First Steps Towards the AEI 10m Prototype Single Arm Test Auto Alignment

Sean Leavey and the AEI 10m Prototype Team

Albert Einstein Institute
Hanover
Germany

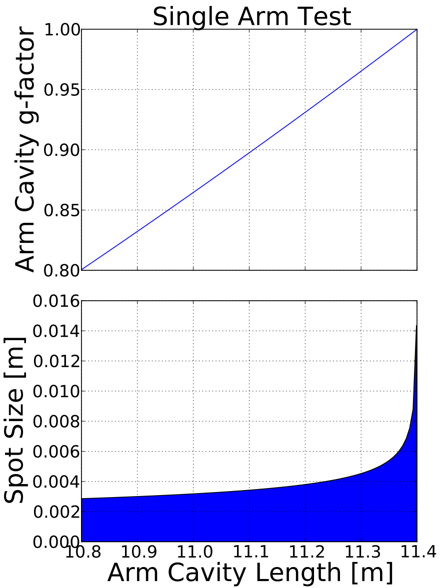
26th March 2014

The AEI 10m Prototype

- Test bed for sub-SQL experiments
- Michelson interferometer with Fabry-Perot arm cavities
- Suspended mirrors on isolated tables
- Nearly-unstable Fabry-Perot cavities

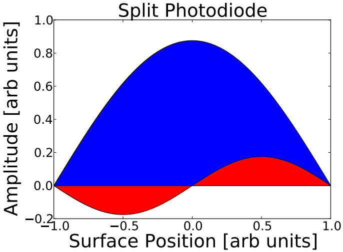
The Single Arm Test

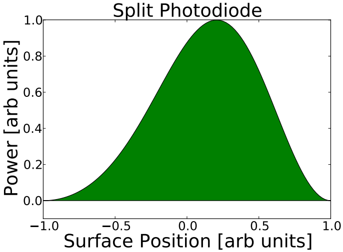
- South arm of the interferometer commissioned as a test
- Opportunity to learn about control of cavities close to instability ($g_1 g_2 = 1$)
- Iterative process of moving cavity length closer and closer to $11.395\,\mathrm{m}$
- Advanced LIGO will have g-factor of 0.832 and Advanced Virgo will have 0.871
- The single arm test will reach g-factors of 0.998



Alignment Sensing and Control

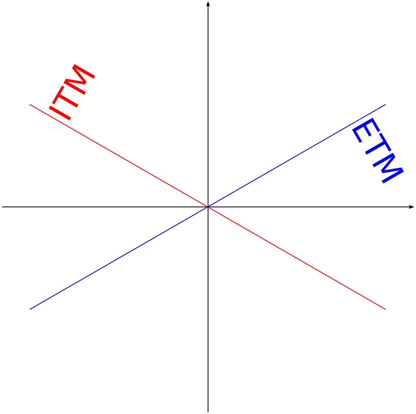
- The Single Arm Test mirrors need to be aligned
- Misalignments to cavity mirrors can be sensed with quadrant photodiodes
- A misaligned cavity mirror will couple light from the 0th order into the 1st order cavity mode, **proportionally to the misalignment** (for small angles)
- A suitable QPD can detect the amount of 1st order light indirectly through summing and subtraction of quadrants





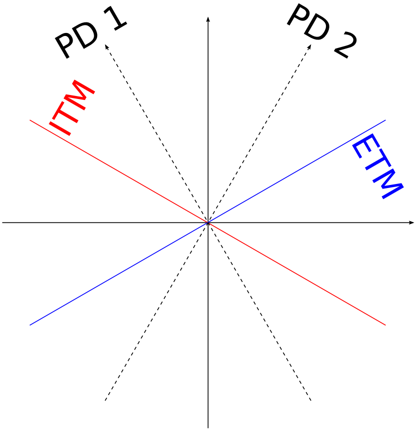
Alignment Sensing and Control

- For stable cavities, mirrors are separated in gouy space
- RF photodiodes can be 'tuned' to listen to a certain gouy phase associated with certain mirrors
- We want a matrix that is as diagonal as possible, simplifying correctional actuation



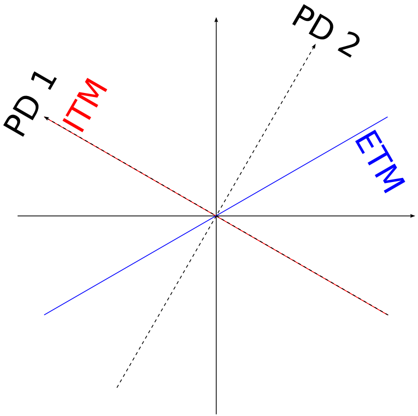
Alignment Sensing and Control

- One approach is to align each photodiode 90° from each mirror in gouy space
- This would provide alignment signals that are completely orthogonal
- However, PDs would need to be realigned for each cavity length



Alignment Sensing and Control

- Another approach is to use orthogonal (in gouy space) photodiodes
- PD 1's signal is 'tuned' to the ITM's gouy phase, seeing all of ITM, plus a small amount of ETM
- PD 2's signal contains none of ITM but most of ETM



Alignment Sensing and Control

The sensing matrix for this configuration might then look like:

$$\begin{pmatrix} a_{ITM,1} & a_{ITM,2} \\ a_{ETM,1} & a_{ETM,2} \end{pmatrix} = \begin{pmatrix} 1.0 & 0.0 \\ 0.1 & 0.9 \end{pmatrix}$$

where $a_{i,j}$ is the component of rotation in the ITM or ETM on PD 1 and PD 2.

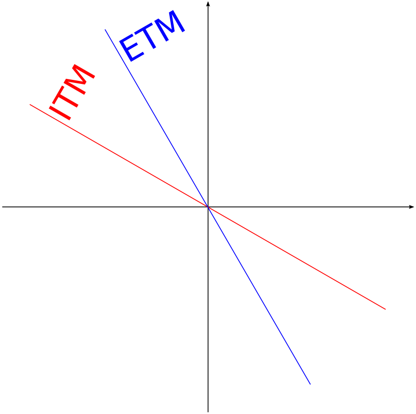
We only see the total in each column on our photodiodes, the vectors a_1 and a_2.

We want a_{ITM} and a_{ETM}, and it's still possible to obtain them with elementary row operations.

Sensing and Control Close to Instability

What happens close to instability?

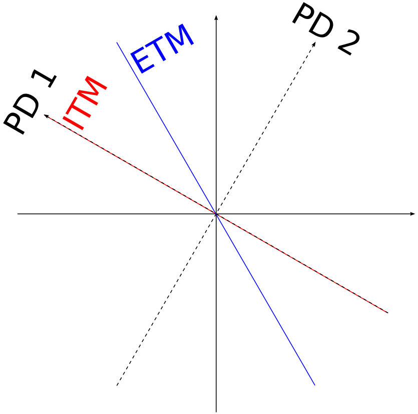
- As the cavity length becomes longer (i.e. as $g_1 g_2 \rightarrow 1$), the mirrors' gouy phases become more degenerate
- Cavity alignment becomes harder to control



Sensing and Control Close to Instability

Why does it become harder to control?

PD 1 contains a lot more of the ETM signal, and PD 2 contains a lot less of the ETM signal



Sensing and Control Close to Instability

Why does it become harder to control?

Even though the amount of 1st order mode and 0th order mode on the photodiodes changes, **the total light power stays reasonably constant** and so **the signal to noise level on PD 2 decreases**. The diagonalisation process of the control matrix then contains more noise for longer cavity lengths.

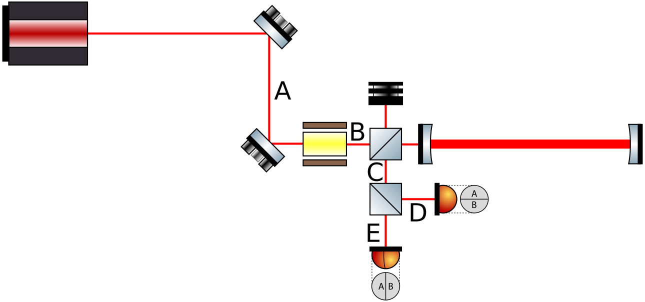
For a cavity close enough to instability, the signal to noise level will be low enough that the **readout noise becomes an issue**. At this point the cavity will potentially be 'uncontrollable'.

It's important, therefore, to know the **signal degeneracy towards cavity instability** so a proper noise budget can be calculated.

Simulations of the Single Arm Test

Layout

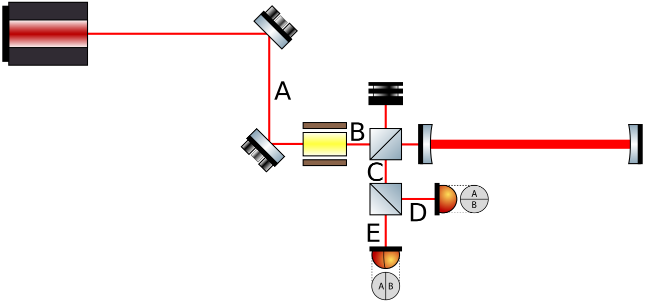
- A FINESSE model was developed using the parameters of the mirrors already purchased for the Single Arm Test.
- Two split photodiodes were positioned behind the ITM to look at light reflected from the cavity
- In FINESSE it is possible to set arbitrary gouy phases for spaces in the model



Simulations of the Single Arm Test

Tuning of Gouy Phases

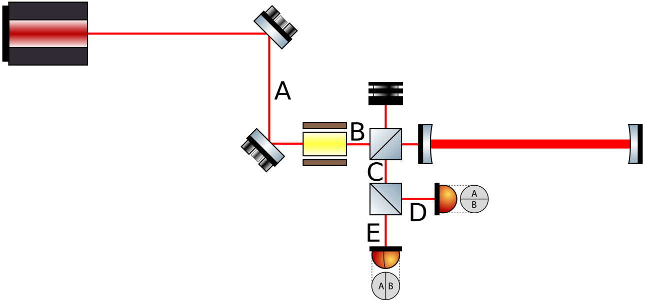
- Setting gouy phases $D = 0^\circ$ and $E = 90^\circ$ forces the photodiodes to be orthogonal
- Rotating the ETM and ITM in separate steps lets us look at the effect on the two photodiodes from each mirror
- Varying C's gouy phase lets us align one photodiode to maximise the signal it sees of one mirror's rotation



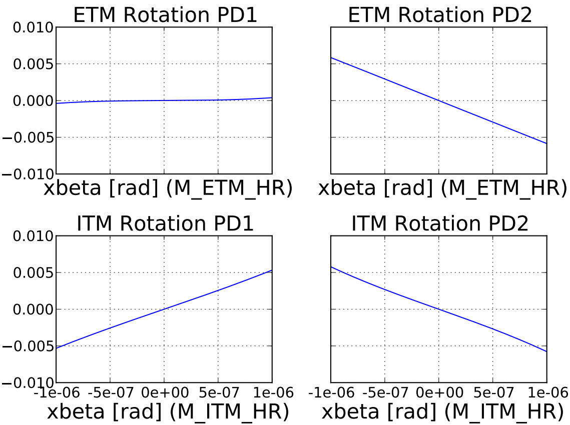
Simulations of the Single Arm Test

Varying the Cavity Length

- Changing the cavity length over multiple steps lets us look at how the signals degrade towards instability



Simulations of the Single Arm Test



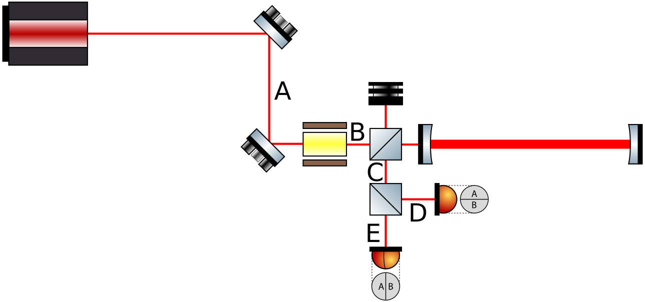
Control Matrix

- For each cavity length and common gouy phase, we want to see four split photodiode signals crossing zero

Simulations of the Single Arm Test

The Brute Force Approach

- For the kind of granularity we desire, this involves two simulations per gouy phase per cavity length at C. If we want gouy phase 'resolution' of 1°, that means $180 \times 2 = 360$ simulations per cavity length (ignoring smarter processes like Jacobian optimisations). For, say, ten cavity lengths, and with each simulation taking of order $4\,\mathrm{s}$ to complete, that's a lot of simulations to perform and store, and a long time.



Simulations of the Single Arm Test

Iteration

To perform these simulations, we have two options:

- SimTools - a MATLAB library for FINESSE
- PyKat - the new kid on the block

SimTools

SimTools runs in MATLAB, so any results produced can be stored in a MATLAB matrix or similar. However, there is no direct access to FINESSE object attributes in SimTools, and instead it performs string substitution.

PyKat

PyKat recreates the FINESSE environment as Python objects, which can be manipulated directly in Python. This is what I used!

Simulations of the Single Arm Test

Storing the Results

- Would be better to store the results in a file
- PyTables is a hierarchical dataset manager similar to ROOT used by particle physicists
- It stores data in rows in a single file, and this file can be queried for specific sets, e.g. all rows with gouy phase 48°
- Prevents simulations being performed twice if the results already exist

Future Analyses

- All data produced by FINESSE/PyKat is stored in PyTables
- This separates the simulations from the analyses
- It is possible to run a different analysis on the data by making a new Python script
- This will hopefully be useful later on when more parameters are known or constrained

Simulations of the Single Arm Test

Modularity

- The FINESSE definition is separate from each simulation script
- Each simulation script is separate from each analysis
- Different PyTables files may be specified for different analyses
- **This makes it possible to change the interferometer being simulated and avoid major revision to other code**

Optimising Common Gouy Phase

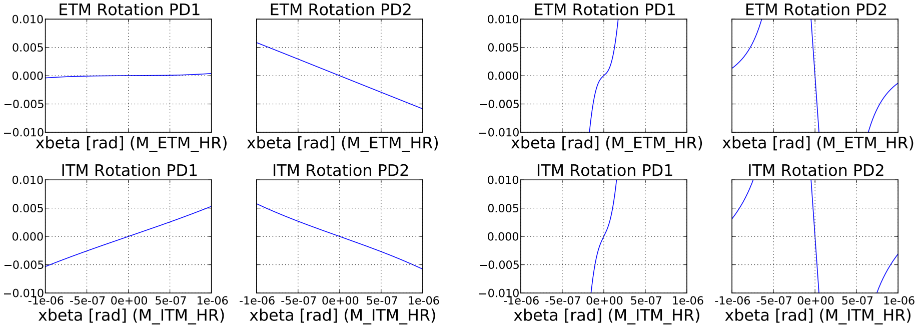
Figure of Merit

- Ultimately we need an error signal from the split photodiodes, so we care about the **gradient** of the zero crossing
- For each cavity length, we want to find a point where one signal's gradient is zero, meaning it sees nothing of one of the mirrors' rotation
- Due to the granularity of the gouy phases simulated, there is unlikely to be a true zero gradient in the dataset
- Instead, interpolate the lowest two gradients to find the gouy phase associated with the 'true zero' gradient

```
sleavey@sean-laptop-igr: ~/Workspace/Repositories/pt-designs/Modelling/Single Arm Test/S
File  Edit  View  Search  Terminal  Help

                Minimum gradient for ITM PD 2 found to be 167.044331723 at a com
mon gouy phase of 68 degrees
                Interpolated gouy phase giving zero gradient in ITM PD 2 = 67.53
55085093
                ITM PD 1 gradient at gouy phase 68 = 20601.7523369
                Interpolated ITM PD 1 gradient at gouy phase 67.5355085093 = 206
```

Looking at PD Signals



Towards Cavity Instability

- Gradients of zero crossings become more degenerate towards cavity instability
- Eventually these gradients will be indistinguishable when readout noise is considered

Looking at PD Signals

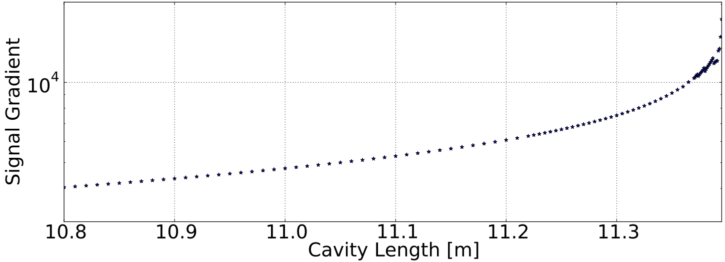
Towards Cavity Instability

- The common gouy phase associated with the **minimum** gradient on PD 2 during ITM rotation should automatically give us the **maximum** gradient on PD 1 (since the PDs are orthogonal)
- Then, looking at the ETM signal on PD 2 for this gouy phase tells us something about how the signal degrades towards instability

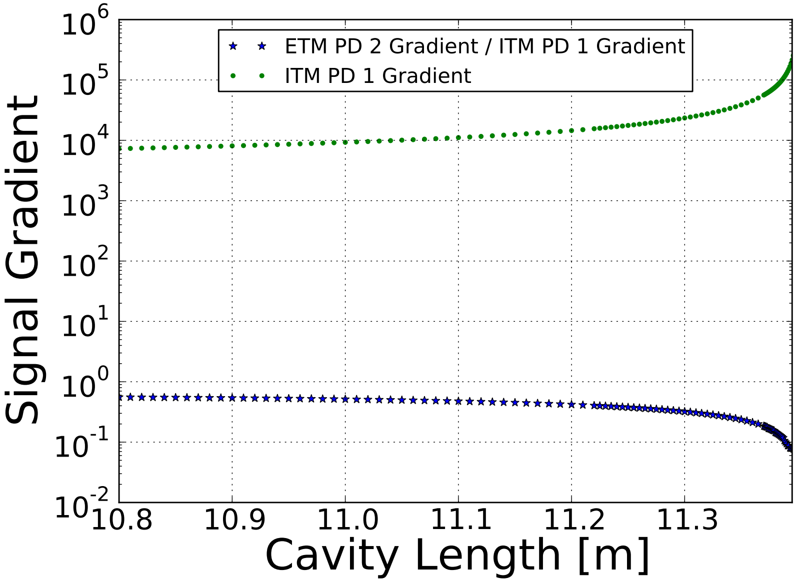
Looking at PD Signals

That's not the whole picture

- It turns out this signal *increases* towards cavity length (i.e. more 1st order mode light is present).
- This signal on its own doesn't tell us much though
- What we really care about is the **ratio of it to the ITM signal on PD 1** - recall the diagonalisation process
- It turns out that the ITM signal on PD 1 increases at an even greater rate towards instability, so the ratio decreases



Looking at PD Signals



What does this mean?

We are seeing the control matrix go from something like:

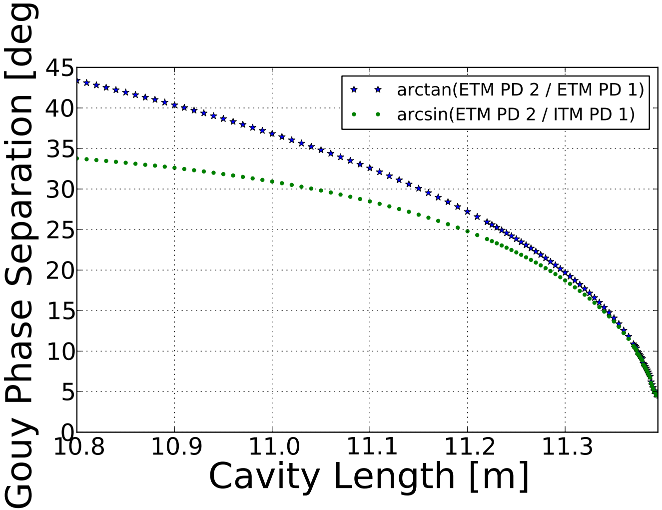
$$\begin{pmatrix} a_{ITM,1} & a_{ITM,2} \\ a_{ETM,1} & a_{ETM,2} \end{pmatrix} = \begin{pmatrix} \mathbf{1} & 0 \\ 0.1 & \mathbf{0.9} \end{pmatrix}$$

to something like:

$$\begin{pmatrix} a_{ITM,1} & a_{ITM,2} \\ a_{ETM,1} & a_{ETM,2} \end{pmatrix} = \begin{pmatrix} \mathbf{1} & 0 \\ 0.99 & \mathbf{0.01} \end{pmatrix}$$

In the latter case, the elementary (column) operation to diagonalise the matrix would involve multiplying the signal on PD 2 by 99, and therefore would also multiply the noise by 99.

How well do the photodiodes need to be aligned?



The photodiodes need to be aligned to within around 4° at the longest cavity length.

Summary

So Far

- Have understood some of the effects during misalignment
- FINESSE simulations built with a (hopefully) easy to use interface for assessing different parameter spaces in the future
- Shown the level of degeneracy towards the cavity length limit
- Shown how well the photodiodes need to be aligned in gouy space

Next Steps

- Need to take into account the noise sources present during control. Control should be shot noise limited, but the amount of light power in each mode for misalignments near instability is not necessarily a straightforward calculation
- Need to understand the effects of mirror distortions. These can couple light into higher order modes even when no mirror misalignment is present

End

Thanks for your attention!