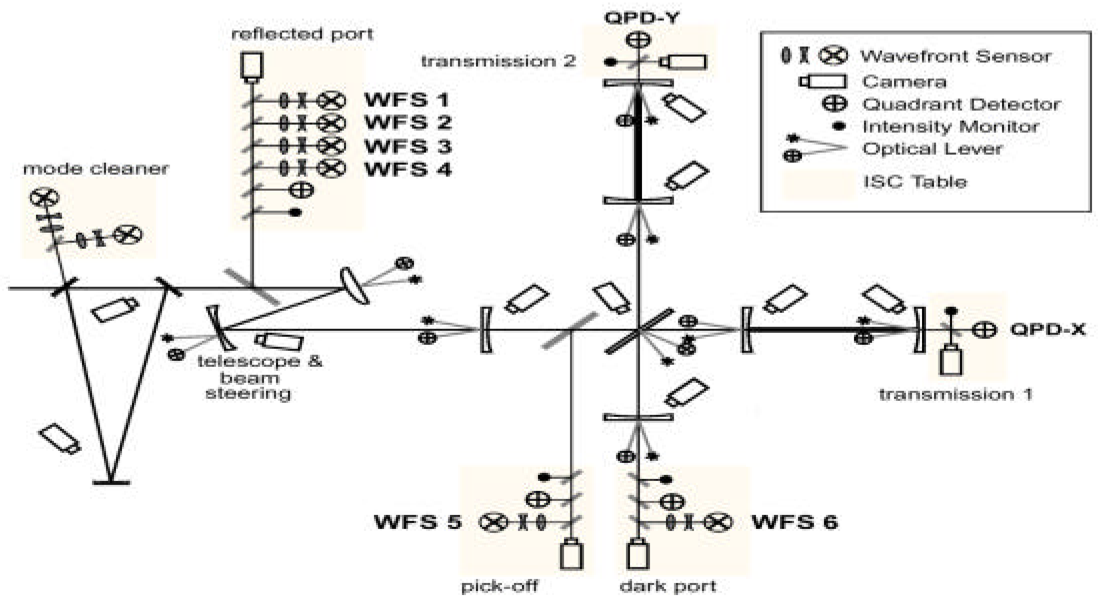
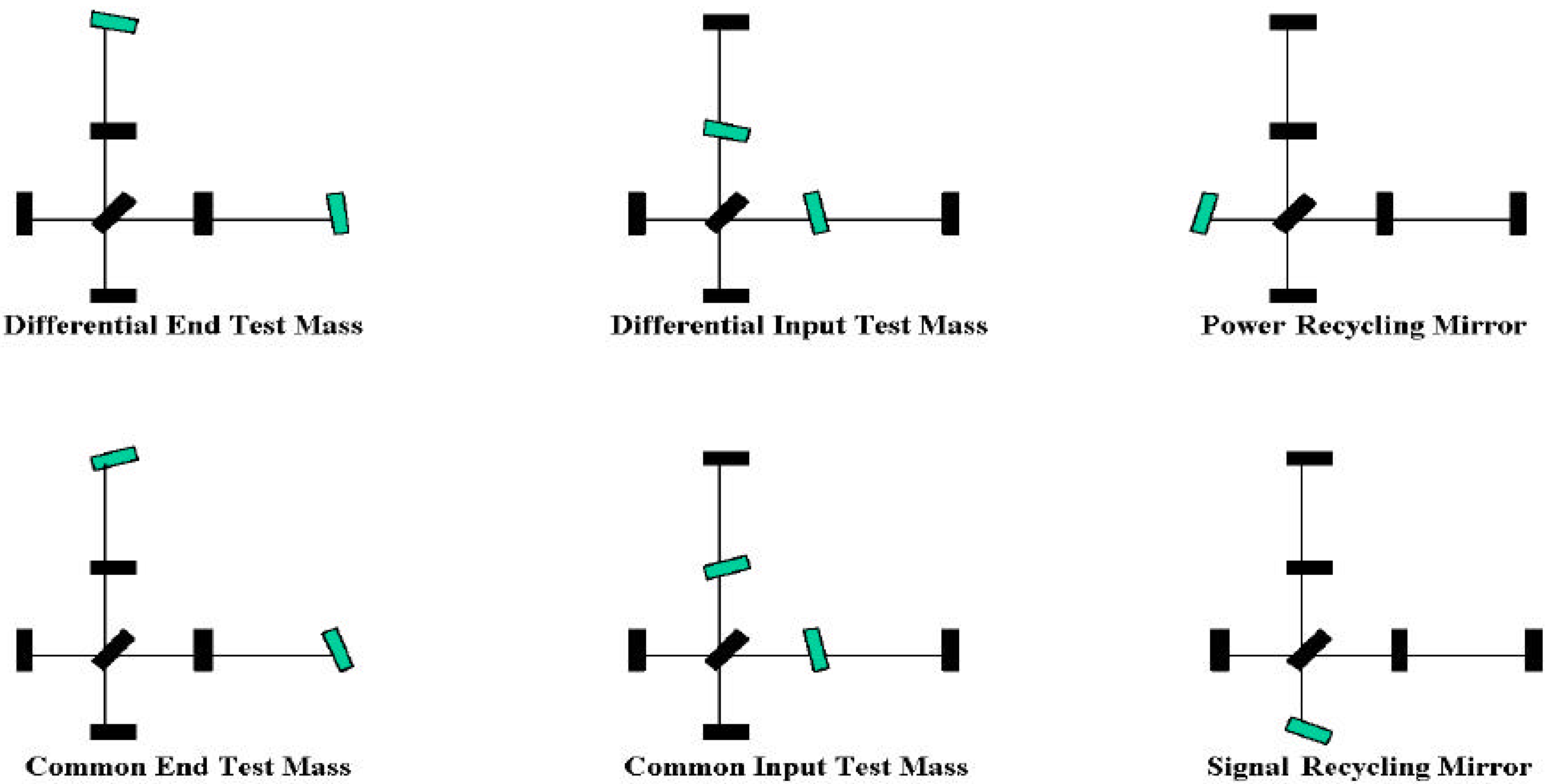
Wavefront Sensing for Advanced LIGO

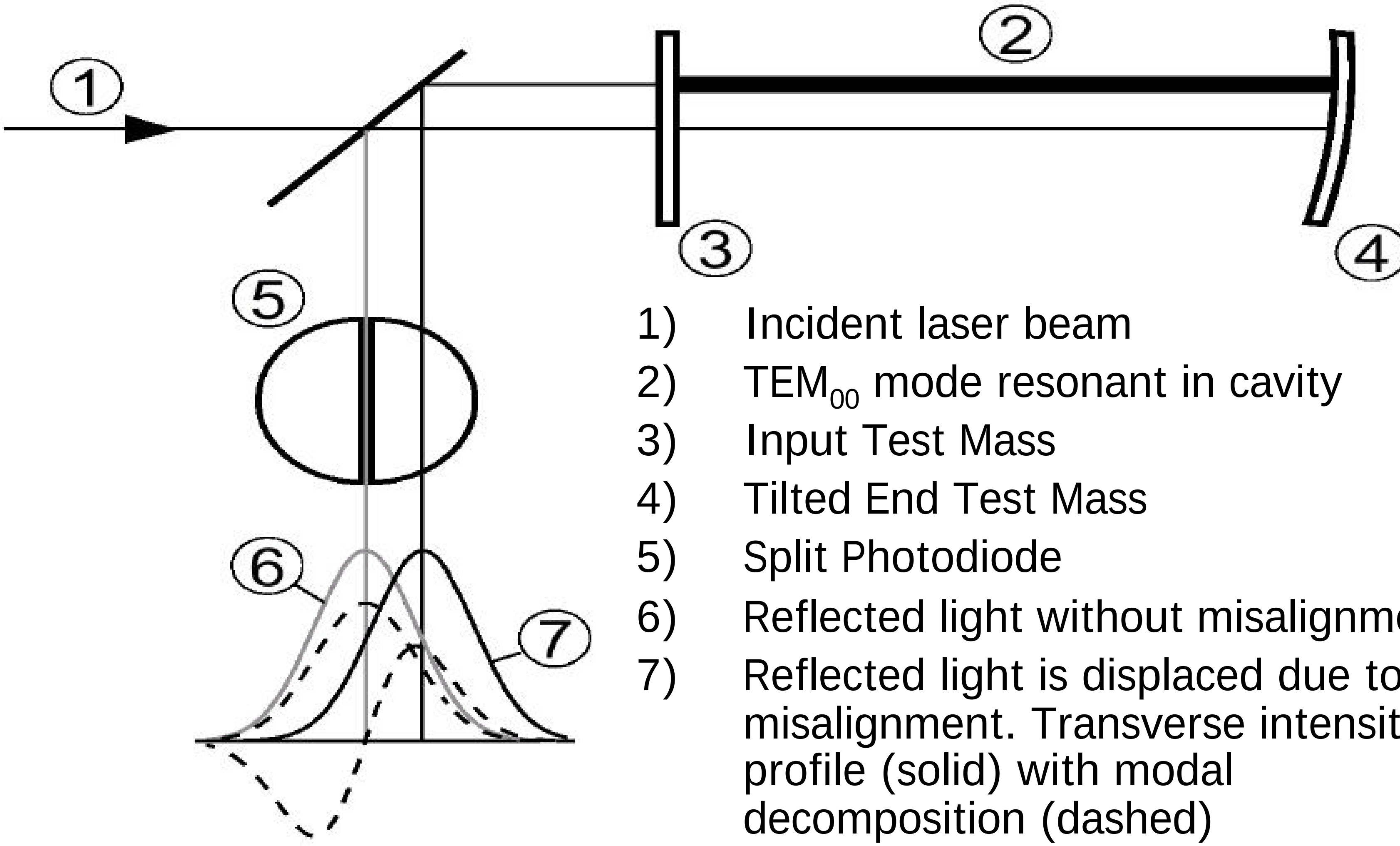


- Model of wavefront sensing in a dual-recycled interferometer
- Consequences for the design of length and alignment control systems for the 40m prototype and Advanced LIGO

Angular degrees of freedom



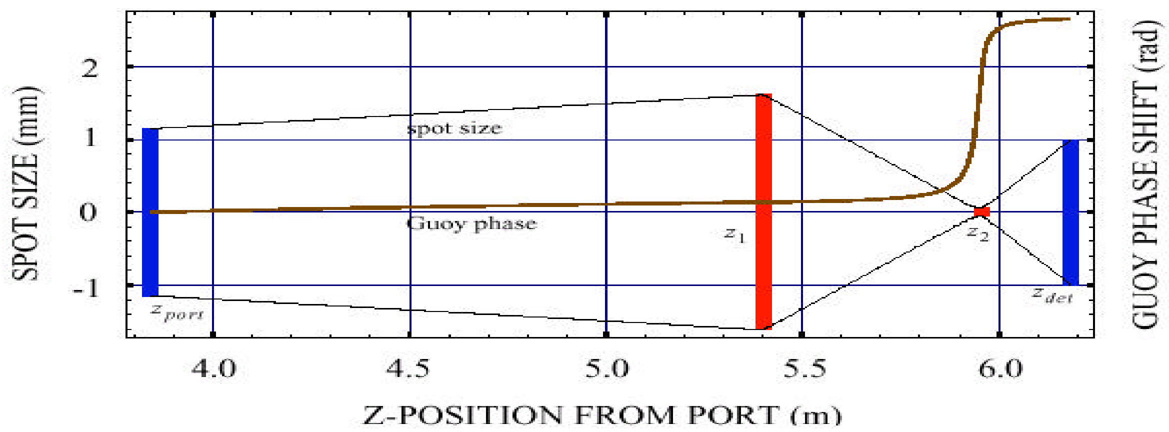
Misalignment of a simple Fabry-Perot cavity

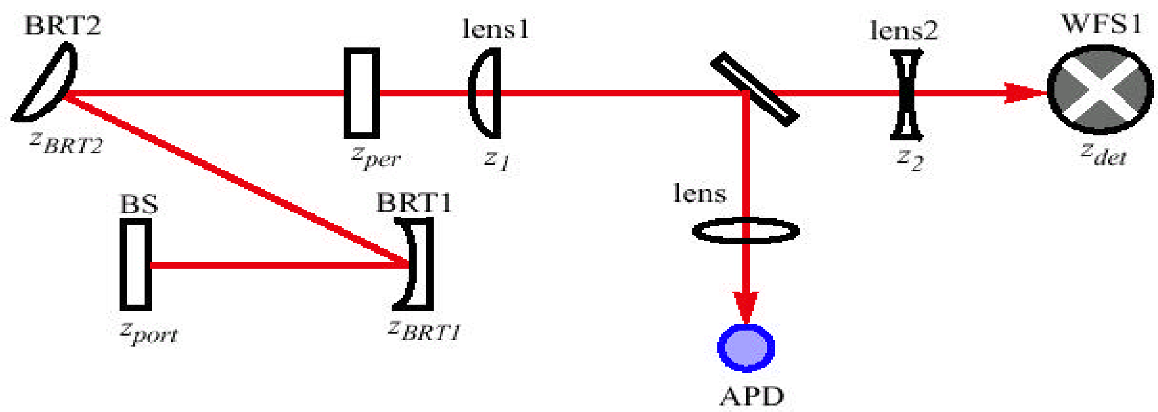


1) Incident laser beam
2) TEM_{00} mode resonant in cavity
3) Input Test Mass
4) Tilted End Test Mass
5) Split Photodiode
6) Reflected light without misalignment
7) Reflected light is displaced due to misalignment. Transverse intensity profile (solid) with modal decomposition (dashed)

Guoy Phase Telescope

- Adjusts beam diameter to make spot fit onto photodiode
- Introduces Guoy-phase advance of our choice





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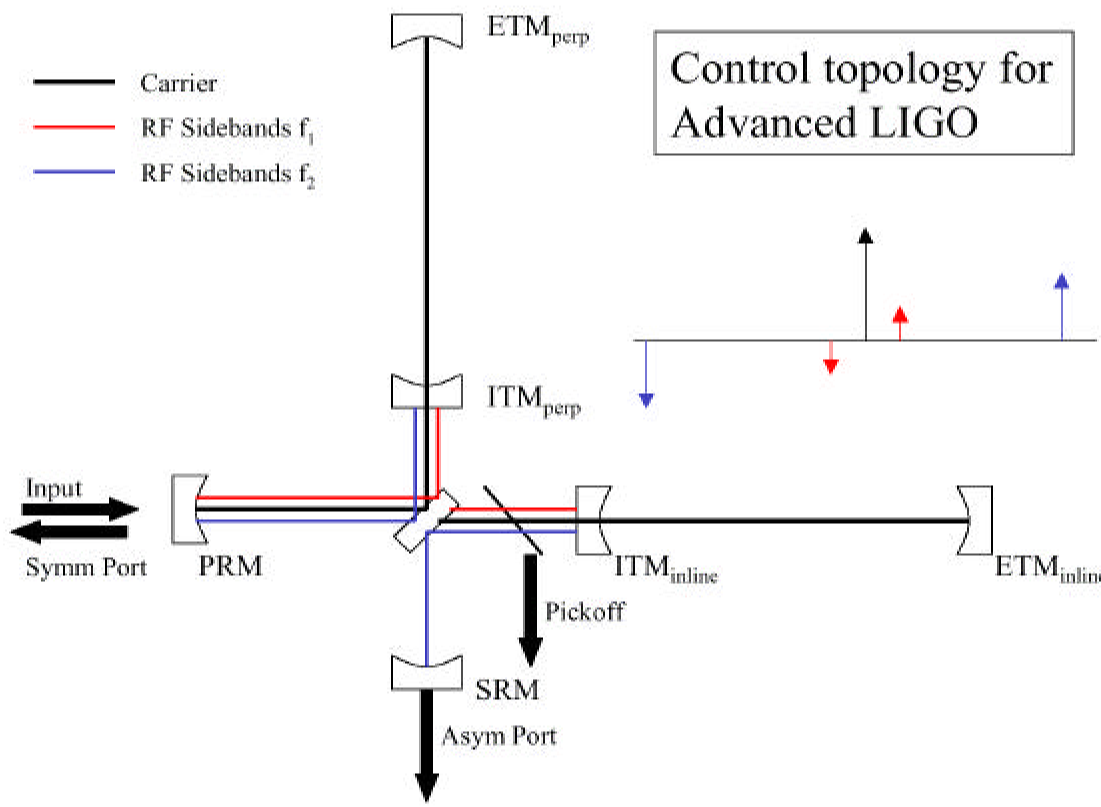
Current Design of the Advanced LIGO Control System

- Two pairs of resonant sidebands
- One resonant in both power recycling and signal recycling cavity, the other one only in power recycling cavity
- One pair of sidebands as low as possible in frequency (limited by dimensions of vacuum envelope) the other as high as possible (limited by current demodulation technology)
- Three output ports: Bright port, dark port, pick-off



Wavefront sensing at 180 MHz

- Initial-LIGO wavefront sensors are tuned RF quad-segmented photodiodes
- At 166 Mhz, capacitive coupling between the segments would be far too large to provide adequate geometric separation of the signals
- Solutions are possible:
  - Geometric splitting of the beam into 4 beams, via a prism or pyramidal mirror array
  - Scanning of the beam across an array of independent photodiodes
  - spiral scan around a pinhole as in the wavefront camera

Building a model of alignment sensing in a dual-recycled interferometer

- Calculate steady state field of TEM_{00} mode in perfectly aligned state
- Treat any tilted mirror as a source of TEM_{10} mode
- Propagate both modes to the various output ports and perform demodulation
- Construct the most favorable wavefront sensing matrix, which relates misalignments in the six different degrees of freedom to signal levels in the six wavefront sensors, by choosing appropriate locations, demodulation frequencies and phases for the sensors
- The goal is to make this sensing matrix as diagonal as possible
- Implement all this in a Mathematica notebook
- Calculation for initial LIGO was done by “Modal Model” software developed by D. Sigg – but for Advanced LIGO we had to start from the scratch.
- Involves numerous approximations...

How do you construct a reasonable wavefront sensing scheme?

- Given a set of parameters defining the interferometer as such, there are potentially many ways to construct a sensing scheme
- For each of the six wavefront sensors, we pick:
  - A demodulation frequency, which determines whether we detect beats of sideband 1 against carrier, sideband 2 against carrier or of the two sidebands against each other
  - A location at one of the three output ports
  - An RF phase for the demodulation process
  - An artificially introduced Guoy phase advance that effectively shifts TEM_{00} and TEM_{10} components with respect to each other

- You have to choose wisely, otherwise it won't work!
- Intuition built up from Initial LIGO, LSC, is less useful for AdvLIGO

Wavefront Sensing Matrices

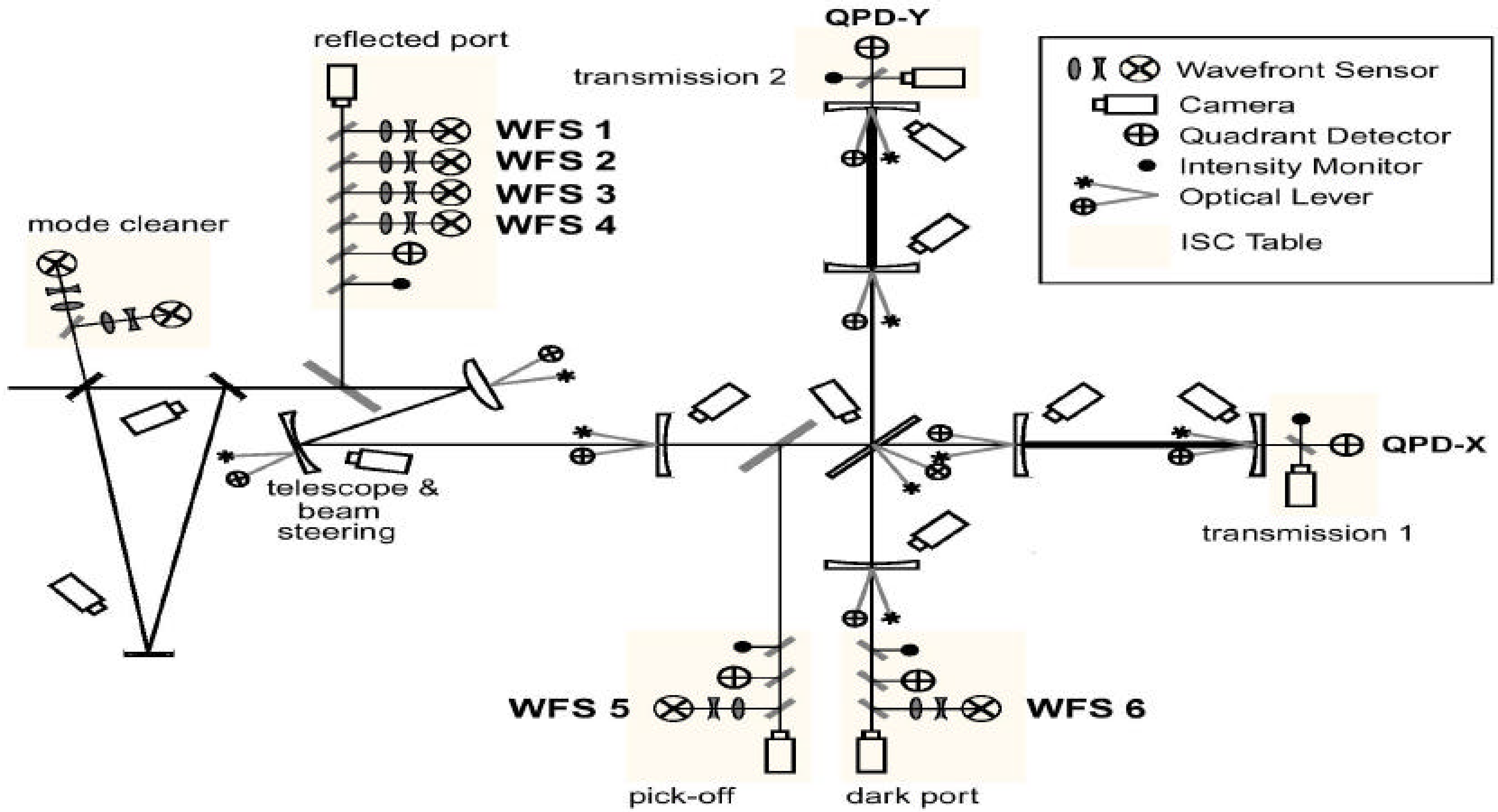
"Port"	"Demodulation"	"Guoy"	"RF"	"DETM"	"DITM"	"CETM"	"CITM"	"PRM"	"SRM"
"Asym. Port"	"Carrier_Sideband2"	130	49	2.32	1.33	0	0.01	-0.02	0
"Sym. Port"	"Carrier_Sideband1"	42	79	0	0.18	0.03	0.04	-0.01	0
"Sym. Port"	"Carrier_Sideband2"	126	147	0.02	0.04	0.73	-0.02	0.25	0.22
"Sym. Port"	"Carrier_Sideband1"	108	175	-0.01	0.04	-0.32	-1.76	0.78	0.04
"Pickoff"	"Carrier_Sideband1"	133	7	0	0	0	0.10	-0.09	0
"Sym. Port"	"Sideband1_Sideband2"	98	47	0	-0.02	0	0.24	-0.07	-0.13

For the 40m prototype: Not diagonal, but it could be worse...

"Port"	"Demodulation"	"Guoy"	"RF"	"DETM"	"DITM"	"CETM"	"CITM"	"PRM"	"SRM"
"Asym. Port"	"Carrier_Sideband2"	128	53	26.12	24.17	0	0	0	0
"Asym. Port"	"Carrier_Sideband1"	164	85	3.08	2.85	0	0	0	0
"Sym. Port"	"Carrier_Sideband1"	89	168	0	-0.01	-2.67	-3.13	0.66	0
"Sym. Port"	"Carrier_Sideband2"	100	140	0	-0.01	0.81	1.17	-0.51	-0.21
"Sym. Port"	"Carrier_Sideband1"	163	158	0	-0.04	-0.71	-4.09	2.48	0.01
"Sym. Port"	"Sideband1_Sideband2"	157	114	0	0.02	0	-0.79	1.51	-0.71

For Advanced LIGO: This is worse! Can you see why?

A Possible Wavefront Sensing Scheme for the 40m or Advanced LIGO



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Results of Simulation

- Wavefront sensing in a dual-recycled interferometer is more complex than for the LIGO I configuration (as expected)
- Nevertheless it's possible to obtain all necessary information by using just two pairs of resonant sidebands
- No need for non-resonant sidebands
- Most favorable place for pickoff is antireflection coating of beam splitter
- Crucial points:
  - Alignment of signal recycling mirror, which has a weak error signal that never appears in isolation
  - Distinguishing between the differential modes of the input and end test masses
  - Distinguishing between common input test mass motion and power recycling mirror motion
- Even though one can construct a manifestly non-singular wavefront sensing matrix, it will never be perfectly diagonal, i.e. we need a ***multiple-input multiple-output control system***

Design of a Control System for Advanced LIGO

- Design needs to take into account alignment sensing as well as length sensing
- Current design of control system is optimized only with respect to sideband power in the recycling cavities
- We find that high power levels ***do not*** guarantee optimal alignment signals
- We propose changes in the parameters for Advanced LIGO, to reconcile the requirements of length and alignment sensing
- In particular, we suggest altering the Schnupp asymmetry, the signal recycling cavity length and potentially the sideband frequencies
- For the 40m prototype we (luckily) find that the current design offers a reasonable sensing scheme

Conclusions

- Using our model we can calculate wavefront sensing matrices for both initial and advanced LIGO for any given set of parameters
- The model has been tested, compared with other simulations and was found to be correct
- Given such a tool, we can chose sets of parameters for Advanced LIGO and the 40m prototype that optimize both length and alignment sensing
- We determine the wavefront sensing matrix for the 40m interferometer and propose an improved configuration for the Advanced LIGO control scheme