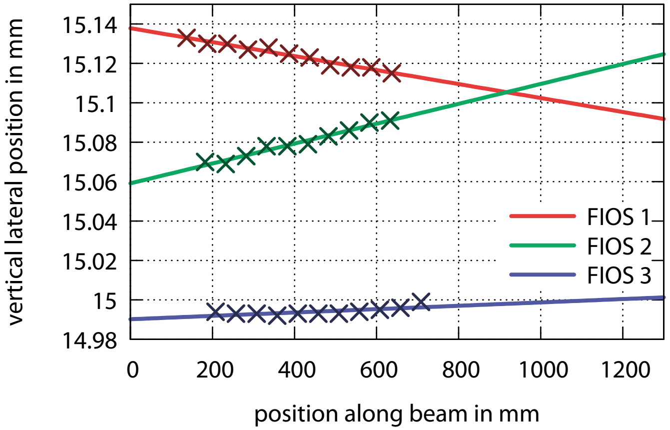


Intensity profiles for FIOSs 1, 2, 3
(measured at different positions)



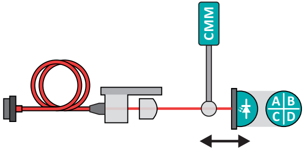
4th-order Hermite-Gaussian fit
⇒ over 99.25 % of laser power present in the fundamental mode

FIOS 2.0 Results – Geometric Beam Properties



Positional measurements

CMM's tactile ball acting as ball lens in front of QPD



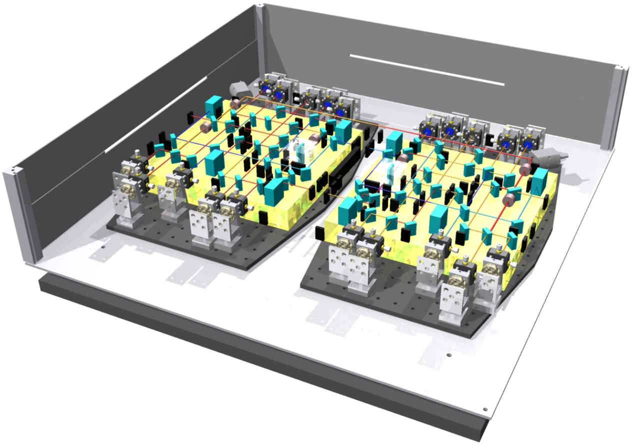
Slow axis fiber misalignments

- FIOS 1: 1.295°
- FIOS 2: 0.240°
- FIOS 3: 0.615°

Three-Backlink Experiment

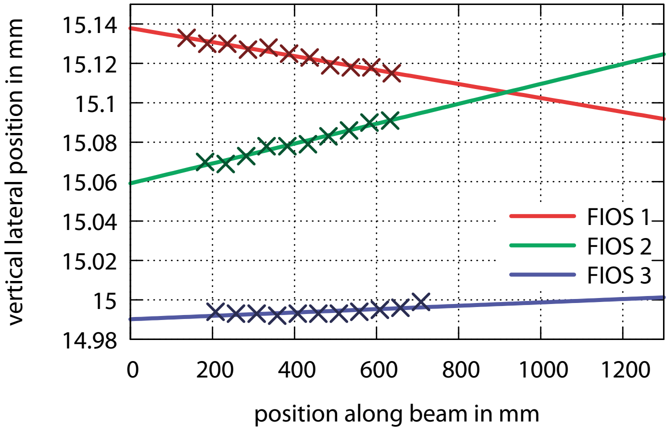
Objective and Requirements

- direct comparison between several alternative realizations of an optical backlink between a LISA S/C's two optical benches ⇒ Three-Backlink talk by Oliver Gerberding
- two complex optical benches with a multitude of fused silica components on Clearceram® baseplates ⇒ attempt to purely rely on UV adhesive bonding
- calls for a total of eight FIOSs
- requires coupling light from one FIOS into another on four separate occasions



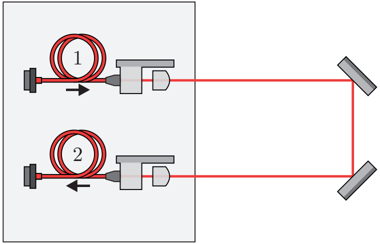
IfoCAD/Inventor model: Katharina-Sophie Isleif & Oliver Gerberding

FIOS 2.0 – Quick Coupling Test



Choice of FIOSs 1 and 2

- opposing beam angles
- similar beam heights



- FIOSs 1 and 2 optically contacted to a common slab of Zerodur®
- two adjustable mirrors used to couple light from one FIOS into the other
- the beam's waist lay in the middle of the total optical path length ($\approx$ 1.05 m)

Part 1: Ideal Coupling

- piece of Plexiglas inserted between receiving fiber end and lens to temporarily blur the beam
- mirrors adjusted for maximum throughput

$\Rightarrow$ coupling efficiency: 93.7 %

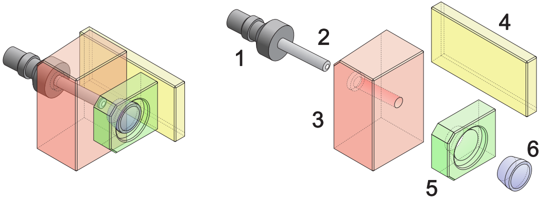
Part 2: Purely Horizontal Coupling

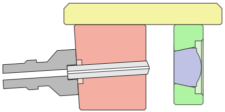
- Zerodur® baseplate and mirrors geometrically probed by CMM
- mirrors adjusted to be oriented perpendicularly to baseplate

$\Rightarrow$ coupling efficiency: 38.9 %

Can we do better?

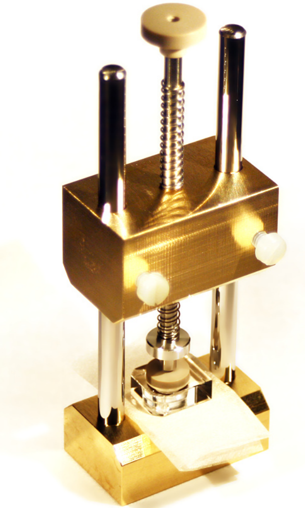
FIOS 2.1 – Improvements

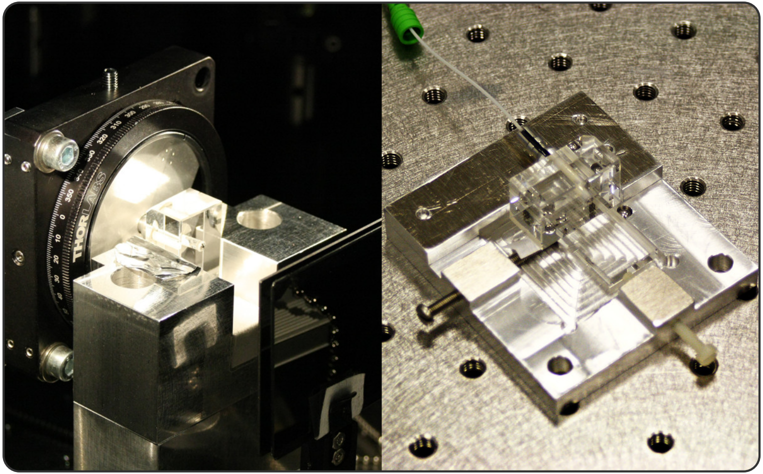




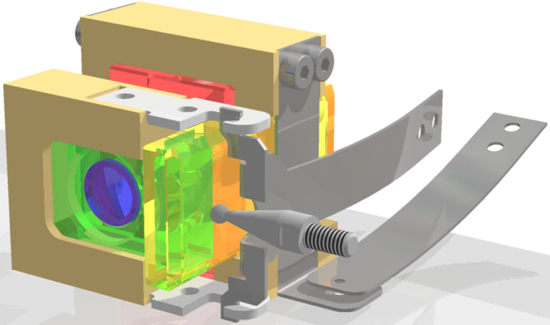
- tapered lateral surface of the lens (whereas the 2.0 FIOSs used a classical lens glued into the lens holder only by its annular frontal surface)
- extremely tight fit of the ferrule within the FMA's through hole
- biggest advantage in terms of inter-FIOS coupling expected to stem from a new and improved assembly process

FIOS 2.1 – Enhanced Assembly Process





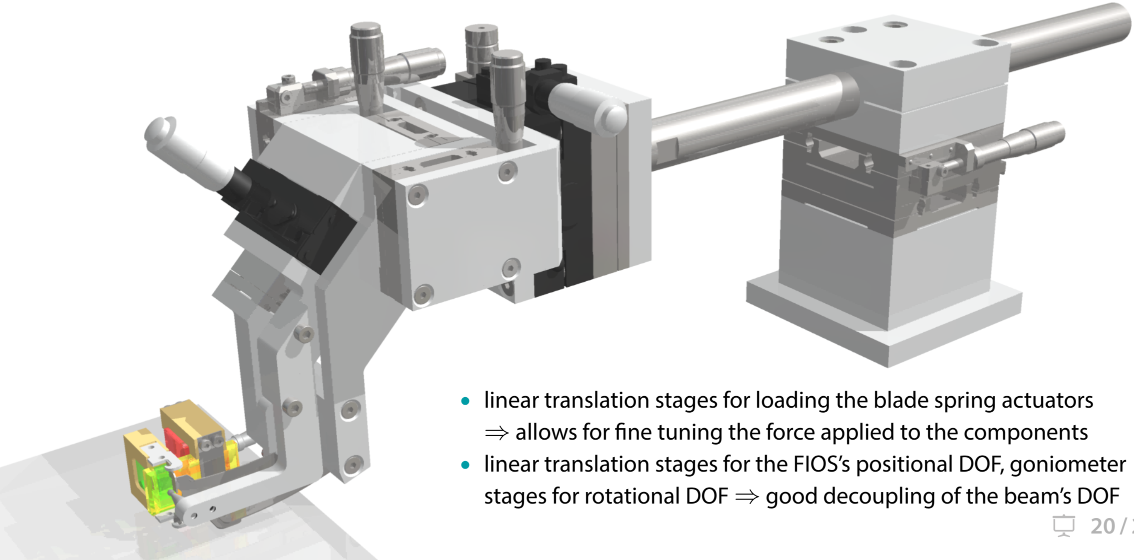
FIOS 2.1 – FIOS Adhesive Alignment Tool



Simultaneous 5-Axis Beam Adjustment Concept

- FMA cage with winglets ⇒ full control over beam's horizontal position and angle
- two blade springs as positional actuators ⇒ thin and non-wedged adhesive layer
- Lens holder cage with hooks ⇒ full control over beam's vertical position and angle as well as its waist position
- single blade spring actuator+ counter force finger ⇒ thin and non-wedged adhesive layer
- girder can still be probed by coordinate measurement machine ⇒ time efficient coarse positioning of the FIOS

FIOS 2.1 – FIOS Adhesive Alignment Tool

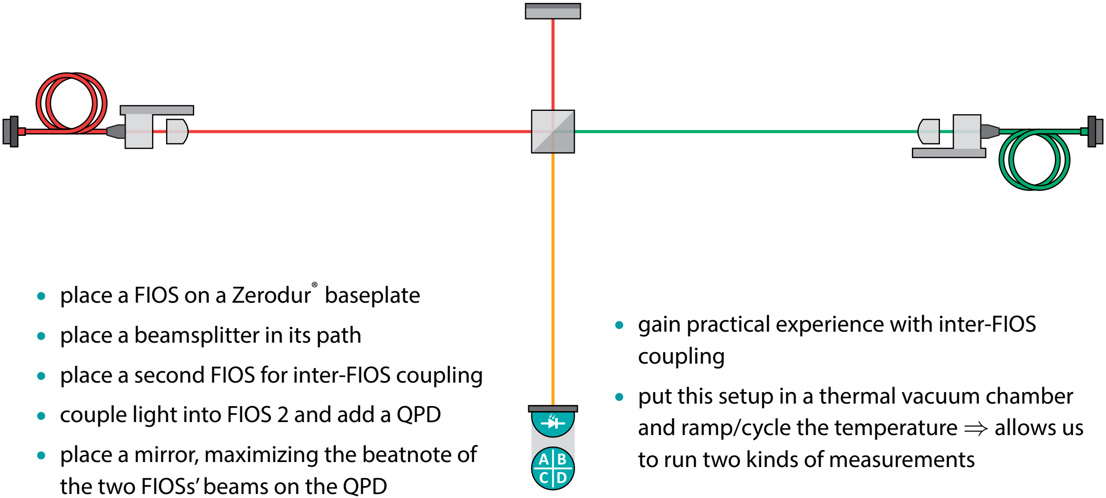


- linear translation stages for loading the blade spring actuators
  ⇒ allows for fine tuning the force applied to the components
- linear translation stages for the FIOS's positional DOF, goniometer stages for rotational DOF ⇒ good decoupling of the beam's DOF

Thermal Stability

How thermally stable will our FIOSs really be?

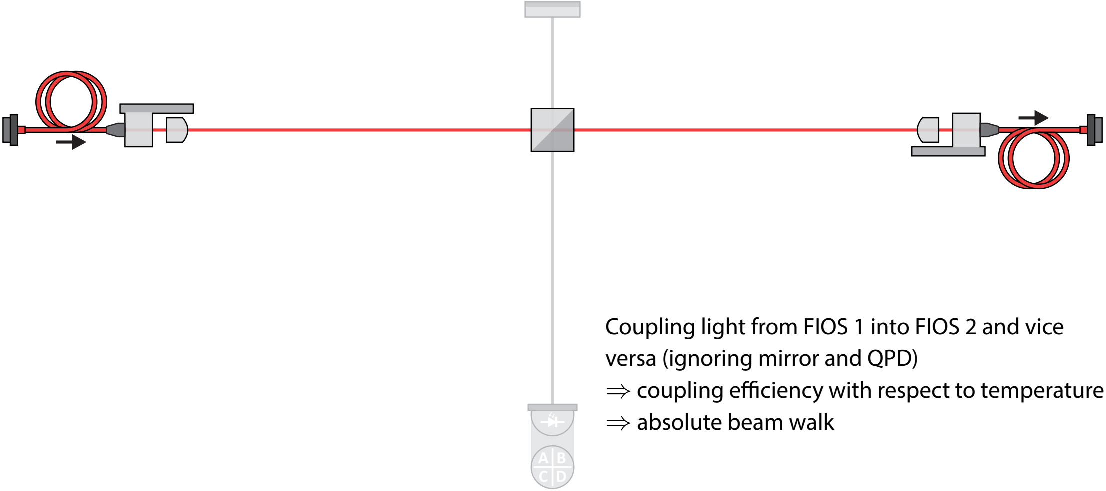
Proposed Interferometric Test Setup



- place a FIOS on a Zerodur® baseplate
- place a beamsplitter in its path
- place a second FIOS for inter-FIOS coupling
- couple light into FIOS 2 and add a QPD
- place a mirror, maximizing the beatnote of the two FIOSs' beams on the QPD

- gain practical experience with inter-FIOS coupling
- put this setup in a thermal vacuum chamber and ramp/cycle the temperature ⇒ allows us to run two kinds of measurements

Test 1: Coupling Efficiency

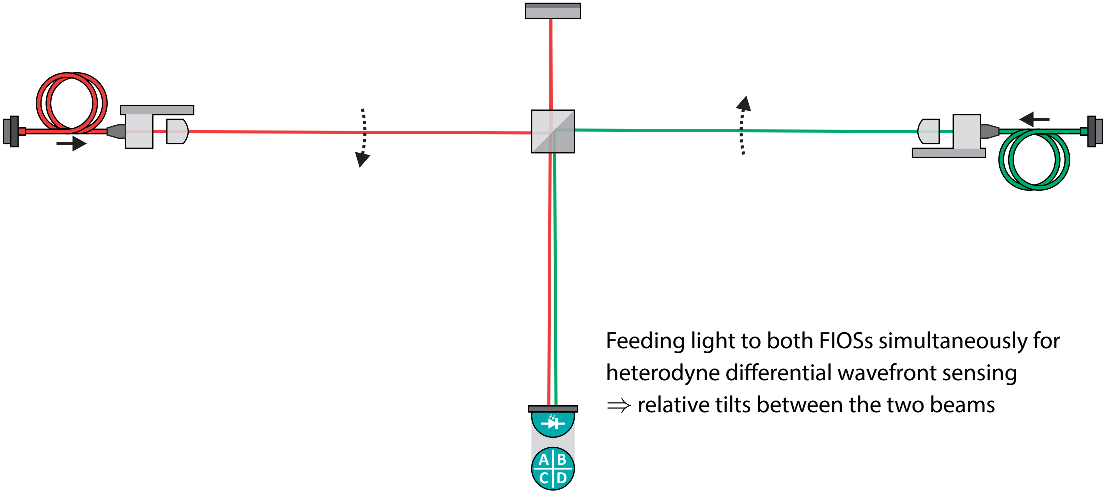


Coupling light from FIOS 1 into FIOS 2 and vice versa (ignoring mirror and QPD)

⇒ coupling efficiency with respect to temperature

⇒ absolute beam walk

Test 2: Relative Beam Tilt



Feeding light to both FIOSs simultaneously for heterodyne differential wavefront sensing
$\Rightarrow$ relative tilts between the two beams

Summary of this presentation

- fiber injector optical subassemblies (FIOSs)
  - mechanically and thermally ultra-stable fiber injectors
  - our approach optimized for cost efficiency and rapid development cycles
- 2.0 FIOSs currently in use on the Hexagon interferometer
  - optical three-signal test for phasemeter
  - capable of testing the full LISA arm metrology chain
- 2.1 FIOSs under construction for the Three-Backlink Experiment
  - direct comparison between several alternative implementations of a LISA backlink
  - new assembly process optimized for inter-FIOS coupling
- very simple test interferometer
  - gain some practical experience with the new assembly process
  - obtain a lower bound for the FIOSs' thermal stability

Thank you very much!