Arm Length Stabilisation for Advanced Gravitational Wave Detectors

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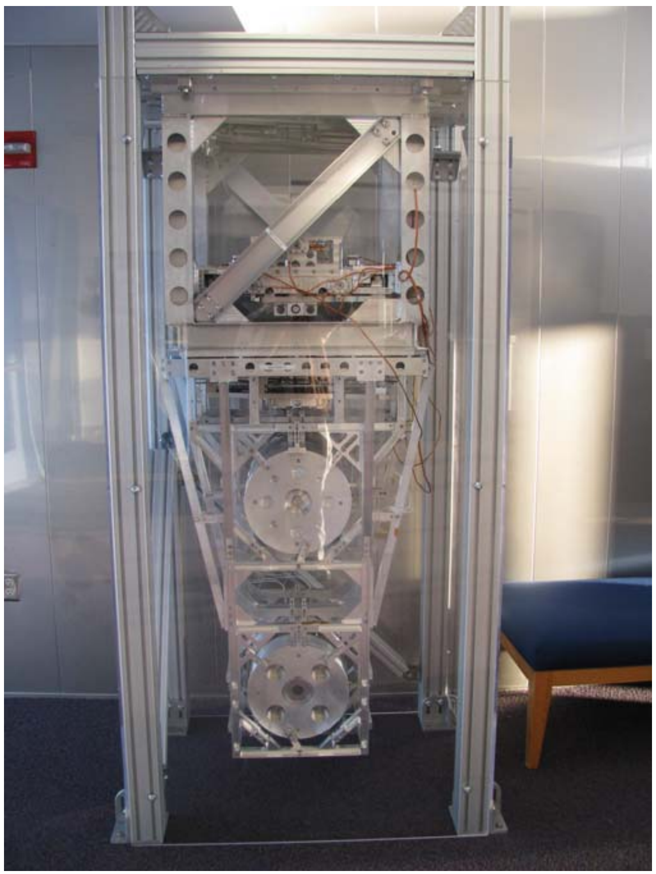
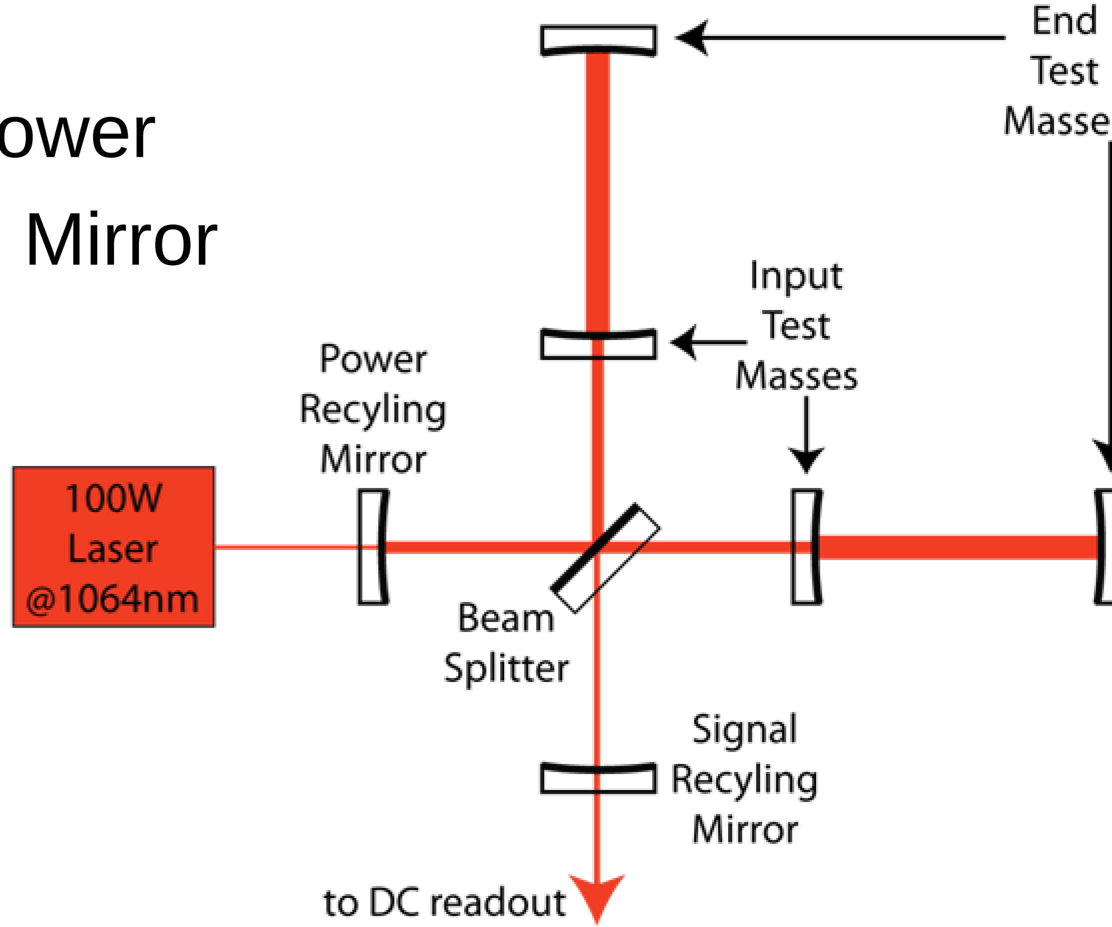
Advanced LIGO

- Higher Optical Power
- Signal Recycling Mirror





- New Seismic Isolation systems
  - Quadruple Suspensions for the test masses

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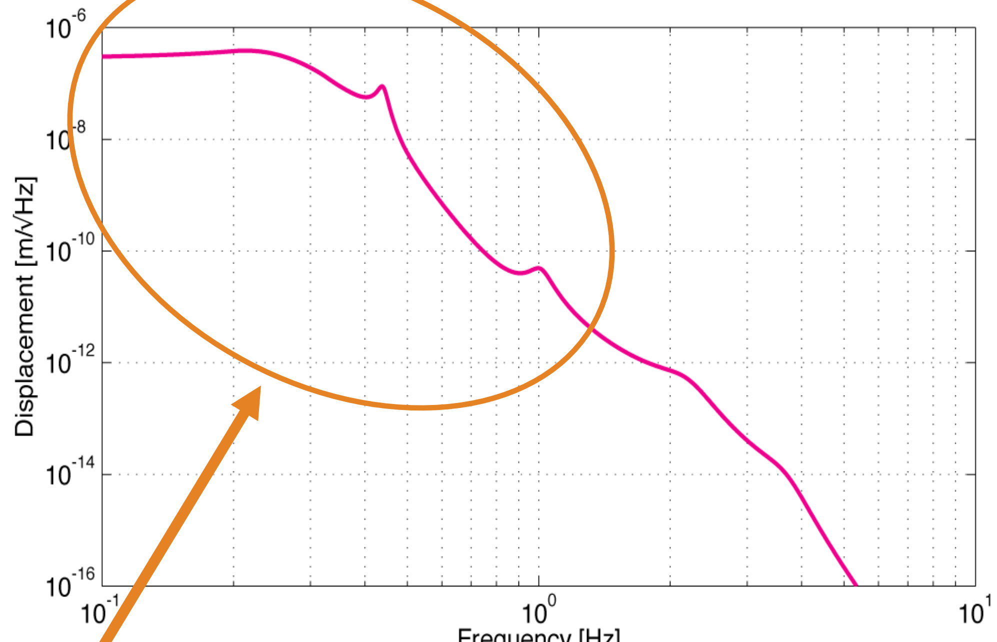
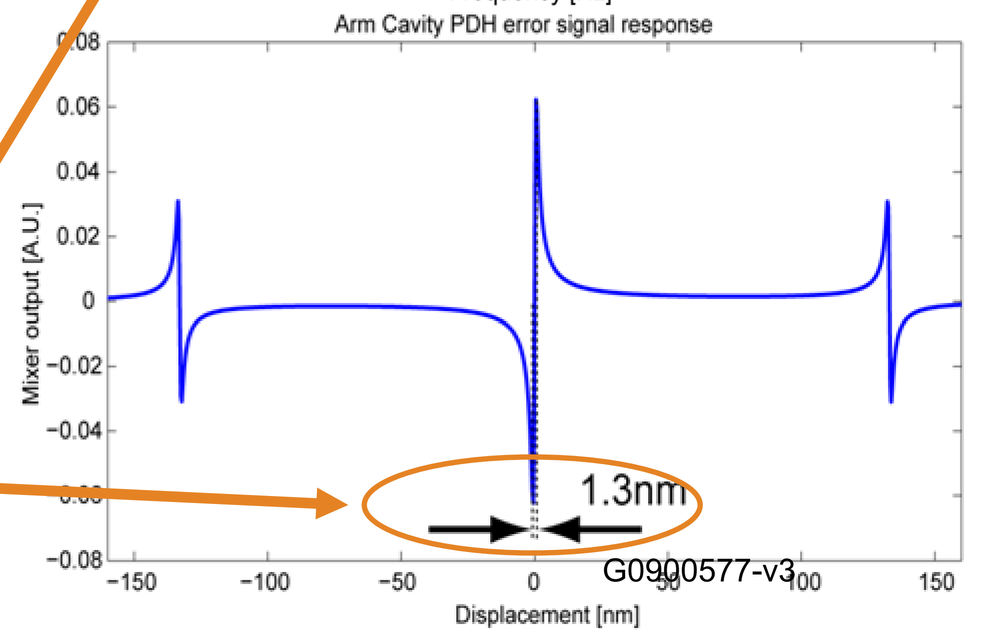
[1] http://www.ligo.caltech.edu/advLIGO

The Lock Acquisition Challenge

- Initial LIGO lock acquisition was probabilistic
- Advanced LIGO lock acquisition more complicated than for initial LIGO
  - Extra cavity (signal recycling cavity)
  - Weaker actuation of test masses
  - Residual displacement noise of test masses, at low frequencies
  - Finesse of arm cavity ~ 400, linewidth ~ 94Hz, range of linear error signal very small ~ 1.3nm



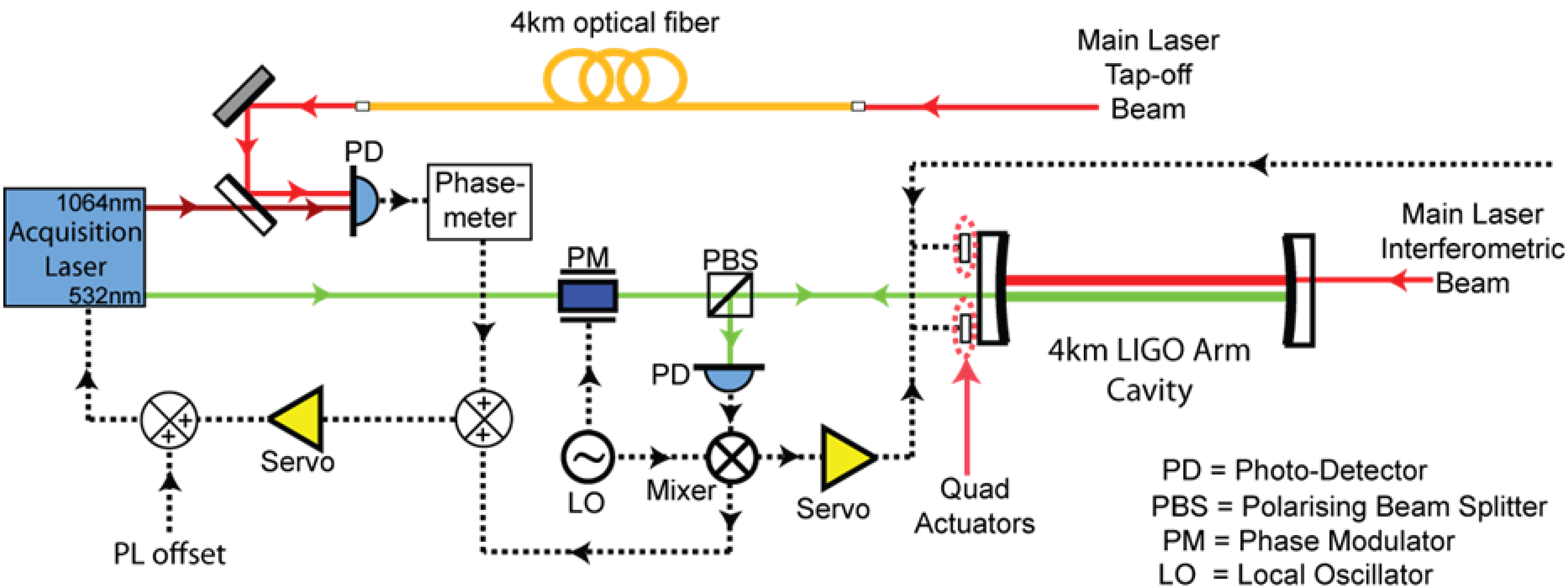


The Lock Acquisition Challenge

- Advanced LIGO will acquire lock using a deterministic approach
- Arm cavities locked independent of the rest of the interferometer, i.e. Arm Length Stabilisation
  - Seismic Platform Interferometer[2], Digitally Enhanced Interferometry[3], Pound Drever Hall[4]
  - Advanced LIGO going ahead with a PDH based scheme

[2] Y. Aso, et al; *Physics Letters A Volume 327, Issue 1*
[3] D. Shaddock; *Optics Letters, Vol. 32, No. 22*
[4] R. W. P. Drever et al; *Appl. Phys. B* 31, 97

Arm Length Stabilisation



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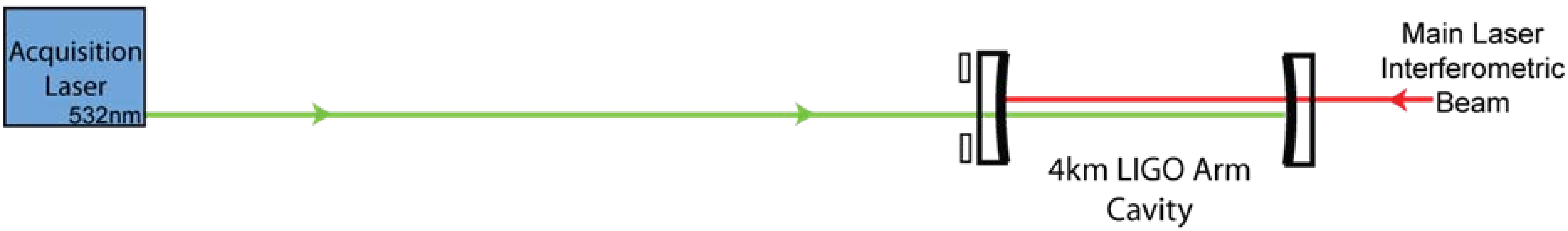
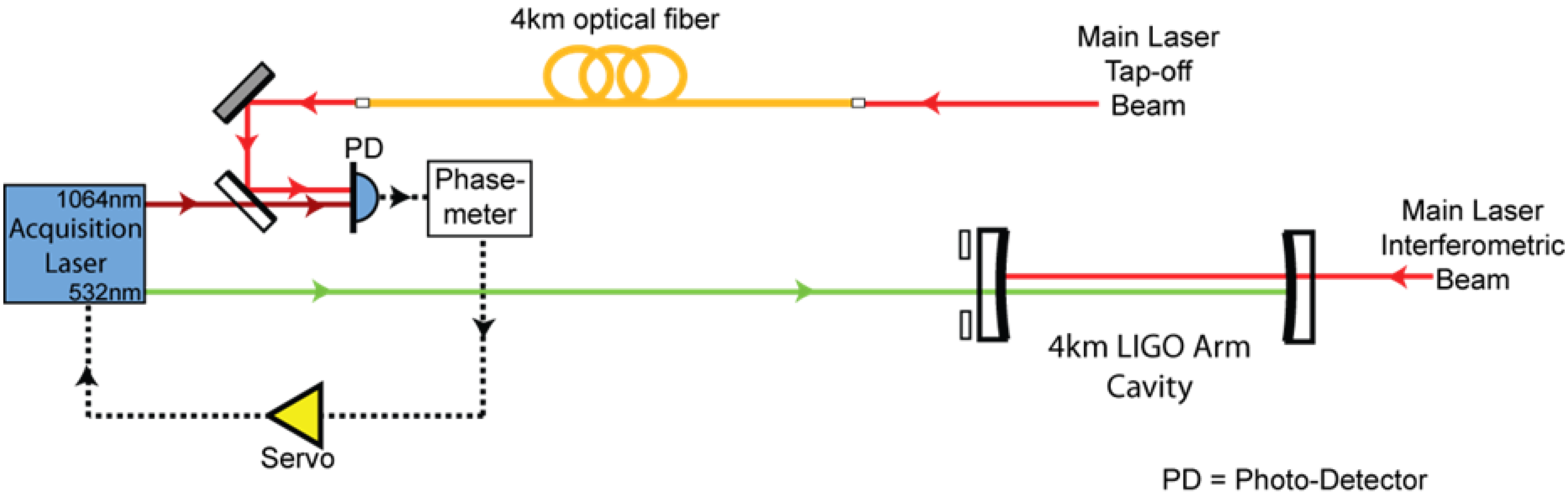
[5] B. Slagmolen et.al. ; LIGO-T0900144-v1-D

Arm Length Stabilisation



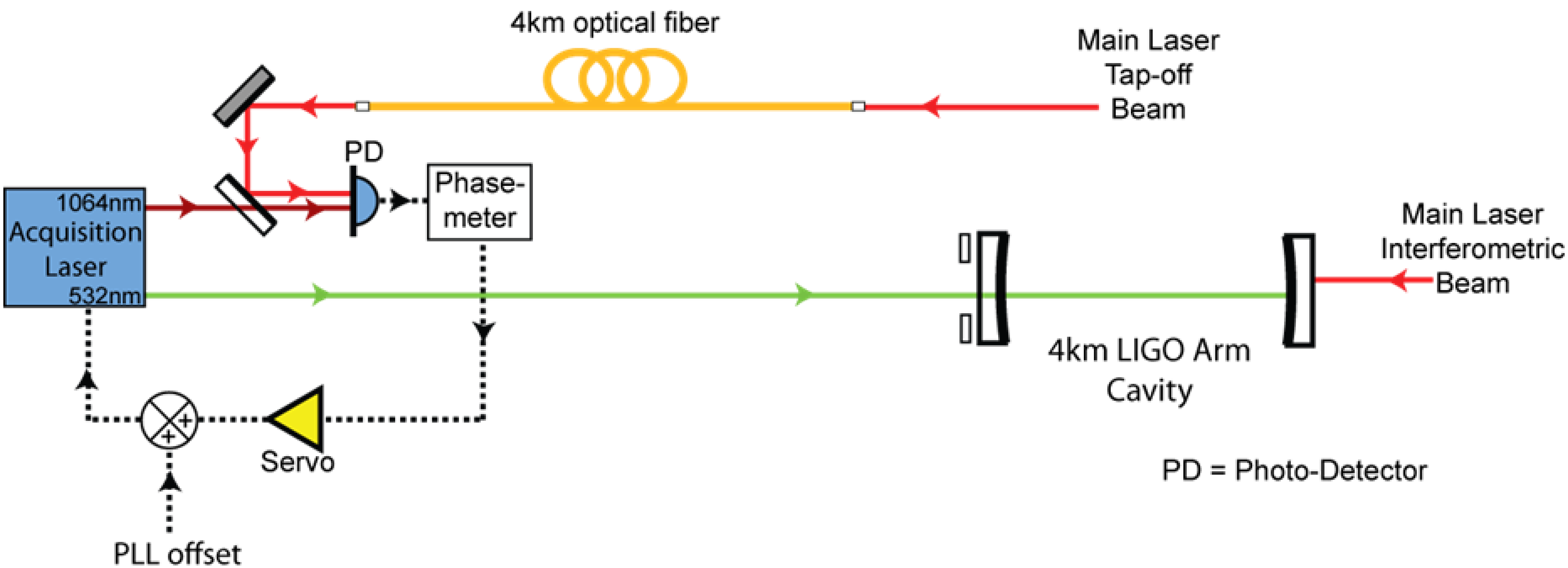
- Step 1: Inject 532nm beam from "Acquisition Laser" into each arm cavity
  - Different wavelength doesn't interfere with other interferometer beams
  - Uses light with double the frequency of the main laser

Arm Length Stabilisation



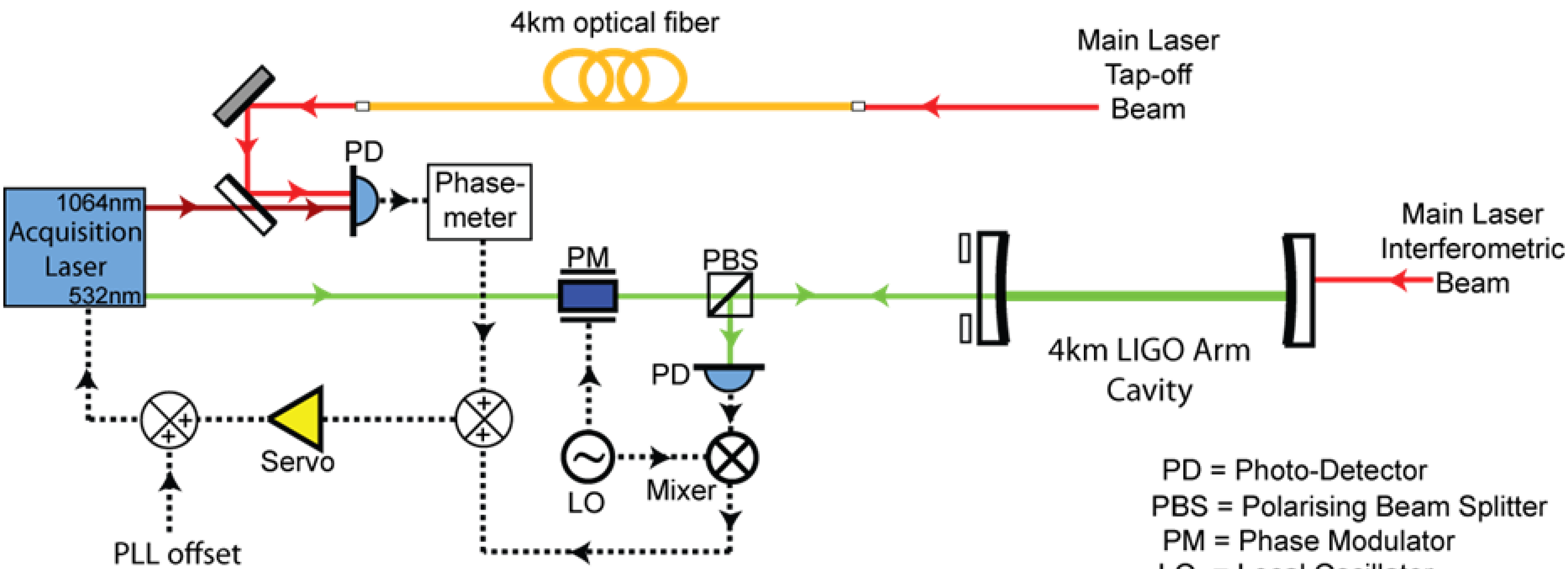
- Step 2: Phase lock the Acquisition Laser to the Main Laser
  - Optical fiber used to transfer main laser tap-off to end station for phase reference
  - Acquisition laser - dual frequency laser, 1064nm beam exactly half the frequency of the 532nm beam
  - Beating of the two 1064nm beams gives heterodyne signal that is fed back to the acquisition laser to phase lock the two lasers

Arm Length Stabilisation



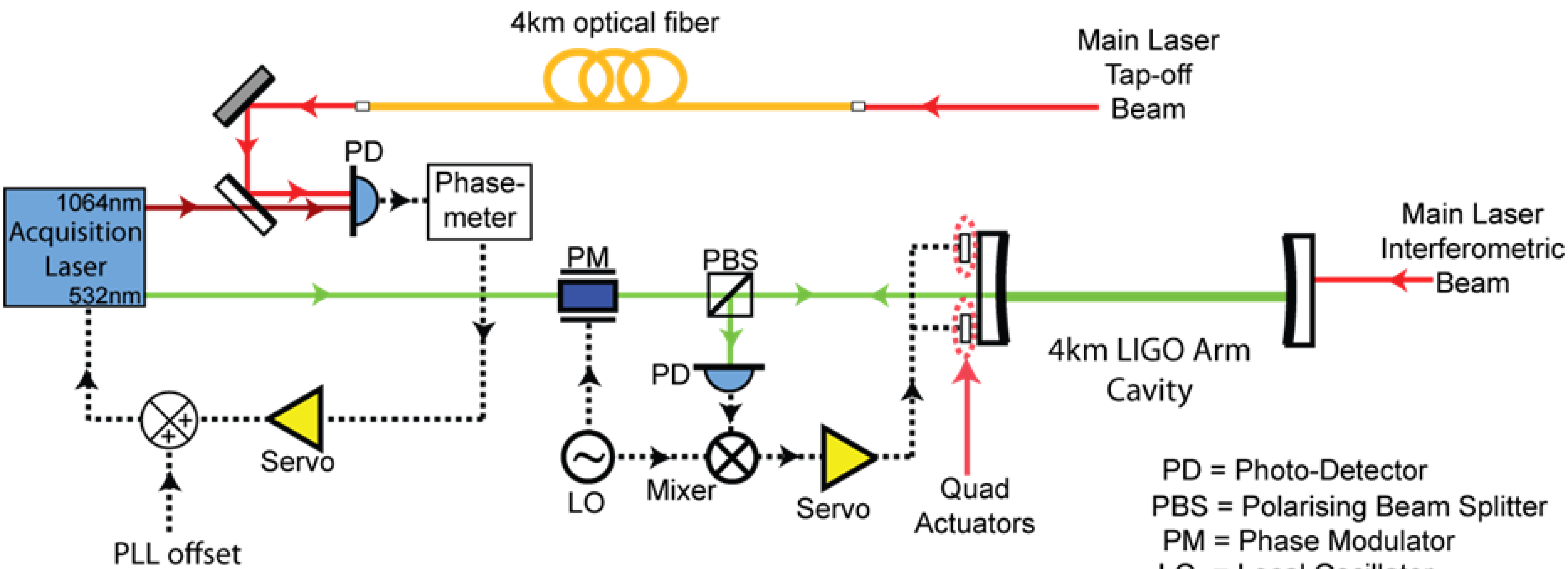
- Step 3: Inject offset into Phase Locked Loop
  – Will eventually allows us to tune the length of the arm cavity

Arm Length Stabilisation



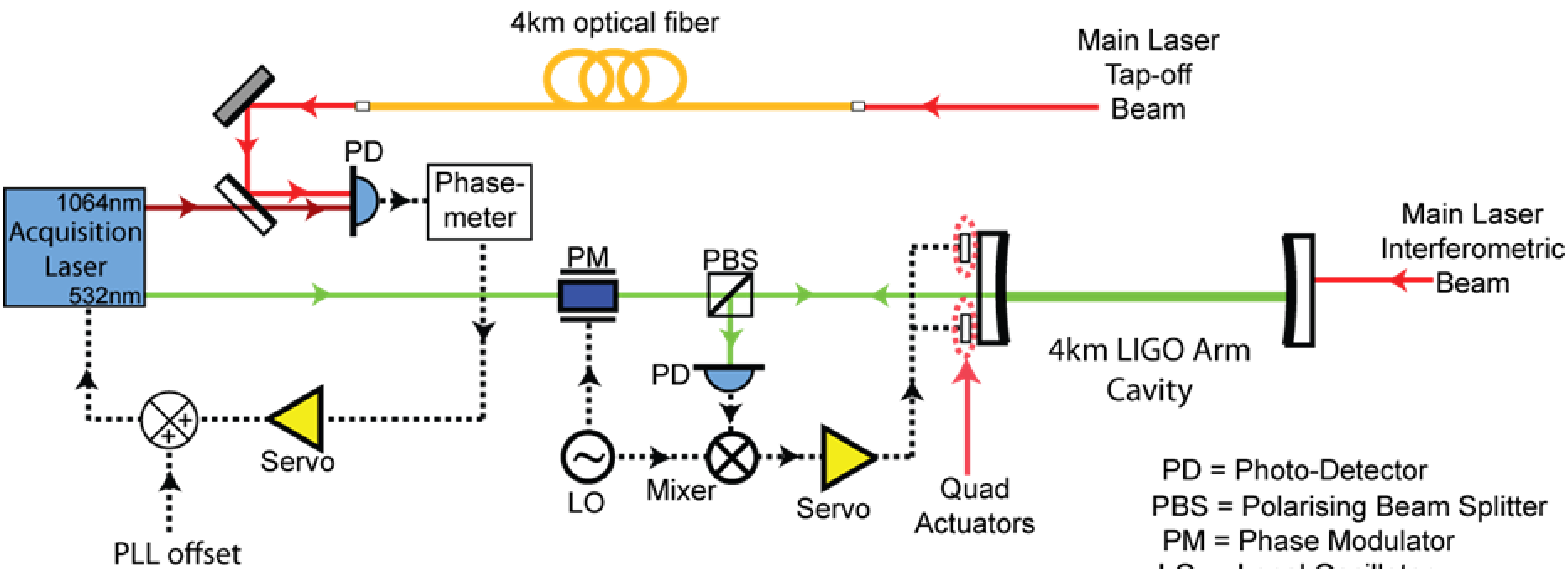
- Step 4: Lock the frequency of the acquisition laser to the arm cavity length
  - Use PDH technique
  - The frequency actuator has a much larger dynamic range than the quad test mass actuators
  - Acquiring lock not a problem

Arm Length Stabilisation



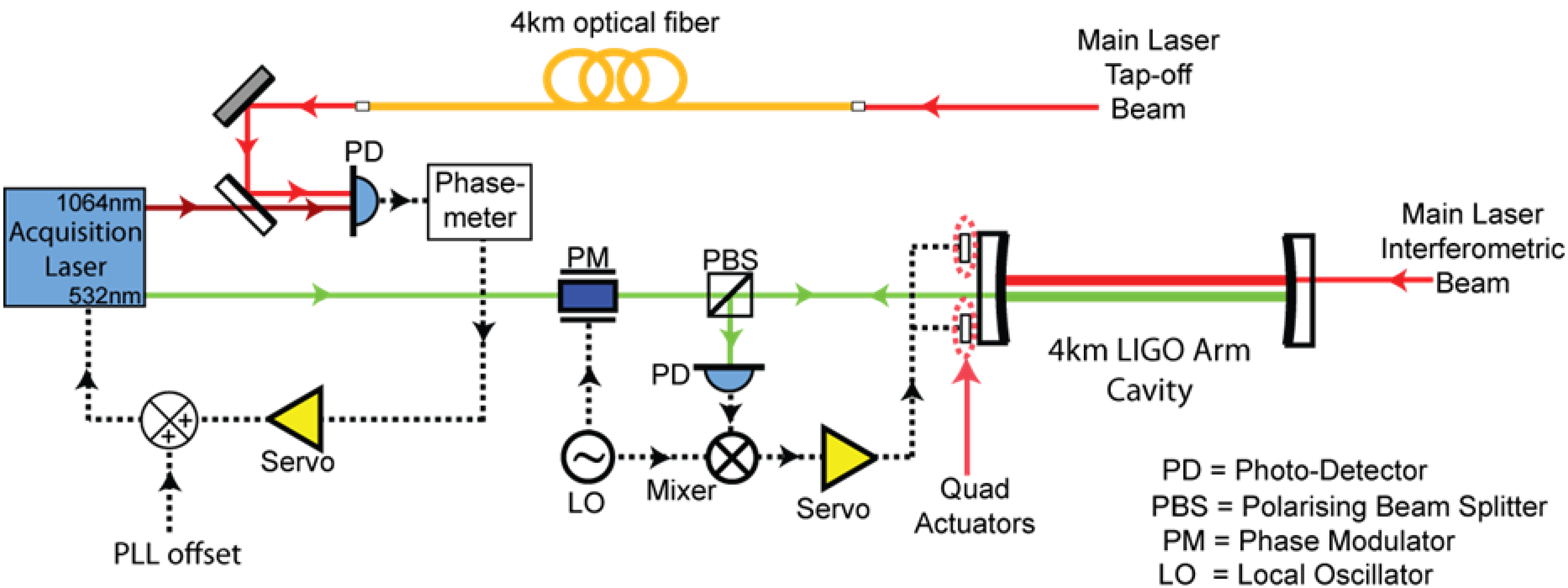
- Step 5: Hand-off the feedback to the quad actuators, to lock the cavity length to the frequency of the laser.

Arm Length Stabilisation



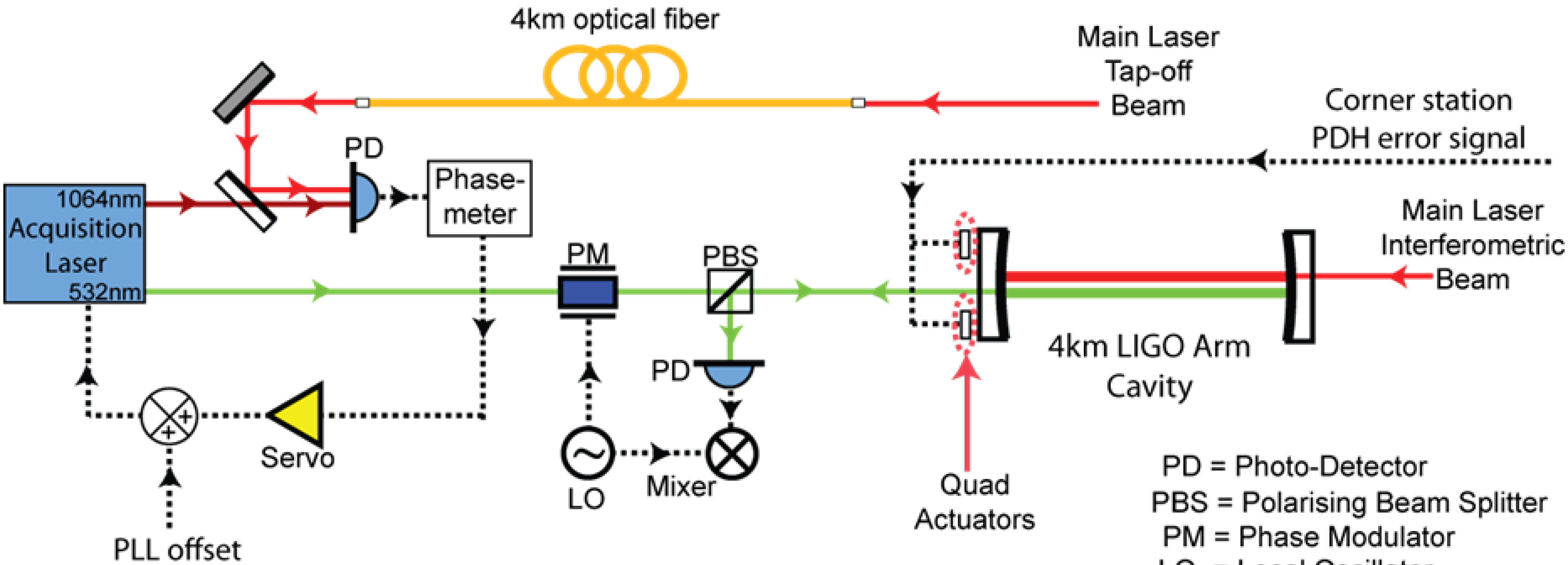
- Step 6: Acquire lock of the rest of the interferometer
  - Recycling cavities
  - PLL offset tuned so that cavity is non-resonant with the main laser

Arm Length Stabilisation



- Step 7: Tune PLL offset to bring cavity onto resonance with the main laser

Arm Length Stabilisation



- Step 8: Finally, switch feedback from the Acquisition Laser to the Main Laser.

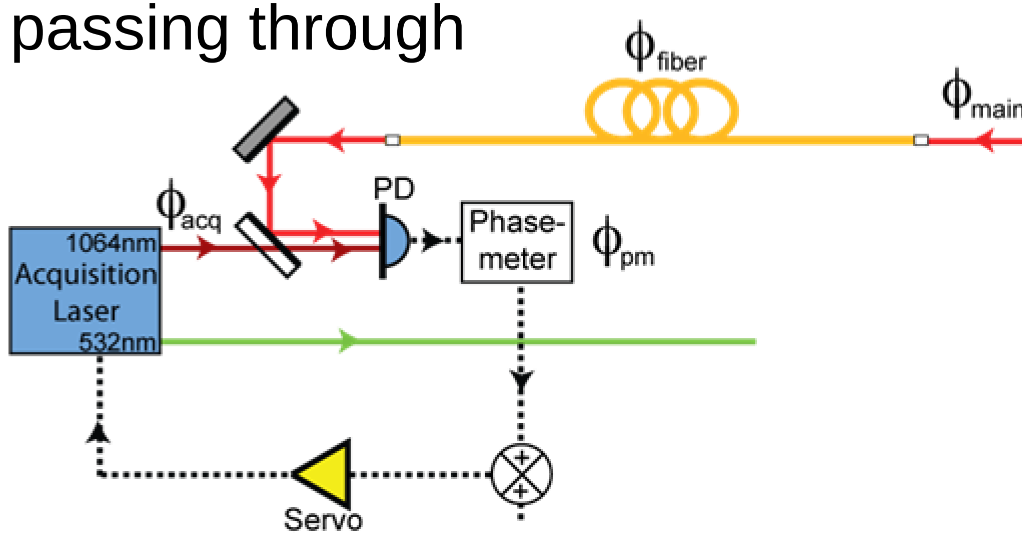
Possible ALS issues

- Modifying the HR coating of the test masses
  - @532nm: ITM reflectivity ~ 99%, ETM reflectivity ~95%, Finesse ~ 100, overcoupled cavity
  - The modification has minimal effect on the coating thermal noise for the 1064nm beam
- Noise induced by the fiber
  - Polarisation drift
  - Scattering effects
  - Optical path length fluctuations

Fiber Induced Phase Noise

- Mechanical and temperature fluctuations in the fiber induce phase noise onto the beam passing through
- Limits how well the lasers are phase-locked
- Is ultimately imposed onto the cavity length fluctuations seen by main laser
- Maximum sensor noise equivalent to 1pm/√Hz [6] or 75mHz/√Hz in differential frequency noise

$$\frac{\Delta \nu}{\nu} = \frac{\Delta L}{L}$$



$$\phi_{pm} = \phi_{main} + \phi_{fiber} - \phi_{acq}$$

BAD!!!

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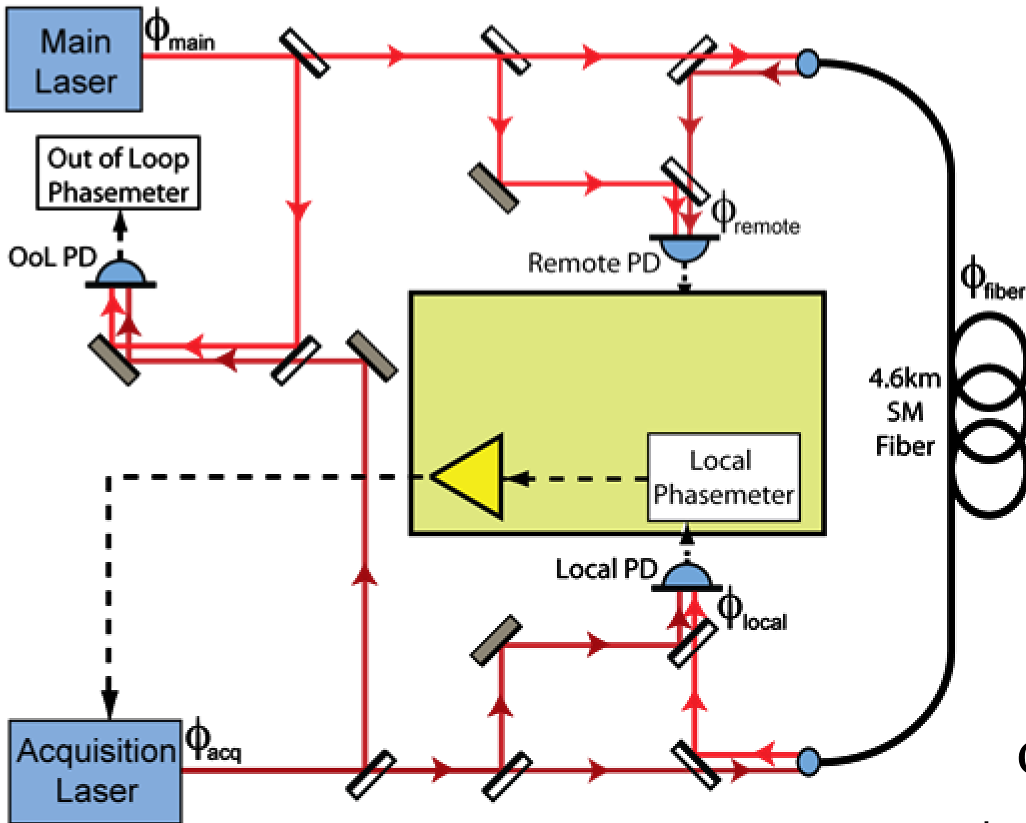
[6] B.J Slagmolen et.al. ; LIGO-T0900144-v1-D

Fiber Noise Experiment



Local Feedback Only

Dual Feedback

$$\phi_{local} = (\phi_{main} + \phi_{fiber}) - \phi_{acq}$$

$$\phi_{remote} = \phi_{main} - (\phi_{acq} + \phi_{fiber})$$

$$\phi_{local} + \phi_{remote} = 2(\phi_{main} - \phi_{acq})$$

Drive ϕ_{local} to zero

ϕ_{remote} to zero

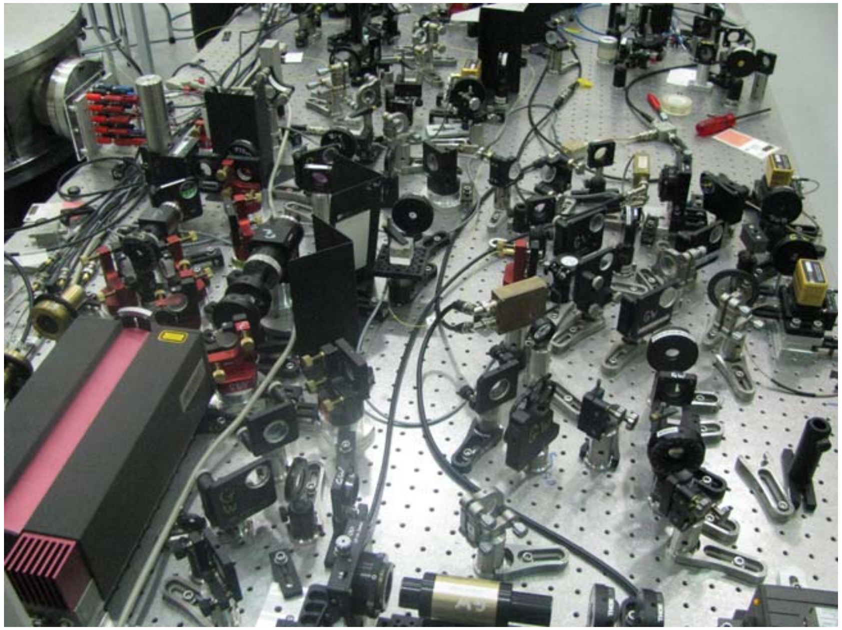
$$\phi_{acq} = \phi_{main} + \phi_{fiber}$$

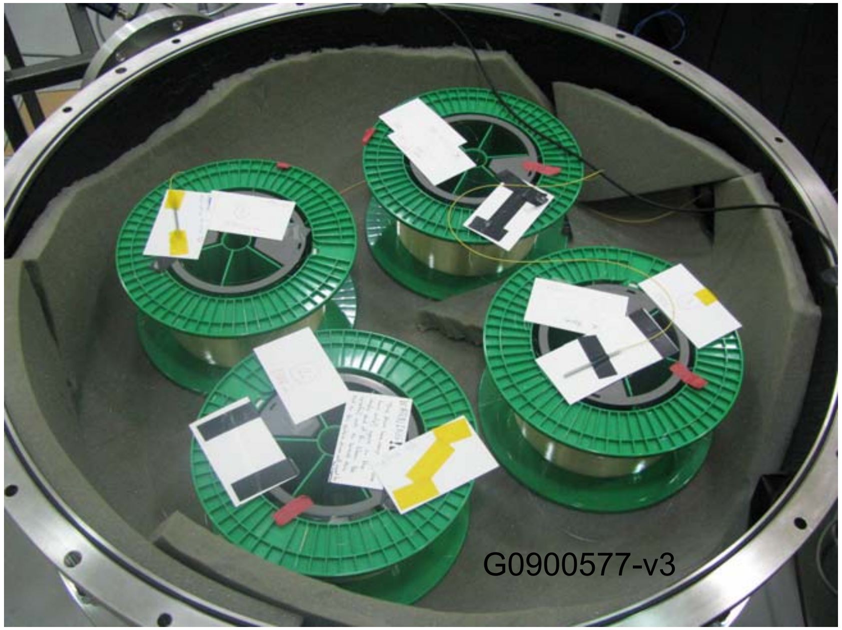
Very Cool!

Not Cool!

Fiber Noise Experiment

- 4.6km single mode optical fiber used.
- Power into fiber ~ 100uW (Minimise scattering effects).
- Signal power onto detector ~5uW.
- LO power onto detector ~50uW.
- Phase-meters immune to the small amount of polarisation drift present.
- Results measured using out-of-loop detector and phase-meter.





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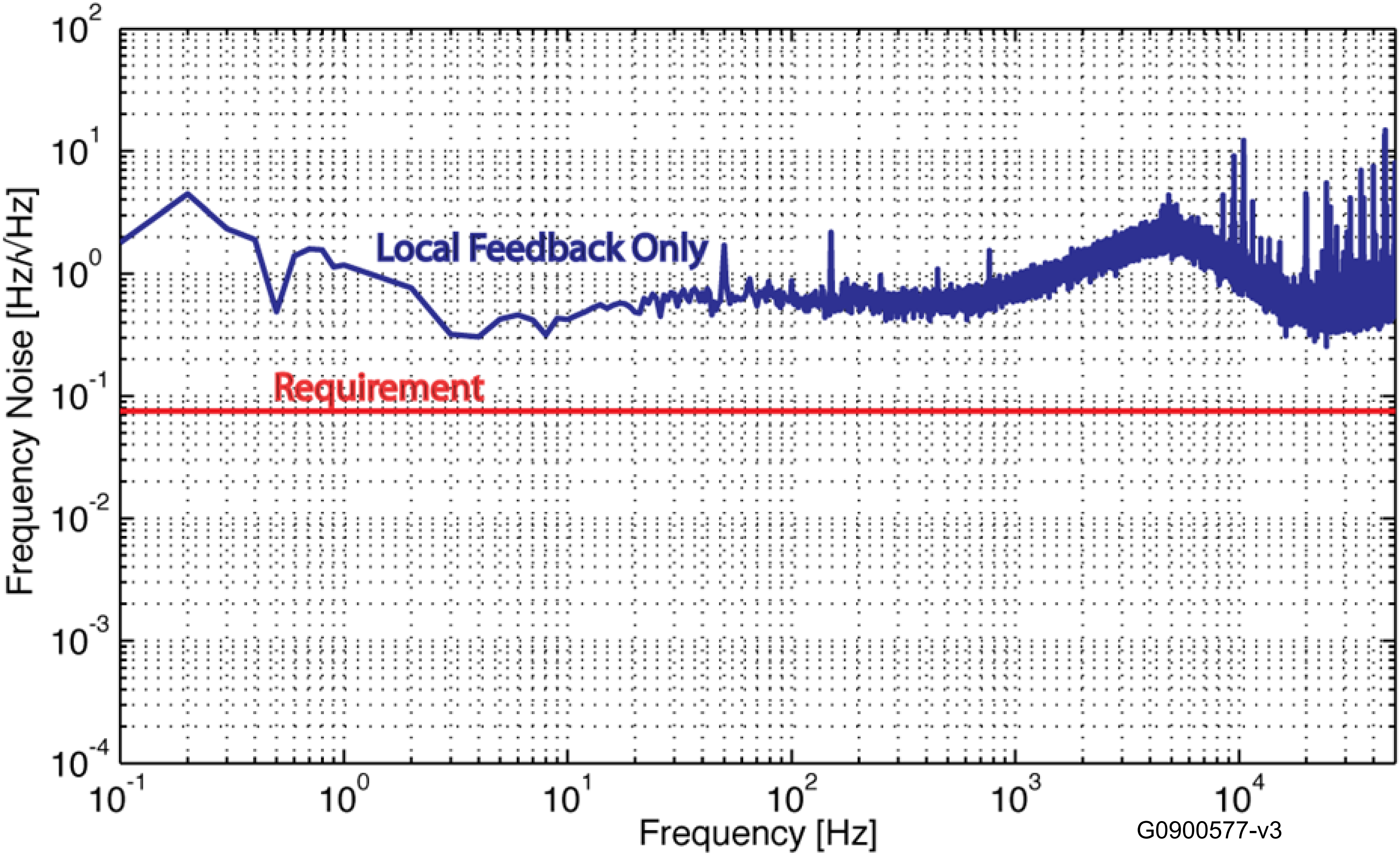
Fiber Noise Results



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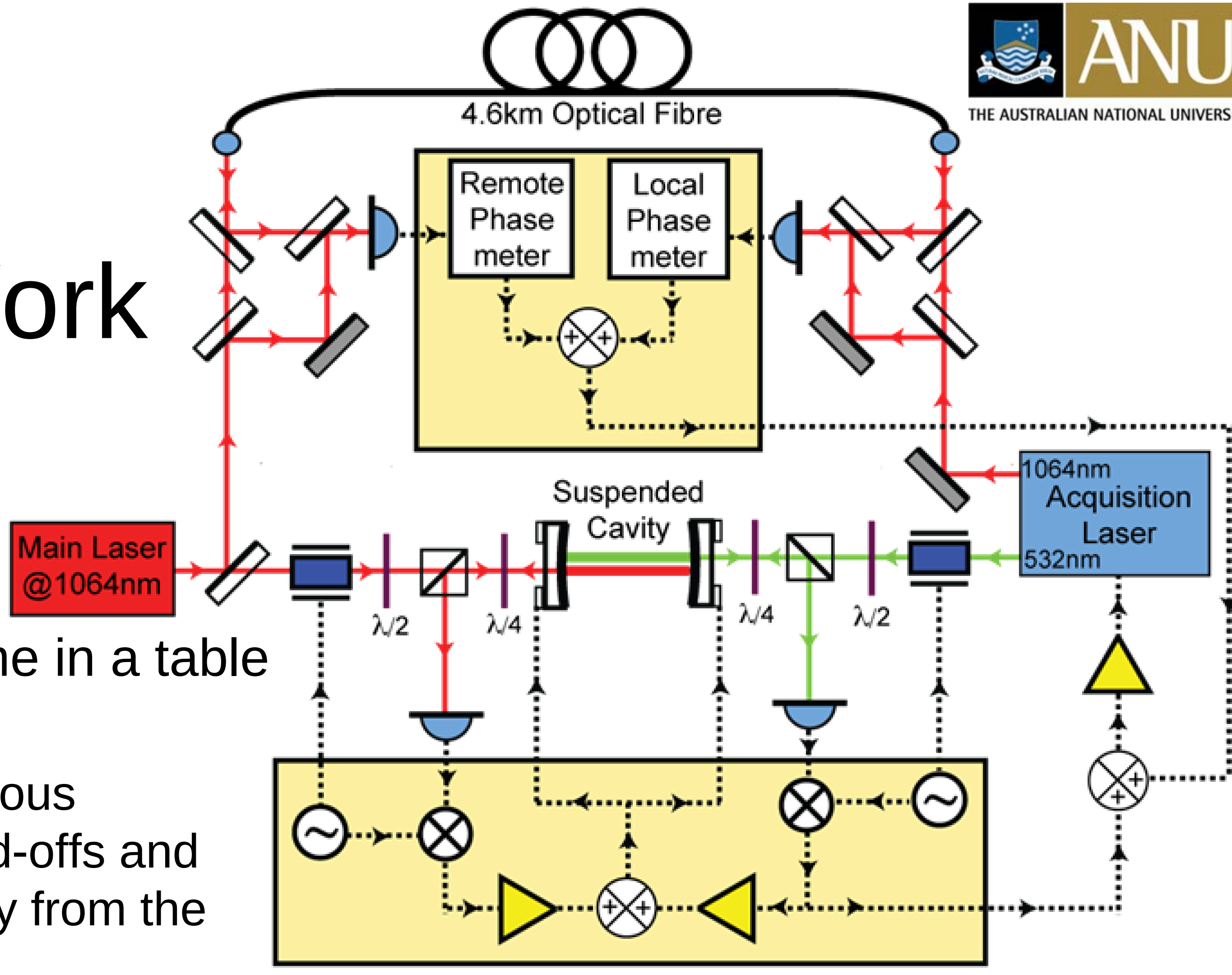
Future Work



- Test ALS scheme in a table top experiment
  - to test the various feedback hand-offs and offsetting away from the main laser
- Fiber noise cancellation scheme used
- Suspended cavity
- Testing fiber noise cancellation at caltech 40m
- Eventual testing of ALS at LIGO Hanford observatory (Nov 2010?)

Conclusion

- Advanced LIGO going ahead with PDH based “Arm Length Stabilisation” scheme to achieve deterministic Lock Acquisition of the interferometer.
- Technical issues being mitigated
  - Fiber phase noise issue solved
    - Need to integrate system into Advanced LIGO hardware

References

[1] http://www.ligo.caltech.edu/advLIGO

[2] Y. Aso, M. Ando, K. Kawabe, S. Otsuka and K. Tsubono; *Physics Letters A Volume 327, Issue 1;* "**Stabilization of a Fabry–Perot interferometer using a suspension-point interferometer**"; June 21, 2004

[3] D. Shaddock; *Optics Letters, Vol. 32, No. 22*; "**Digitally Enhanced Heterodyne Interferometry**"; November 15, 2007

[4] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley and H. Ward; *Appl. Phys. B* 31, 97; "**Laser phase and frequency stabilization using an optical resonator**"; June 1983

[5] B.J Slagmolen et.al. ; LIGO-T0900095-v2-D; **"Adv. LIGO Arm Length Stabilisation Requirements";** 2009-04-29

[6] B.J Slagmolen et.al. ; LIGO-T0900144-v1-D; **"Adv. LIGO Arm Length Stabilisation Design"**; 2009-04-29

[7] J. Ye et.al. ; *J. Opt. Soc. Am. B/Vol. 20, No.7; "***Delivery of high-stability optical and microwave frequency standards over an optical fiber network***";* July 2003

[8] P. A. Williams, W. C. Swann and N.R. Newbury; *J. Opt. Soc. Am. B/Vol. 25, No.8*; "**High Stability Transfer of an optical frequency over long fiber-optic links**"; August 2008