Testing and validating the performance of LISA on ground

Beams Simulator and IDS Test Set Up

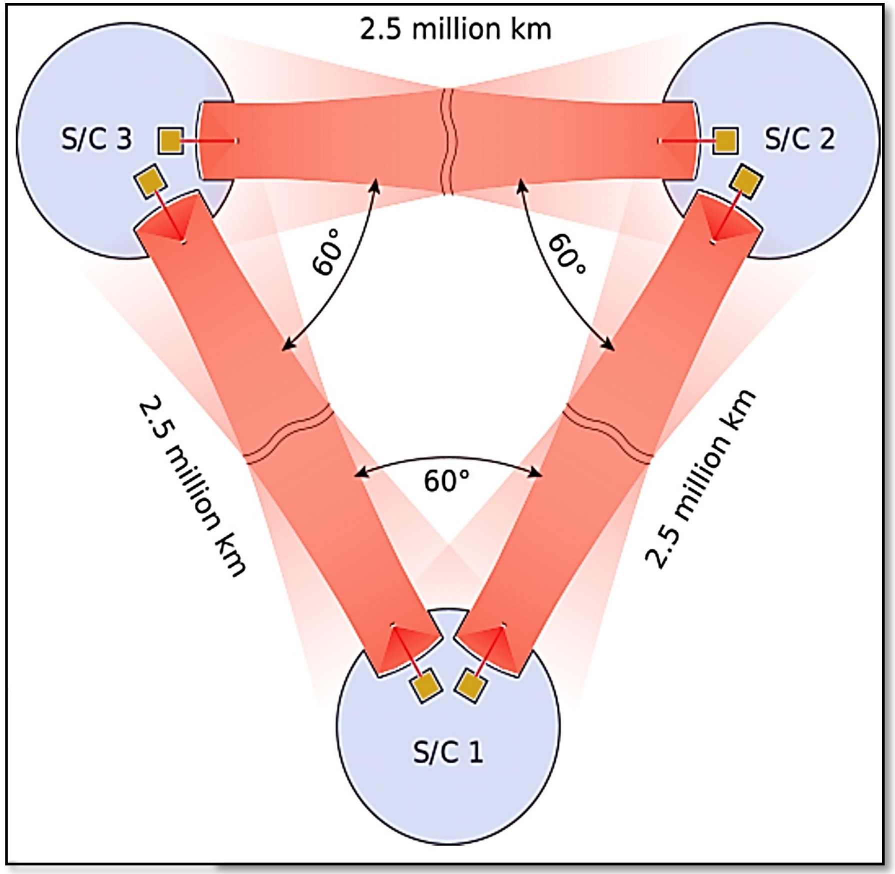
GDR Ondes Gravitationnelles

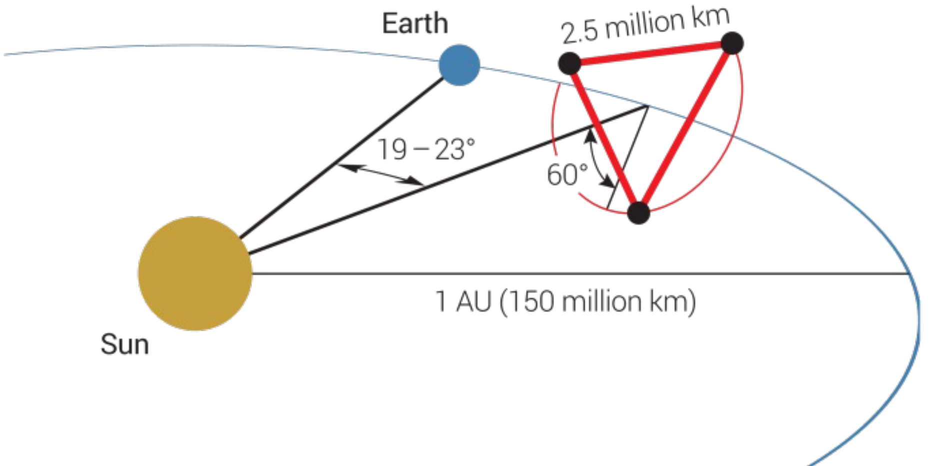
Workshop "développement des détecteurs"

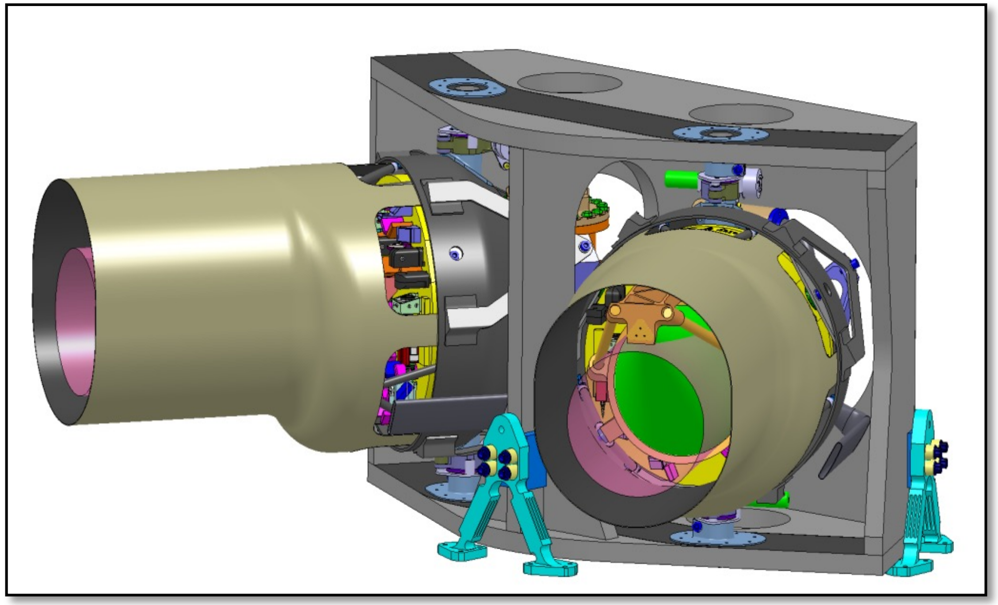
Maxime Vincent

LISA : a few reminders

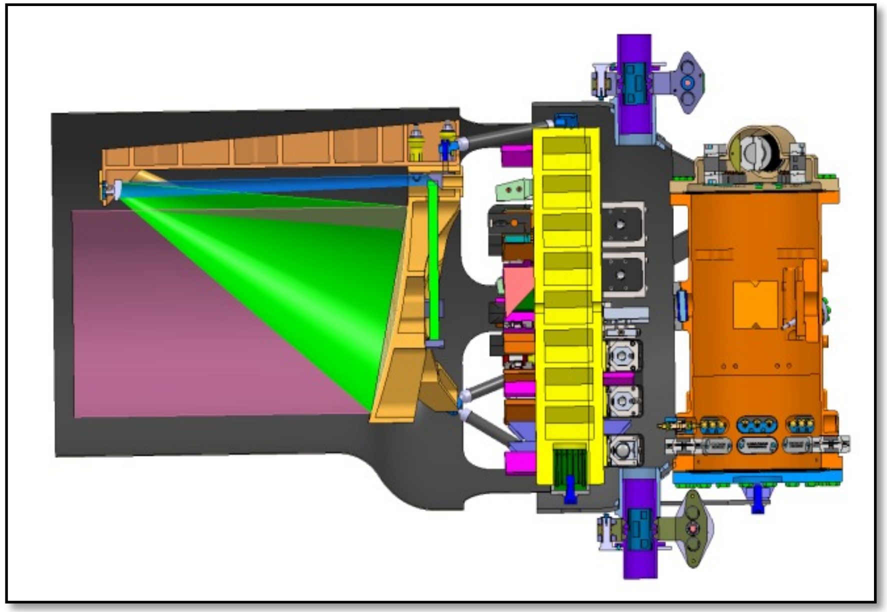
- Three satellites constellation in a triangular formation, forming 3 interferometers with 2.5 MKm arms
- Split measurement : TM-SC, SC/SC, SC/TM
- Frequency band : 0.1 mHz to 1 Hz
- Heterodyne interferometry
  - 5-25 MHz frequency offset between two beams
  - results in sine wave oscillating at Δf with a phase proportionnal to the variations in OPL
- OPD measurement stability requirement : 10 *pm/√Hz* at 1mHz
- Laser frequency stability : 30 *Hz/√Hz*







LISA Core Assembly (2 MOSA)



Movable Optical Sub Assemble (MOSA)

- **Main payload elements (per link)**
    - Telescope (TEL)
    - Optical Bench (OB)
    - Test Mass (TM)
    - Phasemeter (PMS)
    - Laser (Tx Laser)

Interferometric Detection System

IDS +

- The IDS (Interferometric Detection System) is a subset of the payload elements: OB and PMS (& OBMCU)

- **France is tasked with the full functionnal and performance testing of the EM/QM IDS**

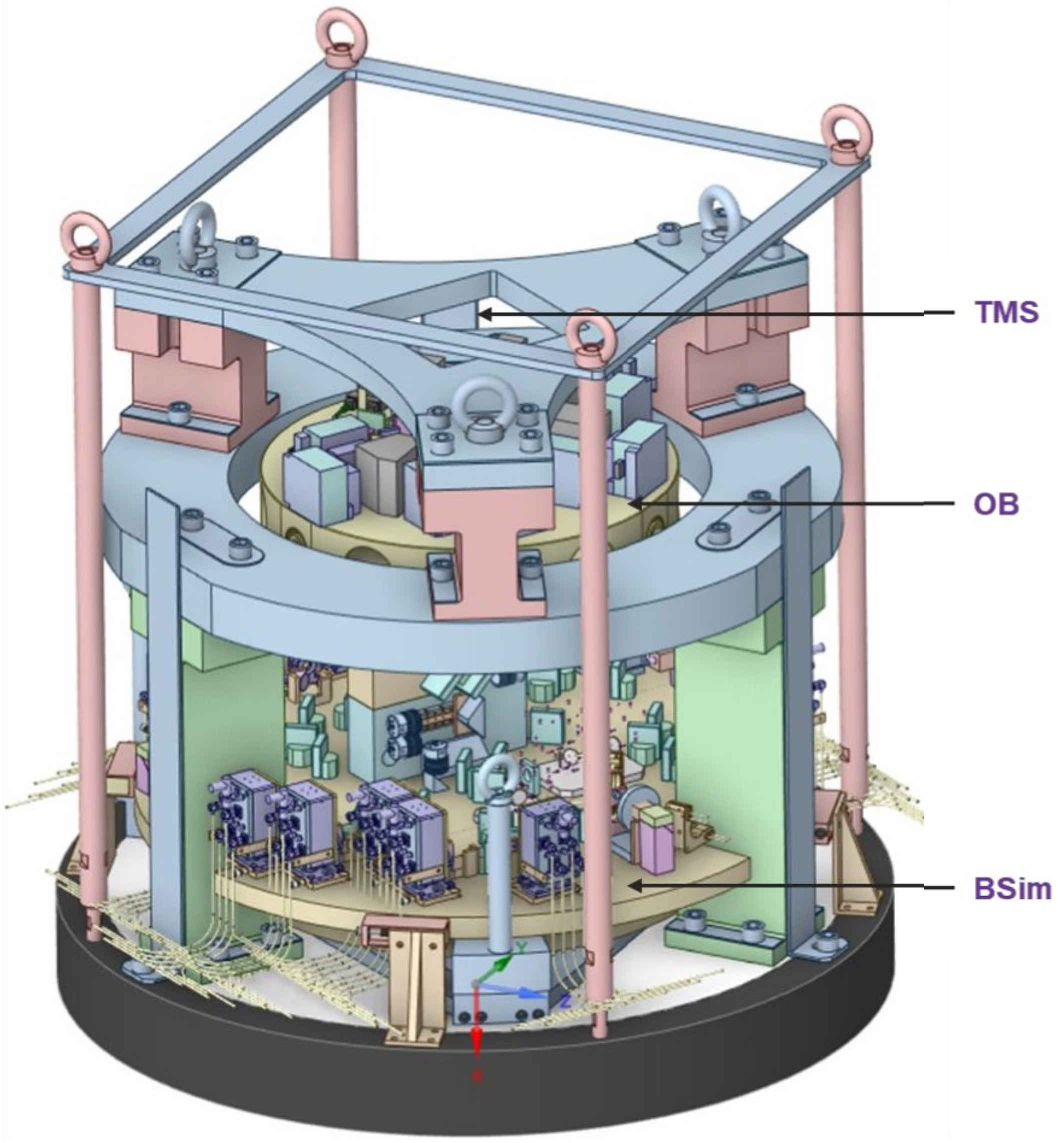
IDS Test Set Up : primary objectives

- **PO1** : measure the inteferometric noise floor of the Inter-Satelite IFO (ISI) and Test Mass IFO under near operational conditions (vacuum, temperature stability, high power differentials)

→ The IDS test campaign is the only moment where PO1 can be tested with a level of noise comparable to IDS requirements : 10 *pm/√Hz*

- **PO2a** : Measure the OB Rx TTL coefficient on ISI-OB over a range of ±100 µrad with an accuracy <15µm/rad and a resolution of 20 µrad

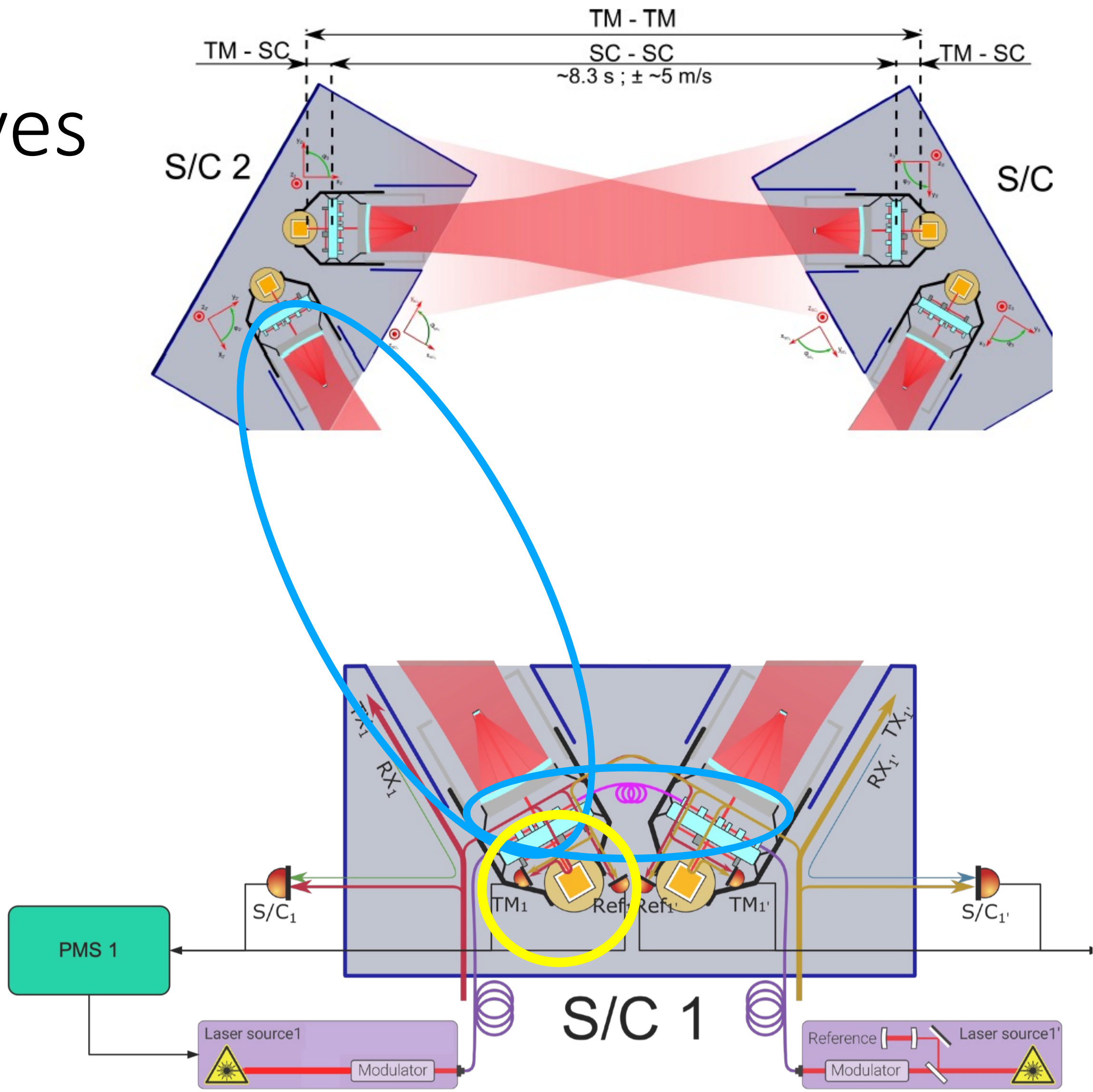
- **PO2b** : Measure the TM IFO TTL coefficient on the optical bench



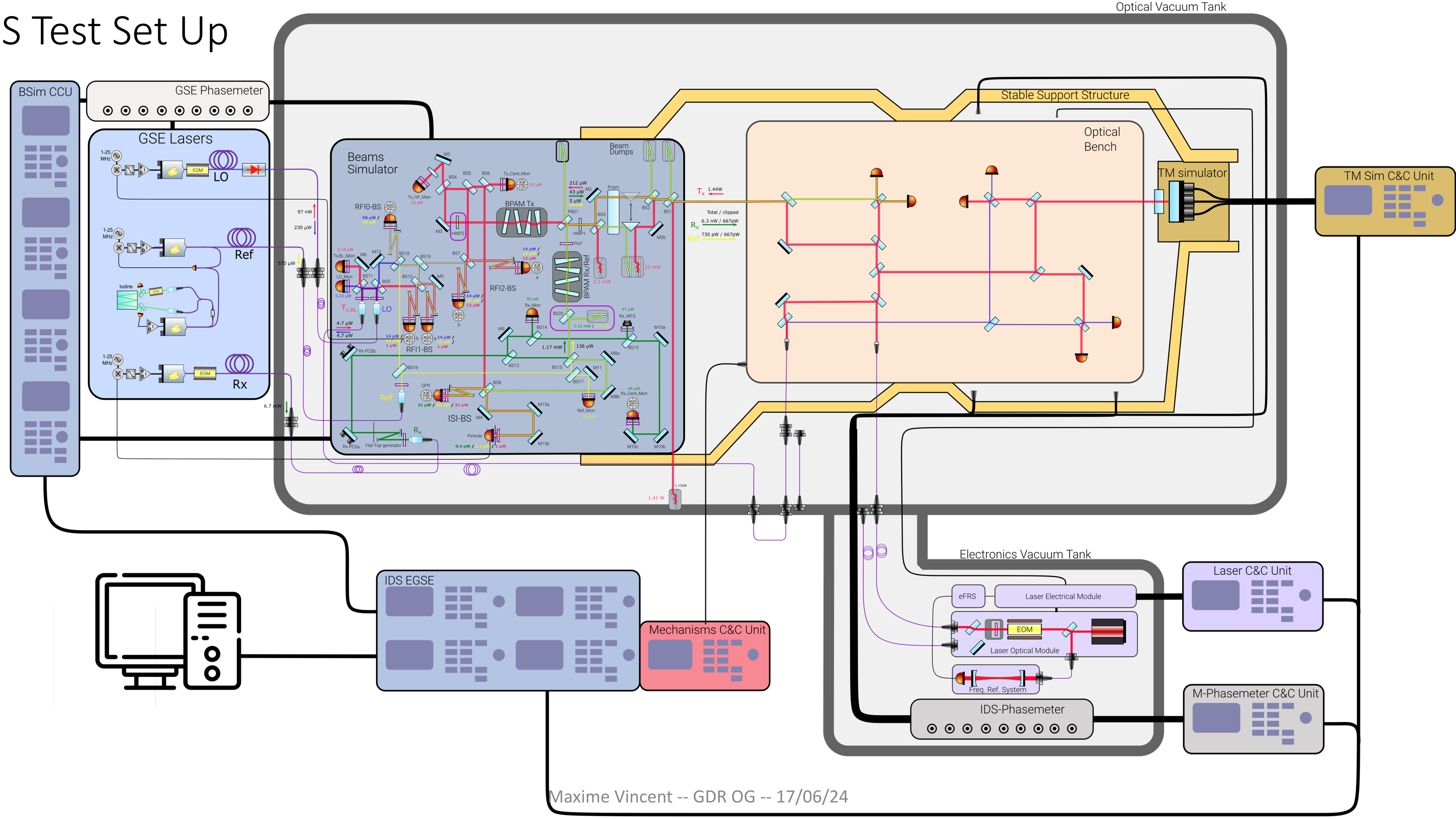
IDS Test Set Up : primary objectives

- **PO3** : Explore the performance accross the parameter space of the system
  - Picometric stability at different heterodyne frequencies, with doppler simulating modulation, different optical powers, Rx beam tilted, different locking schemes
  - Tilt To Length tests at different temperatures

→ For this, we need to simulate the interfaces with those systems :
  - Test Mass Simulator (CEA) to simulate the TM in the GRS : 5 DoF actuated mirror
  - Beams Simulator (APC) to simulate the OB on the distant spacecraft and the OB on the adjacent MOSA



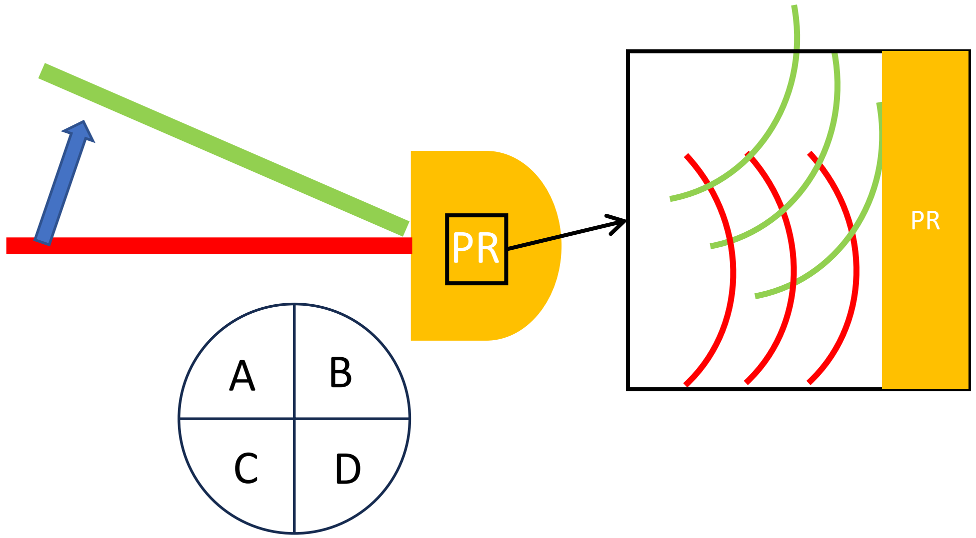
IDS Test Set Up



Maxime Vincent -- GDR OG -- 17/06/24

Tilt to Lenght coupling

- The LISA S/C will have some residual angular and lateral jitter
- There is a coupling between this residual jitter and the phase/OPD read out of the interferometer
- There is a 4 *pm/√Hz* allocation for TTL within the 10 *pm/√Hz* overall specification, a misalignement between OB and telescope of 1µm in each DOF would consume all the budget
- The OPD read out of the interferometer will be a function of the relative angle between beams but also of the beam parameters, profile and alignement



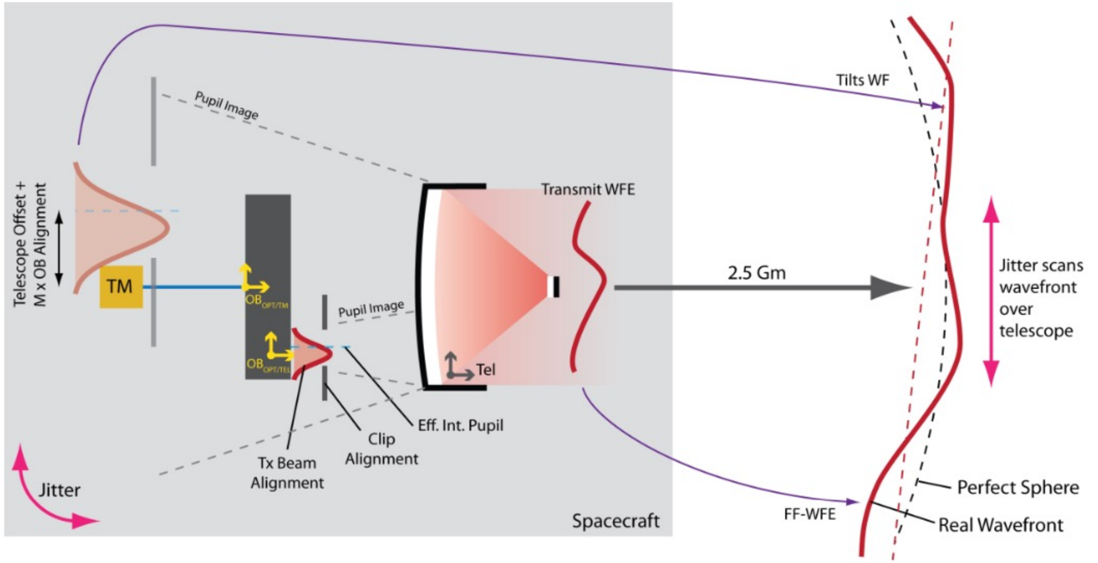
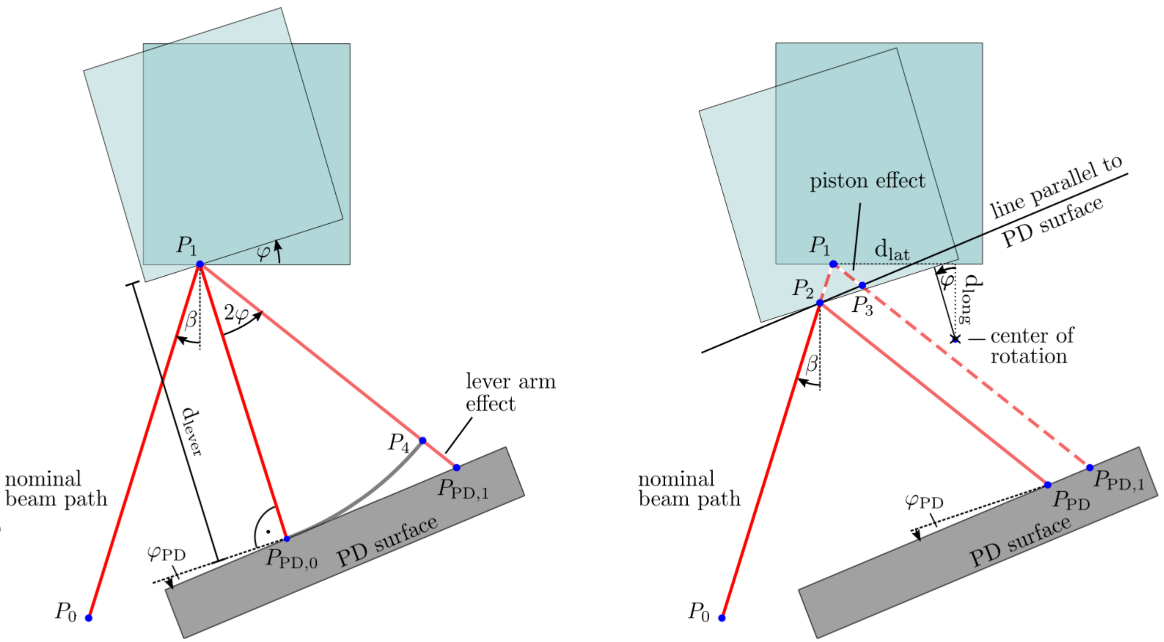


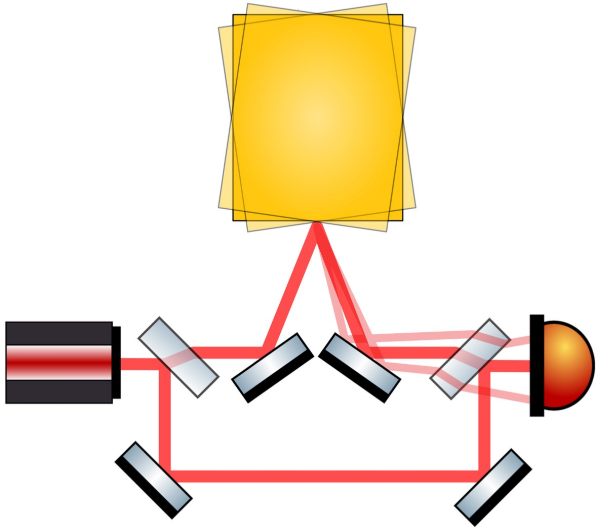
Figure 11: *Diagram showing the primary contributors to TTL coupling in the TX Path.*

Tilt to Lenght coupling

- Geometric tilt to lenght coupling
- Fully dependant on design and independant of beam type
- Angular jitter of the interferometric beam affects it's geometric path thus adding an unwanted aditionnal OPL component
- This coupling can be minized by having dedicated imaging systems and adequat design of the interferometer

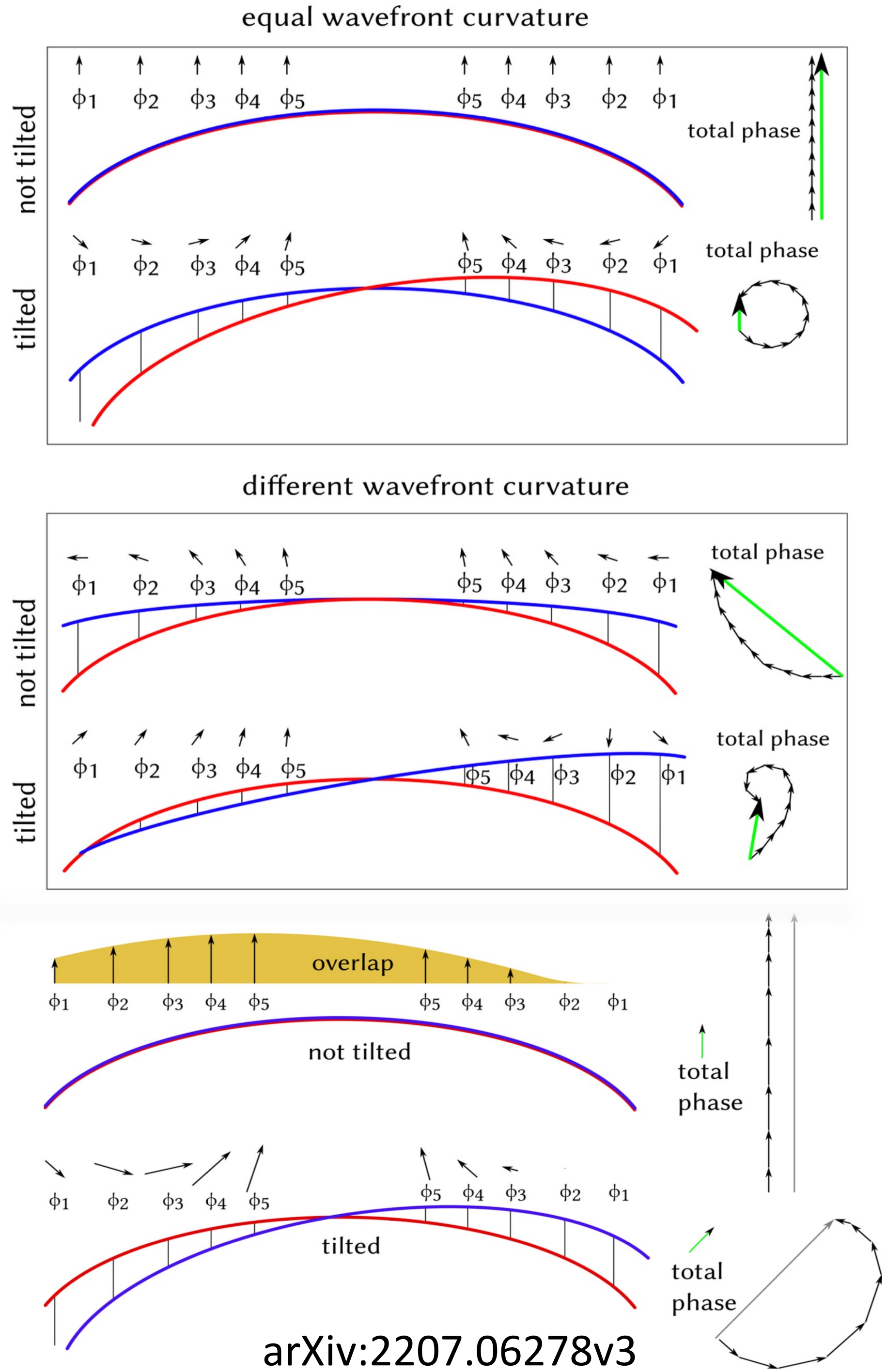


Marie-Sophie Hartig et al 2022 J. Opt. 24 065601



Tilt to Lenght coupling

- Non geometric TTL is every contributor to the coupling that does not originate from direct spatial OPD changes
- The jitter of one of the interefering beams will induce changes in the interference pattern and thus the phase integrated over the quadrant of the photoreceptor might be different inducing a variation in the read out of the interferometer
- Those changes will be dependant on the beam parameters, detector geometry or even on the way to calculate the OPD from phase
- Some sources of N-G TTL : wavefront curvature differences, intensity distribution, waist position wrt to QPD, WFE, beam overlap, QPD geometry (Single element or quadrant photoreceiver)



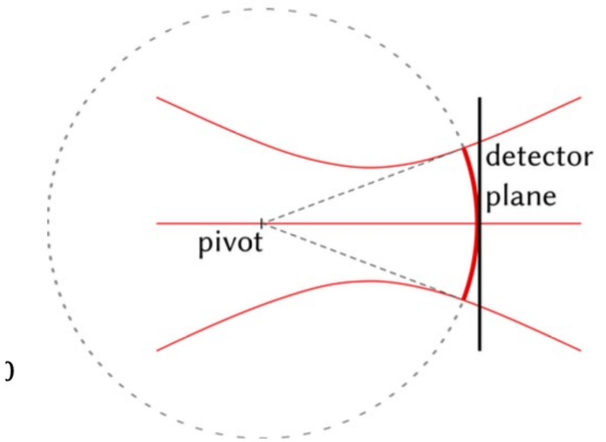
arXiv:2207.06278v3

Center of Phase CoP

- **Center of Phase (CoP)** or pivot pivot point: a point in space where the relative phase between the reference beam and the measurement beam being tilted is kept constant.

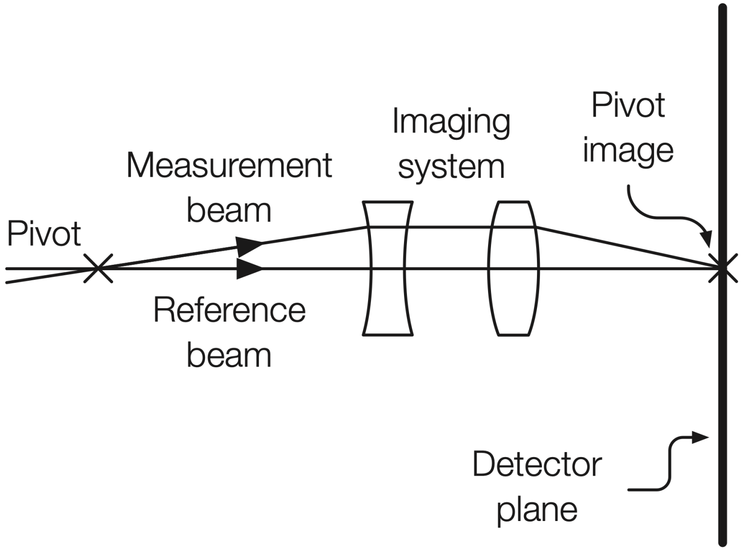
- More than just the relative phase, if a beam is tilited arround this pivot point and the distance from this pivot to the detector plane is equal to the radius of curvature of the beam, the phase of this beam is constant while being rotated

- TTL is thus minimized at this point in space. Any lateral displacement of this CoP will lead to an equivalent TTL contribution (1 µm lateral offset = 1 µm/rad TTL contrib).



(b) While the beam is tilted, the wavefront curvature on the detector stays unchanged. [16]

Sonke Schuster, PhD Thesis, 2017 ,Tilt-to-length coupling and diffraction aspects in satellite interferometry



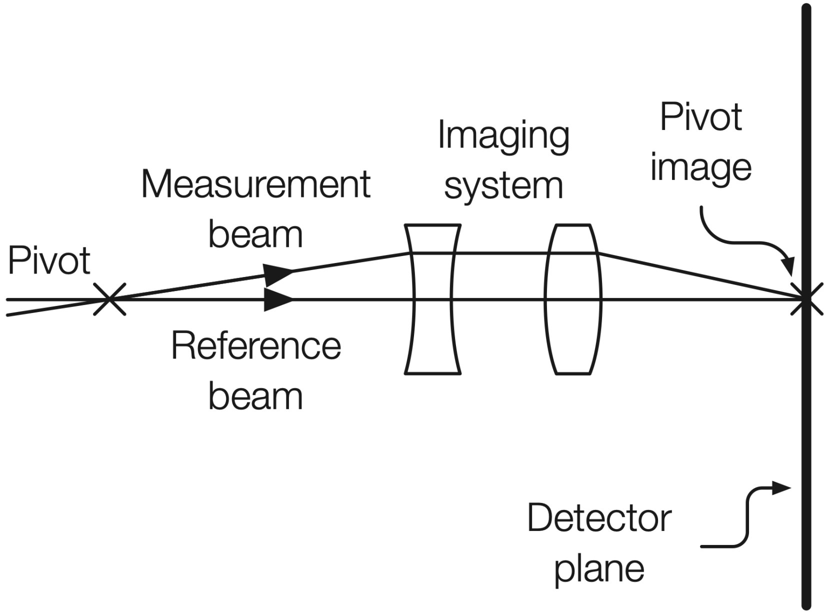
Beams Simulator

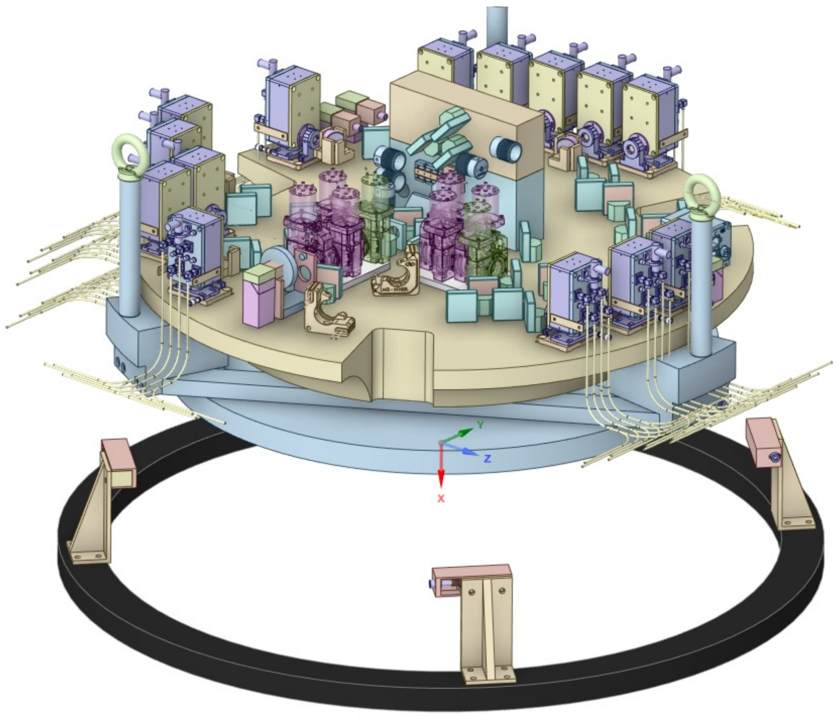
The Beams Simulator and LISA optical bench are designed to be pupil imagers, they will image an optical copy of their entrance pupil onto their photodetectors.

Thus the CoP is placed on the entrance pupil of the the OB where the exit pupil of the telescope would be placed.

With this property, TTL is minized at the detector plane.

Dedicated 3 optics imaging systems were designed to help further reduce the importance of the TTL coupling on the detector plane.





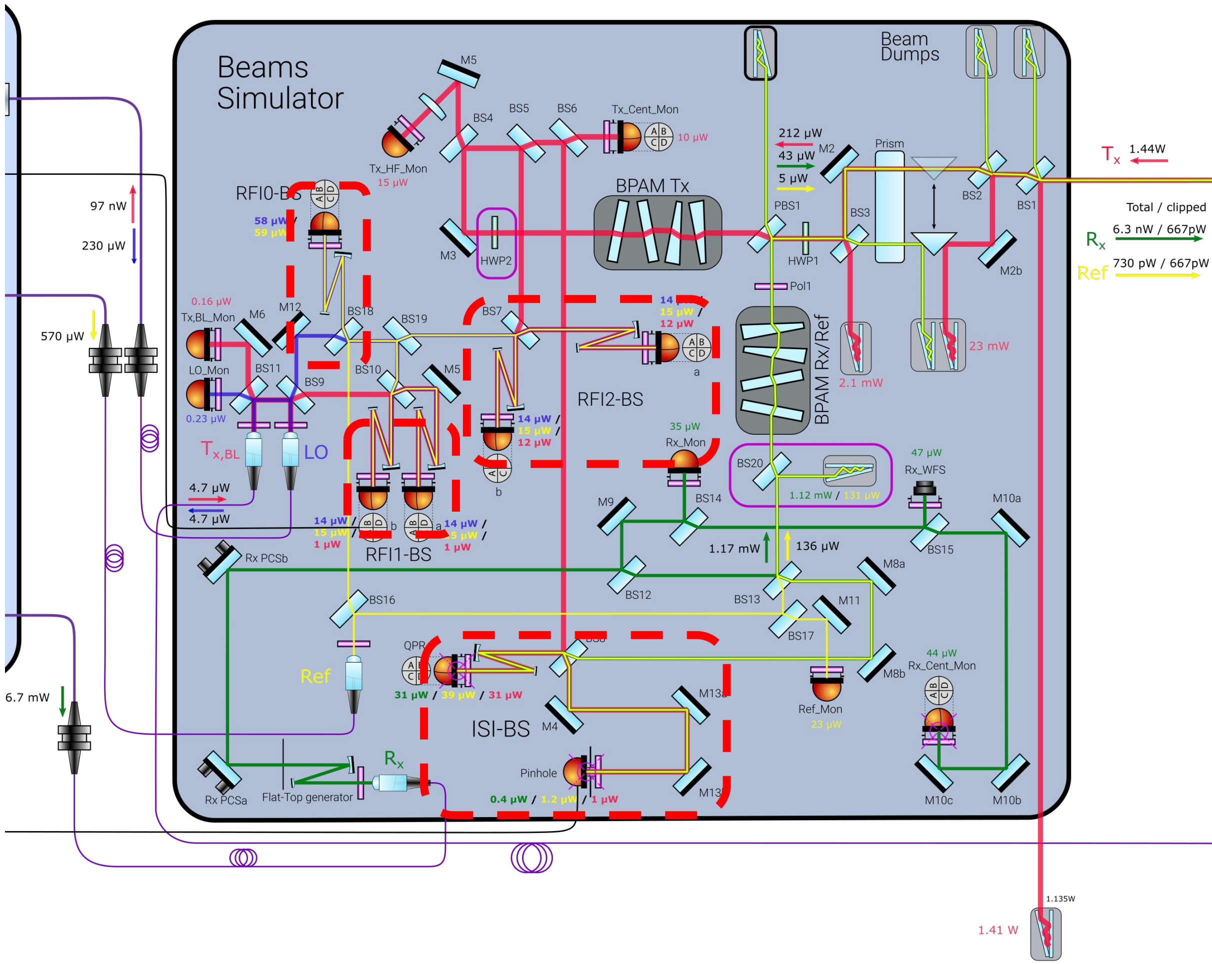
Beams Simulator

5 Beams with different frequencies :

- Rx flat top beam: simulate the beam coming from distant spacecraft
- Tx gaussian beam : simulate the beam out going from the local spacecraft
- Tx Back Link: simulate the beam coming from the adjacent IDS
- REF : reference beam serving as proxy for alignement
- LO : local oscillator provided to the OB

4 interferometers :

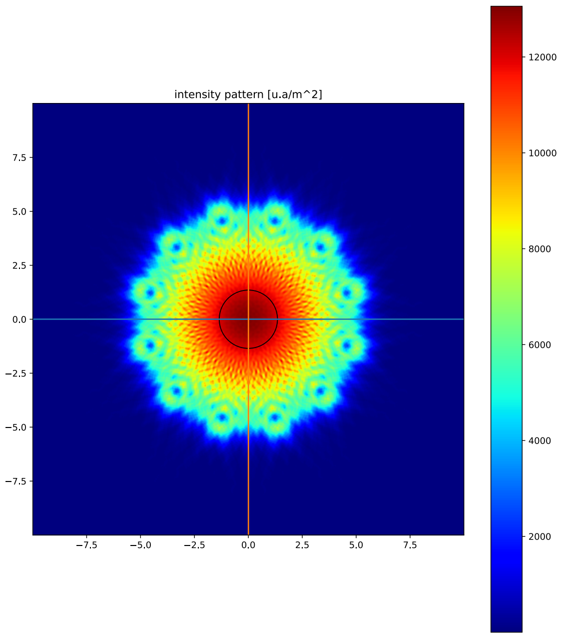
- ISI BS: main IFO, simulates the science IFO on the distant spacecraft. One of it's port has a pinhole photoreceiver to minimize the TTL contribution.
- RF0, RF1, RF2 : monitoring of phase stability, backlink interface, straylight estimation and removal…

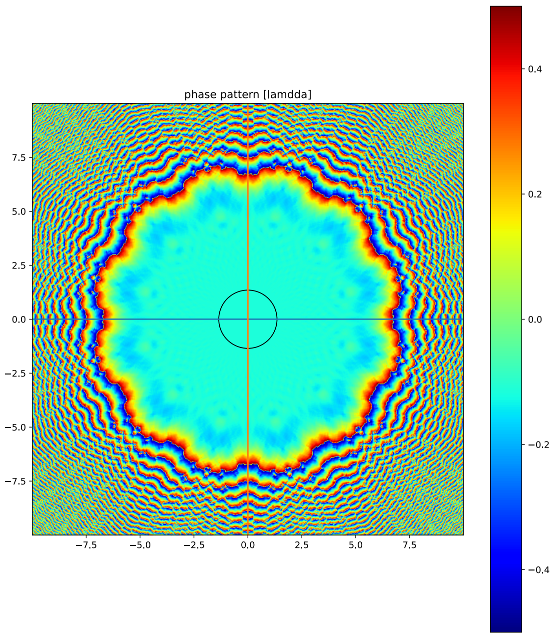


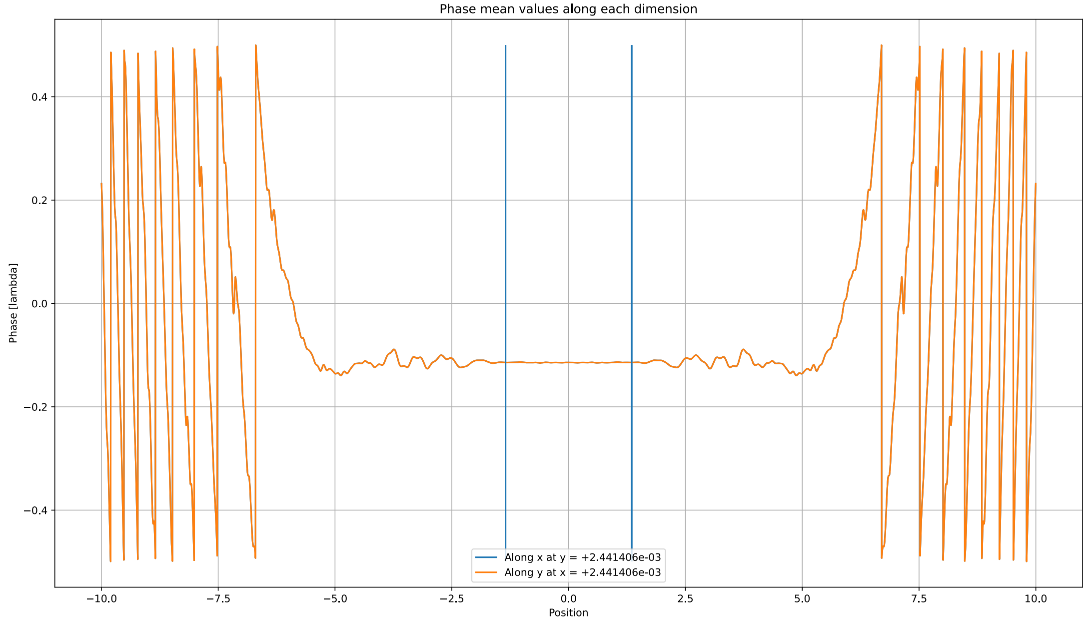
Beams Simulator

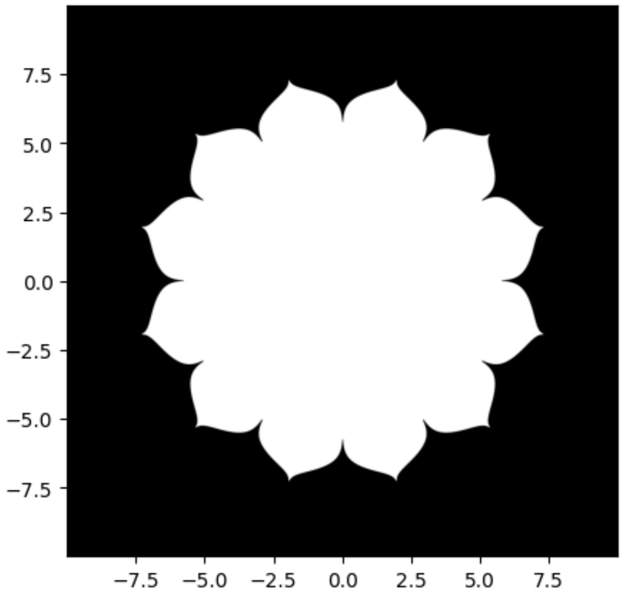
Tx Flat Top Generator :

Beam expander + appodization mask to smooth the intensity and phase profile and reduce the diffraction induced oscillation on the peripherial areas of the beam

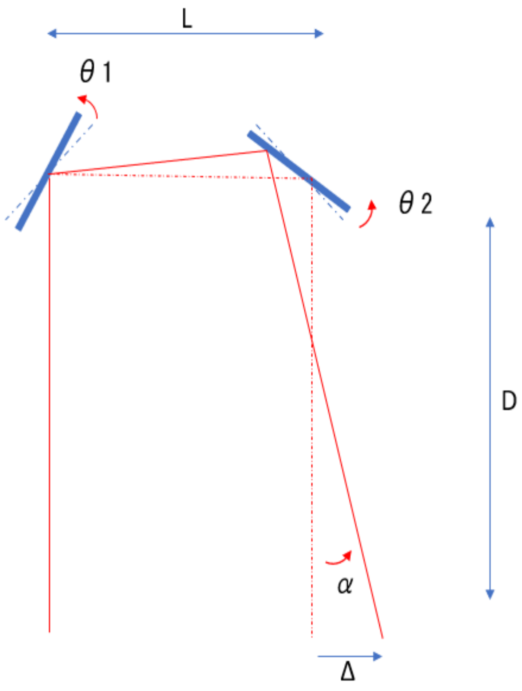


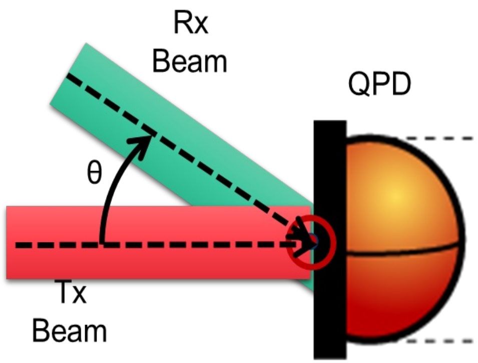






Beams Simulator



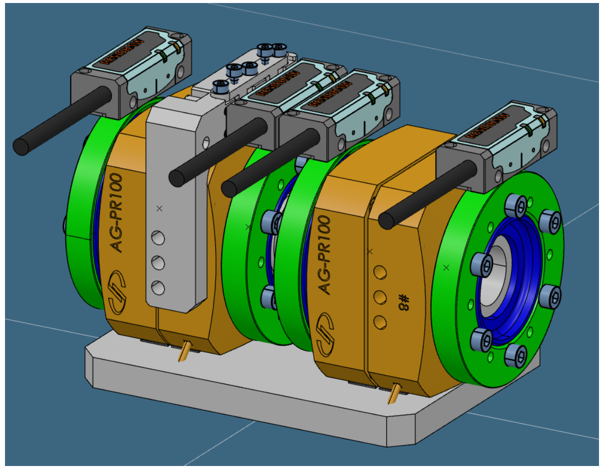


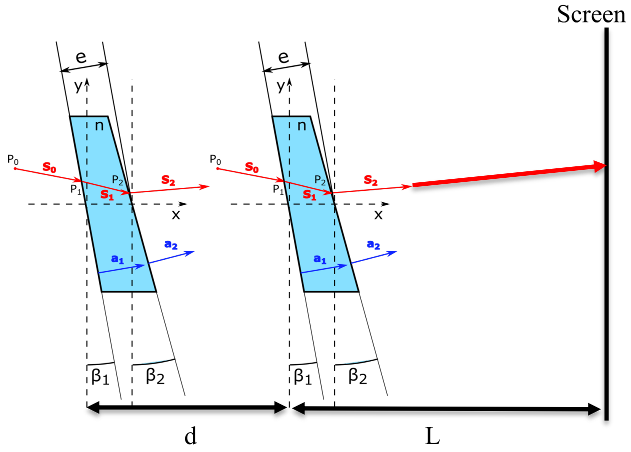
Rx Pointing Control System (Rx-PCS) :

- two actuated mirrors that allow to tilt the beam without inducing beam walk on the QPD surface
- DWS and DPS signals from QPDs are used as feedback in a closed loop control system of the mirrors to get the beams relative angle at 0° at the position of interest (CoP) and the beam centered

Beam Pointing and Alignment Mechanism (BPAM) :

- two optical flats (1 mm thick) to accurately displace the beam transversally : 300 µm with a 15 nm resolution
- followed by a set of two wedged windows (1 mm with 2.3' wedges) to accurately tilt the beam : 850 µrad with a 10 nrad resolution





Beams Simulator

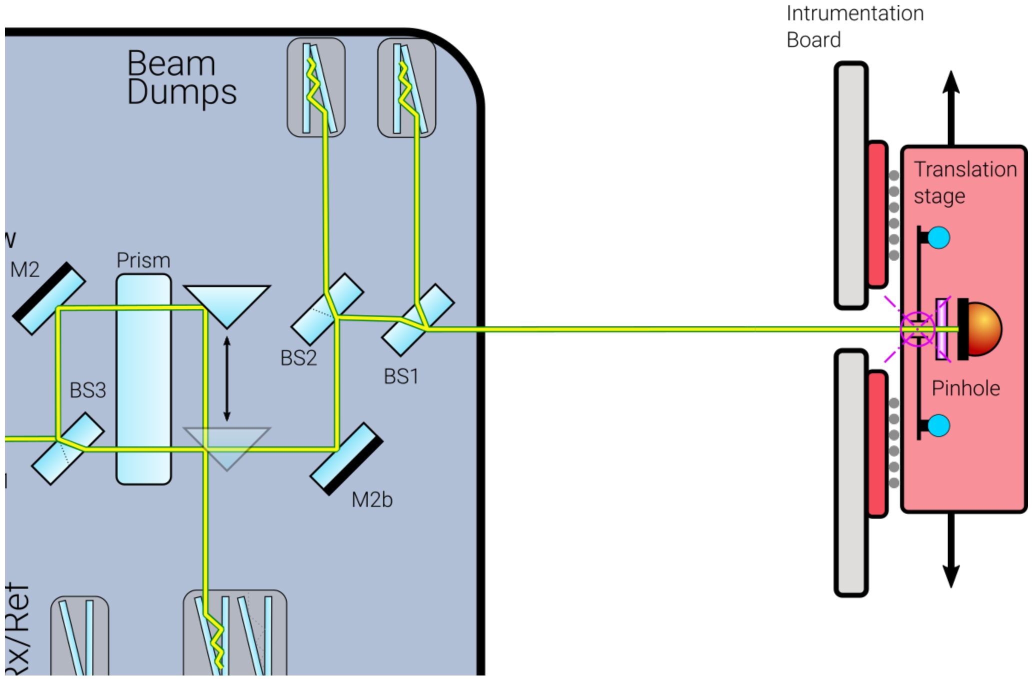
CoP calibrator :

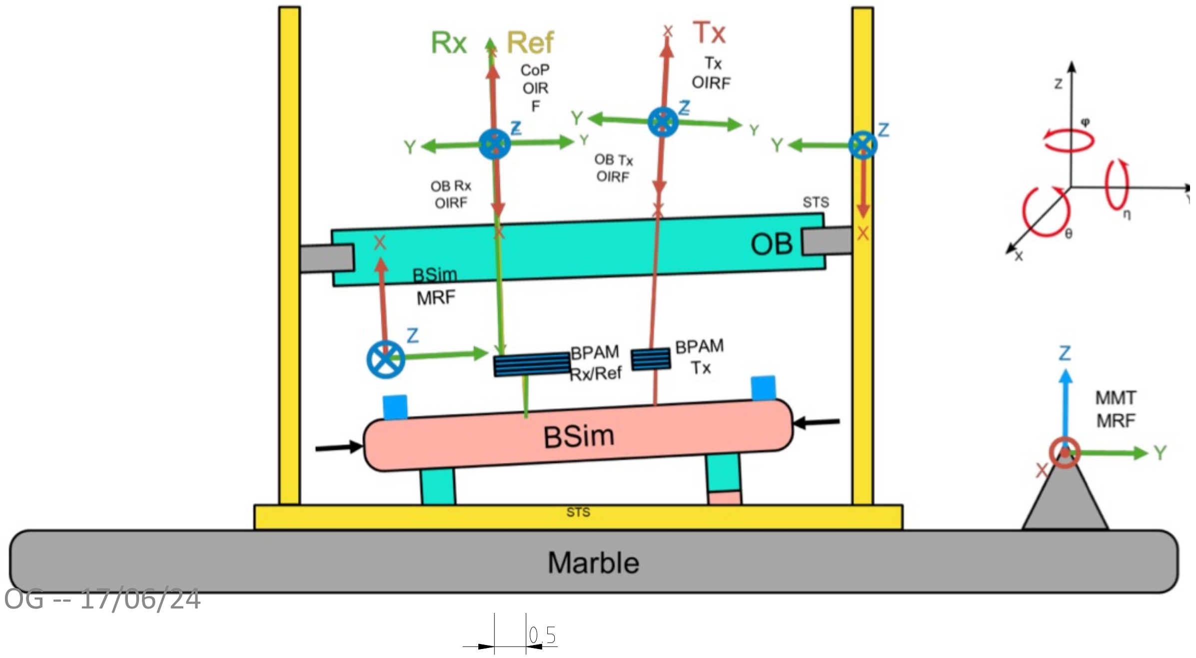
- SEPD with pinhole mask on an 2 axis precision translation stage itself on the instrumentation board (additional support equipment)

- Placed above the BSim to find the location of the CoP (wrt the mechanical reference frame) at a few µm precision

- The CoP will be at the position that minimizes the TTL between REF and Rx

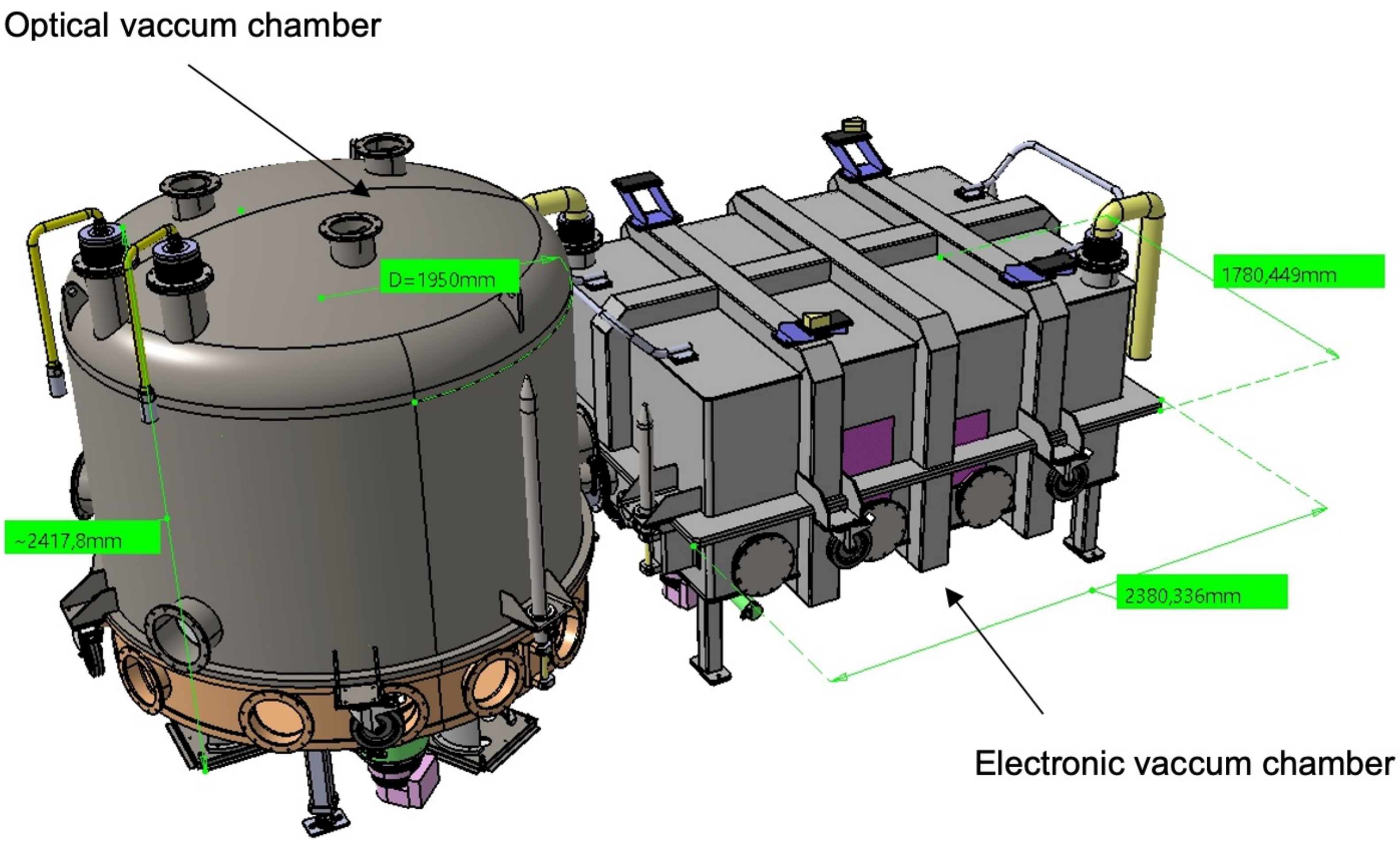
The BPAM is used to adjust the position of the CoP on the OB pupil (if needed). Two BPAMs are needed, one on the REF/Rx path and one on the Tx path to precisely control position and angle of the beams on ISI-OB and ISI-BS.



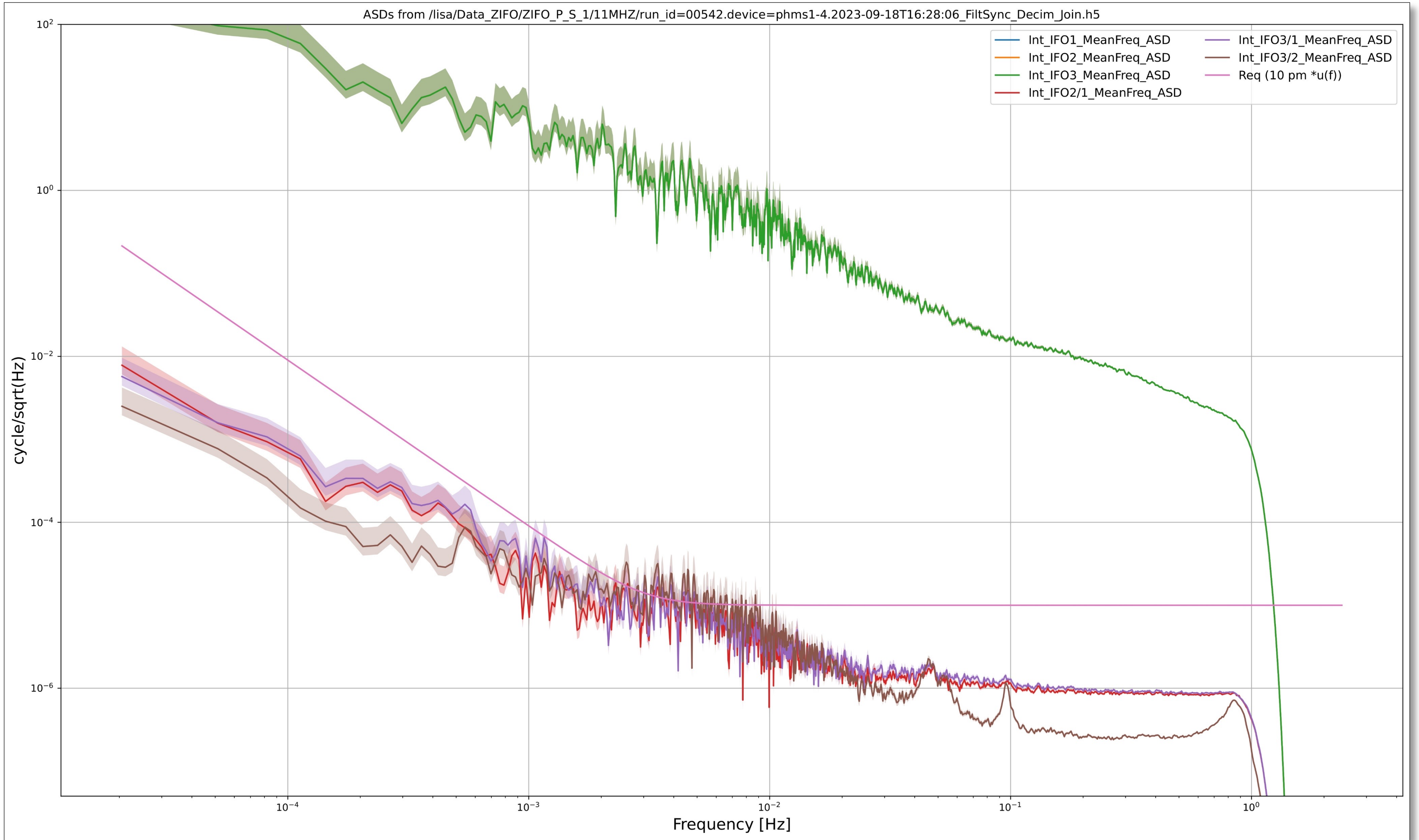


Thank you for listening !

Additionnal slides



Additionnal slides



TTL Rx Measurement on BSIM/OB

- The main goal of this measurement is to measure the TTL coupling coefficient of the incoming Rx beam on ISI OB with an accuracy better than 20 µm/rad
- The Rx PCS actuators are used to rotate the Rx beam around the pivot point on an angular range of ±300 µrad around DWS=0° in both directions (η and φ)

Configuration	Locked Laser	Master laser	Interferometric measurement	Measurement unit
Configuration 2 (Local S/C)	Tx	LO	REF-OB	PMS
	Rx	REF	ISI-BS	GSE-PMS
	LO	REF	RFI0-BS	GSE-PMS

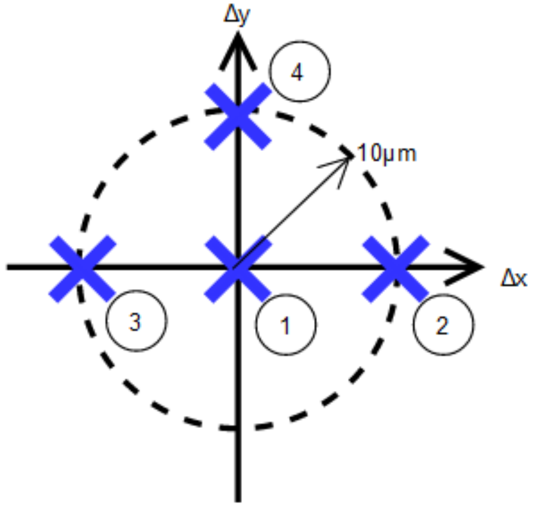
- The REF / Rx phaselock, is essential and allows to supress the geometric TTL internal to the BSim during the actuation of the beam with the RxPCS.
- A 100 µm pinhole on ISI BSim (placed at the unfolded location of the CoP) is used for the locking to avoid TTL effects from beam tilts (due to PCS angle scan) and WFE.

TTL Rx Measurement on BSIM/OB

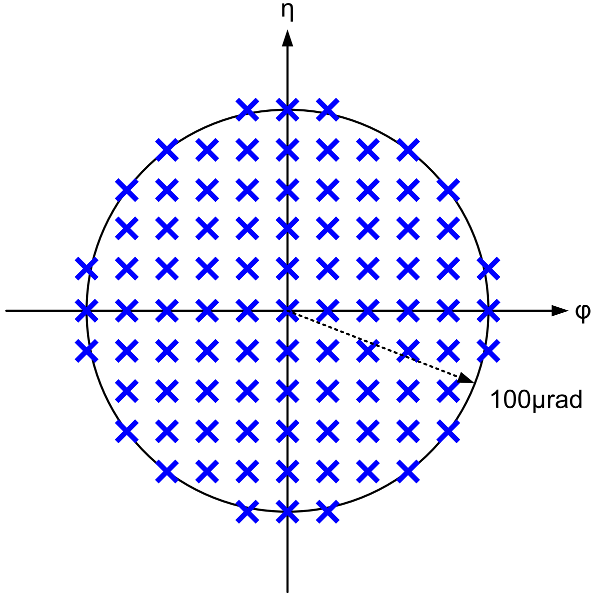
- TTL measurement will be done at 10°C, 20°C and 30°C to check the influence of temperature on the coupling (and on global IDS performance).

- The baseline will be to do the measurement (±300 µrad rotation around the CoP) centered on the QPDs (1), but other configurations will be tested to measure the influence of beam offset on the coupling (2,3,4).

- Another measurement scheme is also proposed : scan the detector surface with a 20 µrad grid and perform a ±10 µrad excursion around these grid points to get local measurements



Baseline scenario



Second scenario