Final Design Document For REGH

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Contents

1 Scope

This document contains the final design and initial alignment procedure of the photon regeneration system for heterodyne detection (REGH). The system is located in:

1. the central room
2. the end room towards the East of HERA North named NR (R for right side looking North)

It also includes the regeneration cavity which spans the space between the two rooms.

Functionally, the design includes the

1. Central bench fully assembled including all optical components, shutter, light-tight boxes, all of which will be placed inside the vacuum tank.
2. The optical, opto-mechanical, and electro-optical components on the optical tables surrounding the central experimental vacuum tank in HERA North.
3. The opto-mechanical, and electro-optical components on the optical table next to the experimental vacuum tank in clean room NR east of HERA North.
4. The mechanical and optical components of the regeneration cavity (RC mirrors and mounts).
5. Control system for laser frequencies (PDH locking and PLLs), cavity length including analog electronics and digital waveform generators.
    - The RF frequencies for the PLLs have to be generated by Moku:Labs to ensure exact frequency values relative to each other. The Moku:Labs are part of REGH.
    - The gains and filter settings inside the analog control electronic can be set via DOOCS from the control room via the field box for the TTFSS. The digital part including the DACs and ADCs is not part of REGH.
6. Sensing and actuation system for alignment of the cavities and the lasers
    - This includes the in-vacuum Quad Detectors and the out of vacuum wavefront sensors, the demodulation boards for the wavefront sensors and the formation of the error signals for the alignment systems
    - This also includes the actuators and the necessary electronic (HV-Amplifier etc.) for the actuated mirrors.
    - The feedback will be activated via a CompactRIO system. The filters and gains will also be controlled via CompactRIO (LabVIEW).
7. REGH also provides optical fiber links between the end stations and the central station to exchange laser beams for diagnostic and potentially lock acquisition purposes.
8. REGH also provides the front ends of the REGH detection system in HERA North East as well as for the veto signal in HERA North. This includes Lab computers to interface with Moku:Labs and provided by DOOCS

Notes:

- All beam sizes are given in Gaussian beam radii ω as defined here:

$$I(r) = I_0 \exp\left(-2\frac{r^2}{\omega^2}\right)$$

- A collimated beam of a give beam size is a beam which does not change size appreciably until the next power optical element. In Gaussian mode terms: It's Rayleigh range is large compared to the propagation distance.

1.1 Applicable documents

The top level requirements are based on:

- ALPS II - design requirement document (J. Poeld and H. Grote, 2019)
- ALPS II – Things ALPS IIc must measure, (H. Grote et al, 2019)

Design Documents:

- Central area Conceptual Design for TES and HET Designs (G. Messineo et al., 2018)
- Control and Alignment Conceptual Design for TES and HET Designs (A. Spector and G. Mueller, 2018)
- Technical Note: Signal generation and recovery for HET @ ALPS (G. Mueller et al., 2018)
- Final Design of ALPS Generation System (GEN) (H. Grote et al., 2019)
- Conceptual Design and Requirements Document: Slow Control and Data Acquisition System (DOOCS) v2 (G. Messineo, 2019)
- ALPS II initial alignment system – final design (J. Poeld, 2019)

Interface Documents:

- ALPS II interface document: generation system (GEN) – regeneration system HET (REGH) (June 04, 2019)
- Interface Document: Regeneration System HET (REGH) - Room Design **(TBC)**
- Interface Document: Regeneration System HET (REGH) - Experimental vacuum **(TBC)**

2 System Overview

The heterodyne detection system uses the beat signal between the regenerated electromagnetic field and a local oscillator field for detection. Shot-noise-limited detection requires a stable phase evolution between the measured and expected beat signal such that differential phase variations between the generating field inside the production cavity and the final detected beat signal stay well below a fraction of π (Goal: $< 0.1\,\mathrm{rad}$). The design presented here is expected to ensure this while maintaining alignment between the cavities and the lasers. The description of the design will follow the locking hierarchy which counter-propagates with respect to the axion field.

The end table in NR is used to inject the local oscillator (LO) laser into the regeneration cavity (RC). The frequency of the LO will be stabilized to the length of the RC using a PDH system. The alignment of the LO into the RC will be maintained by a wavefront sensing system (WFS) which is identical to the one implemented in GEN. A second set of sidebands will be added to the LO to measure and control the overall length of the RC also known as FSR locking. The end table will also host a pre-mode cleaner cavity which will likely only be used for laser diagnostic purposes although we provide the option to insert it into the beam path to pre-stabilize the laser frequency and mode (similar to GEN). The end table will also include a fiber injection system to send a small fraction of the LO beam to the central optical table (outside vacuum) as well as receive a field from it.

A small fraction of the LO will propagate through the RC onto the central optical bench (COB) where its position will be monitored by a quadrant detector (QPD) which is mounted next to the RC flat end mirror. This signal will be used to maintain alignment of the spatial eigenmode inside the RC by actuating on the curved RC input mirror in the end station. The largest fraction of the light will be superimposed with the reference laser (RL) which is injected on the central bench. This beat signal will be used to offset phase lock the RL to the LO with a difference frequency of Ω_1. The same beat signal will also be used as a veto or control signal for optical contamination with HPL light which would create a beat signal at a frequency $\Omega_1 + \Omega_2$ (or

$\Omega_1 - \Omega_2$) where Ω_2 is the offset frequency used in the PLL between RL and the PC transmitted light. These two fields are combined in the central portion of the COB which is separated from the RC by a light-tight wall which only allows light to enter through a HR mirror. A Mach-Zehnder (MZ) like interferometer setup is used to split the RL into the two separate beams, one to be superimposed with the LO, the other with the PC transmitted light. The MZ is installed on a ULE bench to ensure long term phase stability between the two interferometer arms. The alignment of RL onto the COB is actively controlled using a WFS which measures the relative alignment of RL with respect to the LO. The alignment of the COB is monitored using a WFS which measures the relative alignment of RL with respect to the PC transmitted light.

The left (west) side of the COB includes another area which is separated from the central part of the COB with another light-tight wall and a HR mirror. This light-tight area includes the flat PC mirror and a second QPD. This QPD monitors the position of the spatial eigenmode of the PC and creates a controal that feeds back to the curved PC mirror located in the west (NL) end station. This area of the COB also includes waveplates which partly reflect the beam back towards the PC to monitor optical path length changes within the flat PC mirror substrate (OPL sensing). The remaining components of this polarization-multiplexed interferometer are located outside the vacuum tank on the optical table. Most of the PC transmit light will be dumped outside the vacuum tank. Several waveplates between the two cavities are used to (a) create an OPL sensing interferometer for the PC mirror substrate, (b) allow to increase the light transmitted through the MZ with shutter open to improve SNR during commissioning activities, and (c) switch between scalar and psudo-scalar searches. The last application also requires to change the polarizations of the lasers on tne end tables.

The optical tables outside the central tank host the beam injection optics for RL, the main beat detectors for the PLLs (including the veto signal) and the WFS systems, and the OPL sensing system. These areas are separated from each other by light-tight walls to minimize optical contamination from stray light. The optical tables also host two fiber injectors to exchange laser beams with the two end stations and some laser diagnostic equipment.

2.1 Notes on actuation, actuators, and RF frequencies

- The LO and the RL are 500 mW single frequency NPRO lasers. They include a slow, large-range temperature actuator and a fast (~40 kHz), small-range PZT actuator to change the laser frequency. For the LO an EOM for fast phase correction (~300 kHz bandwidth) has been added to the beam path. The feedback electronic will use the TTFSS board from LIGO which is also used in GEN. Note that the fast phase correction is now base-lined although it might not be needed pending on the seismic noise on site. If the EOM is not needed, a standard PI controler with ~40 kHz of UGF actuated on the laser PZT will be used.

- The RC curved mirror east of the central bench will be mounted such that alignment actuation and longitudinal actuation over a larger range (maybe up to a mm) but with low bandwidth is possible to maintain cavity alignment and FSR locking.

- All frequencies that enter into the heterodyne sensing system ($\Omega_{1,2}$) have to be defined by frequency numbers inside the Moku:Labs to ensure that the same NCOs with identical bit depths and look up tables are used. All have to be clocked from a common clock with phase noise between them that should not exceed 0.1 rad (rms) over the duration of the measurement.

- The phase locking of the PC transmit light onto RL requires to actuated the PC curved mirror with ~4 kHz UGF. It is still under investigation if that bandwidth is sufficient or if an additional faster actuator has to be integrated into the loop to increase the low frequency gain.

2.2 Interfaces

Interfaces between REGH and other systems include:

1. REGH to Vacuum:

   (a) Central optical bench inside vacuum tank

(b) Location of vacuum tank and windows on optical table in HR clean room (East tunnel from HERA North)

2. REGH to Clean Room Hall NR:

   (a) Location and dimensions of the optical tables surrounding the vacuum tank. Issues are size, location, beam height.

   (b) Location and dimensions of the electronic racks and supply systems

3. Optical interface with initial alignment system (IA) on COB and on End station

4. Electrical interface with Data Acquisition and digital signal processing system including controls of feedback loops (on/off, gain and filter settings), monitoring of state vector (status of shutter, waveplates, lock state etc.), laser power at various locations, error signal residuals, veto signal, alignment monitor signal, etc.

5. Interface with GEN:

   (a) Optical interface at PC

   (b) Actuation signal for PC locking and alignment

6. Interface to laser safety system:

   (a) Laser shutter and interlock in end station (NR)

   (b) Laser shutter and interlock in central station (NL)

These interfaces are partly described in the following chapters but are or will have to be defined in the interface documents listed under section 1.1.

3 End Table

3.1 ET Optical Layout

A general optical layout of the end table (commercial size: 240cm x 90cm) is shown in figure 1. The beam height on the optical table will be 145 mm. The LO is an NPRO Mephisto S laser (COHERENT) with 500 mW maximum output optical power and a beam waist of 160 μm located at -10 cm inside the laser head. **The beam first passes through a laser shutter ET_SH51 provided and controlled by the laser safety team. It then passes through a Faraday isolator ET_FI51.**

The first optical lens (ET_L51) collimates the beam to ~940 μm (radius). ~5000 ppm transmitted pick-off light through ET_MT51 is fiber coupled by ET_FC51 to the input port of a 50/50 fiber coupler beam splitter (ET_FCS51). One of the output ports of the ET_FCS51 will be used to sent LO light to the central table via the long PM fiber. The second input port of the ET_FCS51 is used to receive RL light from the central table, by switching the same long PM fiber to the ET_FCS51 free input port, and interfere with LO light to create a beat note on ET_PD53, a Thorlabs trans-impedance photodetector, which is also equipped with a fiber coupler connector. Only one port will be used at a time selected by moving the fiber from one coupler to the other. The design ensures that less than 1mW of laser power will be injected into the fiber at any given moment in time. Depending on the mode of operation a beat note between RL and LO will be formed on the fiber coupled photodetector (ET_PD53). The main power control stage is made of a half-wave plate (ET_HW51) and a polarizer (ET_PO51). The light in the s-pol is sent to an optical power meter for continuous power monitoring, while the p-pol is sent towards the second lens ET_L52, which is part of an analyzer cavity (ET_PMC51, for commissioning) and the RC mode matching described in figure 2. The half-wave plate ET_HW52 is used to flip the linear polarization from p- to s-pol at the input of the RC changing from pseudo-scalar to scalar particle searches. It is currently not motorized as this is not a procedure which will be required on a regular basis.

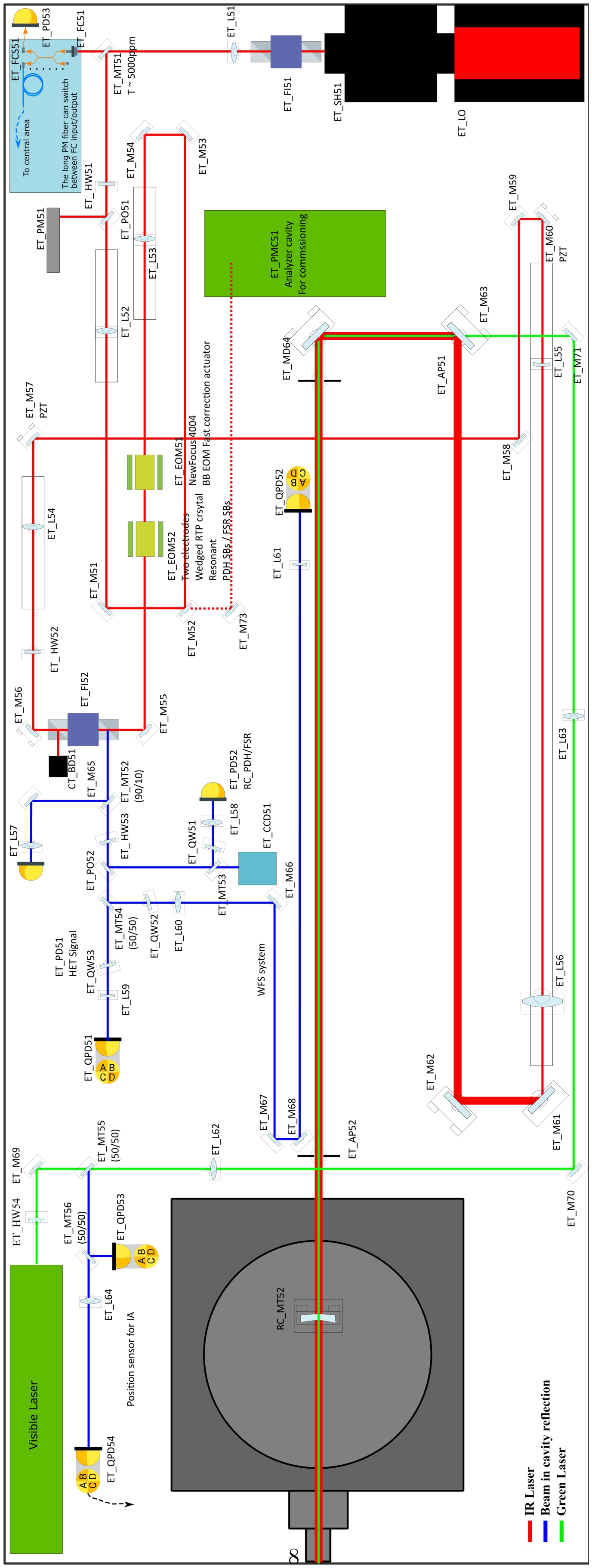
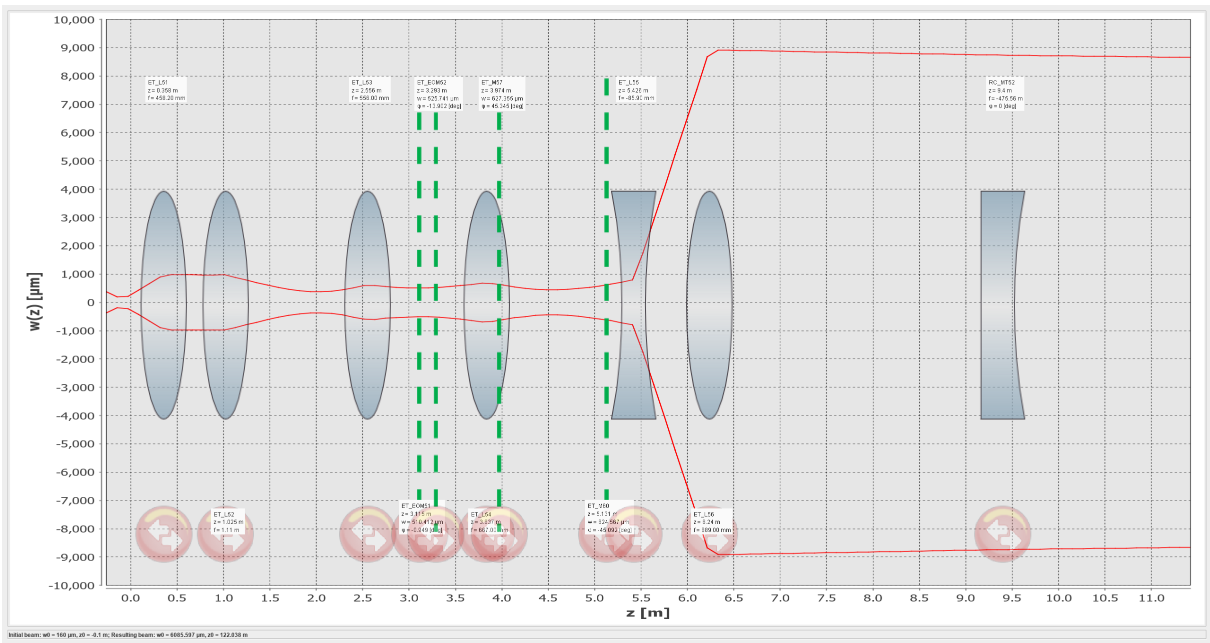


Figure 1: **Optical layout of the end table**



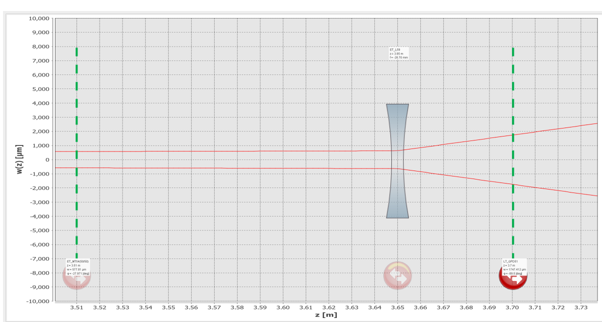
Optics	Specs	Position from the laser waist @-100 mm
ET_L51	f = 458 mm	358 mm
ET_L512	f = 1111 mm	1025 mm
ET_L53	f = 556 mm	2556 mm
ET_EOM51	NewFocus 4004 EOM	~3115 mm
ET_EOM52	Two RTP crystals, custom EOM	~3290 mm
ET_L54	f = 667 mm	3837 mm
ET_M57	PZT mirror actuator (x, y) @+45 Gouy phase	3974 mm
ET_M60	PZT mirror actuator (θx, θy) @-45 Gouy phase	5131 mm
ET_L55	$f = -85.9$ mm	5426 mm
ET_L56	f = 889 mm	6240 mm
RC_MT52	RC curved mirror ROC = 214 cm	~9500 mm
RC_MT51	RC flat mirror @COB waist = 6 mm	122 m from RC_MT52

Figure 2: LO laser to RC mode matching. The mode matching From ET_L53 is similar to GEN. This table shows the ideal position and focal values which is approximated in practice.

ET_L52 focuses the beam to 369 um (position 2 m from the laser initial waist) in order to mode match into the pre-mode cleaner cavity (see FDD of GEN for details). ET_L53 is positioned to re-collimate the beam to ~510 um (radius) where the two Electro-Optic phase modulators ET_EOM51and ET_EOM52 are located. Each EOM hosts a wedged RTP crystal in a custom housing. ET_EOM51 is used as an actuator for fast control corrections to increase the servo bandwidth to above 100 kHz. The second EOM (ET_EOM52) uses a two pairs of electrodes which are connected to two resonant circuits to generate two pairs of PM sidebands at frequencies f_1 and f_2 (see figure 4). After the EOM outputs, the beam is sent to a series of 4 lenses ET_L54, ET_L55 and ET_L56. ET_L54. ETL54 and ET_L55 lenses create a new waist between the actuated mirrors ET_M57 and ET_M60 which are located at $\pm$ the Rayleigh range before and behind the waist. These mirrors are used for the auto-aligment system of the LO to the RC Eigenmode (see also section 3.2.2). The last two lenses ET_L55 and ET_L56 are used to mode match into the RC. We note here that the distance between ET_L55 and ET_L56 is critical for the cavity mode matching: Both lenses will be mounted on a single rail to simplify their precise placement.

The Faraday Isolator ET_FI52, placed between ET 53 and ET_L54, is used to recover the RC reflected beam. This beam also contains the regenerated photon field. On ET_MT56 reflected side, 90% of the reflected beam power is sent to the heterodyne photodetector ET_PD51. The remaining 10% passes through wave plate ET_HW53 and the polarizer ET_PO52 which are used to adjust the power on the PDH sensing diode ET_PD52 and the two WFS-QPDs ET_QPD51 and ET_QPD52.

ET_PD51 (Custom made, provided by UF) is a shot-noise limited PD for an input power range of 1 to 10 mW, with a best operation frequency at ~15 MHz where the ratio between the shot noise to the PD NEP and the LO RIN is optimized. A transimpedance photodiode (ET_PD52) (Thorlabs, PDA05CF) detects the beat notes used in the PDH and FSR sensing, while the CCD camera (ET_CCD51) is used for diagnostic of the reflected beam mode. The WFS system contains two Gouy phase telescopes constituted by lenses ET_L59, 60 and 61 in front of the QPDs ET_QPD51 and ET_QPD52 to correct for lateral displacements and angular tilt miss-alignments (see figure 3). The quarter-wave plates ET_QW51, 52 and 53 are used in an optical diode configuration to reduce back-reflected light from the photodiode surfaces to enter the vacuum system again. The alignment system uses a visible laser (green HeNe-laser for the initial alignment of the central and the end tables with respect to the magnet bore.



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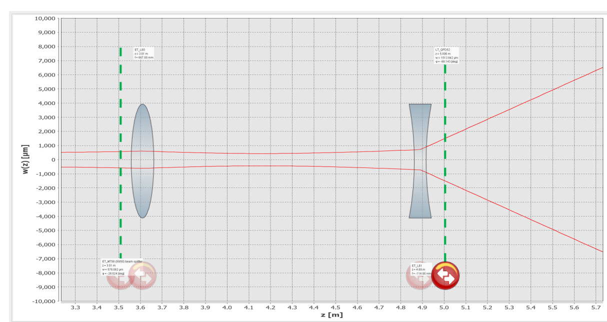


Left figure:

Optics	Specs	Position from the ET_ MT54 waist 578 um
ET_MT54	50/50	0 mm
ET_L59	f = −29.1 mm	~140 mm
ET_QPD51	QP50-6 (First Sensor)	~190 mm

Right figure:

Optics	Specs	Position from the ET_ MT54 waist 578 um
ET_MT54	50/50	0 mm
ET_L60	f = 667 mm	~100 mm
ET_L61	f = −114 mm	1280 mm
ET_QPD52	QP50-6 (First Sensor)	~1380 mm

Figure 3: Gouy telescope for ET_QD51 (left) and for ET_QD52 (right). The optical system is similar to the GEN system.

RC_MT52 is the curved RC cavity mirror inside the vacuum tank which is located on the end table. The mirror is placed in a piezo-actuated mount which allows to maintain the alignment of the RC. The alignment of RC_MT52 is adjusted using the signal from the in vacuum QPD on the central bench. The error signal from the QPD signal is digitized and controlled by an NI CompactRIO system located at the central area (see the subsection 4.3). The correction signal is transferred digitally via Ethernet cable to the end table, to a LabVIEW interface, in order to generate the appropriate actuation signal to the RC curved mirror.

The optical power injected into the RC will be defined once the RC losses and mirror power transmissivities are measured but will be in the 10 to 30 mW range. The required optical power range in reflection must be between 1 to 10 mW, while in transmission we require an optical power of at least 1 mW, in order to maintain reasonable beat note power levels for the WFS and the PLL+HET veto channel located at the central area RC side.[1]

3.1.1 Regeneration Cavity

The Regeneration Cavity (RC) is a two mirror cavity, RC_MT51 is a flat mirror mounted on the central optical bench (COB) while the RC_MT52 is a curved mirror mounted on the end table in CR-NR. Below are three tables 1, 2 and 3, which provide the cavity parameters.

Cavity length	122	m
Cavity waist	5.99 $\pm$0.15	mm
FSR	1.23	MHz
Finesse	120 000 (TBC)	
FWHM	TBC: 10 = FSR/Finesse	Hz

Table 1: Regeneration Cavity Parameters

[1] If the impedance of the as-built RC does not allow to reach these values, a sideband locking scheme could be implemented or an additional local oscillator phase locked to the carrier could be added (additional laser or double-path AOM).

Parameter	RC_MT51	RC_MT52	Unit
Size (Ø x thickness)	50.8 x 9.53	76.2 x 12.7	mm
Dimensional tolerances	+0.0, -0.5 mm on all dimension		mm
ROC S1	Flat, > 5 000	214 ±10	m
ROC S2	Flat, > 5 000	Flat, > 5 000	m
Material	Fused Silica Corning 7980 HPFS Grade 0A		
Clear aperture	85%		
Roughness S1	< 1 Å RMS		
Roughness S2	< 1 Å RMS		
Wedge between front and back faces	< 5 microradian with a best effort for < 1 microradian	0.5° ±0.1° in S2	
Sides	Polished to standard optical quality		
Bevels	1 mm x 45° , both sides. Polished standard optical quality		
Birefringence	< 1 nm/cm within central 85% area		
Scratches S1	There shall be no scratches and sleeks within the central 15 mm diameter. The total area of scratches and sleeks within the central 85 % area shall not exceed 6 times 103 square micrometers, width times length. The total area of scratches and sleeks outside the central 85 % area shall not exceed 25 times 103 square micrometers		
Scratch-dig S2	10-5 in the central 85% area. 20-10 outside the central 85 % area.		
Marking on barrel	Serialized as FL-XX, where XX increments starting at 01. Arrow points to Side 1	Serialized as 214m-XX, where XX increments starting at 11. Arrow points to the concave surface	

Table 2: Substrates specifications

Parameter	RC_MT51 | RC_MT52	Unit
S1 @1064	2 (TBC) | 25 (TBC)	ppm
S2 @1064	AR 500 ppm	
Absorption	< 1	ppm
Coating deposit method	Ion Beam Sputtered	
Angle of incidence	Normal	

Table 3: RC Coating Specifications (TBC)

3.2 ET Control

3.2.1 Laser frequency control and FSR sensing (Figure 4)

Requirements:

- Frequency lock LO to RC with less than 0.7 Hz RMS residual frequency noise.
- Maintain the absolute length of the RC; the allowed length changes are $< 5\,\mu$m

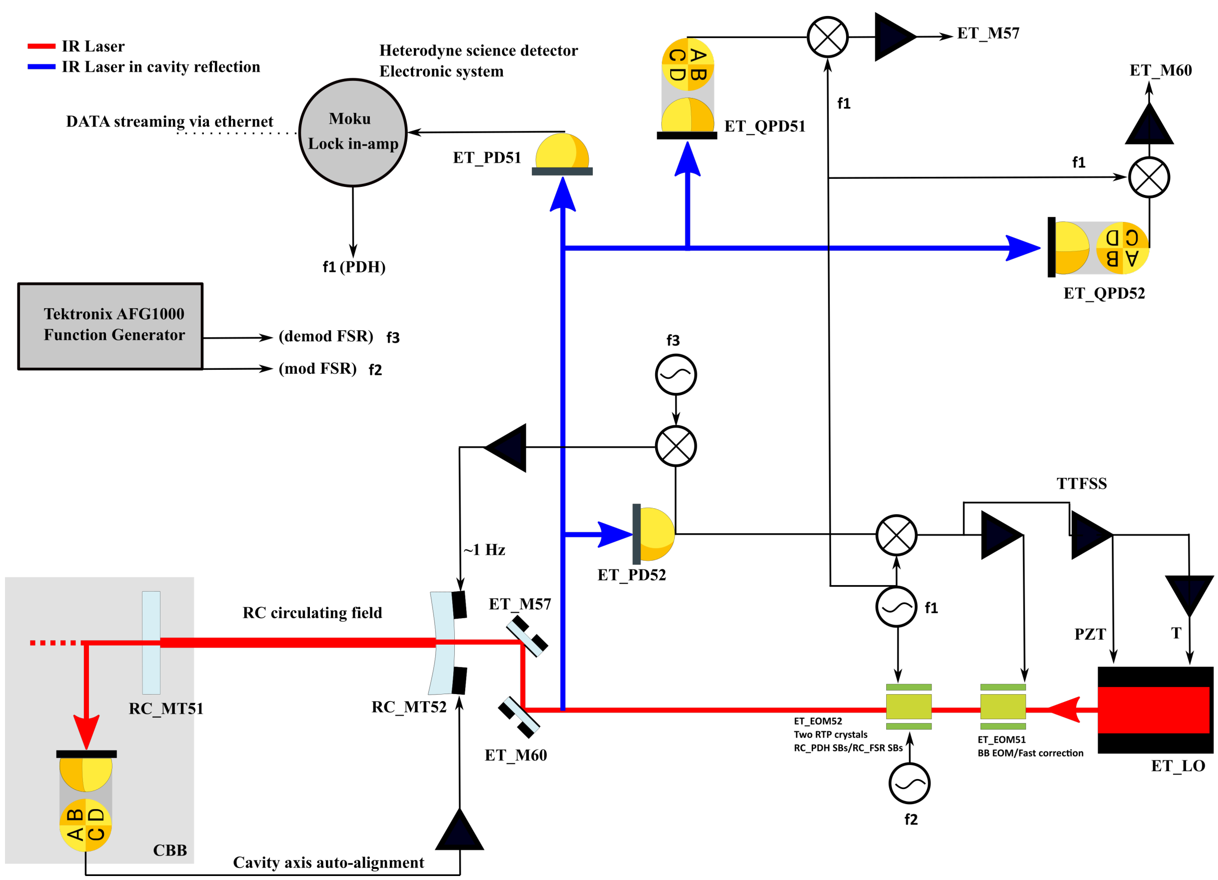


Figure 4: Control architecture scheme for the end table

Frequency lock LO on RC: Figure 4 shows a more detailed layout for the lock and the alignment controls at the end table. The laser frequency of the LO will be locked to the RC using a conventional PDH locking scheme. The frequency $f_1 = 9.22\,\mathrm{MHz}$ of the phase modulation side bands, on ET_EOM52, wedged RTP crystal, for the PDH LO-RC lock is generated by the auxiliary RF output of the Moku:Lab used in a lock in-amplifier mode for the heterodyne science signal detection. A Thorlabs PDA05CF2 model phototdector (ET_PD52) detects the carrier-side band beat for LO-RC PDH.

The TTFSS and field box electronic control system and lock acquisition for the frequency lock LO on RC are similar to what will be used in GEN (frequency lock HPL on PC).

FSR sensing : FSR locking allows generation of an error signal for the stabilization of the overall length of the RC and stabilize the RC slow length drift against a RF reference oscillator. For this task we will use the electronic sideband technique described in [I. Thorpe et al., Optics Express Vol. 16, No. 20 pp. 15980]. Additional sets of sidebands are added to LO with the electro-optic modulator ET_EOM52. The drive signal on ET_EOM52 has a carrier frequency of $f_2 = 10 \cdot \mathrm{FSR} \approx 11.68\,\mathrm{MHz}$ and is phase-modulated at $f_3 \approx 10\,\mathrm{kHz}$ with a depth β_2. This creates 6 additional sidebands at $\omega_c \pm f_2$, $\omega_c + f_2 \pm f_3$, and $\omega_c - f_2 \pm f_3$. The error signal is generated by placing the $\omega_c \pm f_2$ sidebands on resonance and demodulating the ET_PD52 signal at f_3.

- Controller: NI CompactRIO (National Instrument ADC-DAC FPGA card).
  - CompactRIO Model: cRIO-9054. 1.33 GHz Dual-Core CPU, 2 GB DRAM, 4 GB Storage, Artix-7 A100TFPGA, 4-Slot CompactRIO Controller. Has 2 Ethernet ports.
  - The cRIO-9054 is supported by an NI Linux Real-Time (64-bit) operating system and programmed on LabVIEW FPGA Module 2018 or later.
  - ADC Model: NI 9205, 16 AI Differential/32 AI Single-Ended, ±200 mV to ±10 V, 16 Bit, 250 kS/s Aggregate.
  - DAC Model: NI 9264. 16 AO, ±10 V, 16 Bit, 25 kS/s/ch Simultaneous.

Actuator mount for RC curved mirror RC_MT52 A SMARACT model mirror actuator mount is currently under investigation at DESY (TBC).

3.2.2 Automatic Alignment of LO laser on RC

- Sensor: Two Quad detector boards (QP50-6 (TBC))
- Demodulation stage: Moku:Lab (UF-provides) generates RF signal, feeds into a demodulation board which generates Pitch/Yaw/Sum signals. (Cardiff provides demod board)
- Controller: National Instrument CompactRIO system.
  - CompactRIO controller Model: cRIO-9054. 1.33 GHz Dual-Core CPU, 2 GB DRAM, 4 GB Storage, Artix-7 A100TFPGA, 4-Slot CompactRIO Controller. Has 2 Ethernet ports.
  - The cRIO-9054 is supported by an NI Linux Real-Time (64-bit) operating system and programmed on LabVIEW FPGA Module 2018 or later.
  - ADC Model: NI 9205, 16 AI Differential/32 AI Single-Ended, ±200 mV to ±10 V, 16 Bit, 250 kS/s Aggregate.
  - DAC Model: NI 9264. 16 AO, ±10 V, 16 Bit, 25 kS/s/ch Simultaneous.
- Alignment actuators on alignment mirrors: we plan to use a commercial Thorlabs PZT mounts (KC1-P, ±275 urad of dynamic range).

3.2.3 Rack

The rack is located in the greyroom. It contains:

- GEO style crate contain the TTFSS fieldbox (ALPS version) developed at AEI
- CompactRIO system for the alignment of LO to RC and FSR locking
- RF source (SRS DS345) for FSR locking
- **TBD** HU for signal conditioning (TBD what is needed, pending discussion in DAQ subsystem)
- **TBD** HU for 10 MHz reference signal provided by DOOCS subsystem
- power distribution for all electronics components in the rack and on the table

All instruments in rack are synched to the 10 MHz reference signal.

3.3 ET DAQ and Slow Control

The frequency of the LO is locked to the RC using LIGO's Table-Top Frequency Stabilization Servo (TTFSS). It is an analog system which provides a slow actuation signal to the L) temperature, an intermediate one to the LO PZT, and a fast one (if needed) to EOM ET_EOM51. This box is connected to a TTFSS field box which connects to a manual control box and the DOOCS system. The manual control box and the DOOCS system allow to change gain settings and switch actuators in and out as needed either locally or remote. The switches use TTL level signals, while gain settings and offset control require voltage signals with continuous tuning capabilities.

Key points of the interface with Slow Control and Data Acquisition subsystem (DOOCS) are:

- interface is located at the 19 inches DOOCS rack outside the clean room and gray room
- REGH provides interface electronics to the TTFSS control loop that allows to engage/disengage loops, adjust offsets and gains
- DOOCS provides a 10 MHz synchronization signal at the rack in the gray room.
- DOOCS provides software environment in Control Room that allows to program:
  - GUI for control loops (on/off, offset/gain adjust, lock acquisition logic)
  - monitoring tools using DAQ channels (times series, spectrograms, band-limited rms) and watchdogs
- REGH manages space allocations on the end table and in the gray room. REGH provides rack space in the gray room to DOOCS for the signal conditioning unit and the clock signals.

3.3.1 Channel List

I/O convention in table

Signal lists is seen from point of view of DOOCS:

- Inputs: signals that are being digitized by DOOCS ADCs. For example: error and actuation signals, monitors.
- Outputs: signals that need to be generated by DOOCS DACs. For example: remote control of loops.

CompactRIO is an independent system from DOOCS and, during initial phases and commissioning, it will take care of acquisition of photodiode signals and generation of actuation signals independently from DOOCS system. Some, maybe most of the acquisition channels, might later migrate to DOOCS while the digital control of feedbacks will remain in the Compact RIO system. For signals that are connected to a CompactRIO system, the convention used is:

- Inputs: signals that are being digitized by NI ADCs. For example: error signal, remote control of loops.
- Outputs: signals that need to be generated by NI DACs. For example: actuation signals.

	I/O	bandwidth	impedance	range (V)	bits	interface	Comments
C1. LO PDH							
TTFSS fieldbox							
DB9 Connector 1 (In1)							
IN2	I	F		± 10	14	uTCA (TEWS)	FSS loop errorpoint
IN1	I	F		± 10	14	uTCA (TEWS)	LEMO input IN1 at TTFSS fieldbox
FastM_OUT	I	F		± 10	14	uTCA (TEWS)	monitor of NPRO PZT signal
PCM_OUT	I	F		± 10	14	uTCA (TEWS)	monitor of signal to phase correcting EOM
DB9 Connector 2 (In2)							
LOMOUT	I	S		± 10	14	uTCA (TEWS)	strength of local oscillator signal
TEST2	I	F		± 10	14	uTCA (TEWS)	LEMO input TEST2 at TTFSS fieldbox
RFPDDC	I	F		± 10	14	uTCA (TEWS)	reflection photodiode (DC coupled)
DB9 Connector (Out1)							
CGI	O	S			16	EL4104 (1.1)	common gain
OSI	O	S			16	EL4104 (1.2)	signal to be added into error point
FGI	O	S			16	EL4104 (1.3)	fast path gain (NPRO PZT)
RMPE	O	S			1	EL2124 (1.1)	open/close control loop after error point and infront of ramp injection in fast path
DB9 Connector (Out2)							
TST1E	O	S			1	EL2124 (1.2)	enables BNC TEST1 IN (summation at output of MIXER (at input of LP filter)
TST2E	O	S			1	EL2124 (1.3)	enables BNC TEST2 IN (summation at error point, at output of MIXER LP filter)
SLOWI	O	F			16	Beckhoff (TBD)	signal to SLOW of TTFSS (connected to RAMP IN, for autolock only!)
TEMP	O	S			16	EL4104 (1.4)	signal to LEMO TEMP at TTFSS FB
C2. AutoAlignment LO							
Input (DSUB)							
	I	F	HI	± 10	16	Compact RIO	DWS error signal 1x from ET_QPD51
	I	F	HI	± 10	16	Compact RIO	DWS error signal 1y from ET_QPD51
	I	S	HI	± 10	16	Compact RIO	DC power monitor ET_QPD51
	I	F	HI	± 10	16	Compact RIO	DWS error signal 2x from ET_QPD52
	I	F	HI	± 10	16	Compact RIO	DWS error signal 2y from ET_QPD52
	I	S	HI	± 10	16	Compact RIO	DC power monitor ET_QPD52
Output (DSUB)							
	O	F		± 10	16	Compact RIO	DWS actuation signal 1X to ET_M57
	O	F		± 10	16	Compact RIO	DWS actuation signal 1Y to ET_M57
	O	F		± 10	16	Compact RIO	DWS actuation signal 1X to ET_M60
	O	F		± 10	16	Compact RIO	DWS actuation signal 1Y to ET_M60
Control (Ethernet)							
feedback loop X on/off	I	S			1	Ethernet	Control in Labview VI
X gain	I	S			16	Ethernet	Control in Labview VI
X offset	I	S			16	Ethernet	Control in Labview VI
X integrator	I	S			16	Ethernet	Control in Labview VI
feedback loop Y on/off	I	S			1	Ethernet	Control in Labview VI
Y gain	I	S			16	Ethernet	Control in Labview VI
Y offset	I	S			16	Ethernet	Control in Labview VI
Y integrator	I	S			16	Ethernet	Control in Labview VI
C3. FSR locking							
Input (Ethernet)							
Compact RIO	I	S			1	Ethernet	engage/disengage, Control in Labview VI
Compact RIO	I	S			16	Ethernet	offset, Control in Labview VI
Compact RIO	I	S			16	Ethernet	gain, Control in Labview VI
Input (DSUB)							
FSR locking error point	I	S	HI	± 10	16	Compact RIO	Demodulated signal
Output (DSUB)							
FSR locking control signal	O	S		± 10	16	Compact RIO	Control to SMARACT stage
C4. Monitors							
LO power after motorized HWP	I	S	HI			DOOCS RS232	ET_PM51
RC reflection PD signal	I	S	HI			Beckhoff analog	ET_PD52
HET shotnoise PD DC level	I	S	HI			Beckhoff analog	ET_PD51
Seismometer/geophone	I	S	HI			uTCA (TEWS)	3 channels (TBD if required)
LO diagnostics	I	S	HI			EL3008	Beckhoff, 8 ch from DSUB25 controller Mephisto S
C5. Detector							
HET science detector	I	S			12	Ethernet	Python script controls Moku, I and Q signals out
C6. CCD							
CCD beam monitor (PMC transm, RC refl)	I	S				Ethernet	2 + 1 spare, Basler, Power over Ethernet (PoE)
C7. Optomechanics							
Laser shutter	O	S				TBD	LS1 - DESY
Remote controlled HWP for LO pwr	O	S				TBD if needed	ET_HW51
C8. RC curved mirror actuation							
RC length	I	S				Ethernet	RC_MT52, SMARACT stage controlled in DOOCS
RC mirror angular actuation	I	S				Ethernet	RC_MT52, SMARACT stage controlled in DOOCS
C9. Clock synchronization							
	O					1.2 GHz	Reference signal for µTCA
	O					10 MHz	Reference synch signal for instruments and Mokus

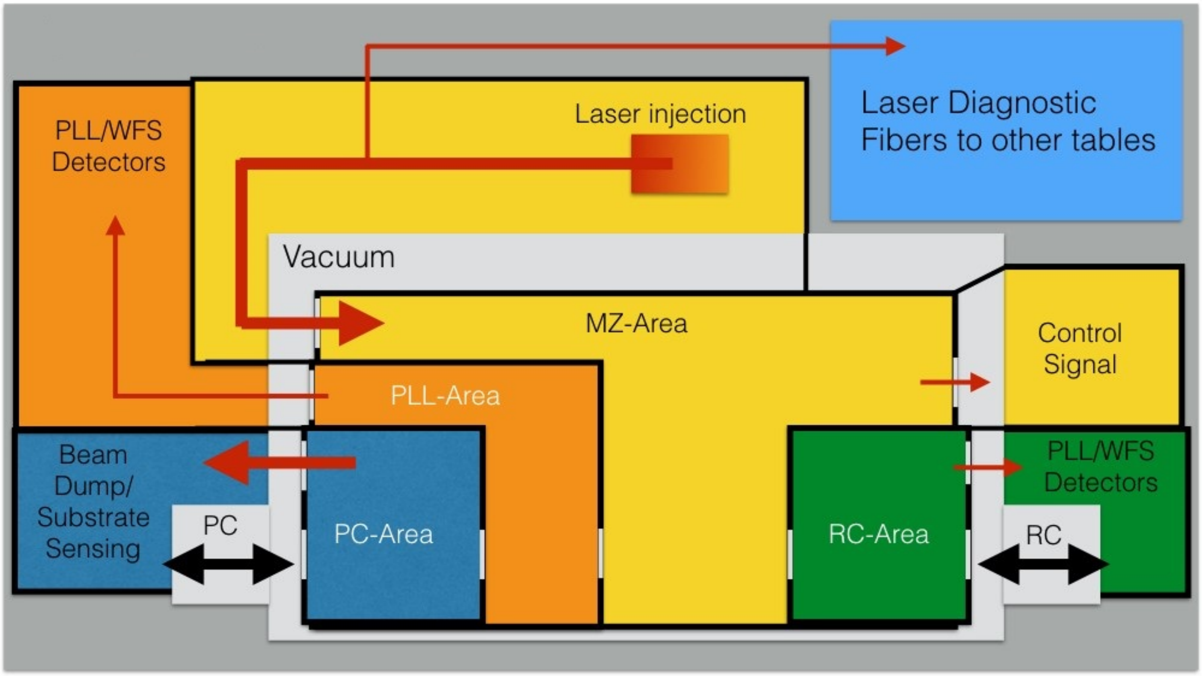


Figure 5: Different areas of the HET design concept

3.4 Commissioning and Operation

The latest changes to the magnet and clean room installation schedule allows to start installation of the LO in the end station in the fall of 2020. This installation will have to be coordinated with the installation of the IA system. The REGH installation will start with the installation of the LO and the optical components up to beam expanding telescope. Following the characterization of the laser (spatial mode, power, power stability, single mode operation), the alignment of the other components will start.

4 Central table

Figure 5 shows the various functional areas inside the vacuum tank and on the optical table for the HET design. The black lines between the areas indicate light-tight walls to minimize the chances of scattered light entering into the RC. The shape and size of these areas are not to scale. The laser injection area hosts RL and the mode matching optics to inject the laser beam into the Mach-Zehnder (MZ) area inside the vacuum system. A fraction of the laser beam will be directed toward the laser diagnostic area where also optical fibers are located which allow to exchange laser beams between the three optical areas of ALPS II. In the PLL area inside the vacuum tank a small fraction of the RL and of the PC transmitted beam will be superimposed and guided out of the vacuum system towards the PLL/WFS Detectors area on the left side. The PC area is used to measure the position of the PC transmitted beam; this signal is used to align the curved PC mirror (PC_MT1). Most of the PC output will be guided out of the vacuum system where it will be dumped. A small fraction of this beam will also be used to sense the thermal expansion of the substrate of the flat PC cavity mirror PC_MT2. The MZ area hosts the Mach-Zehnder interferometer in which we split the RL beam in two parts that are direct to overlap one with the PC transmitted beam and the other with the RC transmitted beam. The MZ area also injects parts of RL into the RC area and creates one of the control signals. The RC area inside the vacuum system houses the quadrant detector for the alignment of the RC. Outside the vacuum, beatnotes between LO and RL are used for the PLL and WFS signals. Not all of the walls are really light tight, we limit this to central areas, PC area and RC area.

Mirror	AoI	T_S	T_P	Comment
PC1	0°	107 ppm	107 ppm	Vendor data
PC2	0°	6.7 ppm	6.7 ppm	Vendor data
RC2	0°	107 ppm	107 ppm	Vendor data
RC1	0°	6.7 ppm	6.7 ppm	Vendor data
LT1	35°	0.5 ppm	16 ppm	Design Value
LT2	35°	0.5 ppm	16 ppm	Design Value
MZ1	35°	0.943	0.983	Uncoated glass
MZ2	35°	0.5 ppm	16 ppm	Design Value
MZ3	35°	9.6 ppm	322 ppm	Measured
MZ4	35°	9.6 ppm	322 ppm	Measured

Table 4: Transmissivities of mirrors and beamsplitters critical to managing the laser power inside ALPS II. AoI: Angle of incidence.

4.1 CT Optical Layout

4.1.1 In Vacuum optical Design

The in vacuum design (Figure **6**) contains the Mach-Zehnder interferometer, the first stages of the beam reducing/expanding telescopes that exchange beams with the out-of-vacuum optics, some routing and polarization optics and the light-tight boxes. The reflectivities and transmissivities of the various mirrors are presented in table 4. The optics beam height in vacuum is 56 mm.

In vacuum PC side: A maximum of 225 mW of s-polarized light injected by GEN into the production cavity (see GEN-REGH interface document in section 1.1) is transmitted through the flat mirror PC_MT2. Most of it is reflected by a high reflectivity mirror (CB_MT51, T=3ppm) to CB_MT57, CB_M61 and CBM51 and then sent outside the vacuum chamber through optical window CB_W1 towards the power monitor stage. Inside the vacuum chamber a 1% (TBD) pick-off is taken in transmission of CB_MT57 and sent to a QPD detector (CB_QPD51) that tracks the alignment of the PC cavity axis with respect to a reference position. A quarter-wave plate (CB_QW51, R=4% on exit surface, fast axis at 45°) reflects back a portion of the PC transmission towards the flat cavity mirror PC_MT2 to probe the optical pathlength change in the substrate. The back-reflected beam is rotated in polarization due to the double pass in CB_QW51, reflected off the (highly under-coupled) PC and overlapped with the main cavity output traveling out of the vacuum. A second quarter-wave plate (CB_QW52) follows in the beam path and is mounted on the same optical mount as CB_QW51 due to limited space in the light tight box. During pseudoscalar runs (normal operation) the fast axis of CB_QW52 will be set orthogonal to the one of CB_QW51, producing a null rotation of the polarization (the effect of one waveplate cancels the other). When we switch to scalar runs, the fast axis of CB_QW52 will be rotated and aligned with the one of CB_QW51.[2]

CB_QW51, CB_QW52 and the PC end mirror PC_MT2 are mounted on an ULE breadboard to ensure the path length stability for the OPL sensing system described later in Section 4.1.2. All of the components described above are enclosed in a light-tight box to minimize the amount of HPL scattered light that can enter the MZ area. An additional half-wave plate (CB_ HW52), located outside the light-tight box and mounted on a motorized vacuum compatible rotation stage, allows us to change the polarization of the PC transmitted field when we want to check the alignment.

In vacuum Upper-left side (RL injection): About 100 mW (p-pol) from RL enters the vacuum chamber through an optical viewport CB_W3, the left of the three vacuum viewports, just after the turning mirror CT_M58. Two steering mirrors (CB_M54 and CB_M55) send the beam to a mode matching curved mirror CB_M56, which is part of a beam expanding telescope that is described in the out of vacuum section. CB_M56 is a curved mirror that reflects the beam with an incidence angle of 15° and re-collimates it again

[2]The two quarter-wave plates effectively behave like a single half-wave plate. Furthermore, there is not enough space for an actuated rotation stage. We will have to open the light-tight box.

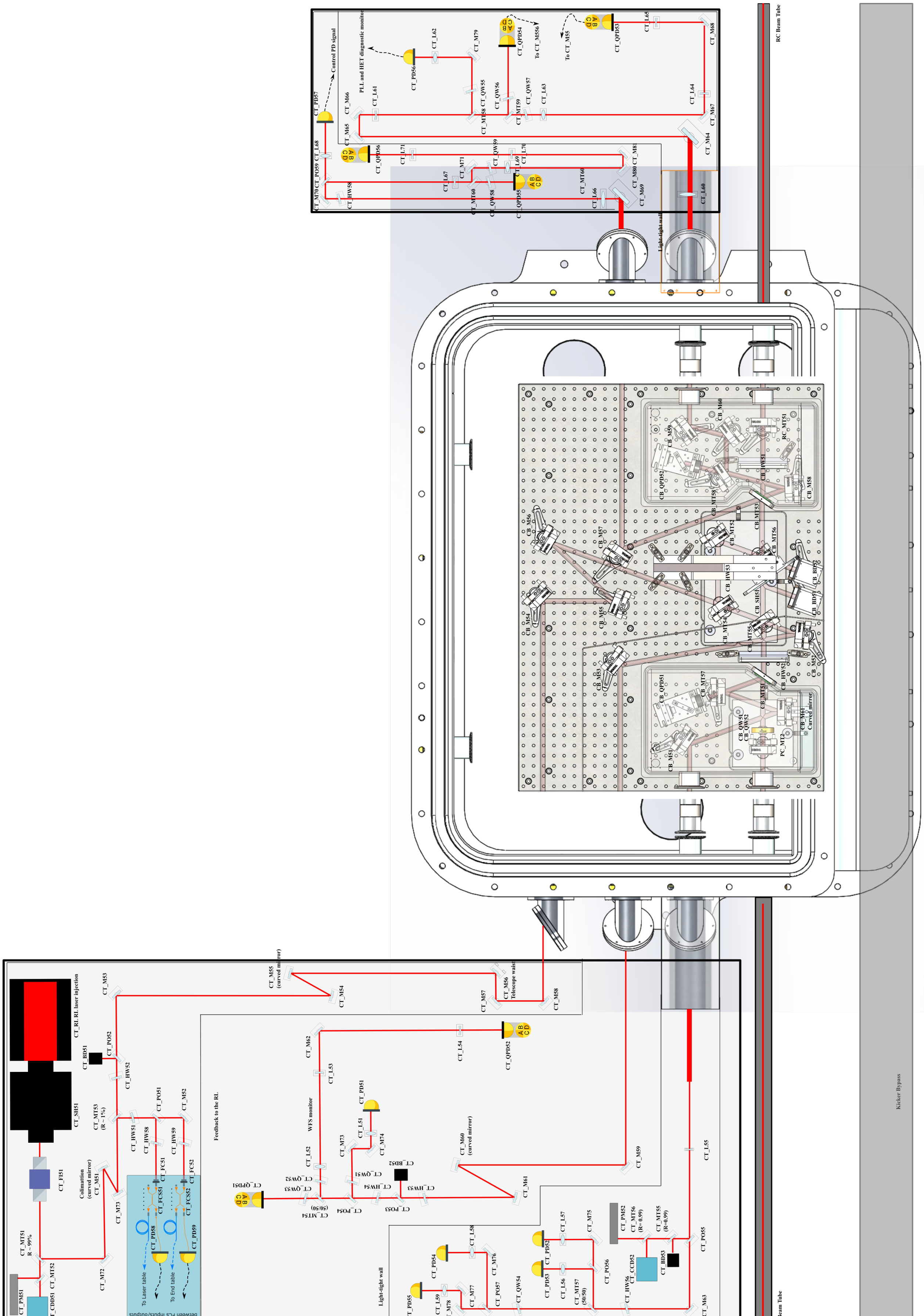


Figure 6: CT optical layout in general overview

to a beam radius of about 6 mm. The Keplerian telescope is divided in and out of vacuum (see section **4.1.3**), in order to maintain a reasonable beam size of ~2 mm at the vacuum window.

The RL beam is injected in the Mach Zehnder and split in two parts: one is used to form the beatnote with the PC transmission, the other is sent towards the RC. The MZ assembly consists of three 2" beam splitters (CB_MT54, CB_MT55, CB_MT56) with 500 ppm of transmissivity for s-pol and 30% transmissivity for p-pol and a 2" high reflectivity mirror (CB_MT52) with 3ppm transmissivity for both polarizations. The half waveplate CB_HW53 mounted between the top MZ mirrors is to flip the RL polarization from p to s-pol, enabling more optical power in the RC side for the PLL/WFS systems, where the s-pol match with the same polarization of the RC transmitted light.

The PC transmitted light through CB_MT51 is about 750 nW and is sent to the first mirror of the MZ CB_MT55 to create the PLL-WFS beatnote with 10 mW from RL. This beatnote is directed, with an incidence angle of 15°, to the first curved mirror CB_M52 of the beam reducing telescope and sent out of the vacuum through the vacuum window CB_W2. The other output of the beamsplitter CB_MT55 is sent to a high reflectivity mirror with a metal coating on the back (CB_SH51) which sends the beam to the beam dump CB_BD51. CB_SH51 acts as mirror shutter and is mounted on a flipper mount so it can be removed from the beam path when checking the cavity axis alignment.

In vacuum RC side: The regeneration cavity flat mirror RC_MT51 (T = 2 ppm) transmits 1 mW of LO laser power in s-polarization. after passing through a half-wave plate CB_HW51, the RC transmitted beam is reflected at CB_MT53 (T=3ppm). A small fraction of the RL beam leaving the MZ via CB_MT56 passed through CB_MT53 and is combined with LO at RC_MT51. Both beams are then steered towards CB_MT58 which picks off 1% of the light for alignment control using CT_QPD2.

The rest is directed out of the light-tight box and of the vacuum chamber by a steering mirror CB_M59 towards the second PLL, the WFS monitor, and the HET signal monitor. The half-wave plate CB_HW51 in front of the RC is mounted on a motorized rotation stage. This rotation stage is used to phase shift any potential HPL light by 180° (for example every 1000s) to integrate it away in the HET data; ie. a spurious signal would change sign and go from the I quadrature to −I, while a real signal would stay in I.

A general requirement for HET detection is that distances between the mirrors of the MZ do not change by more than 100 nm during each science run. For this reason the central breadboard, which is made in aluminum, has also two separated inner parts made of ULE to satisfy the requirement for pathlength stability: one hosts the MZ optics, while the other hosts the PC flat mirror and quarter-wave plates CB_QW51 and CB_QW52.

Mirrors CB_MT51 and CB_MT53 are fixed directly on the walls of the light-tight boxes, while the other mirrors are mounted on high stability Polaris mirror mounts on the COB (see section 4.2 for further design details).

4.1.2 Out Vacuum optical Design

The table size at the left side of figure 6 is 180 cm x 90 cm, and the other one, at the right side of the figure, is 100 cm x 50 cm. The beam height from both table surfaces is 100 mm **(TBD)**.

Laser Injection area (left in Figure 6) : The laser injection area hosts the reference laser RL, a 500 mW Coherent Mephisto S laser. **The beam first passes through a laser shutter CT_SH51 provided and controlled by the laser safety team.** After the Faraday isolator (CT_FI51), a partly transmissive mirror is used to pick off a portion of the beam for power diagnostic and monitoring (CT_PM51, CT_CDD51). In the main beam path a half-wave plate (CT_HW52), slightly tilted to reduce back reflection, and a polarizer (CT_PO52) will act as the first power control stage. The polarizer is aligned to transmit p-polarized light while the reflected power is sent to a beam dump (CT_BD51). In the same beam path, two piezo actuated steering mirrors (CT_M55, CT_M56) control the injection of the beam in the vacuum chamber. These mirrors are controlled by the WFS system in the PLL/WFS Detector area on the RC side. A 1% reflected pick off is taken at CT_MT53 and coupled into two single mode PM optical fibers through a 50/50 fiber coupler beam splitter (CT_FCS51 and CT_FCS52). The working principle is the same as the one described in the End Table section and we generate beatnotes on fiber coupled photodetectors CT_PD58 and CT_PD59.

These optical links enable the exchange laser beams between the central table and the two end stations. A half-wave plate (CT_HW51) and a polarizer (CT_PO51) are used to adjust the ratio of the injected powers into the fibers. Two other half-wave plates (CT_HW58, CT_HW59) adjust the polarization of the injected beams to either the fast or slow axis of the PM fibers. The laser beam from RL (waist = 160 µm) is collimated with a curved mirror CT_M51 (RoC= 200 cm) to a beam radius of about ~2 mm. Then the beam is expanded with a Keplerian telescope (CT_M55, RoC = 100 cm and CB_M56, RoC = 300 cm) to about ~6 mm to match the spatial mode of the transmitted beam from the PC (more detail in section 4.1.3).

Substrate OPL sensing/PC output monitor area (Left in Figure 6): The OPL probe beam (described in the in vacuum section) and the main cavity output beam exit the vacuum chamber in orthogonal polarization states from viewport CB_W1. The in-vacuum curved mirror CB_M61 (ROC = 300 cm) and an out of vacuum divergent lens (CT_L55, f = -57 cm), spaced by ~90 cm (see section 4.1.5), reduces the size of the optical beam to ~2.3 mm. Out of vacuum, the polarizing beamsplitter CT_PO55 transmits 4% of s-polarized light and all p-polarized light, the rest is reflected to the power and beam monitoring stage consisting of power meter CT_PM52 and beam cam CT_CDD52. Both fields after CT_PO55 are now equal in amplitude. A half-wave plate CT_HW56 rotates both polarizations by 45° and a 50/50 beamsplitter (CT_MT57) splits the beams in two paths each consisting of a polarizer, two lenses and two photodiodes. In one of the arms a quarter-wave plate CT_QW54 delays the reference beam (PC transmitted beam) and the probe beam by $\pi/2$ radians. The signal outputs from the four PDs are digitezed on an National Instrument ADC model NI 9205. The differential signals in each pair of photodiodes measure the in-phase (I) and out of phase (Q) of the OPL signal. Those differential signals are processed on a LabView interface.

PLL/WFS areas (Right and left in Figure 6, RC and PC side respectively) : The two PLL/WFS areas are used to generate the error signals for the PLL between the three lasers and for the alignment of the RL injection with respect to the RC transmitted beam. A second WFS signal is generated in this area and used to monitor the alignment of RL and the PC transmitted beam. We implement a beam reducing telescope for the beams that come out of the vacuum chamber through CB_W2. The incidence angle on the curved mirrors of the telescope (CT_M60 and CB_M52 inside the vacuum) is 15°. On the PC side, 10 mW from RL (p-pol) and 750 nW from the PC output (s-pol) exit the vacuum chamber through window CB_W2 and are directed to a half-wave plate (CT_HW53) and a polarizer (CT_PO53) by mirrors CT_M59, CT_MT60 and CT_M61. Adjusting the half-wave plate axis we project about 70% of PC light and 30% of RL light on a common polarization and send the excess power to a beam dump (CT_BD52) in reflection. After that another combination of a halfwave plate (CT_HW54) and a polarizer (CT_PO54) is used to split and balance the beatnote power between PLL and WFS. The arm in reflection of the polarizer is send to a focusing lens (CT_L51) and a photodetector (CT_PD51) for the PLL; in transmission of the polarizer, a 50/50 beam splitter (CT_MT54) divides the optical power on the WFS detectors (CT_QPD51, CT_QPD52). Lenses CT_L52, CT_L53 and CT_L54 are used for Gouy phase telescopes (see section 4.1.6). Three quarter-wave plates CT_QW51, CT_QW52, CT_QW53 are positioned in front of every photodiode and, in combination with the polarizers, act as optical diodes to prevent backscattered light from re-entering the beam path. On the PLL-WFS area on the RC side, about 210 nW from RL (p-pol) and 1 mW from LO (s-polarized) exit the vacuum chamber through window CB_W5. Two lenses CT_L60 (f = 167 cm) and CT_L61 (f = −57 cm) form a telescope to reduce the beam size to ~2 mm (see section 4.1.4). A mirror CT_M66 directs the beam to CT_MT58, which split it into two paths: 30% is sent to the WFS stage (CT_QPD53, CT_QPD54), the other 70% is sent to the shot noise limited photodetector (CT_PD56). The beatnote signal on CT_PD56 is then amplified and split between the PLL electronic system and the heterodyne monitor detector.

Any stray light that reaches RC_MT51 will see an under-coupled cavity which will reflect even on resonance and modematched 90% of the light. This light will be detected by CT_PD56. If properly calibrated the combination of the two HET detectors will allow us to distinguish if a signal has originated from inside the cavity or from stray light.

A much stronger contamination signal will also be available at the control photodiode CT_PD57 where we will monitor the beatnote between RL and any potential HPL light directed towards the cavity, before it enters the RC light-tight box, Contamination from stray light can be measured here with several orders of magnitude higher SNR than in the HET monitor detector. This will serve as an additional veto signal. This beat signal is generated in reflection from CB_MT53, comes out of the chamber through vacuum viewport

CB_W4. The beam is reduced in size to ~2 mm by lenses CT_L66 and CT_L67 (f= 167 cm, f = −57 cm, see section 4.1.4). The power control stage (CT_HW58 aand CT_PO59) enables to adjust power levels between the CT_PD57, and the WFS system (CT_QPD55 and CT_QPD56). This WFS system is an additional option for the alignment and the dual resonance verification (see section 6).

4.1.3 Mode Matching Keplerian telescope for RL injection @CB_W3 and beam reducer for vacuum output @CB_W2

The RL injection is first collimated to roughly 2.1 mm beam waist with the curved mirror CT_M51 of ROC: 200 cm. Remind that the NPRO Mephisto S from Coherent has 160 um beam waist at z0 = -10 cm. The figure 7 shows beam mode matching for the RL injection using optical lenses, instead in the CT optical layout we use commercial curved mirrors at 15 degrees incidence angle.

Beam expanding telescope mode matching at 0 incidence angle:

- First convergent curved mirror: ROC = 100 cm
- Second convergent cuurved mirror: ROC = 300 cm
- Magnification: 3. Beam expanded from 2.1 mm to 6.3 @CB_W3 or reduced @CB_W2.
- Telescope waist: 80 µm
- Rayleigh range: 1.9 cm
- Position of the first curved mirror form telescope waist: 49.9 cm
- Position of the second curved mirror form telescope waist: 150.1 cm
- Distance between the two curved mirrors: 200 cm

Telescope total length is divided between in and out of the vacuum chamber:

For RL injection @CB_W1:

- Length in vacuum: 107.7 cm (Unchangeable length calculated from the vacuum and COB designs)
- Length out vacuum: 92.3 cm
- Beam size at the vacuum window: ~1.9 mm (radius)

For PLL-WFS (PC side) output @CB_W2:

- Length in vacuum: 97.1 cm (Unchangeable length calculated from the vacuum and COB designs)
- Length out vacuum: 102.9 cm
- Beam size at the vacuum window: ~2.2 mm (radius)

4.1.4 Beam reducer Galilean telescope for vacuum outputs @CB_W4 and CB_W5 (Figure 8)

- Beam waist in : 6 mm (collimated beam, exit CB_W4 and CB_W5))
- Beam waist out: 2 mm (Magnification: 3)
- First convergent lens (CT_L60 and CT_L66): f1 = 1670 mm
- Second divergent lens (CT_L61 and CT_L77): f2 = -572 mm
- Distance between the two lenses: 109 cm

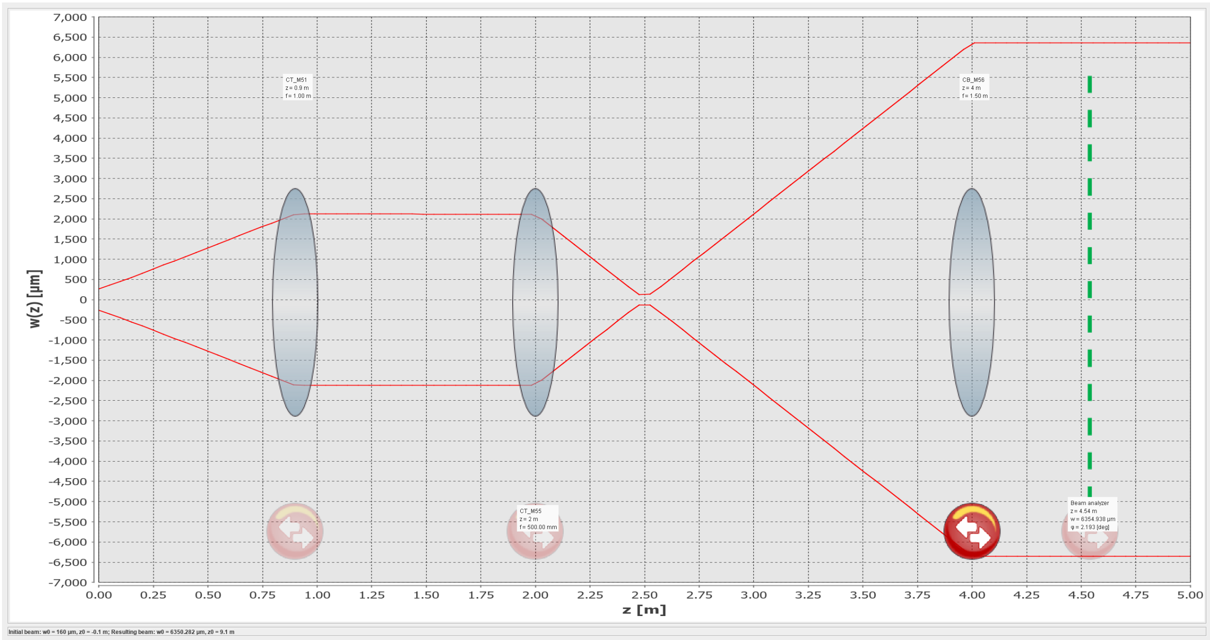


Figure 7: RL injection beam expanding telescope. Simulation with optical lenses. CT Optical layout uses curved mirror instead with 15 degree incidence angles.

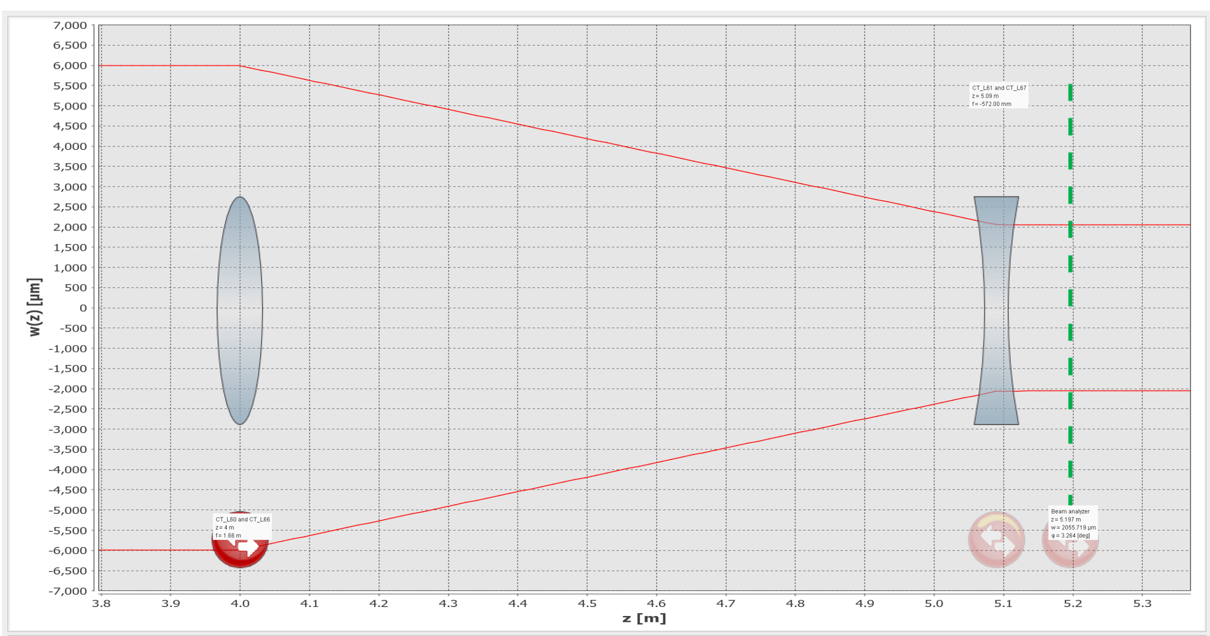


Figure 8: CT RC side out of vacuum Galilean beam reducer.

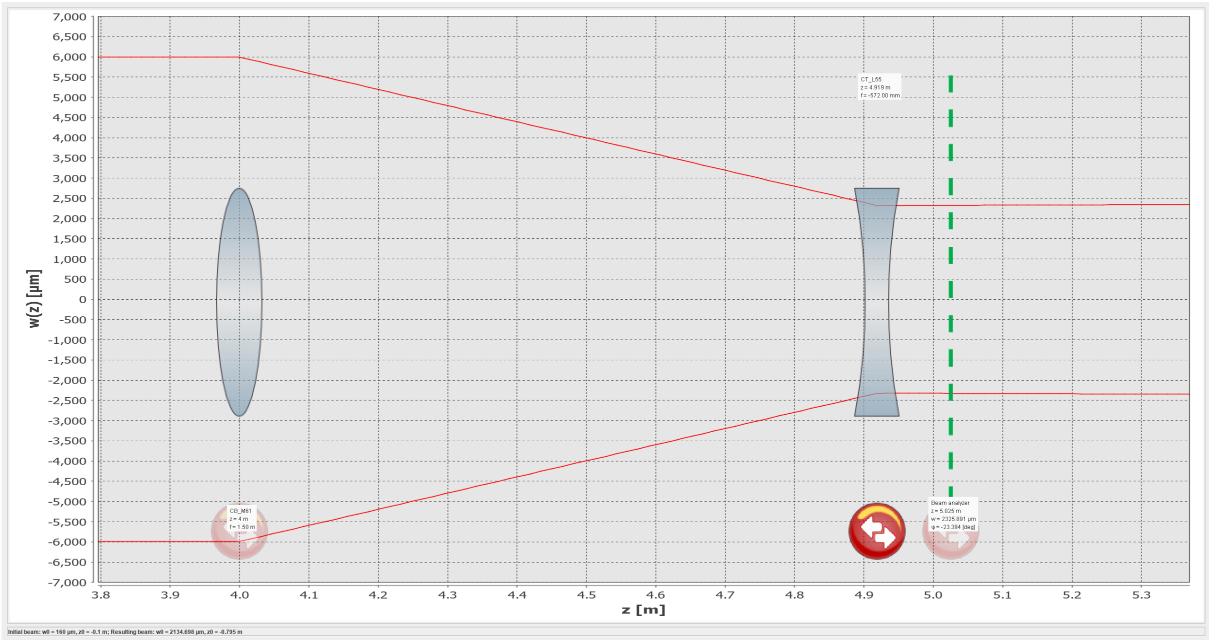


Figure 9: CT PC side out of vacuum Galilean beam reducer. Towards OPL sensning optics. Note fist optic shown in this figure is the in-vacuum curved mirror CB_M61.

4.1.5 Beam reducer Galilean telescope for vacuum outputs @CB_W1 (Figure 9)

- Beam waist in : 6 mm (collimated beam, exit CB_W1)
- Beam waist out: 2.3 mm
- First curved mirror (CB_M61): ROC = 300 cm
- Second divergent lens (CT_L55): f2 = -572 mm
- Distance between the in-vacuum curved mirror and the out-of vacuum divergent lens: ~91 cm

4.1.6 Alignment Gouy phase telescope for the WFSs

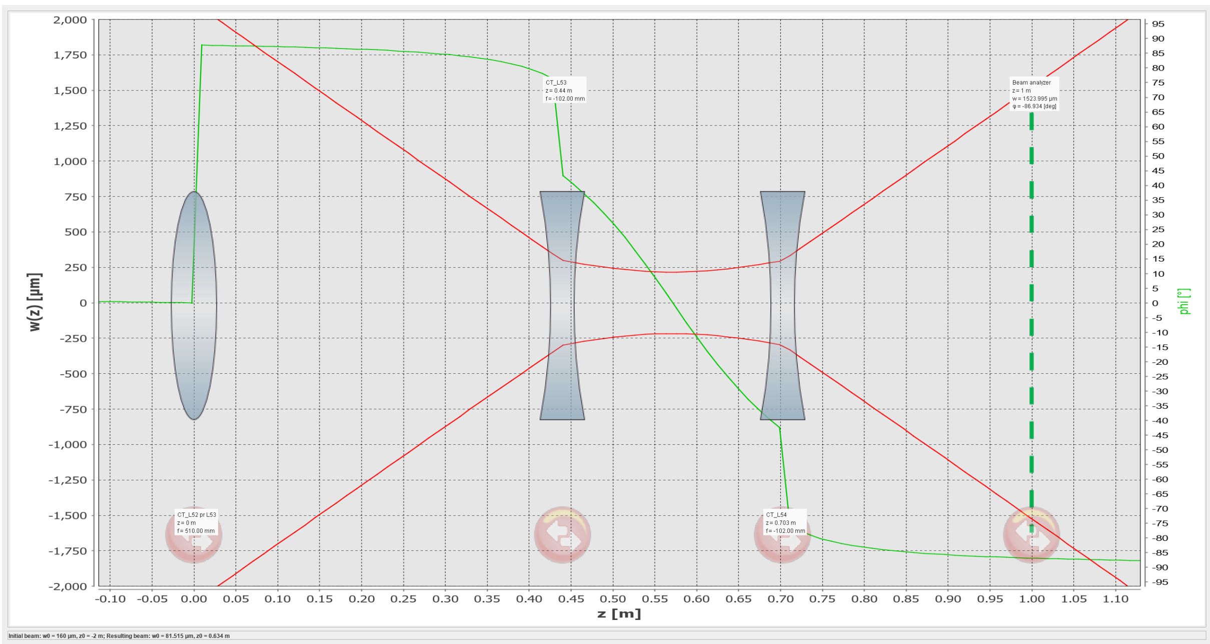
- QPDs: QP50-6 from First Sensor. Electronics (Trans-impedance and demodulation from Cardiff). Test and gain adjustments will be done at UF.
- QPDs: 7.8 mm active area and are best operated with a beam spot size on the PD of 1.5 to 2mm (radius)

Figure 10 shows a Gouy phase telescope design suitable for keeping both (1) a reasonable telescope length on top of the central optical tables in both PC and RC sides (see figure) and (2) a beam spot size on the First Sensors QP50-6 QPD in its best operated range. The first lens ET_L53 focuses the beam with a focal of 510 mm. The second lens CT_L54 is a divergent (-114 mm) placed slightly on front of the Rayleigh range of the waist created (~200 um), while a third divergent lens (CT_L55) with similar focal is placed slightly behind the Rayleigh range to expand the beam at the right beam size for CT_QPD52.

4.2 Central breadboard and vacuum window designs

4.2.1 Central breadboard

- Al / ULE plate mounting design



Optics	Specs	Position from CT_L52 or L53, beam wasit ~2 mm
CT_QPD51	QP50-6 First Sensor	0 mm (~2 mm beam waist)
CT_L53	f = 510 mm	0 mm
CT_L54	f = −102 mm	440 mm
CT_L55	f = −102 mm	703 mm
CT_QPD52	QP50-6 First Sensor	1000 mm (~1.5 mm beam waist)

Figure 10: Gouy telescope for CT_QD51 and for CT_QD52

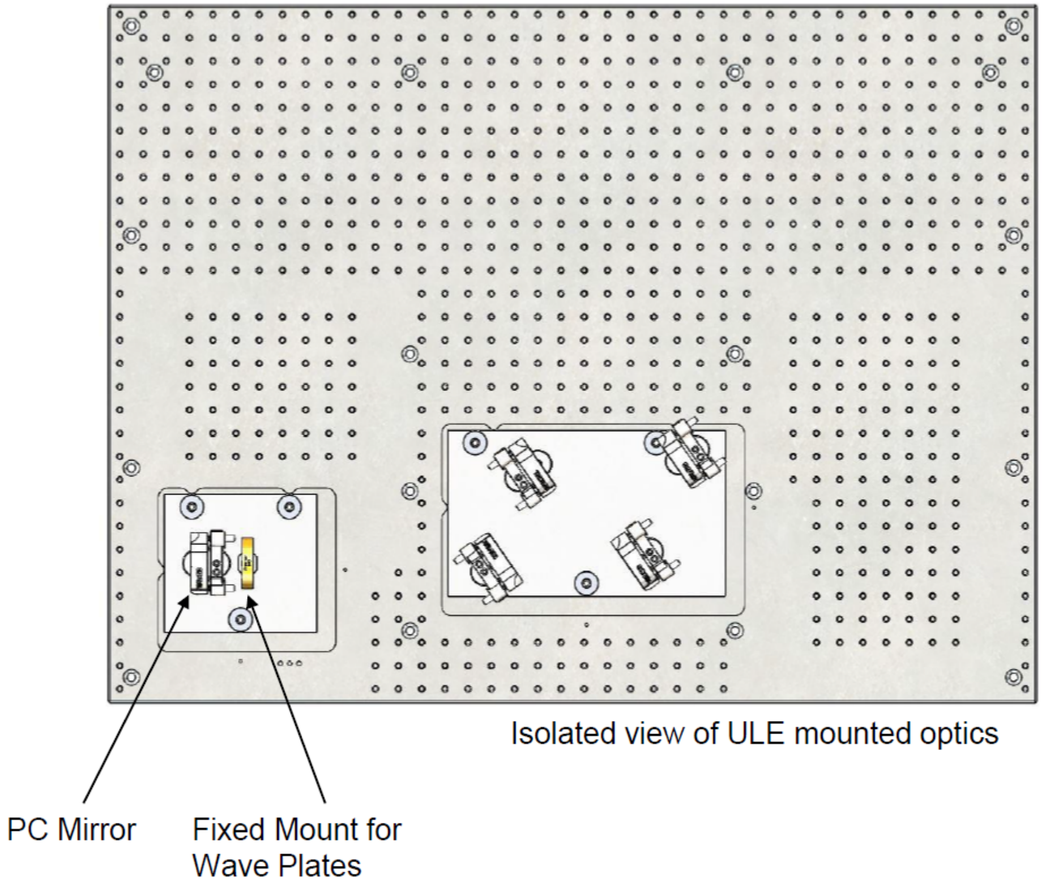


Figure 11: Main plates of COB

- Shutter / beam dumps
- Light-tight boxes

Figure 11 shows the main aluminum breadboard including the two inner ULE plates. The Al breadboard size is 100 cm x 75 cm. As described in the CT optical layout section, the ULE plates are to maintain the optical path length stability requirement in both the MZ and the OPL sensing schemes. The ULE plates are fixed using vertical clamping screws as shown in the figure 12 with step washer and O-ring clamps ULE to support pads. Furthermore, the ULE plate mounts feature guides for the longitudinal and Yaw axes as well as support pads for tip and tilt motions. This feature is to minimize mirror drifts due to differential thermal expansion between the ULE and metal components. The shutter shown in the CT optical layout (CB_SH51) is technically a two inch high reflectivity mirror with metal coating at its back surface, mounted on a filter wheel (SMARACT SFW-5-50.8, figure 13). While the beam dumps CB_BD51 and CB_BD52 are a Brewster angle black glass dumps inspired from LIGO, with an aperture of 36 mm x 46 mm (figure 14). The light-tight-boxes shown in the isometric view of the COB (figure 15) houses the cavity end mirrors and some other optics. Those boxes are machined from solid aluminum and form a light tight seal to the breadboard surface. Two 19 pin circular bayonet connectors (Amphenol PT06PG-14-19S(072)) on each housing are used as electrical feedthroughs for the in vacuum QPD and the waveplate rotators signals. These type of connectors have been used successfully in the light-tightness tests at UF.

The rotator and QPD signals are routed out of vacuum by dual sub D 25 pin electrical feedthroughs on CF63 flange. One for each side. An additional dual sub D 15 pin feedthrough will be used for the SMARACT filter wheel control and the HWP rotator (CB_HW52).

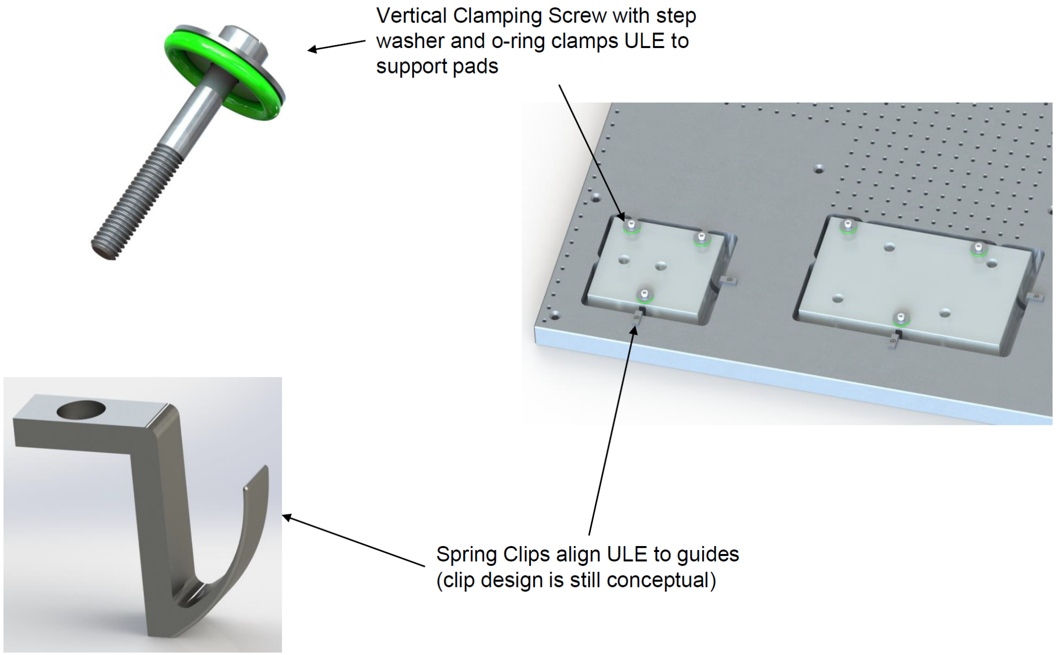


Figure 12: ULE plate mount design

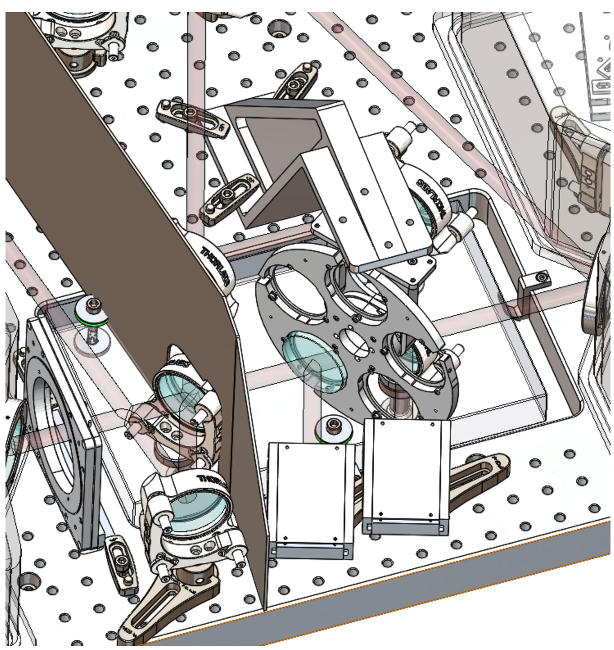


Figure 13: Motorized filter wheel as an optical shutter from SMARACT

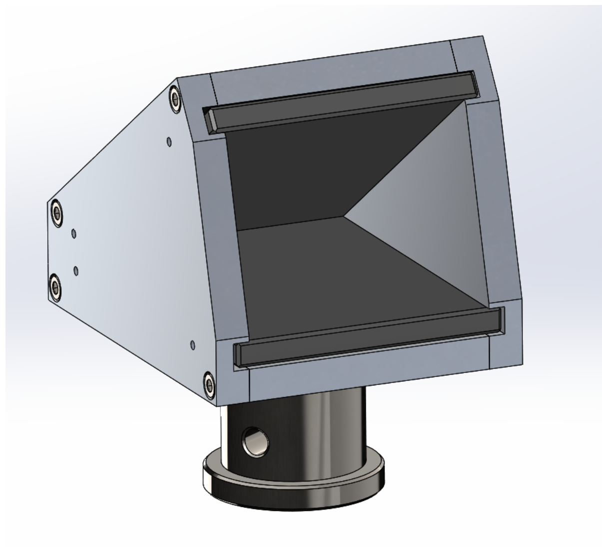


Figure 14: Beam dump design in COB

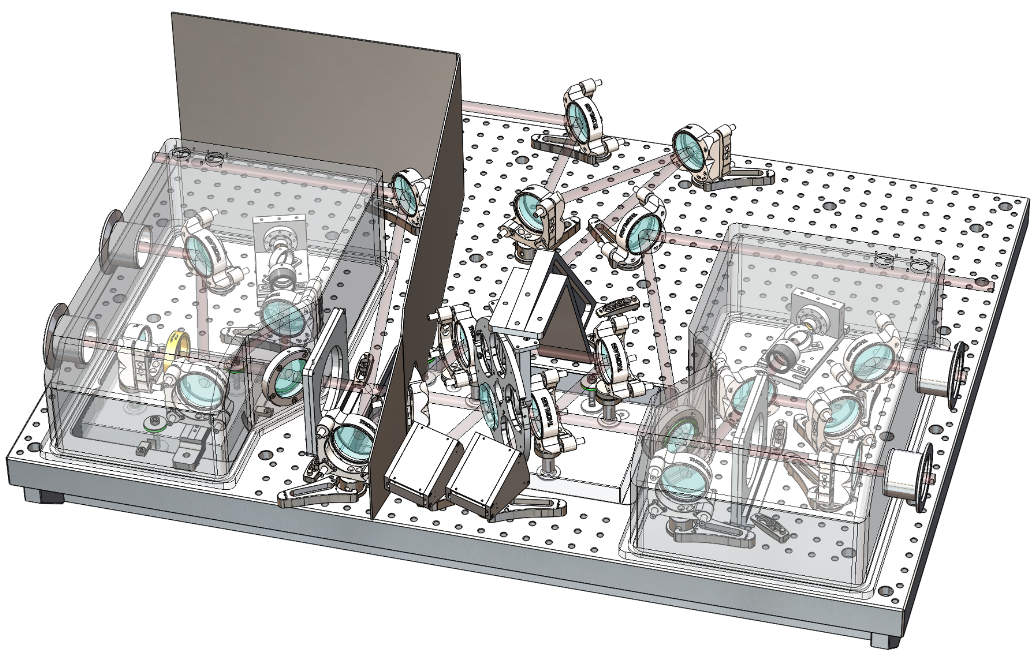


Figure 15: COB Isometric View

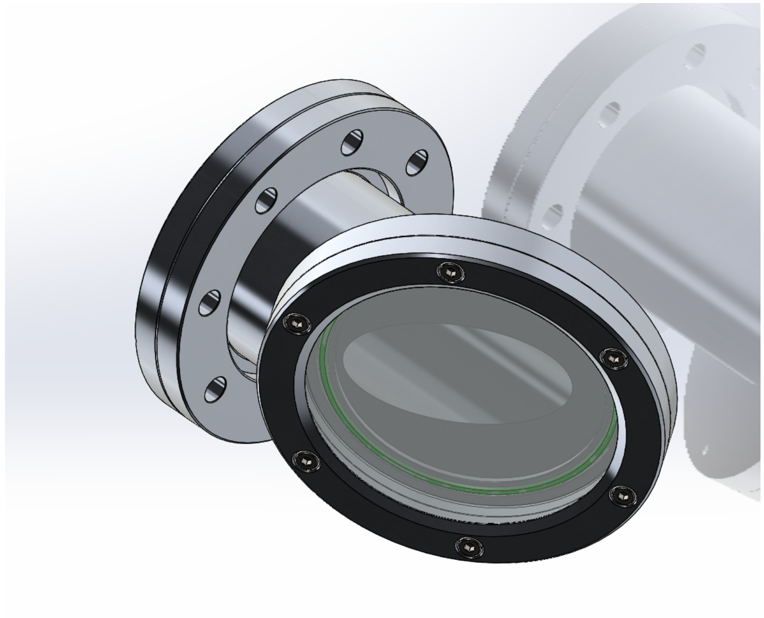


Figure 16: Design of vacuum window at Brester angle for minimum s-pol back reflection light

4.2.2 Vacuum windows /

To minimize scatter and back reflections we will implement Brewster angle vacuum windows for the beams on the central tank. The Brewster angle vacuum window assembly is shown in figure 16 and figure 17. The window glass is a 4" x 0.4" uncoated fused silica round optic. The assembly utilizes a rotatable CF63 flange to allow proper alignment with the polarization of the light from the COB. Back reflection from the window will be captured in a black glass filter inside the Brewster window assembly. In order to make a light tight connection from the tank flanges to housings on the in-air central tables we will use the light pipe assembly shown in figure 18. The tube of the light pipe assembly connects to a split ring that clamps to the central tank's CF flanges. The other end of the light pipe will be coupled to the in-air light tight housing via either a telescoping or flexible metal pipe.

4.3 CT Control

Requirements:

- Offset phase lock RL to RC output with less than 0.1 cycles RMS and below ~0.7 Hz RMS residual phase and frequency noise successively. Those requirements are valid in the frequency range of actuation of the second PLL with PC transmitted light, which is limited by the PC length actuator. The required UGF is expected to be ~ 50 to 70 kHz with aggressive gains below ~10 kHz.
- Offset phase lock the PC transmitted light to RL with with less than 0.1 cycles RMS and below 0.7 Hz RMS residual phase and frequency noises successively. UGF limited to 4 kHz on the fast PZT mirror actuator PC_MT1.
- Maintain auto-align RL beam to PC transmitted light to less than 5 urad of angular tilt and 100 um of lateral displacement by WFS system at the central table
- Maintain DC cavity axes auto-alignment to less than 100 um lateral displacement.

Figure 19 shows a general overview architecture of the phase and frequency controls and the auto-alignment systems in and between the three stations. The end table control systems are described in section 3.2. The first table control systems are described GEN FDD.

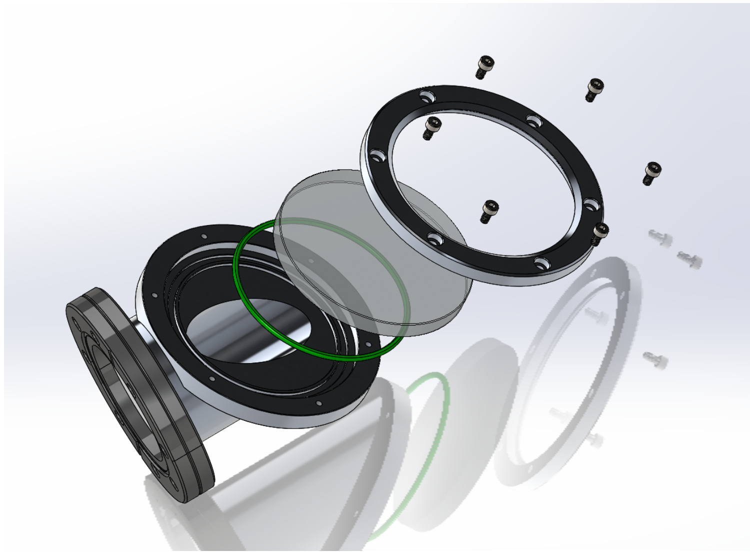


Figure 17: Window exploded at Brewster angle

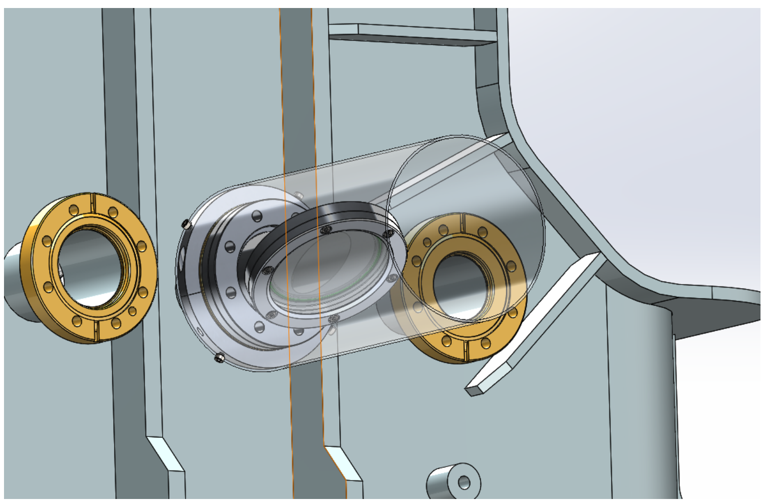


Figure 18: Brewster angle vacuum window with light pipe

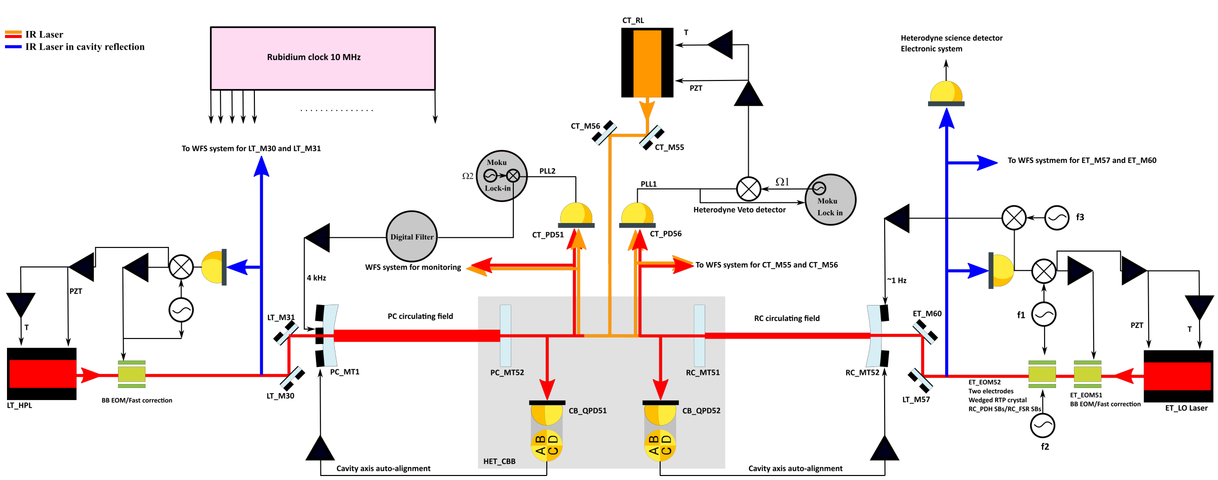


Figure 19: Overview of the control architecture scheme for the entire experiment

Length sensing and control at the CT include

1. PLL of RL to RC transmitted light
2. Length PLL of PC transmitted light to RL

Each system includes a sensor head (photodetector), demodulation stage (mixer and RF reference signal), controller stage and actuator.

PLL of RL to RC transmitted light:

- Sensor: Shot noise PD (provided by UF) outside vacuum in central station
- Demodulation stage: Moku:Lab generated RF signal connected to external mixer (UF provided)
- Controller: a table top phase servo system (UFservo) is an analog electronic control system (provided by UF) reads demodulated signal and generates two control signals (Temp and PZT).
  - Remote Slow Control: the UFservo will be equipped by remotely control gains, offset and switches. During commissioning an independent analogue electronic box includes potentiometers and switches is made to generate the voltage commands to the UFservo. While the BECKHOFF system will provides these voltage commands during the science run.
- Actuator: Laser head (Temperature and PZT).

Length PLL of PC transmitted light to RL:

- Sensor: Thorlabs PDA05CF2 (provided by UF) outside vacuum in central station
- Demodulation stage: uTCA system, provided by DESY (Richard)
- Digital filter for PZT resonance reduction: Moku:Lab (DESY-provided)
- Controller: Uniservo Anlogue control (provided by Desy) and controlled via DOOCS.
- Actuator: the fast 4 kHz piezo mirror actuator.

Alignment sensing and control at the CT include:

1. QPD of PC transmitted light to control PC-Curved mirror
2. QPD of RC transmitted light to control RC-Curved mirror
3. WFS of RL to RC transmitted light to align RL into Central breadboard
4. WFS of RL to PC transmitted light to monitor alignment drifts on central breadboard
5. WFS of RL to PC transmitted light after in vacuum MZ to monitor alignment drifts on central breadboard

Each system includes a sensor head (photo detector), controller stage and actuator. The WFS also include demodulation stages and require sensing of both Gouy phases. In some designs these stages might be combined; in some further split up.

QPD of PC transmitted light:

- Sensor: In-vacuum Quad detector head and demod board (provided by AEI)
- Controller: National Instrument CompactRIO system . The demod signal is digitized and controlled at the central area.
  - CompactRIO controller Model: cRIO-9054. 1.33 GHz Dual-Core CPU, 2 GB DRAM, 4 GB Storage, Artix-7 A100TFPGA, 4-Slot CompactRIO Controller. Has 2 Ethernet ports.
  - The cRIO-9054 is supported by an NI Linux Real-Time (64-bit) operating system and programmed on LabVIEW FPGA Module 2018 or later.
  - ADC Model: NI 9205, 16 AI Differential/32 AI Single-Ended, ±200 mV to ±10 V, 16 Bit, 250 kS/s Aggregate.
- Alignment actuators on the curved mirror PC_MT1. The correction signal is transferred digitally via Ethernet cable from the central table to the end table, to a LabVIEW interface, in order to generate the appropriate digital actuation signal to the RC curved mirror mount (TBC). Analogue cables as risk reduction should be provided as well.

QPD of RC transmitted light

- Controller: National Instrument CompactRIO system. The demod signal is digitized and controlled at the central area.
  - CompactRIO controller Model: cRIO-9054. 1.33 GHz Dual-Core CPU, 2 GB DRAM, 4 GB Storage, Artix-7 A100TFPGA, 4-Slot CompactRIO Controller. Has 2 Ethernet ports.
  - The cRIO-9054 is supported by an NI Linux Real-Time (64-bit) operating system and programmed on LabVIEW FPGA Module 2018 or later.
  - ADC Model: NI 9205, 16 AI Differential/32 AI Single-Ended, ±200 mV to ±10 V, 16 Bit, 250 kS/s Aggregate.
- Alignment actuators on the curved mirror RC_MT52. The correction signal is transferred digitally via Ethernet cable from the central table to the end table, to a LabVIEW interface, in order to generate the appropriate digital actuation signal to the RC curved mirror mount (TBC). Analogue cables as risk reduction should be provided as well.

WFS of RL to PC transmitted light:

- Sensor: Two Quad detector boards (QP50-6 **(TBC)**)
- Demodulation stage: Moku:Lab (UF-provides) generates RF signal, feeds into a demodulation board which generates Pitch/Yaw/Sum signals. (Cardiff provides demod board)
- No controller needed, signal digitized on compact RIO ADC Model: NI 9205 and monitored via DOOCS.

WFS of RL to RC transmitted light:

- Sensor: Two Quad detector boards (QP50-6 **(TBC)**)
- Demodulation stage: Moku:Lab (UF-provides) generates RF signal, feeds into a demodulation board which generates Pitch/Yaw/Sum signals. (Cardiff provides demod board)
- Controller: National Instrument CompactRIO system.
  - CompactRIO controller Model: cRIO-9054. 1.33 GHz Dual-Core CPU, 2 GB DRAM, 4 GB Storage, Artix-7 A100TFPGA, 4-Slot CompactRIO Controller. Has 2 Ethernet ports.
  - The cRIO-9054 is supported by an NI Linux Real-Time (64-bit) operating system and programmed on LabVIEW FPGA Module 2018 or later.

- ADC Model: NI 9205, 16 AI Differential/32 AI Single-Ended, ±200 mV to ±10 V, 16 Bit,250 kS/s Aggregate.
- DAC Model: NI 9264. 16 AO, ±10 V, 16 Bit, 25 kS/s/ch Simultaneous.

- Alignment actuators on alignment mirrors. We currently prefer to use a commercial Thorlabs system (KC1-P, ±275 urad of dynamic range).

WFS of RL to PC transmitted light after MZ optics (in reflection of CB_MT53, the RC housing HR mirror):

- Sensor: Two Quad detector boards (QP50-6 **(TBC)**)
- Demodulation stage: Moku:Lab (UF-provides) generates RF signal, feeds into a demodulation board which generates Pitch/Yaw/Sum signals. (Cardiff provides demod board)
- No controller needed, signal digitized on compact RIO ADC Model: NI 9205 and monitored via DOOCS.

4.3.1 Rack

The rack is located in the greyroom. It contains:

- UFservo PLL system
- Uniservo PLL
- CompactRIO system for the 3 DWS Systems, Cavity axes alignment and OPL sensing
- **TBD** HU for signal conditioning (TBD what is needed, pending discussion in DAQ subsystem)
- **TBD** HU for 10 MHz reference signal provided by DOOCS subsystem
- power distribution for all electronics components in the rack and on the table

All instruments in rack are synched to the 10 MHz reference signal.

4.4 DAQ and Slow Control

Key points of the interface with Slow Control and Data Acquisition subsystem (DOOCS) are:

- interface is located at the 19 inches DOOCS rack outside the clean room and gray room
- REGH provides interface electronics to PLL control loops that allows to engage/disengage loops, adjust offsets and gains
- DOOCS provides a 10 MHz synchronization signal at the rack in the gray room.
- DOOCS provides software environment in Control Room that allows to program:
  - GUI for control loops (on/off, offset/gain adjust, lock acquisition logic)
  - monitoring tools using DAQ channels (times series, spectrograms, band-limited rms) and watchdogs
- REGH manages space allocations on the tables in the central room and in the gray room. REGH provides rack space in the gray room to DOOCS with the following specifications:
  - TBD HU for signal conditioning
  - TBD HU for 10 MHz reference signal

4.4.1 Channel List

I/O convention in table

Signal lists is seen from point of view of DOOCS:

- Inputs: signals that are being digitized by DOOCS ADCs. For example: error and actuation signals, monitors.
- Outputs: signals that need to be generated by DOOCS DACs. For example: remote control of loops.

CompactRIO is an independent system from DOOCS and, during initial phases and commissioning, it will take care of acquisition of photodiode signals and generation of actuation signals independently from DOOCS system. Some, maybe most of the acquisition channels, might later migrate to DOOCS while the digital control of feedbacks will remain in the Compact RIO system. For signals that are connected to a CompactRIO system, the convention used is:

- Inputs: signals that are being digitized by NI ADCs. For example: error signal, remote control of loops.
- Outputs: signals that need to be generated by NI DACs. For example: actuation signals.

	I/O	bandwidth	impedance	range (V)	bits	interface	Comments	Sampling rate
B1. PLL RL - RC transmission								
UF PLL fieldbox								
DB9 Connector (In1)								
	I	F		± 10	14	uTCA (TEWS)	Error signal	10 MS/s
	I	F		± 10	14	uTCA (TEWS)	Error signal 2	10 MS/s
	I	S		± 10	14	uTCA (TEWS)	monitor of NPRO T correction	100 S/s
	I	F		± 10	14	uTCA (TEWS)	monitor of NPRO PZT correction	1 MS/s
DB25 Connector (Out1)								
	O	F	HI	± 1	16	Beckhoff (TBD)	test input	1 MS/s
	O	S	HI	± 5	16	EJ3108 (1.1)	NPRO TEMP	100 S/s
	O	S	HI	± 5	16	EJ3108 (1.2)	offset	
	O	S	HI	± 5	16	EJ3108 (1.3)	common gain	
	O	S	HI	± 5	16	EJ3108 (1.4)	fast path gain (NPRO PZT)	
	O	S	HI	± 5	16	EJ3108 (1.5)	EOM path gain (optional)	
DB9 Connector (Out2)								
	O	S	HI	0-5	1	EL2124 (1.1)	enable common path	
	O	S	HI	0-5	1	EL2124 (1.2)	enable slow path	
	O	S	HI	0-5	1	EL2124 (1.3)	engage integrator	
	O	S	HI	0-5	1	EL2124 (1.4)	enable EOM path (optional)	
Beatnote monitor	I	F		0-10	14	uTCA (TEWS)	Beatnote RL and LO through PM fiber	100 MS/s
B2. PLL PC transmission - RL								
Uniservo fieldbox (TBD)								
DB9 Connector (In1)								
	I	F		± 10	14	uTCA (TEWS)	Error signal	1 MS/s
	I	F		± 10	14	uTCA (TEWS)	Error signal 2	1 MS/s
	I	S		± 10	14	uTCA (TEWS)	monitor of NPRO T correction	100 S/s
	I	F		± 10	14	uTCA (TEWS)	monitor of NPRO PZT correction	1 MS/s
DB25 Connector (Out1)								
	O	F	HI	± 1	16	Beckhoff (TBD)	test input	1 MS/s
	O	S	HI	± 5	16	EL3104 (1.1)	NPRO TEMP	100 S/s
	O	S	HI	± 5	16	EL3104 (1.2)	offset PZT path	
	O	S	HI	± 5	16	EL3104 (1.3)	common gain	
	O	S	HI	± 5	16	EL3104 (1.4)	fast path gain (NPRO PZT)	
DB9 Connector (Out2)								
	O	S	HI	0-5	1	EL2124 (2.1)	enable common path	
	O	S	HI	0-5	1	EL2124 (2.2)	enable slow path	
	O	S	HI	0-5	1	EL2124 (2.3)	engage integrator	
Beatnote monitor	I	F			16	uTCA (TEWS)	Beatnote RL and HPL through PM fiber	100 MS/s
B3. WFS RL-RC trans								
Input (DSUB)								
	I	F	HI	± 10	16	Compact RIO	Signal 1x from CT_QPD53	10 kS/s
	I	F	HI	± 10	16	Compact RIO	Signal 1y from CT_QPD53	10 kS/s
	I	S	HI	± 10	16	Compact RIO	DC power monitor CT_QPD53	
	I	F	HI	± 10	16	Compact RIO	Signal 2x from CT_QPD54	10 kS/s
	I	F	HI	± 10	16	Compact RIO	Signal 2y from CT_QPD54	10 kS/s
	I	S	HI	± 10	16	Compact RIO	DC power monitor CT_QPD54	
Output (DSUB)								
	O	F		± 10	16	Compact RIO	DWS control signal 1X to CT_M55	10 kS/s
	O	F		± 10	16	Compact RIO	DWS control signal 1Y to CT_M55	10 kS/s
	O	F		± 10	16	Compact RIO	DWS control signal 1X to CT_M56	10 kS/s
	O	F		± 10	16	Compact RIO	DWS control signal 1Y to CT_M56	10 kS/s
Control (Ethernet)								
feedback loop X on/off	I	S			1	Ethernet	Control in Labview VI	
X gain	I	S			16	Ethernet	Control in Labview VI	
X offset	I	S			16	Ethernet	Control in Labview VI	
X integrator	I	S			16	Ethernet	Control in Labview VI	
feedback loop Y on/off	I	S			1	Ethernet	Control in Labview VI	
Y gain	I	S			16	Ethernet	Control in Labview VI	
Y offset	I	S			16	Ethernet	Control in Labview VI	
Y integrator	I	S			16	Ethernet	Control in Labview VI	
B4. WFS PC trans to RL								
Input (DSUB)								
	I	F	HI	± 10	16	Compact RIO	Signal 1x from CT_QPD51	10 kS/s
	I	F	HI	± 10	16	Compact RIO	Signal 1y from CT_QPD51	10 kS/s
	I	S	HI	± 10	16	Compact RIO	DC power monitor CT_QPD51	
	I	F	HI	± 10	16	Compact RIO	Signal 2x from CT_QPD52	10 kS/s
	I	F	HI	± 10	16	Compact RIO	Signal 2y from CT_QPD52	10 kS/s
	I	S	HI	± 10	16	Compact RIO	DC power monitor CT_QPD52	

B5. Control WFS								
Input (DSUB)								
	I	F	HI	± 10	16	Compact RIO	Signal 1x from CT_QPD55	10 kS/s
	I	F	HI	± 10	16	Compact RIO	Signal 1y from CT_QPD55	10 kS/s
	I	S	HI	± 10	16	Compact RIO	DC power monitor CT_QPD55	
	I	F	HI	± 10	16	Compact RIO	Signal 2x from CT_QPD56	10 kS/s
	I	F	HI	± 10	16	Compact RIO	Signal 2y from CT_QPD56	10 kS/s
	I	S	HI	± 10	16	Compact RIO	DC power monitor CT_QPD56	
B6. Alignment control Cavities								
Input (DSUB)								
	I	S	HI	± 2.5	16	Compact RIO	PC alignment error signal X CB_QPD51	1 kS/s
	I	S	HI	± 2.5	16	Compact RIO	PC alignment error signal Y CB_QPD51	1 kS/s
	I	S	HI	0-5	16	Compact RIO	power monitor CB_QPD51	1 kS/s
	I	S	HI	± 2.5	16	Compact RIO	RC alignment error signal X CB_QPD52	1 kS/s
	I	S	HI	± 2.5	16	Compact RIO	RC alignment error signal Y CB_QPD52	1 kS/s
	I	S	HI	0-5	16	Compact RIO	power monitor CB_QPD52	1 kS/s
Control (Ethernet)								
feedback loop PC on/off	I	S			1	Ethernet	Control in Labview VI	
X gain	I	S			16	Ethernet	Control in Labview VI	
X offset	I	S			16	Ethernet	Control in Labview VI	
X integrator	I	S			16	Ethernet	Control in Labview VI	
Y gain	I	S			16	Ethernet	Control in Labview VI	
Y offset	I	S			16	Ethernet	Control in Labview VI	
Y integrator	I	S			16	Ethernet	Control in Labview VI	
feedback loop RC on/off	I	S			1	Ethernet	Control in Labview VI	
X gain	I	S			16	Ethernet	Control in Labview VI	
X offset	I	S			16	Ethernet	Control in Labview VI	
X integrator	I	S			16	Ethernet	Control in Labview VI	
Y gain	I	S			16	Ethernet	Control in Labview VI	
Y offset	I	S			16	Ethernet	Control in Labview VI	
Y integrator	I	S			16	Ethernet	Control in Labview VI	
B7. OPL sensing								
CT_PD52	I	S	HI	0-10	16	Compact RIO	Differential signals calculated in Labview VI	
CT_PD53	I	S	HI	0-10	16	Compact RIO	Differential signals calculated in Labview VI	
CT_PD54	I	S	HI	0-10	16	Compact RIO	Differential signals calculated in Labview VI	
CT_PD55	I	S	HI	0-10	16	Compact RIO	Differential signals calculated in Labview VI	
B8. Monitors								
RL injected power	I	S	HI		16	DOOCS RS232	CT_PM51	
PC transmission power	I	S	HI		16	DOOCS RS233	CT_PM52	
RC transmission power / HET shotnoise PD DC level	I	S	HI		16	Beckhoff analog	CT_PD56	
Seismometer/geophone	I	S	HI		14	uTCA (TEWS)	3 channels (TBD if required)	
RL diagnostics	I	S	HI		16	EL3008	Beckhoff, 8 ch from DSUB25 controller Mephisto S	
B9.Veto signals								
Control PD after demodulation	I	F	50	± 1	14	uTCA (TEWS)	CT_PD57	
HET monitor detector	I	S			12	Ethernet	Python script controls Moku, I and Q signals out	
B10. CCD								
CCD beam monitor (PC transm, RL input to COB, RC transm, MZ / shutter view)	I	S				Ethernet	4 + 1 spare, Basler, Power over Ethernet (PoE)	
B11. Optomechanics								
Laser shutter	O	S				TBD	LS1 - DESY	
Remote controlled HWP for RL power adjustment	O	S				TBD	CT_HW52	
In-vacuum rotators SMARACT	O	S				Ethernet	SR-12012-S-V x 2ch MCS, CB_HWP51-52	
COB shutter SMARACT	O	S				Ethernet	rotator x1ch MCS, CB_SH51	
B13. Clock synchronization								
	O					1.2 GHz	Reference signal for µTCA	
	O					10 MHz	Reference synch signal for instruments and Mokus	

4.5 Commissioning and Operation

The installation on the CT starting with the central breadboard could begin following the installation of the clean room in HERA North.

5 Assembling and initial Alignment Procedure of COB

This section describes the assembly of the COB optics, including the two cavity flat mirrors, and the initial alignment for these optics outside the vacuum in the assembly room optical table.

5.1 Requirements:

1. Flat cavity mirror alignment error below 10 µrad; uncertainty below 1 µrad.
2. Lateral offset of cavity eigenmodes below 1 mm; uncertainty below 100 µm.
3. Optics in between Flat cavity mirrors:

- Lateral shift compensation: below 100 µm.
- Unwedged optics are required.

5.2 Tools:

- Assembly room optical table (size: 180cm x 120cm)
- Autocollimator (TriAngle 300-57 from TRIOPTICS) with 3.6 µrad accuracy and 0.15 µrad of resolution.
- HeNe laser (Green) 1 position sensor (Thorlabs PDP90A with max resolution of ~0.7 µm) .
- Two IR lasers: (as HPL and LO).
- Collimated Beams to 2 mm of beam waist. EOM creating side band as an RL laser The two flat cavity mirrors PC_MT2 and RC_MT51.
- Two centering mask with 1-2- 3 mm of different apertures.
- Couple of pinhole apertures (1mm minimum hole diameter) (Thorlabs).
- Couple of IR and green cards.
- The two AEI DC QPDs ~100 um of long term stability for ~10% of humidity changes.
- Two broadband photodiodes. Jig plate for MZ mirrors.
- Alignment jig plate for Flat cavity mirrors
- Alignment jig plate for PC and RC housings

5.3 Steps (Figure 20):

1. **Flat cavity mirrors:** place first all optical and mechanical components in their nominal positions and orientations on the COB except for the mirrors along the axion beam line. Use the MZ jig plate for the mirrors CB_MT52 and CB_MT54 mount the flat cavity mirror PC_MT52 on the inner ULE plate and orient its angle using the PC mirror alignment jig plate. Mount the autocollimator on its adjustable mount, ~20 cm of distance from the COB. Find the reflected autocollimator beam from PC_MT2 and align the autocollimator itself to center the crosshair on its camera. Use now the RC mirror alignment jig plate to position the second flat cavity mirror RC_MT51. Align RC_MT51 to PC_MT52 using the autocollimator by setting the two crosshair markers on top of each other. RC_MT51 and PC_MT52 are now parallel with ~3.6 µrad of accuracy.

2. **Green laser:** mount the 2 mm aperture centering masks on both flat cavity mirrors. Set up the HeNe laser from the PC side of the COB (as Green HPL). Align the Green HPL beam to the center of the flat cavity mirrors with two dichroic steering mirrors. Take a pick off from the green HPL and send it to the RC side (as Green LO) and align it also to the center of the flat cavity mirrors.

3. **Optics between flat cavity mirrors:** center the green HPL beam coming out from the RC_MT51 to a 2D lateral position sensor mounted on the optical table. Use first the PC housing alignment jig plate to position the PC light-tight box to the COB in such way the HR mirror CB_MT51 is at 35-degree incidence angle. Use the MZ jig plate to position the first beam splitter mirror CB_MT55. Fine tune CB_MT55 incidence angle using the green position sensor for a minimum relative lateral shift between CB_MT51 and CB_MT55. Do the same between the HR mirror CB_MT53 and the mirror beam splitter CB_MT56. The same position sensor will also be able to accurately measure the angular tilt from the residual wedge angles of the mirror substrates along the axion beam line: ~ 1 urad for a distance of above 1 m from the last substrate in the line.

4. **MZ mirrors:** take a second green laser pick off to the top of the MZ (as Green RL). Overlap the Green RL to the Green HPL on the mirror CB_MT55 by using a green detection card. Tune the mirrors CB_MT52 and CB_MT54 to overlap Green RL to Green LO.

5. **IR lasers:** position one pinhole aperture at each COB main sides using HPL and LO green beams. Set up two IR lasers (as IR HPL and IR LO) on both COB main sides (2 mm collimated beam). Align the IR HPL and the IR LO with two steering mirrors mounted behind the dichroic steering mirrors for the green beams (in order to not misalign the green beams from both sides). Put the IR lights on top of the green beams using the pinhole apertures and the cavity centering masks. For fine tuning the normal incidence angles of the IR lights on the flat cavity mirrors, use another two pinholes as optical lever arms ~distance ~>1 m, using the the back reflection light of PC_MT52 and RC_MT51. Take a pick off from the IR HPL light to create a IR RL beam with phase modulated side bands. Optimise the alignment of the IR RL by forming beat notes with HPL and LO on both sides, using the WFS systems. Still making a fine tuning on CB_MT54 and CB_MT52 is allowed. Don't re-tune the optics between the flat cavity mirrors.

6. **DC QPDs:** mount the DC QPDs on the main breadboard and center the IR HPL and the IR LO beams to the QPDs active areas.

6 Alignment procedure and alignment and dual resonance verification

As a project we carry a requirement of 95% efficiency for technical imperfections. These include alignment between the two cavities and that the regenerated field is resonant in the RC cavity as two of the main contributing loss factors. ALPS II Design Requirements Document (v4) derives the following requirements (these values need to be checked):

1. Longitudinal offset of cavity length: 0.6 pm or 0.7 Hz if expressed as offset from resonance (this assumes a cavity length of 120 m).

2. Angular offset in a single direction: θ_x, $\theta_y < 14\,\mu$rad, we aim for $\theta < 10\,\mu$rad for the total angle or $\theta_x, \theta_y < 7\,\mu$rad.

   (a) WFS systems will be used to verify and maintain angular alignment between the laser beams. A 1 μrad tilt over a 6 mm beam gives 6 nm or 37 mrad. This is the assumed sensitivity for the WFS system on the central bench. Note that the WFS systems for AA into the cavities are not heterodyne interferometers but use the PDH modulation sidebands as a reference which is slightly different.

3. Lateral offset: Assuming a similar contribution from this degree of freedom would allow a lateral offset of $\delta l < 1$ mm or δx, $\delta y < 0.7$ mm. We place an internal requirement or goal of $\delta l < 0.3$ mm on this degree of freedom.

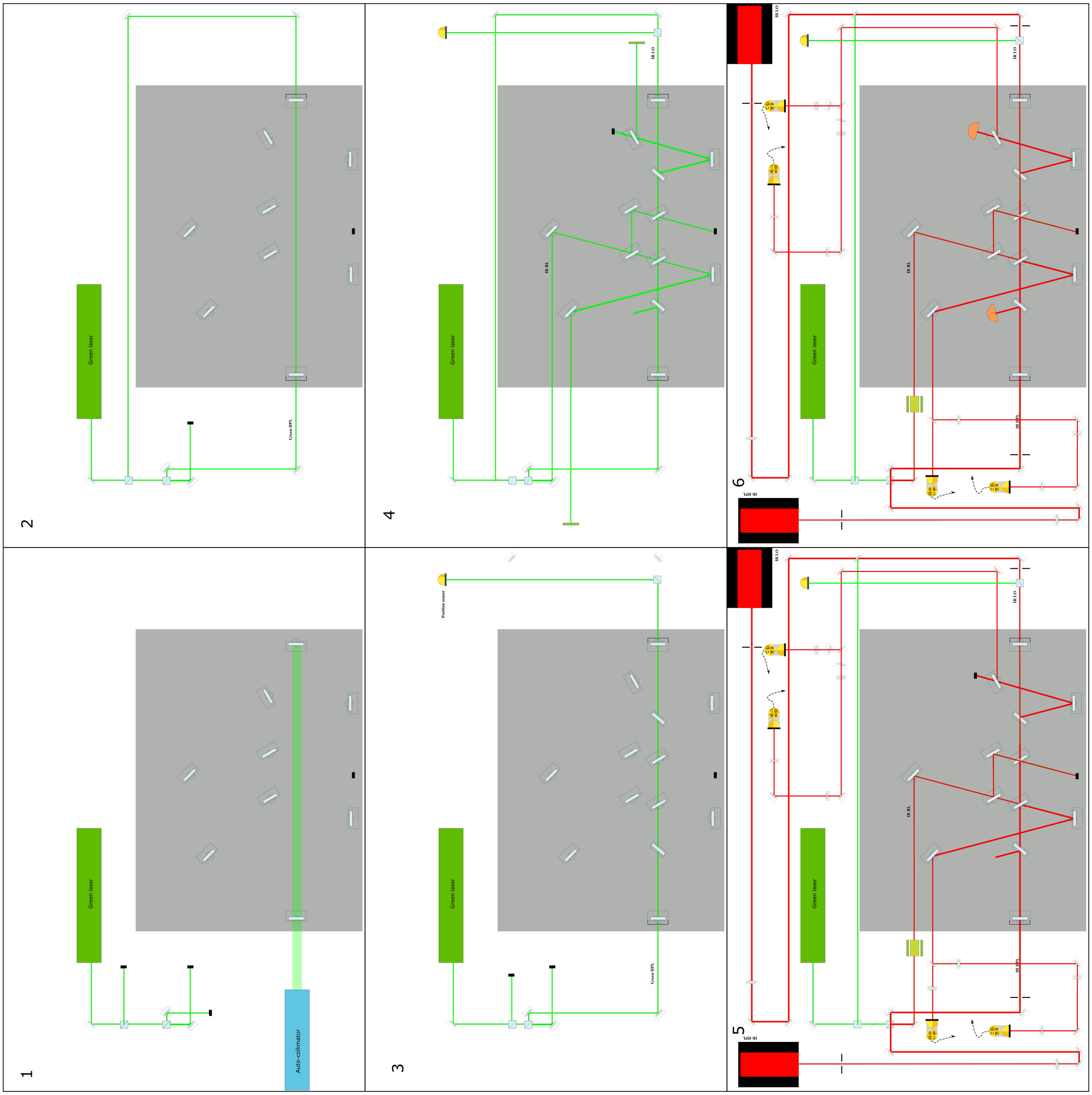


Figure 20: COB initial aliment procedure, steps 1 to 6. Note: these figures show just the essential mirrors.

6.1 Assumptions

The here described part assumes that:

1. the transmissivities of PC_MT2, RC_MT51, CB_MT51, CB_MT55, CB_MT53, CB_MT56, and CB_W5 are known with 1% accuracy for both polarizations. This includes the transmissivity through the AR coated surfaces.

2. The reflectivities of CB_M58, CB_MT58, CB_M60, CB_M59 inside the vacuum tank and of CT_M64, CT_M70, CT_M66, CT_M67, CT_M68 on the optical bench.

3. the alignment procedure of the COB described in the earlier section ensures that the surfaces of the flat cavity mirrors (RC_MT51, PC_MT2) on the central bench are parallel to within $5\,\mu$rad **(TBC)**.

4. the wedge angles and misalignments of the auxiliary optics on the COB between RC_MT51 and PC_MT2 do not refract the beam by more than $5\,\mu$rad. The additional refraction due to residual wedge angle $\delta\alpha$ in each optic is:
$$\delta\theta = \frac{n_2 \cos\theta_2}{n_1 \cos\theta_1}\delta\alpha = 1.6 \cdot \delta\alpha$$
and has been minimized by using unwedged optics and by clocking the optics in the mounts. Furthermore, the refraction angle and direction, ideally either horizontal or vertical to avoid miscommunications, is known to $1\,\mu$rad accuracy.

5. the COB and the end mirrors are aligned such that we see flashes in both cavities and that both lasers can be locked to their respective cavities without any additional alignment.

   - The alignment on the HR end table will be described in more detail in section (TBD) and will have to be coordinated with IA (initial alignment). For the purpose of this discussion, we assume that all automatic alignment loops between the LO and RC are engaged and meet their requirements[3].

6. the optical axis of the magnets (lowest loss axis) and the optical axis as defined by the COB are within 1 mm and $10\,\mu$rad of each other (IA task).

7. the RL should be aligned such that it will leave the vacuum view ports once the COB is aligned inside the tank and the tank is evacuated.

6.2 Available signals

Following the placement of the COB into the vacuum tank, evacuation of the tank, the initial alignment of the RL onto the COB, and the locking of the laser frequencies of HPL to PC and LO to RC, the two AA systems to align the HPL into the PC and the LO into the RC should be engaged and working. In addition, the following signals should be immediately available

1. CB_QPD51 on the COB, used to align the curved PC mirror in NL

2. CB_QPD52 on the COB, used to align the curved RC mirror in NR

These two loops have to be closed next using the initial QPD offsets as determined in the COB alignment procedure (see above). These alignment systems have to provide long term stabilization of the relative cavity alignments with a precision (or repeatability) of $< 1\,\mu$rad and $< 100\,\mu$m (precision should be significantly better than the required accuracy to simplify commissioning).

The LO should be injected into the single mode fiber at NR and the HPL into the single mode fiber at NL to monitor beat signals between these lasers and the RL on the central table when needed. It has to be possible to phase lock RL to either of these beat signals with a tunable difference frequency of order 10 MHz.

[3]These requirements are TBD but should be of the order of $1\,\mu$rad and 0.3 mm relative misalignment which is achievable with the WFS system.

6.3 Alignment procedure

This procedure will allow to finalize the alignment of all optical components outside the vacuum tank and verify the alignment of the components inside the tank. The steps are:

1. Alignment of the WFS (CT_QPD53, CT_QPD54) and the PLL PD (CT_PD56) with respect to the RC transmitted beam on the RC side of the COB. During this step, RL should be blocked. HPL is not needed. The RC transmitted beam will leave the vacuum tank (LO power ~ 750 μW) through CB_W5. This beam will now be centered on the lenses (Gouy phase telescopes) and on all three detectors using the appropriate out of vacuum steering mirrors. The total power levels on all elements should be monitored once this alignment is completed. The differences of the QPD signals are a measurement of the residual angular noise between the COB and the outside table.
   - The DC WFS sensor signals (QPD53, QPD54) monitor the drift of the COB with respect to the Optical tables. If the drift is too large, centering servos might be needed.
2. Alignment of the RL onto the COB (HPL off). During this procedure RL should be phase locked to LO using the fiber link. RL (100 mW) will be injected into the vacuum tank through CB_W3 and a small fraction (~ 250 nW) should leave the tank through CB_W5. The RL injection has to be aligned to maximize the beat signals with the RC transmitted field on the PDs and minimize the WFS signals from QPD53 and QPD54.
   (a) Once the WFS signals are sufficiently strong, the AA system for the RL should be engaged and the actuation signals as well as the error point noise should be characterized to verify performance.
   (b) The PLL controlling the frequency of RL should be switched from the fiber to the CT_PD56 signal to evaluate performance. The residual phase noise in the fiber link should follow a fiber phase noise model but also reveal for example mechanical and electronic resonances in the setup.
   (c) The appropriate fractions of the RL beam should now leave the vacuum chamber through viewports CB_W4 (~70 mW) and CB_W2 (~ 10 mW).
3. The RL beam through CB_W4 will now be used to finalize the alignment of CT_PD57 using the lenses and mirrors on the optical table. (We could add position monitoring capabilities here as CT_QPD55 and CT_QPD56, see figure **??**)
4. The RL beam through CB_W2 will be centered through the lenses, on the mirrors and on the WFS sensors CT_QPD51 and CT_QPD52 as well as CT_PD51 (PLL with PC-trans). The DC signals should be monitored to measure again beam fluctuations and power fluctuations on all detectors.
5. The HPL will be turned on and locked to the PC. RL should be phase locked to HPL using the fiber link. Once the AA loops and the PC cavity alignment loop are engaged, a beat signal between HPL and RL should be visible on PD51 as well as on QPD51 and QPD52. The power of the HPL beam through CB_W2 should not exceed 1 μW at full HPL power.
6. At this stage most of the PC transmitted power should leave the vacuum system through CB_W1. This light will be used to finalize the alignment of the OPL sensing system comprised of the detectors CT_PD52, CT_PD53, CT_PD54, and CT_PD55. Also the power monitor CT_PM52 and the CCD camera CT_CCD52 and the beam dump CT_BD53 will now be aligned.
7. The power levels of all lasers at all outputs will be recorded as much as possible (all power levels above 1 nW) with at least 5% absolute and 2% relative accuracy. This will require to turn off RL to measure PC and RC trans as well as turn off LO and HPL to measure RL.

This concludes the initial alignment process.

6.4 Efficiency verification

The next steps verify the alignment between PC trans and RC trans or the injection of PC_trans into RC.

1. Setup for this step using the low R MZ:

   (a) The LO and the HPL will be locked to the RC and PC, respectively using the PDH system in the end stations. The AA systems as well as the RC and PC alignment servos are engaged. The shutter is closed.

   (b) The RL will be phase locked to the PC trans at a frequency which ensures that it is not resonant in the PC, the alignment servos of RC will be engaged and

      i. the power of the RL through CB_W4 will now be monitored at CT_PD57.

      ii. the RF amplitude at CT_PD56 will be used to measure the amplitude of RL. This value will be compared with the expected beat signal amplitude derived from the measured power levels of the individual lasers.

      iii. The RF amplitude at ET_PD51 will also be measured while the RL is antiresonant. The expected power in RL is the product of the cavity mirror transmissivities divided by 4 (antiresonant) or by 2 (for 90° round trip phase shift) and should be on the order of 10^{-16} W.

   (c) The PLL frequency between RL and RC trans will now be changed to a multiple of the FSR of the RC and the measurements under (b) will be repeated now on resonance. These RF amplitudes together with the RF amplitudes measured under (b) will allow us to measure the on-resonance transmissivity of the undercoupled RC while the RL is kept aligned via the WFS system.

   (d) Assuming 150 mW of light leaving the PC, a transmissivity of CB_MT51 and CB_MT56 of 3 ppm, and a transmissivity of the CB_MT55 and CB_MT53 of 1% total (30% each), we expect about 135 fW of PC transmitted light reaching the RC cavity and about 40.5 nW of PC transmitted light reaching CT_PD57 once the shutter is open.

      i. With the PLL between RL and RC trans being again detuned from resonance, we can now measure the amplitude of PC trans on CT_PD57. Installing two WFS in the same beam path, we can also measure the relative alignment between PC trans and RL.

      ii. It will also be possible to measure the amplitude of the PC trans and RC trans beat signal on CT_PD56 while PC trans is off resonant in the RC. The 135 fW is sufficient to first demodulate the signal with the beat signal between PC trans and RL and then demodulate with the RL and RC trans. Or, if the beat signal is stable enough in frequency, just use a spectrum analyzer and integrate the power over the spectrum to measure the power of the beat signal.

   (e) Engage the PLL between RL and PC trans to control the PC trans frequency and tune the difference frequency to have the PC trans resonant in the RC. Once this is done, we can measure the amplitude of the beat signal on ET_PD51, the WFS sensors and again on CT_PD56 to verify alignment and resonance condition.

   (f) Detune PC trans from RC resonance and repeat the measurements under (e) to verify transmissivity of cavity and also measure scattered light on ET_PD51. Note that if the power levels are correct, a non-resonant RC should reduce the 135 fW by 10 orders of magnitude to 10^{-24} W which allows scattered light searches of light bypassing the RC and studying EMI issues even with shutter open. But this becomes a commissioning effort.

7 HET detectors

There are two heterodyne detectors: one at the central table for monitoring and veto detection, and another at the end table for the main science signal. These heterodyne detectors receive their signal from a shot-noise limited photodetector (see section 3.1). This signal is then sent to a Moku:Lab which serves three purposes: to digitize the signal, perform initial signal processing, and data acquisition. Digitization occurs through the Moku:LabLab's 12-bit ADC, which has a sampling rate of 500 MS/s. This digitized signal is then mixed with an internal NCO producing two signals I and Q. This is the result of mixing at the same frequency, however with signals that differ by 90 degrees in phase. The low pass filter that follows this stage serves to strip the signal of the higher frequency terms from mixing as well as any spurious signals. This processed signal is then passed to the DAQ system over Ethernet at a rate of 21 Hz. This process can be seen as a block diagram in figure 21

7.1 Moku:Lab programming

Interaction with the Moku:Lab is handled remotely using PyMoku:Lab, a python API that Liquid Instruments provides and maintains. Through the API you can initialize any preset instruments with the user's desired settings, as well as manage data streaming. For the heterodyne detector, we make use of the lock-in amplifier. As such, we can set the frequencies for the NCO, LPF, and sampling rate of the data stream. These frequencies will all be referenced to a 10 MHz clock. Setting static parameters is straight forward and needs no explanation, however, to produce a continuous stream one must make use of the inheritance hierarchy of the object-oriented PyMoku:Lab API.

When streaming data, certain instruments within the Moku:Lab make use of data frames, which are a set of data points that occur over a time frame; this is dependent on the sampling frequencies and the number of points contained in the frame. Data is streamed into a buffer that when filled is dumped into a container, that provides additional instrument information. This container is the frame. These data frames are used to emulate what is displayed on an oscilloscope, but sacrifice data accuracy for quick display. This can be bypassed by accessing the stream that fills the buffer. This stream of data is then written to file on the PC that initializes the instrument.

The data from the Moku:Lab does not contain a timestamp; however, the time step between each sample is assumed to be stable. As such, we only keep track of the stream start time. The data received is then written to two separate files.

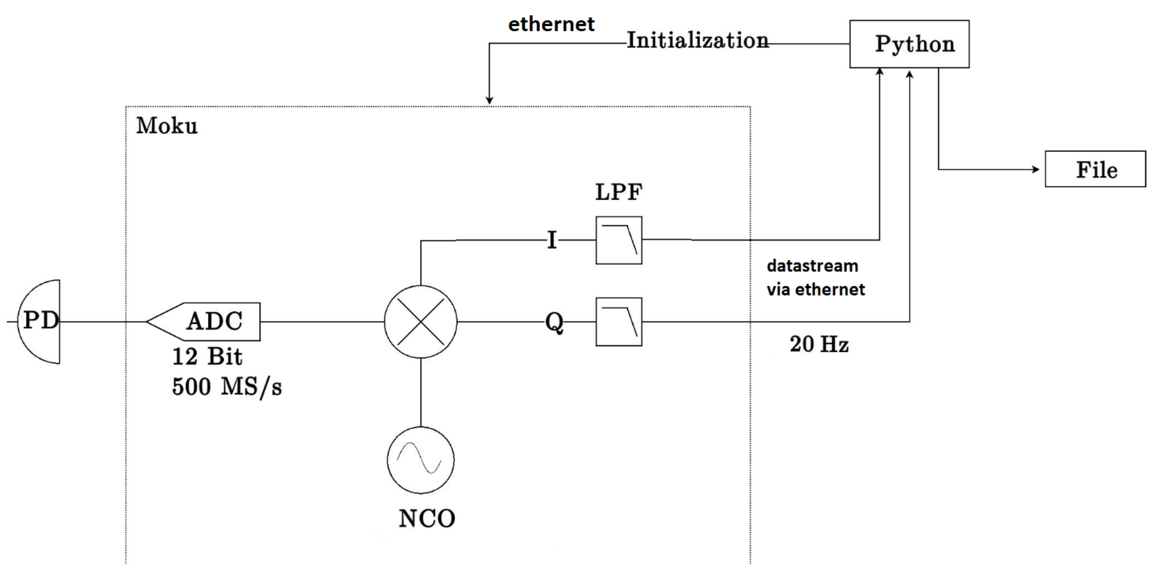


Figure 21: Block diagram of science signal through the Moku:Lab and Python.

8 Lasers and Laser Safety

This section provides condensed information needed for laser safety in the North Right End Station (NR) as well as the central room.

8.1 End Room North Right

The main laser in the North Right (NR) clean room is a

- Mephisto S laser
- Manufacturer: Coherent (See: https://www.coherent.com/lasers/laser/mephisto-mephisto-s)
- Maximum Output Power: > 500mW
  - We expect to operate the laser at a lower power not exceeding 300 mW
- Wavelength: 1064nm
- Beam shape: Gaussian beamshape, slightly elliptical
- Beam waist: 160 μm, 10cm inside the laser head
- Divergence angle: 2.1 mrad

Beam propagation following the laser head is described in detail in section 3, figures 1 and 2. As shown there, the beam size is smallest at the laser output, is then kept between 0.25 and 1 mm (Gaussian radius) before it is expanded into the 9 mm beam which is then injected into the regeneration cavity.

The first pick off at ET_MT51 takes 5000 ppm of the < 500 mW beam to inject less than 2.5 mW into the fiber beam splitter. See fiber link discussion below for more details. Other pick offs are used for power monitoring and laser diagnostics on the optical table. Beam sizes in these areas will be similar to the beam sizes of the main beam. Power levels in these diagnostic beams will not exceed 5 mW.

The light back reflected from the cavity (blue in figure 1) will occasionally be as strong as the injected beam (lost lock) and is directed towards different detectors described in the text. The modal parameters (beam radii along the beam path) of the back reflected beam are identical to the injected beam.

The green laser is a green HeNe laser R-30968 from Newport and belongs to the IA group. It is described in more detail in the initial alignment document. A few key paremeters from the IA document:

- Wavelength: 543 nm
- Minimum Output Power: 0.5mW
- Polarization: Linear > 500:1
- Beam diameter: 0.72 mm
- Beam divergence ange 0.96 mrad

More details about the beam path and mode matching are in the IA document.

8.2 Central Room

The laser in the central room is a

- Mephisto S laser
- Manufacturer: Coherent (See: https://www.coherent.com/lasers/laser/mephisto-mephisto-s)
- Maximum Output Power: > 500mW
  - We expect to operate the laser at a lower power not exceeding 300 mW.
- Wavelength: 1064nm
- Beam shape: Gaussian beamshape, slightly elliptical
- Beam waist: 160 μm, 10cm inside the laser head (all beam waists reported as Gaussian 1/e radii)

- Divergence angle: 2.1 mrad

It is located on the optical table on the west side of the vacuum tank. The optical table is split into three sections; the boundaries are marked by thin black lines. Section one includes the laser injection area, section two is the PLL/WFS detection area and section three includes the main beam bump for the production cavity transmitted beam and the optical path length (OPL) sensing scheme (see also figure 5 for a conceptual sketch). These sections will be separated by a wall system to optically isolate them from each other. The wall system (see Thorlabs optical enclosures as a possible system: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=45) will also be connected to the vacuum flanges; figure 18 shows a preliminary drawing. A similar wall system will be build around at least the third area which contains most of the photons we are 'afraid of' for scientific reasons but likely around the entire table. Note that this wall system will be partly or sometimes totally removed during commissioning.

The laser is located in the first section. Beam propagation following the laser head is described in detail in section 4, figures 6 and 7. About 100 mW **(worst case: 300 mW)** are expected to be injected into the vacuum system. This main beam expands to about 2 mm before it enters the telescope which

- **creates an 80 μm beam waist about 2.5 m behind the laser head** (point of highest intensity away from the laser outputs themselves)

and less than 50 cm before the Brewster angled vacuum window. **The position is marked in figures 6 (just between the last two mirrors before the left bottom viewport in the figure).**

Two pick-offs, transmitted through CT_M51 and reflected by CT_M53 (see figure 6), extract 1% of the light. This reflectivity is given by the coating layers on the optics. The first beam is used for beam diagnostic on the optical table, The second beam is further split into equal amounts using the waveplate CT_HW51 and the polarizer CT_PO51 before the light is injected into the two fibers. See fiber link discussion below.

The second area in the middle of the table includes diagnostic optics. The laser power will not exceed 30 mW (current baseline is 10 mW, but the final number will depend on as-build reflectivities and transmissivities of all optical components). This beam is collimated by a telescope which consists of a curved mirror CB_MT52 inside the vacuum tank and a curved mirror CT_M60 outside the tank (see subsection 4.1.3 for beam sizes at the vacuum window and distances relative to that viewport).

The third area receives well over 99% of the production cavity transmitted light. **The maximum output power is not expected to exceed 300 mW** (150 mW is the current best estimate for high power operation). This beam is collimated by a telescope formed between the curved mirror CB_M61 inside the tank and the lens CT_L55 **outside the tank to 2.3mm radius**; without going through a focus in between (see figure 9 for beam sizes before, within and after the telescope). Most of the light will be directed towards the beam dump CT_BD53. About 4% or less than 12mW will be directed towards the OPL sensing scheme (the four detectors CT_PD52-55).

The optical table on the east side of the vacuum tank contains two areas. Area one includes a few control signals which area two houses the wavefront sensing (WFS) and phase lock (PLL) detectors (see figure 5 for a conceptual sketch). The laser power in area one is dominated by less than 70% of the injected RL power (nominal 70% of 100mW, worst case 70% of 500mW). This beam will be collimated by the out of vacuum lenses CT_L66 and CT_67/68. The power in the second area is dominated by a few mW ($<$ 10 mW) of the regeneration cavity transmitted light field. This beam will be collimated by the two lenses CT_L60 and CT_L61 (see figure 6 for locations). Both telescopes are Galilean beam reducers and the beam sizes before, within, and after these telescopes is shown in figure 8.

8.3 Fiber links

The central table is connected with each of the end stations via a single mode polarization maintaining fiber (PM980-XP from Thorlabs) with a mode field diameter of 6.6 μm and a numerical aperture of 0.12. The fibers will be enclosed in yellow reinforced 3mm furcation tubing with FC/APC connectors at each end.

Based on the optical layouts and assuming max laser power and no optical losses in the beam path, a total of 2.5 mW will be injected into each of the 50/50 fiber beam splitters **such that a maximum of 1.25 mW will propagate through each of the two single mode fibers** in each direction. Using realistic operational power levels, optical losses and injection efficiencies, this value will not exceed 1 mW.

During commissioning, there is no useful operational mode where light will be injected at both ends of each fiber (1mW propagating in each direction) such that only 1 mW will typically propagate through the fiber. The switch between propagation directions is achieved by disconnecting the APC fiber from a fiber beam splitter output to the input and vice versa on the other end (all figures have the fiber connected to a beam splitter output). In the worst case; one side switched, the other side not yet, 2 mW will propagate through the fiber, 1 mW in each direction. During science mode, all fibers will be disconnected from the fiber beam splitter and all the light will be captured by beam dumps.

9 Appendix

9.0.1 Acronyms:

- ADC analogue to digital converter
- AR anti-reflected
- COB Central Optical Breadboard
- DAC Digital to analogue converter
- DAQ data acquisition
- DOOCS Data acquisition and Slow Control System
- EMI electromagnetic immunity
- GEN generation system
- HU height Unit to define space on racks
- HR highly reflected
- HV high voltage
- NL North Left, refers to the clean room where the GEN laser is located
- NR North Right, refers to the clean room and end station described in this document
- OPL Optical Path Length (here refering to the OPL interferometer)
- PZT piezoelectric actuator
- PLL phase lock loop
- PDH Pound Drever Hall
- REGH regeneration system heterodyne
- ROC Radius of curvature
- LPF low pass filter
- NCO numerically controlled oscillator
- WFS wave front sensing

9.1 Naming convention for optical system in ALPS IIc

XX_YYY# with XX for location/cavity , YYY for type of component, ----# numbering The numbering for TES components and components common for the TES and HET option start with “1” numbering for components special for the HET layout start with “51”

XX

- LA laser internal
- LT laser table
- PC production cavity
- CB central optical bench
- CT central table
- RC regeneration cavity
- ET end table

YY

- AOM acousto-optical modulator
- AP aperture/baffle
- BD beam dump
- BL bellows
- CCD camera
- DF dichroic filter
- EOM electro-optical modulator
- FC fiber couple
- FCS fiber coupler splitter
- FI Faraday Isolator
- HW half-wave plate
- L lens
- M HR mirror
- MD dichroic mirror (optional append transmission CT_MD2 (532: 99%;1064: 10ppm)
- MT partially transmissive mirror (optional append transmission LA_MT1 (50ppm))
- ND neutral density filter
- PD photodiode
- PM power meter
- PO polarizer / polarization beam splitter
- QW quarter-wave plate
- QPD quadrant photodiode
- SH shutter
- W window

Examples

- LT_M1 laser table mirror 1
- PC_MT1 (750ppm) production cavity mirror 1
- CT_HW1 central table half-wave plate 1
- CB_L1 central breadboard lens 1
- ET_PO1 end table polarizing beam splitter 1
- CB_M53 third mirror on HET Central Optical Bench

The 50 W laser is called high power laser (HPL), the 500 mW laser on the central table is the reference laser (RL) and the 500 mW laser on the end table is the local oscillator (LO) laser. Note that TES only uses HPL and RL while HET uses all three lasers.

9.2 Component list

9.2.1 End table

	End Table ET_			
	IR locking			
Optics				
Components	Number	Name	Vendor / Specs	Part number
BD	51	Beam dump	Thorlabs	LB2/M
CCD	51	CCD camera	Basler	Provided by DOOCS
EOM	51	EO phase modulator	NewFocus/ BB	4004
EOM	52	EO phase modulator	Two electrode and one wedged RTP crystal	Custom made
FC	51	Fiber couler	Thorlabs	PAF-x-18-C
FCS	51	Fiber coupler splitter	Thorlabs / FC/APC 50:50	PN1064R5A2
FI	51- 52	Faraday Isolator	EOT	110-21052-0001-ISO, 5mm aper
HW	51	Half-wave plate	CVI	
HW	52	Half-wave plate	CVI	
HW	53	Half-wave plate	CVI	
LO		Local Oscillator laser	Coherent	Mephisto S 500 mW
L	51	Plano Convex lens	CVI / f = 412.3 mm	**PLCX-25.4-206.0-UV-1064**
L	52	Plano Convex lens	CVI / f = 1000 mm	**PLCX-25.4-499.7-UV-1064**
L	53	Plano Convex lens	CVI / f = 500 mm	**PLCX-25.4-249.8-UV-1064**
L	54	Plano Convex lens	CVI / f = 600 mm	**PLCX-25.4-299.8-UV-1064**
L	55	Plano Concave lens	CVI / f = -75 mm	**PLCC-25.4-38.6-UV-1064**
L	56	Plano Convex lens, 2"	CVI / f = 800 mm	**PLCX-50.8-399.7-UV-1064**
L	57	Plano Convex lens	Thorlabs / f = 35 mm	LA4052-C
L	58	Plano Convexe lens	LA4148-C / f = 50 mm	LA4148-C
L	59	Plano Convex lens	CVI / f = -25 mm	**PLCC-25.4-13.1-UV-1064**
L	60	Plano Convex lens	CVI / f = 600 mm	**PLCX-25.4-299.8-UV-1064**
L	61	Plano Concave lens	CVI / f = -100 mm	**PLCC-25.4-51.5-UV-1064**
M	51 to 56	HR mirror		
M	57	PZT mirror actuator	Thorlabs / ±275 urad range	(KC1-P)
M	57 to 59	HR mirror		
M	60	PZT mirror actuator	Thorlabs / ±275 urad range	(KC1-P)
M	61 - 62 - 63	HR mirror 2"		
MD	64	HR mirror 2"	Dichoic GREEN/IR	
MT	51	R = 1%		
MT	52	R = 90%		
MT	53	R = 90%		
MT	54	R = 50%		
PD	51	Shot noise PD	AC: ~1.47 V/A @50 Ohms	Custom made (UF)
PD	52	Transimp. PD	Thorlabs / ~3.35 V/A @50 Ohms	PDA05CF2
PD	53	Transimp. PD	Thorlabs / ~3.35 V/A @50 Ohms	PDA05CF2 / S120-APC (fiber adapter)
PO	51	Plate Polarizers	CVI, BHalle	TFPN-1064-PW-1025
PO	52	Plate Polarizers	CVI, BHalle	TFPN-1064-PW-1025
PM	51	Optical power meter	Ophire	NOVA 2 METER + PD300 SENSOR
PMC	51	Pre- mode cleaner	LIGO PMC / 371 um waist	
QPD	51- 52	Quadrant PD	First sensor / 7.8 mm active diameter	QP50-6
QW	51 to 53	Quarter wave plate	CVI	
SH	51	Laser shutter		
Optical fiber			Thorlabs / PM 120 m length	PM980-XP, FC/APC connectors

Green for Initial Alignment (IA)				
Optics				
Components	Number	Name	Vendor / Specs	Part number
AP	51- 52	Pinhole aperture		
HW	53	Half-wave plate		
Green		Initial alignment laser		

L	62	Plano Concave lens	CVI / f = -50 mm	PLCC-25.4-38.6-C-532
L	63	Plano Convex lens	CVI / f = 750 mm	PLCX-50.8-386.3-C-532
M	69 to 71	HR 532nm		
MT	56	R = 50%		
QPD	53- 54	Quadrant PD	SI / DC postion sensors	

9.2.2 Central table

	Central Table CT_			
	Out-of-vacuum components			
Optics				
Components	Number	Name	Vendor / Specs	Part number
BD	51 to 53	Beam dump	Thorlabs	LB2/M
CCD	51 - 52	CCD camera	Basler	Provided by DOOCS
FC	51 - 52	Fiber coupler	Thorlabs	PAF-x-18-C
FCS	51 - 52	Fiber coupler splitter	Thorlabs / FC/APC 50:50	PN1064R5A2
FI	51	Faraday Isolator	EOT	110-21052-0001-ISO, 5mm aper
HW	51	Half-wave plate	CVI	
HW	52	Half-wave plate	CVI /Motorized mount	
HW	53 to 57	Half-wave plate	CVI	
RL		Reference Laser	Coherent	Mephisto S 500 mW
L	51	Plano Convex lens	Thorlabs/ f = 50 mm	LA4148-C
L	52	Plano Convex lens	Newport / f = 500 mm	SPX031AR.33
L	53- 54	Plano Concave lens	Newport / f = -100 mm	SPC028AR.33
L	55	Plano Concave lens	CVI / f = -500 mm	PLCC-25.4-257.5-UV-1064
L	56- 59	Plano Convex lens	Thorlabs / f = 50 mm	LA4148-C
L	60	Plano Convex lens	CVI / f = 1500 mm , 2"	PLCX-50.8-749.5-UV-1064
L	61	Plano Concave lens	CVI / f = -500 mm	PLCC-25.4-257.5-UV-1064
L	62	Plano Convex lens	Thorlabs / f = 35 mm	LA4052-C
L	63	Plano Convex lens	Newport / f = 500 mm	SPX031AR.33
L	64- 65	Plano Concave lens	Newport / f = -100 mm	SPC028AR.33
L	66	Plano Convex lens	CVI / f = 1500 mm , 2"	PLCX-50.8-749.5-UV-1064
L	67	Plano Concave lens	CVI / f = -500 mm	PLCC-25.4-257.5-UV-1064
L	68	Plano Convexe lens	LA4148-C / f = 50 mm	LA4148-C
L	69	Plano Convex lens	Newport / f = 500 mm	SPX031AR.33
L	70- 71	Plano Concave lens	Newport / f = -100 mm	SPC028AR.33
M	51	Curved mirror	/ROC = 200 cm	
M	52 to 54	HR mirror		
M	55	Curved mirror/PZT actuator	ROC = 100 cm	
M	56	PZT mirror actuator		
M	57 to 59	HR mirror		
M	60	Curved mirror	/ROC = 100 cm	
M	61 to 63	HR mirror		
M	64	HR mirror, 2"		
M	65 to 68	HR mirror		
M	69	HR mirror, 2"		
M	70 to 81	HR mirror		
MT	51	R = 99%		
MT	53	R = 1%		
MT	54	R = 50%		
MT	55- 56	R = 99%		
MT	57	R = 50%		
MT	58	R = 70%		
MT	59- 60	R = 50%		
PD	51	Transimp. Photodetector	Thorlabs / ~3.35 V/A @50 Ohms	PDA05CF2
PD	56	Shot noise PD	UF Custom made / AC: ~1.47 V/A @50 Ohms	
PD	57	Transimp. PD	Thorlabs / ~3.35 V/A @50 Ohms	PDA05CF2
PD		Transimp. PD	Thorlabs / ~3.35 V/A @50 Ohms	PD10CF/Fiber coupled
PO	51 to 57	Plate Polarizers 1"	CVI	TFPN-1064
PO	59	Plate Polarizers 1"	CVI	TFPN-1064
PM	51- 52	Optical power meter	Ophire	NOVA 2 METER + PD300 SENSOR
QPD	51- 56	Quadrant PD	First sensor / 7.8 mm active diameter	QP50-6
QW	51 to 59	Quarter wave plate	CVI	
SH	51	Laser shutter		
Optical fibers			Thorlabs / PM 120 m length	PM980-XP, FC/APC connectors
Fiber Isolator			Thorlabs	IO-G-1064B-APC, 300 mW

	Central Table CB_			
	In-vacuum components			
Optics				
Components	Number	Name	Vendor / Specs	Part number
BD	51 - 52	Beam dump	UF Custom design	
HW	51- 52- 53	Half-wave plate, 2"	LAMBDA	WPO-50.8CQ-0-2-1064
M	51	HR mirror, 2"		
M	52	Curved mirror, 2""	/ROC = 300 cm	
M	53 to 55	HR mirror, 2"		
M	56	Curved mirror, 2""	/ROC = 300 cm	
M	57 to 60	HR mirror, 2"		
M	61	Curved mirror, 2""	/ROC = 300 cm	
MT	51- 52- 53	T = 3 ppm (s and p), 2"		
MT	54- 55- 56	R = 70/30 (p) / 500ppm (s), 2"		
QPD	51- 52	Quadrant PD	First Sensor / 7.8 mm active diameter	QP50-6 (provided by AEI)
QW	51, 52	Quarter wave plate, 2"	LAMBDA	WPO-50.8CQ-0-4-1064
SH	51	HR mirror, 2"	Metallic back surface	