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Heterodyne Sensing Scheme (HET): Sensitivity monitoring and verification

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Gravitational Waves

Number of regenerated photons: $N_{\mathrm{S}} = \eta^2 N_{\mathrm{PC}} \frac{\mathcal{F}_{\mathrm{RC}}}{\pi} \frac{1}{16} (g_{\alpha\gamma} BL)^4$

with: $N_{PC} = \frac{P_{PC} t}{h\nu}$

Goal:

- 14 photons total for 5-sigma detection. Assumes:
  - No background beyond shot noise (< 2 x 10^{-25} W)
  - Signal phase is constant or can be tracked (∂ß < 0.1 rad)
  - 2nd demodulation done at 18 different phases (every 5 deg or 0.09 rad)

$$g_{a\gamma\gamma} = \frac{2}{BL} \times \left(\frac{1}{\eta}\right)^{\frac{1}{2}} \times \left(\frac{N_{\mathrm{S}} h\nu}{P_{\mathrm{in}} \tau \mathrm{PB}_{\mathrm{PC}} \mathrm{PB}_{\mathrm{RC}}}\right)^{\frac{1}{4}}$$

$$\eta = 0.9$$

$$g_{a\gamma\gamma}(1\,\mathrm{s}) = 8 \times 10^{-10} \mathrm{GeV}^{-1}$$

$$g_{a\gamma\gamma}(25\,\mathrm{d}) = 2 \times 10^{-11} \mathrm{GeV}^{-1}$$

Gravitational Waves

Number of regenerated photons: $$N_S = \eta^2 N_{PC} \frac{\mathcal{F}_{RC}}{\pi} \frac{1}{16} (g_{\alpha\gamma} B L)^4$$

with: $$N_{PC} = \frac{P_{PC} t}{h\nu}$$

$$1 - \eta^2 = \text{loss}$$

Requirements (**needs some consolidation)**:

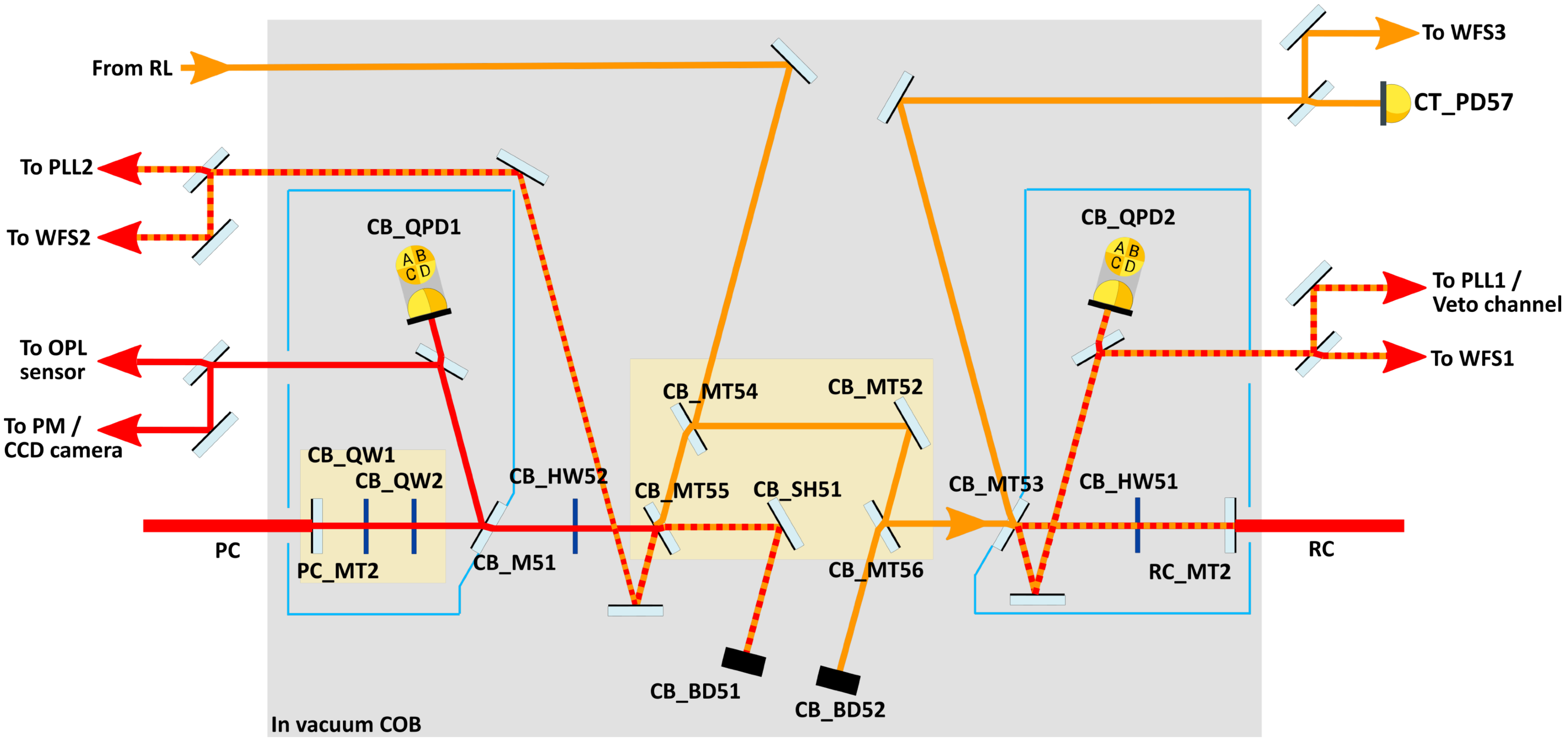
- PC internal power: 150 kW (8 x 10^{23} Ph/s)
- RC build up: 10,000 (Finesse of π x 10,000)
- Cavity mismatch: Length / Frequency: 1.2 pm (rms) or 2.4 Hz (rms) -> 1.5% loss
  - **Goal: < 1 Hz Frequency knowledge (Set by PLLs)**
  - Goal: < 0.01 rad (rms) residual phase noise in PLL1
  - Goal: < 1 pm (rms noise) residual PC length noise in PLL2
- Cavity alignment: Angular / lateral: 14 μrad (no lateral mentioned) -> 6% loss
  - **Goal: Monitor misalignment on COB: 5μrad / 600 μm -> 2% loss**
- Scattered light: 2x10^{-25}W in indistinguishable scattered light photons

COB alignment (see alignment procedure):

- Alignment of Cavity flats: < 5 μrad
- PC-transmitted light aligned with axion field at RC
    - Refraction offsets below 5 μrad and 300 μm (TBC)

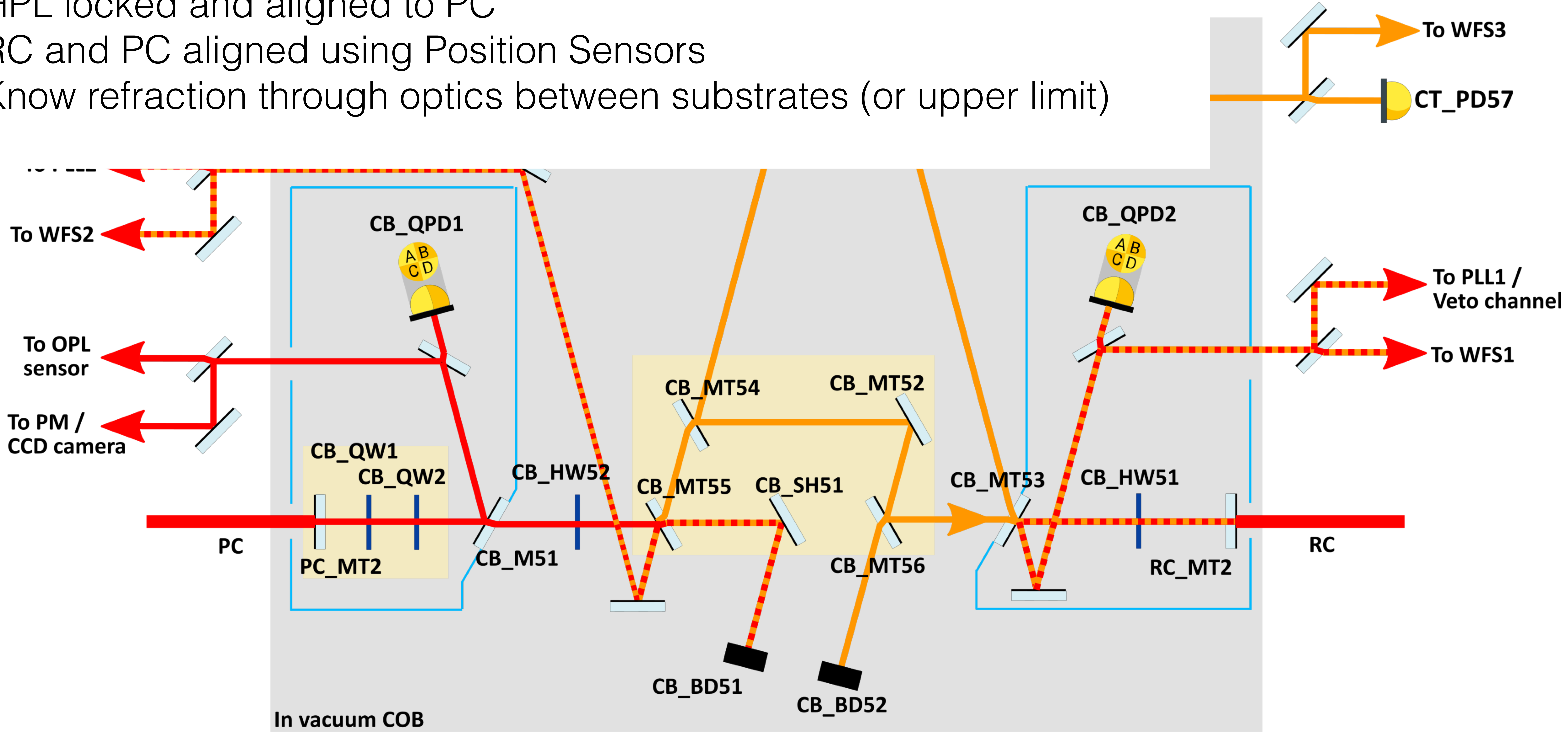
Verification of axion to RC coupling:

- Frequency matching
- Alignment stability
- Impedance of RC from COB


From RL
To WFS3
CT_PD57
To PLL2
To WFS2
CB_QPD1
A B
C D
CB_QPD2
A B
C D
To PLL1 /
Veto channel
To WFS1
To OPL
sensor
To PM /
CCD camera
CB_MT54
CB_MT52
CB_QW1
CB_QW2
CB_HW52
CB_MT55
CB_SH51
CB_MT53
CB_HW51
PC
PC_MT2
CB_M51
CB_MT56
RC_MT2
RC
CB_BD51
CB_BD52
In vacuum COB

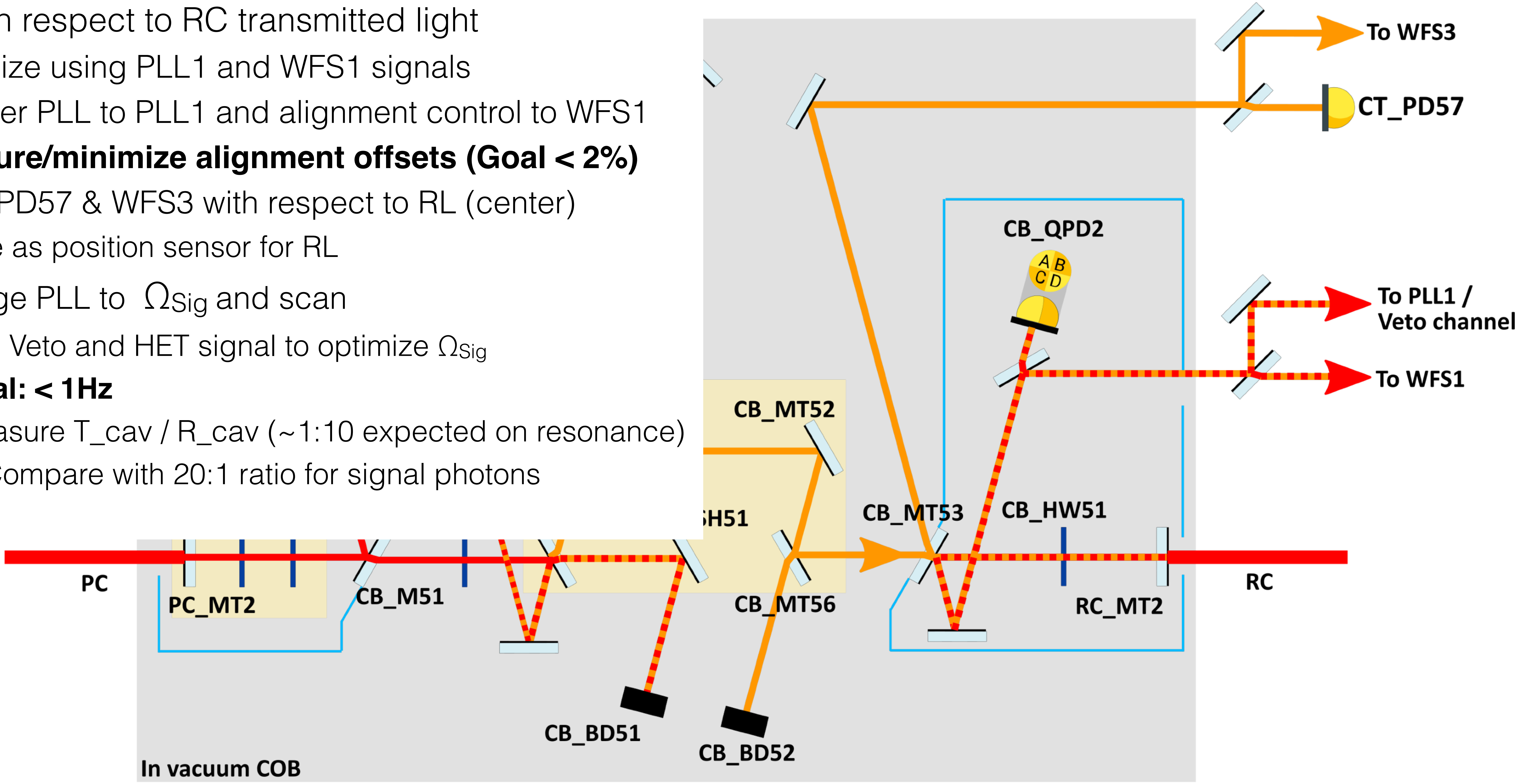
Start:

- LO locked and aligned to RC
- HPL locked and aligned to PC
- RC and PC aligned using Position Sensors
- Know refraction through optics between substrates (or upper limit)



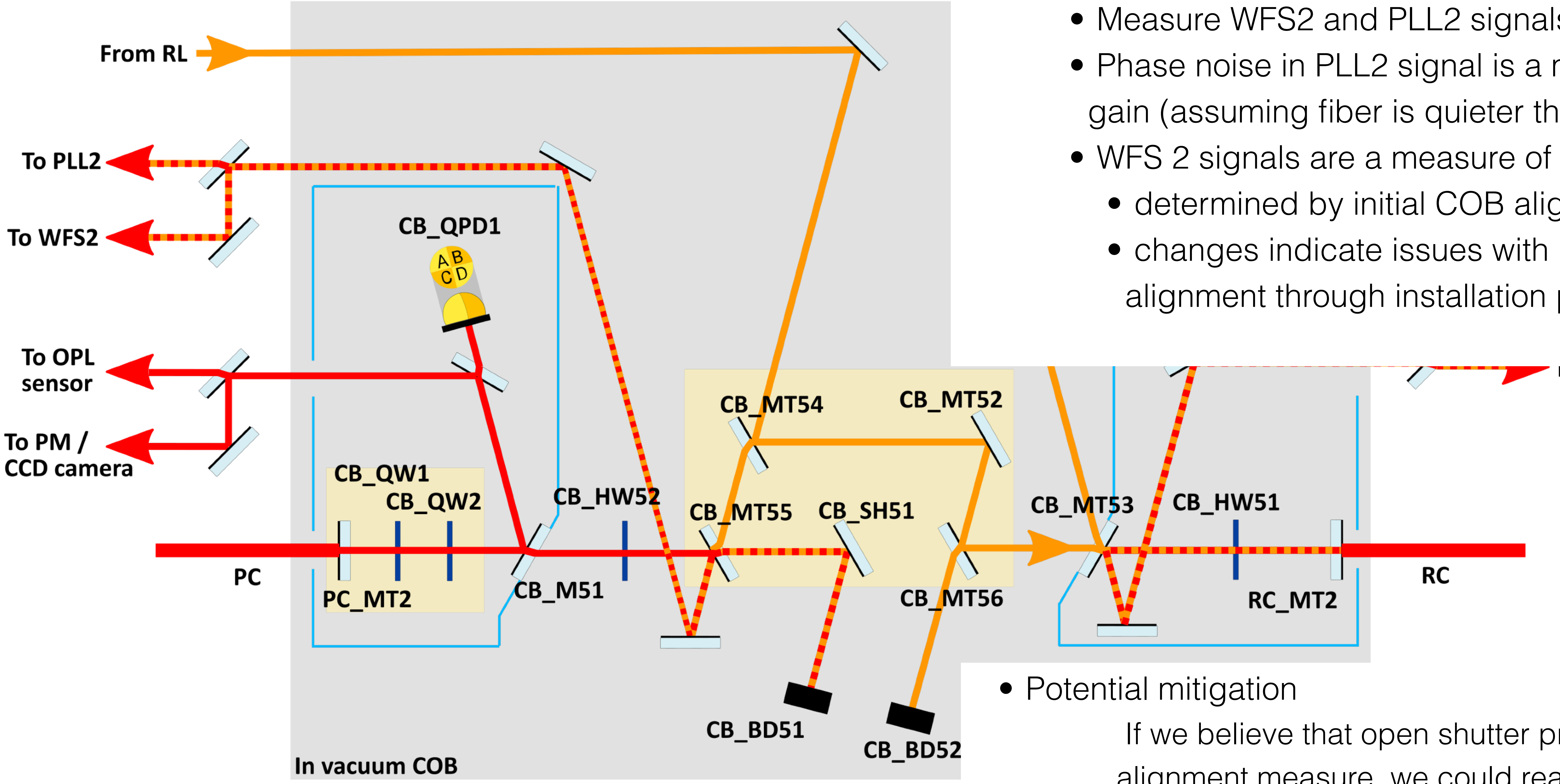
Inject RL (Phase locked to LO via fiber link at Ω_1):

- Initial alignment: Via targets on COB (to be designed)
- Overlap with respect to RC transmitted light
  - Optimize using PLL1 and WFS1 signals
  - Transfer PLL to PLL1 and alignment control to WFS1
  - **Measure/minimize alignment offsets (Goal < 2%)**
  - Align PD57 & WFS3 with respect to RL (center)
    - Use as position sensor for RL
  - Change PLL to Ω_{Sig} and scan
    - Use Veto and HET signal to optimize Ω_{Sig}
    - **Goal: < 1Hz**
    - Measure T_cav / R_cav (~1:10 expected on resonance)
      - Compare with 20:1 ratio for signal photons



PC-side

- Align PLL2/WFS2 detectors to RL
- PLL HPL to RL via fiber
- Lock PC to HPL
  - Measure WFS2 and PLL2 signals
  - Phase noise in PLL2 signal is a measure of required gain (assuming fiber is quieter than PC)
  - WFS 2 signals are a measure of misalignment
    - determined by initial COB alignment
    - changes indicate issues with maintaining alignment through installation process

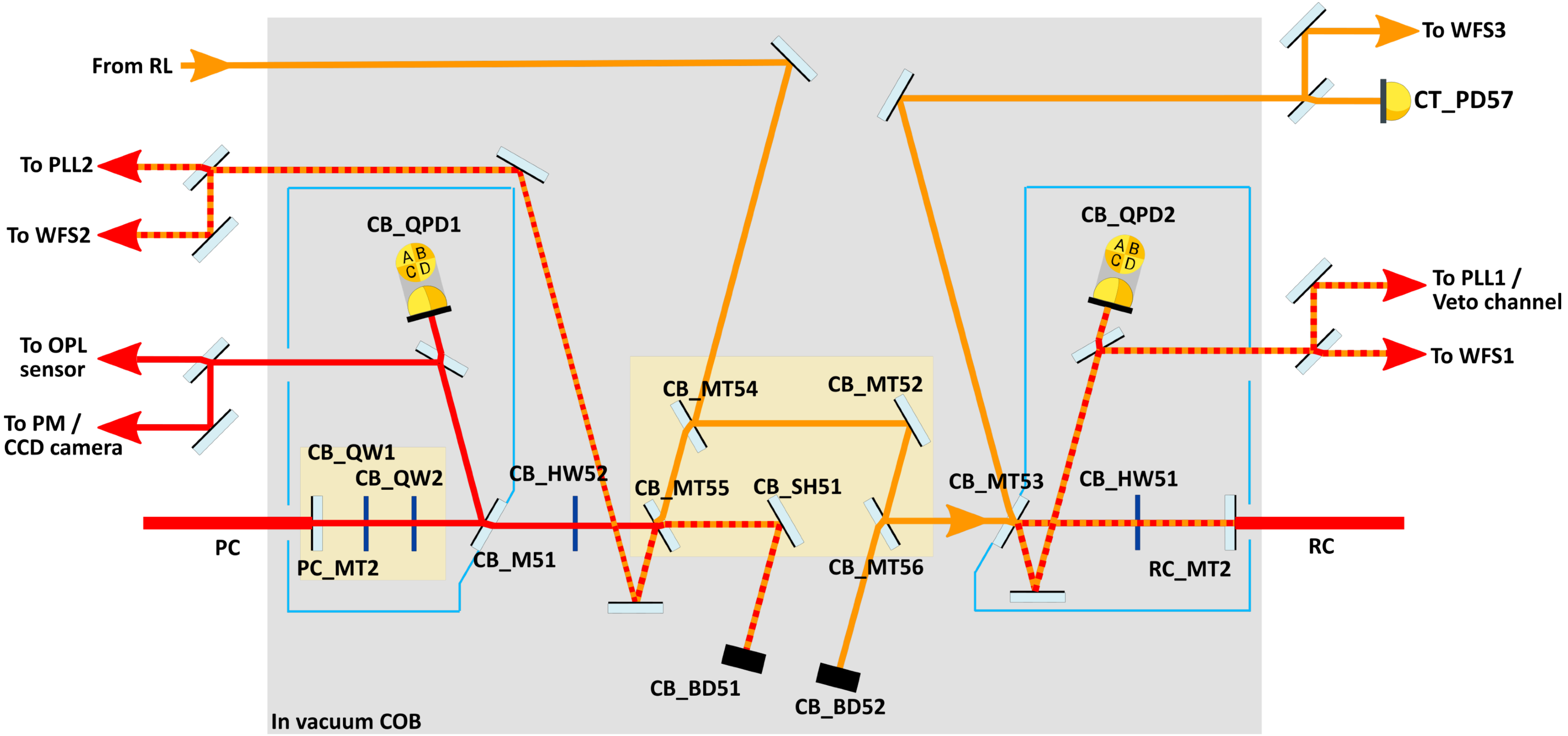


- Potential mitigation
  If we believe that open shutter provides good alignment measure, we could realign MZ and QPD1

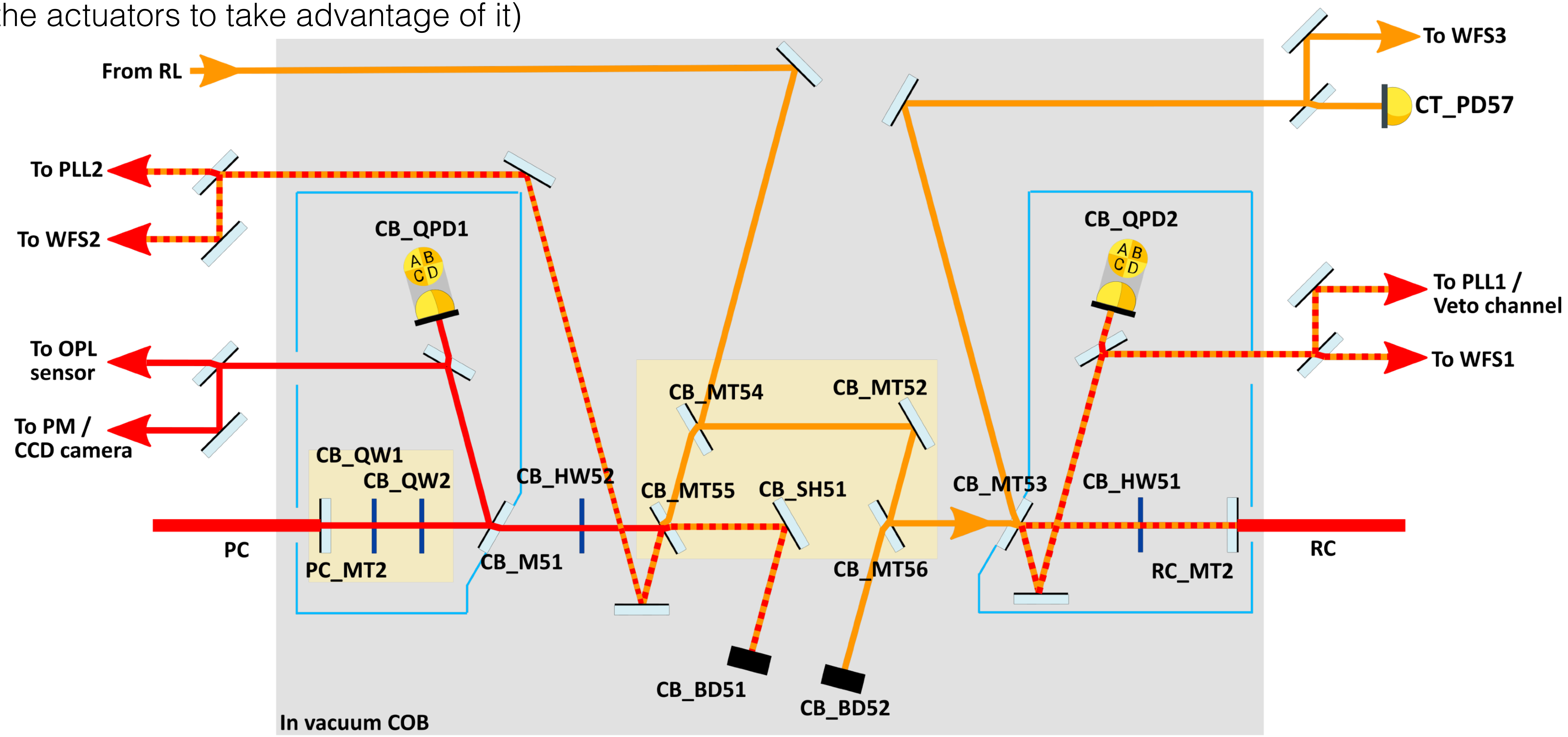
Next: Close all loops. QPD1 for PC, QPD2 for RC, PLL: RL to RC, PC to RL, WFS1 for RL alignment

Open shutter: Measure/calibrate PD57, Veto signal and HET signal. Power ratios ~10^7/10/1 for PC transmitted light.

Measure phases of beat signals over a few days to see drifts between PD57 and PLL2: unaccounted phase noise??



Measure and calibrate WFS signals:
WFS2 and WFS3 monitor alignment of RL and PC with respect to RC.
Close shutter: Measure stray light. If needed, open tank again and find the sources.
Need: WFS with < 0.01 rad sensitivity in each d.o.f. and PLLs with < 0.01 rad sensing noise (and the actuators to take advantage of it)



Summary:

- HET system has stray light and alignment verification signals
  - PD57: 10 million to 1 ratio for stray light compared to HET detector (s-pol, 10^5:1 for p-pol)
    - 1 photon per second on PD57 should be low enough background for HET detector
      - Commissioning does (hopefully) not depend on very long data runs to measure/minimize scatter
  - Veto signal: 10:1 ratio for stray light compared to HET signal
  - HET signal: 20:1 ratio for real signal compared to Veto signal
    - Useful for subtraction in post processing.
- WFS 2 monitors PC-RL alignment (out of loop)
- WFS 3 as position sensor monitors alignment changes between optical tables and vacuum tank

- Open shutter allows to measure phase drifts between different components/parts/signals
  - Confidence in demodulation phase if drifts are low
  - Not sure yet if we can use that to correct for phase drifts
    - We look into low amplitude SB on RL resonant in RC to maybe calibrate the drift (risk reduction)