LIGO-G980155-00-D

ONE YEAR AT THE 40 METER

(School of Hard Locks)

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LIGO Science Seminar

Caltech - PasadenaΓCalifornia

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†Work at Caltech supported by LIGO Visitor's Program

Outline

- Summary of 40 Meter Status

- 40 Meter *vs* LIGO – Comparison
  - Optics Refresher
  - Instrument Comparison

- Why Can't We Align the IFO While Maintaining Lock? (Snapshot of most important investigation underway)

- Wave Front Sensing at the 40 Meter

- Michigan Gravity Wave Group (MGWG)
  - Contributions
  - Plans

Summary of 40 Meter Status

Configuration

- LIGO-like topology
  Recycling cavity with Fabry-Perot (FP) arms;
  Schnupp asymmetry
- Three of six masses with LIGO-like core optics suspensions
  - Single-wire loop
  - Permanent Magnet actuation
  - Four-layer isolation stacks
- Low-loss optics (514 nm)
- Single-frequency frontal modulation servo scheme
- LIGO-like PSL system
- Wave Front Sensing (WFS) available for auto alignment
  (Using hardware / software adapted from MIT FMI)
- Wide scale use of digital controls & filtering
- LIGO-like DAQ and data display programs in place

Summary of 40 Meter Status

Recycling Operation Accomplishments

- Power Recycled Michelson (PRM) cavity locked (2-servo bootstrap) – 11/97
- Full recycled IFO lock – 12/97
- PRM behavior confirmed to agree with design (GainsΓalignment sensitivityΓdegeneracy)
- Investigation of modal structure via RF sideband resonances
- Full control of PRM alignment via WFS
- Control of single end-mass alignment DOF via WFS

Summary of 40 Meter Status

Work in Progress or Immediately Planned

- Investigate lock instability when IFO best aligned

- Confirm previous determination that IFO is under-coupled
  (Due to anomalously high arm losses)

- Determine servo dynamic ranges / gain margin limitations

- Complete WFS control of end-mass alignments
  (Expected to reduce large power fluctuations in arms)

- Identify and fix worst noise sources

- Take one week of data (December 12-18)
  with all DAQ channels recorded

Summary of 40 Meter Status

The 40 Meter Crew in 1998[†]:

Caltech

Mark Coles[1]ΓBill KellsΓJenny Logan[2]Γ
Nergis Mavalvala[3]ΓSteve Vass

U. Michigan

Dick GustafsonΓKeith RilesΓJamie Rollins[4]

Short-term Visitors

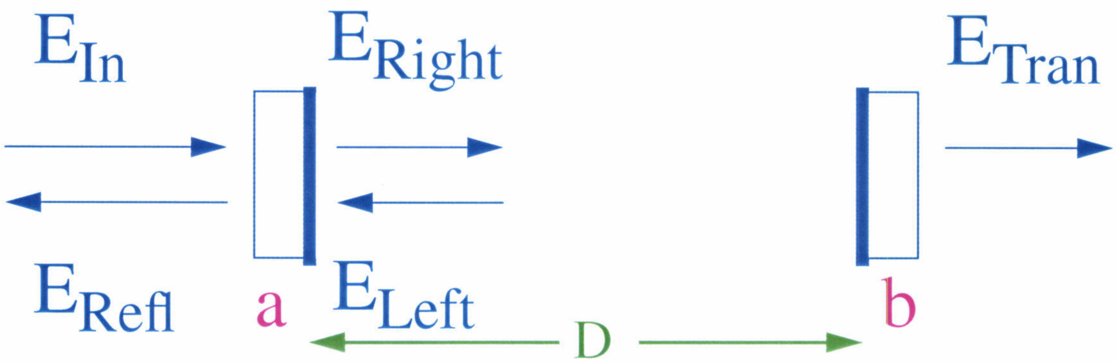
Raffaele Flaminio (VIRGO)ΓKoji Arai (TAMA)

[1]Departed in June for Livingston
[2]Departed in September for JPL
[3]Began 40M work in September
[4]Began 40M work in May

[†] Many thanks to S. AndersonΓR. BorkΓH. DingΓJ. HeefnerΓA. IvanovΓ W. MajidΓS. TilavΓand L. Wallace

40 Meter *vs* LIGO – Comparison

Cavity Optics Refresher:



Conventions used:

$$R_i = r_i^2; \qquad T_i = t_i^2; \qquad L_i = 1 - R_i - T_i$$

$$r_a, r_b > 0; \qquad \phi = 2kD - 2\,\phi_{\mathrm{Guoy}}$$

Steady-state equations†:

$$E_{Right} = t_a E_{In} - r_a E_{Left} \qquad E_{Left} = -r_b e^{i\phi} E_{Right}$$

$$E_{Refl} = r_a E_{In} + t_a E_{Left} \qquad E_{Tran} = t_b e^{i\phi/2} E_{Right}$$

Solutions:

$$\frac{E_{Refl}}{E_{In}} = \frac{r_a - (1-L_a) r_b e^{i\phi}}{1 - r_a r_b e^{i\phi}}$$

$$\frac{E_{Tran}}{E_{In}} = \frac{t_a t_b e^{i\phi/2}}{1 - r_a r_b e^{i\phi}}$$

Resonance (anti-resonance) when $\phi = 0$ (π)

†Time dependence discussed later

Closer Look at Transmission

On resonance:

$$\frac{E_{Tran}}{E_{In}} = \frac{t_a t_b}{1 - r_a r_b}$$

Power away from resonance:

$$\left|\frac{E_{Tran}}{E_{In}}\right|^2 = \frac{t_a^2 t_b^2}{1 + r_a^2 r_b^2 - 2\, r_a r_b \cos\phi}$$

For $r_a, r_b \approx 1\Gamma$

$$\mathrm{FWHM}_\nu \approx \frac{c}{2D}\frac{1 - r_a r_b}{\pi\sqrt{r_a r_b}} \equiv \frac{\mathrm{FSR}}{\mathrm{F}}$$

where FSR = Frequency spacing between cavity resonances

and F = Finesse $\equiv \pi\sqrt{\frac{r_a r_b}{1 - r_a r_b}}$

For $(1 - r_b) \ll (1 - r_a) \ll 1\Gamma$

$$\mathrm{F} \approx \frac{\pi}{1 - r_a}$$

High Finesse $\Longrightarrow$ Sharp Resonance

$\Longrightarrow$ Large Power Buildup

40 Meter *vs* LIGO – Comparison

40 Meter arms:

$$r_a \approx 0.997$$

$$r_b \approx 0.99994$$

$$\Longrightarrow \mathrm{F} \approx 1100$$

LIGO arms:

$$r_a \approx 0.985$$

$$r_b \approx 0.999960$$

$$\Longrightarrow \mathrm{F} \approx 207$$

Closer Look at Reflection

On resonance:

$$\frac{E_{Refl}}{E_{In}} = \frac{r_a - (1 - L_a)\, r_b}{1 - r_a r_b}$$

For $(1 - r_a), (1 - r_b) \ll 1\Gamma$

expand $r_i = \sqrt{(1 - T_i - L_i)} \approx 1 - \frac{1}{2}(T_i + L_i)$

$$\frac{E_{Refl}}{E_{In}} \approx -\frac{T_a - (L_a + T_b + L_b)}{T_a + (L_a + T_b + L_b)}$$

$$\approx -\frac{T_a - \Sigma(\text{Losses})}{T_a + \Sigma(\text{Losses})}$$

Some jargon:

"Overcoupled" means $\frac{E_{Refl}}{E_{In}} < 0$

"Undercoupled" means $\frac{E_{Refl}}{E_{In}} > 0$

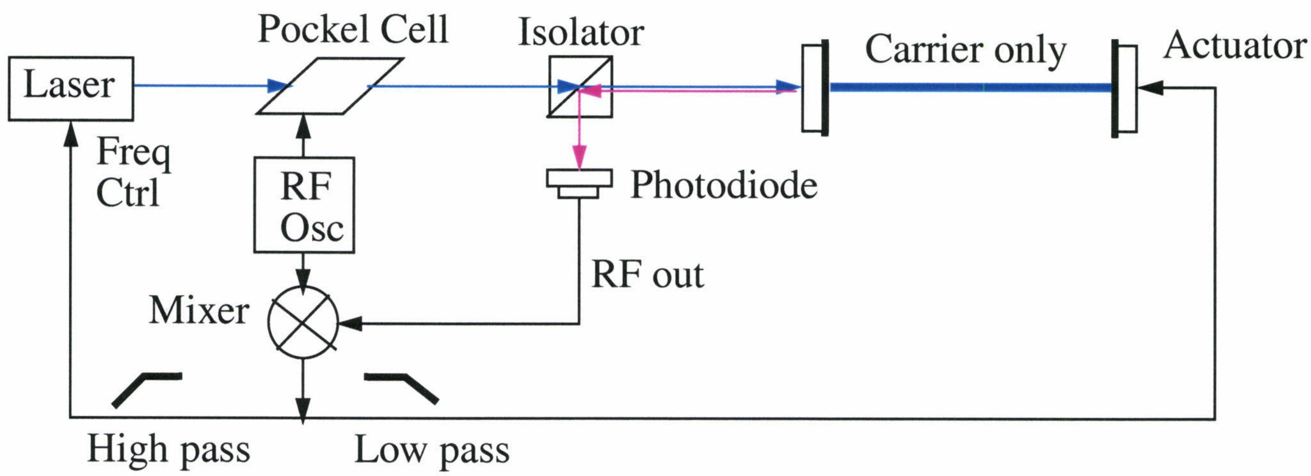
$\Sigma(\text{Losses}) <$ input mirror transmission $\Longrightarrow$ Overcoupled

End mirror absent $(\frac{E_{Refl}}{E_{In}} = +r_a)$ $\Longrightarrow$ Undercoupled

40 Meter *vs* LIGO – Comparison

How does one "lock" to resonance?

Pound-Drever-Hall technique:



Phase-modulate light such that

- Carrier resonates in cavity: $N\lambda_{\mathrm{CR}} = 2\,D$
- Sidebands (nearly) anti-resonate: $(N \pm m + \frac{1}{2})\lambda_{\mathrm{SB}} = 2\,D$

Requires:

Modulation frequency $f_{mod} = (m + 1/2) \times \mathrm{FSR}$

(or $D = \frac{1}{2}(m + \frac{1}{2})\lambda_{mod}$)

40 Meter arms: $f_{mod} = 32.7$ MHz $(m \approx 8)$

LIGO arms: $f_{mod} = 24.6$ MHz $(m \approx 650)$

40 Meter *vs* LIGO – Comparison

What exactly is the locking signal?

Phase modulated light:

Pockel cell gives $E_{In} = E_0\, e^{i\omega t}\, e^{i\Gamma \cos \Omega t}$

where $\omega \gg \Omega\Gamma$ $\Gamma \equiv$ modulation depth$\Gamma$and

$$\begin{aligned} e^{i\Gamma\cos(\Omega t)} \quad \approx \quad & J_0(\Gamma) && \text{(carrier)} \\ & + iJ_1(\Gamma)e^{i\Omega t} + iJ_1(\Gamma)e^{-i\Omega t} && \text{(1st sidebands)} \\ & - J_2(\Gamma)e^{2i\Omega t} - J_2(\Gamma)e^{-2i\Omega t} && \text{(2nd sidebands)} \end{aligned}$$

For time average over many ω cycles (but $\ll 1\ \Omega$ cycle)Γ

Photodiode power $\propto$ $|E_{In}|^2$ $=$ Constant

$\Longrightarrow$ No detectable modulation in power!

Now shift phase of carrier by ϕ:

$$|J_0 e^{i\phi} + iJ_1 e^{i\Omega t} + iJ_1 e^{-i\Omega t}|^2 = J_0^2 + 2\,J_1^2 + 4J_0J_1\sin(\phi)\cos(\Omega t)$$

$\Longrightarrow$ "1 Ω" signal at 1st order in Γ

$\Longrightarrow$ Provides RF error signal for servo to zero out

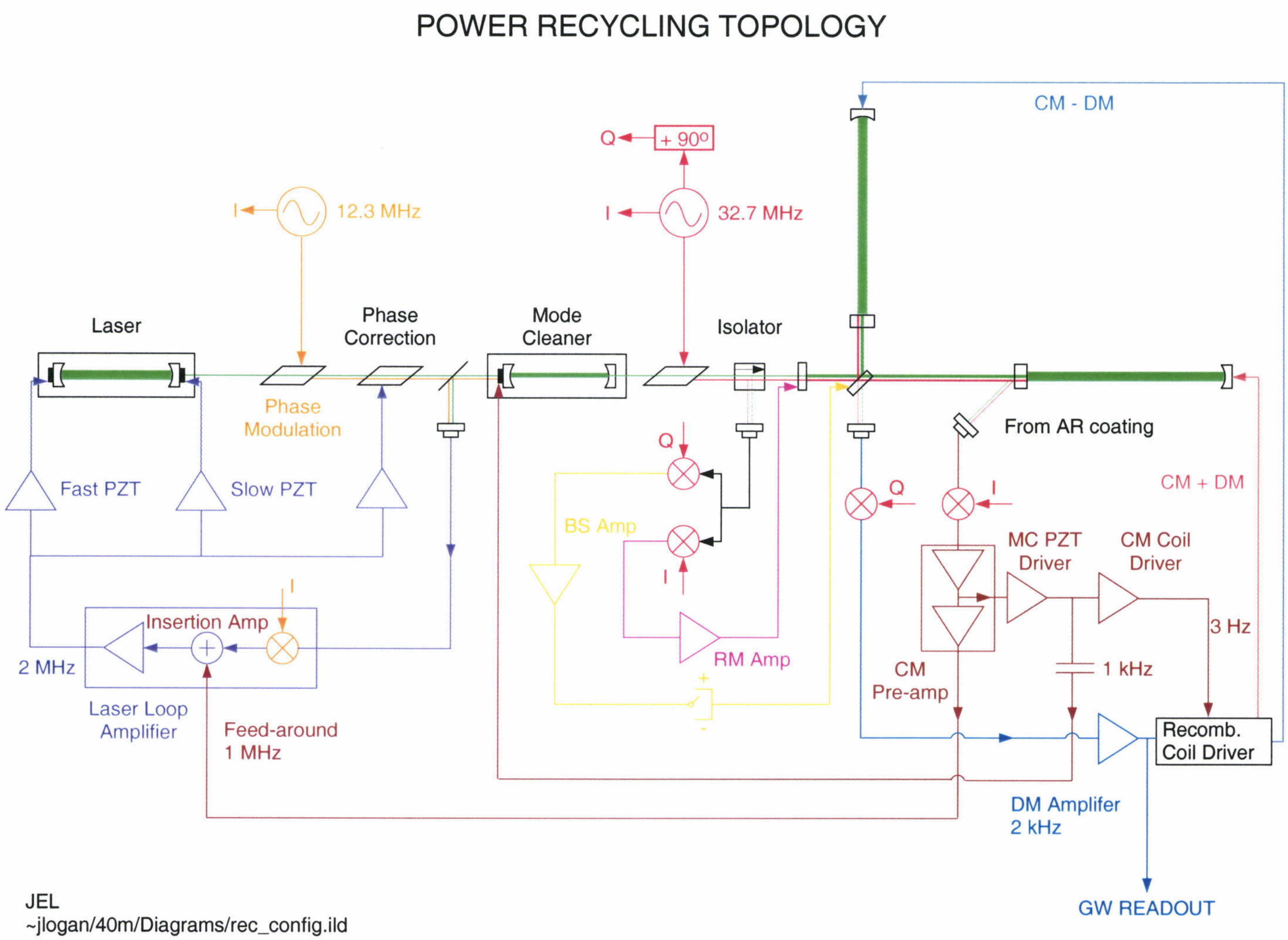
$\Longrightarrow$ Zeroing ϕ brings cavity to resonance

40 Meter *vs* LIGO – Comparison

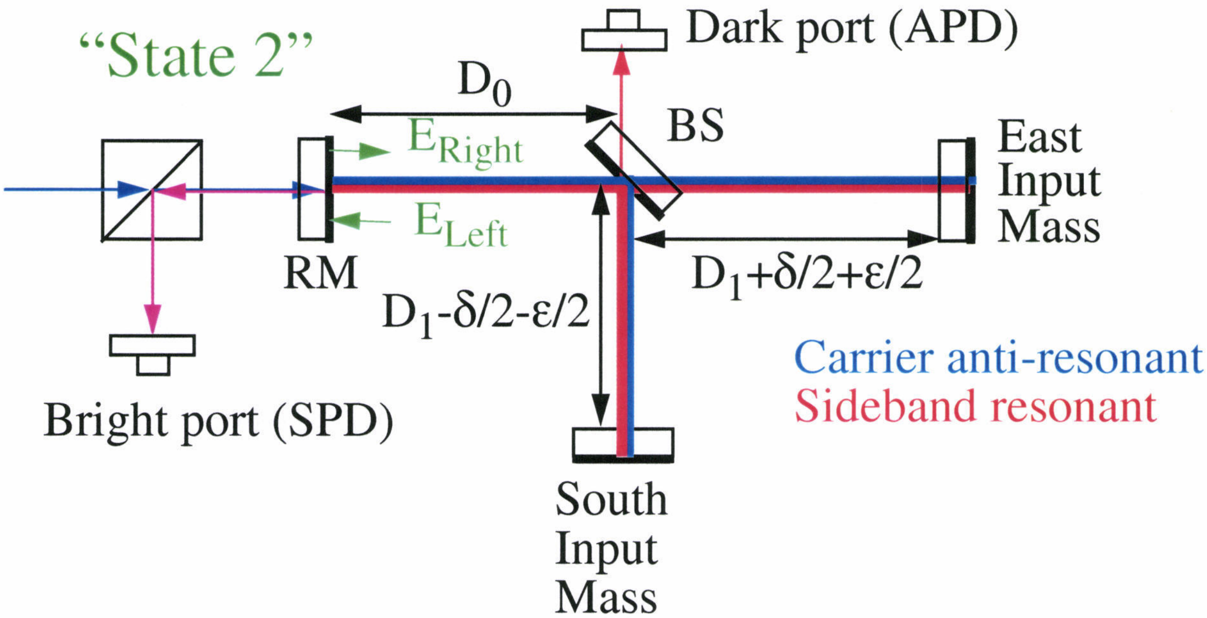
Same basic technique used to lock recycling cavity but

- Average recycling length $= \frac{1}{4}\,\lambda_{mod}$
- Initially sideband resonantΓcarrier anti-resonant ("State 2")
- Then both resonant in full lock ("State 4") (works because carrier overcoupledΓ sidebands undercoupled to arms)
- Will come back to this later

Present Power Recycled 40 Meter Configuration:



Locking the Michelson Servo (BS)



where

δ = Fixed non-zero length asymmetry

ϵ = Transient deviation from ideal (tiny)

$D_0 + D_1$ = Average recycling cavity length

$\alpha \equiv (\Omega_{mod}\,\delta)/c$

$$\begin{aligned} E_{Left} \quad &\propto \quad J_0 - 2\,i J_1 \cos(\alpha)\cos(\Omega t) \\ & \qquad -2\,J_1 \sin(\alpha)\sin(k\epsilon)\sin(\Omega t) \end{aligned}$$

Last term in phase with $J_0 \implies$ Non-zero 1 Ω signal

40 Meter *vs* LIGO – Comparison

Quadrature-phase signal:

$$|E_{Left}|^2 \quad \propto \quad J_0 J_1 \sin(\alpha) \sin(k\epsilon) \sin(\Omega t)$$

Actual SPD quad-phase signal more complicated

But essential behavior the same:

$\Longrightarrow$ Need $\alpha \neq 0$ ($\delta \neq 0$) to obtain error signal

$\Longrightarrow$ Servo drives $\epsilon \rightarrow 0$

40 Meter: $\alpha = 0.37$ rad

LIGO: $\alpha = 0.11$ rad

40 Meter *vs* LIGO – Comparison

Storage Times

Finite speed of light

$\Longrightarrow$ Finite power buildup time

$\Longrightarrow$ Frequency-dependent optical gain

Arms:

$$\begin{aligned}\tau &\approx \frac{\mathrm{F}}{\pi(\mathrm{FSR})} \\ &\approx 87\mu s \qquad \text{(40 Meter)} \\ &\approx 1.7ms \qquad \text{(LIGO)}\end{aligned}$$

Corresponding single-cavity poles:

$$\begin{aligned}f_{\mathrm{pole}} &\equiv \frac{1}{2\,\pi\tau} \\ &\approx 1.8\ \mathrm{kHz} \qquad \text{(40 Meter)} \\ &\approx 91\ \mathrm{Hz} \qquad \text{(LIGO)}\end{aligned}$$

Different f_{pole} values:

$\Longrightarrow$ Different shot noise shapes in GW band

Some recycling cavity signals see double-cavity pole:
(from full IFO power buildup)

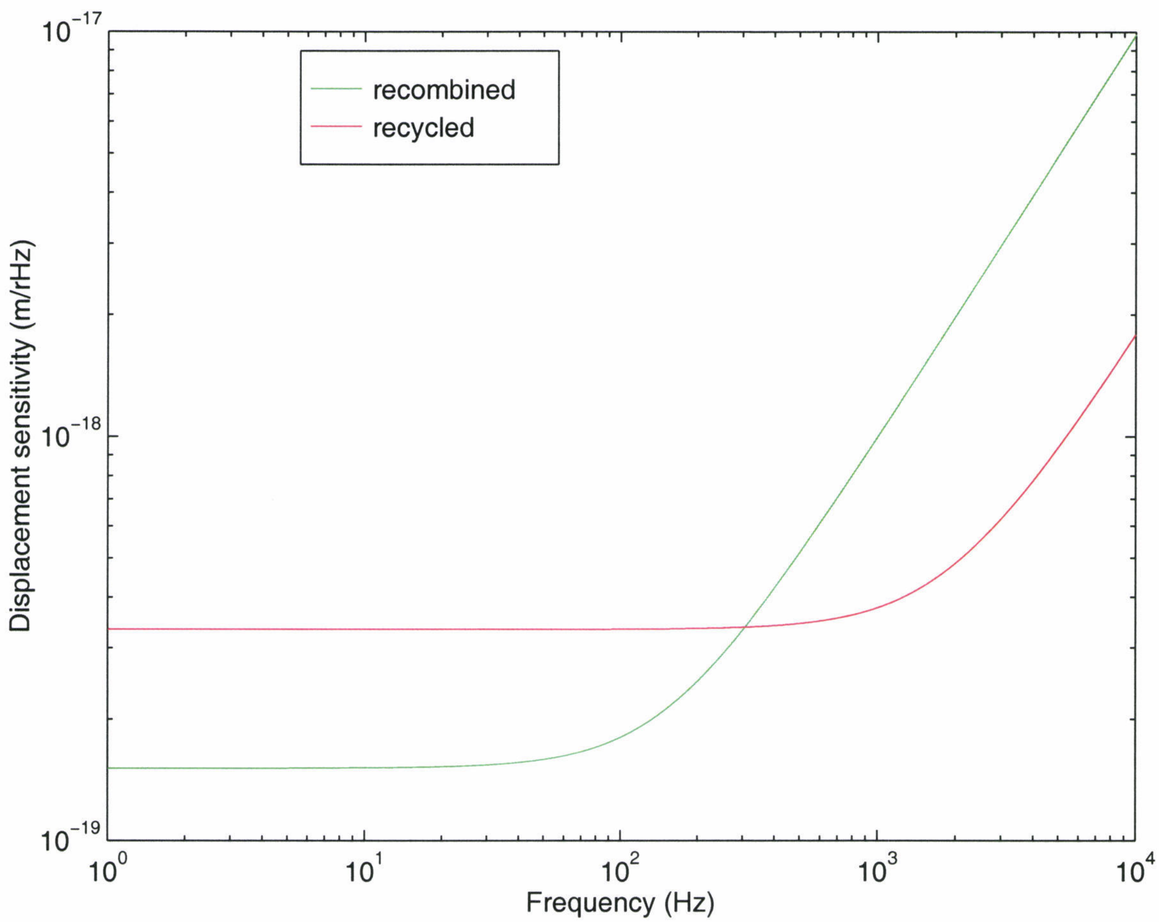
$$\begin{aligned}f_{2-\mathrm{pole}} &\approx 900\ \mathrm{Hz} \qquad \text{(40 Meter)} \\ &\approx 1\ \mathrm{Hz} \qquad \text{(LIGO)}\end{aligned}$$

40 Meter *vs* LIGO – Comparison

Effect of Storage Time on Shot Noise Shape

Green: Previous Recombination (high-finesse arms)

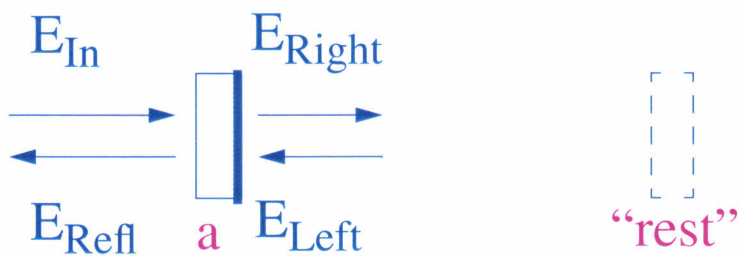
Red: Present Recycling (designΓnot actual)



(Figure courtesy of J. Logan)

Recycling Gain

Recall basic cavity fields (generic):



Impractical to directly measure internal arm field
But IS practical to pick off internal recycling cavity light

$$\frac{E_{Right}}{E_{In}} = \frac{t_a}{1 + r_a r_{\mathrm{rest}}}$$

Where $r_{\mathrm{rest}} \equiv$ reflection coefficient of "rest" of generic cavity (previously $r_{\mathrm{rest}} = -r_b\, e^{i\phi}$)

For "a" $\equiv$ Recycling Mirror (RM) and "rest" $\equiv$ armsΓ
Define $r_c \equiv$ arm reflectivity of carrier on resonance (<0)

Then for the carrier in full IFO lock:

$$\frac{E_{Recyc.\,Cav}}{E_{In}} \equiv g_{\mathrm{CR}} \equiv \frac{t_{\mathrm{RM}}}{1 + r_{\mathrm{RM}} r_c}$$

40 Meter *vs* LIGO – Comparison

Power amplification:

$$\text{Recycling gain} \equiv G_{\mathrm{CR}} \equiv g_{\mathrm{CR}}^2$$

Some numbers:

	40 Meter (≈actual)	40 Meter (design)	LIGO
r_{RM}	0.93	0.93	0.985
r_c	−0.88	−0.94	−0.9898
g_{CR}	2.1	3.0	6.7
G_{CR}	4.4	9.2	46

Sidebands also have a recycling gainΓ
where $r_{\mathrm{rest}} = -r_{\mathrm{Mich}} = -\cos\alpha$

$$g_{\mathrm{SB}} \equiv \frac{t_{\mathrm{RM}}}{1 - r_{\mathrm{RM}} r_{\mathrm{Mich}}}$$

More numbers:

	40 Meter (≈actual)	40 Meter (design)	LIGO
r_{Mich}	0.93	0.93	0.994
G_{SB}	5.5	6.7	17

40 Meter *vs* LIGO – Comparison

Mode Matching

Mode mismatch usually denotes imperfect match of input beam waist location / size to resonant values for cavity

But more generally also refers to misalignments of mirrors that mismatch beam direction and transverse location to resonant cavity values

Both mismatches degrade IFO performance

Relatively easy to tune alignment (and necessary daily)
But have not attempted to tune waist matching in 1998 (should be stable)

How does one check mode matching?

Two techniques used so far; both use reflected light from one resonating arm locked with simple Michelson
(developed by B. Kells)

- Measure DC light on and off arm resonance
- Measure "2Ω" signal on and off resonance

Results:

- 1st technique seems robust
  $\Longrightarrow M \geq 90\%$ (both arms)
- 2nd technique less robustΓmore sensitive to cancellations
  $\Longrightarrow$ Consistent with $M \approx 100\%$ (both arms)

40 Meter *vs* LIGO – Comparison

Other (Nitty-Gritty) 40 Meter / LIGO Differences

- LIGO control dominated by digital servos
- 40 Meter an amalgam of digital / analog controls

- LIGO has uniform suspensions
- 40 Meter has newΓsomewhat newΓoldΓ
  and really old suspensions

- LIGO has fully engineered modern electronics
- 40 Meter has engineered electronics
  plus physicist-designedΓphysicist-built kludges
  plus some stuff so old the solder is crumbling

- LIGO has Pockel cell outside vacuum
- 40 Meter has Pockel cell in vacuum
  - Limits choise of crystal
  - Vacuum aggravates RF heating damage
  - Infrequent access for testing / tuning

- LIGO at seismically quiet sites
- 40 Meter experiences mild quakes $\approx$ 1 / month
  disruptive quakes $\approx$ 1 / 6 months

40 Meter *vs* LIGO – Comparison

But 40 Meter does have some advantages...

- LIGO has invisible IR laser
- 40 Meter has easily visible green laser

- LIGO's end stations are a 5-minute drive away
- 40 Meter's end stations are a 15-second walk away

Why Can't We Align the IFO?

The Problem:

- Cannot acquire / maintain full IFO lock
  when alignment is optimal

Observations:

- Can acquire / maintain lock when one end mass orientation ($e.g.$ΓEE pitch) is grossly misaligned
- As alignment is improvedΓIFO power fluctuations grow (Oscillations at $\approx$1 Hz)

Possible causes:

- Servo instability due to gain increaseΓ
  $i.e.$Γexceeding gain margin
  (Common Mode (CM) or Differential Mode (DM) servos)
- Loss of adequate low-frequency gain due to gain decrease
  (Recycling Mirror (RM) or Beam Splitter (BS) servo)
- Sign change in servo – Critical IFO coupling of carrier
  (RM or BS servo)

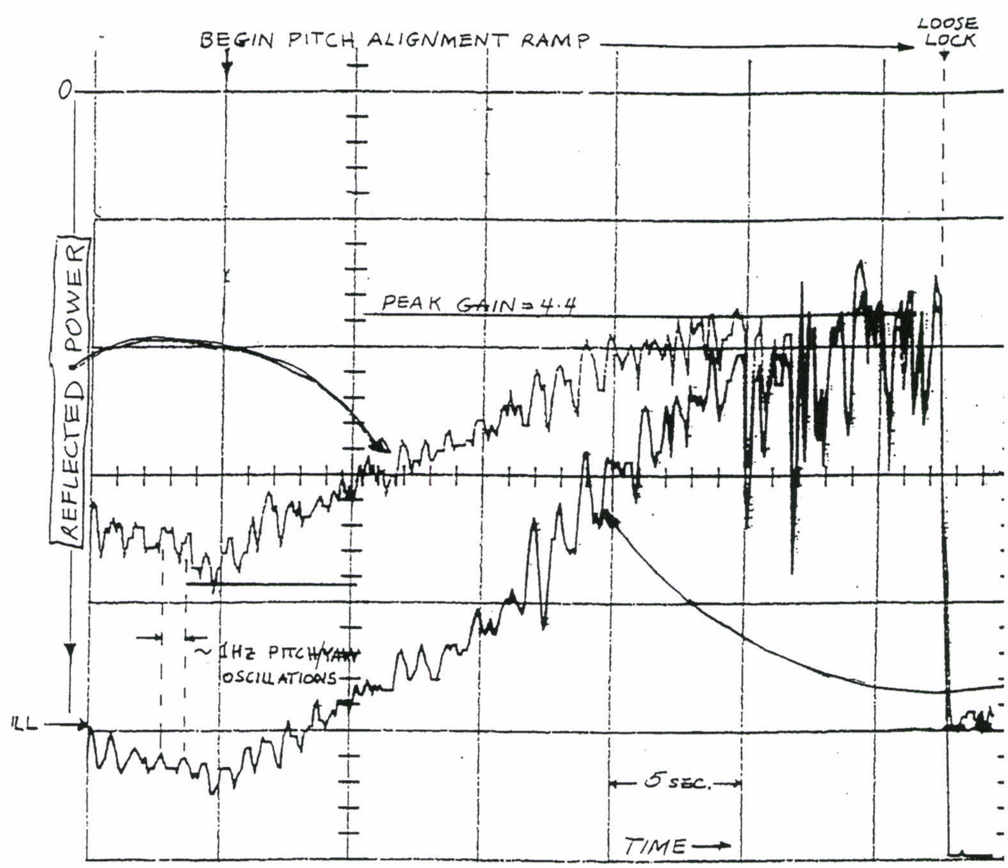
Why Can't We Align the IFO?

Other possible causes:

- Change in shape of servo loop gain (*e.g.*ΓsaturationΓstorage time effects)
- Interaction between longitudinal servos (*e.g.*Γbreakdown of CM / RM gain heirarchy)
- Interaction between longitudinal / orientation servos
- Interaction between longitudinal / PSL servos
- Hidden electronic saturation

Why Can't We Align the IFO?

Illustration of effect:



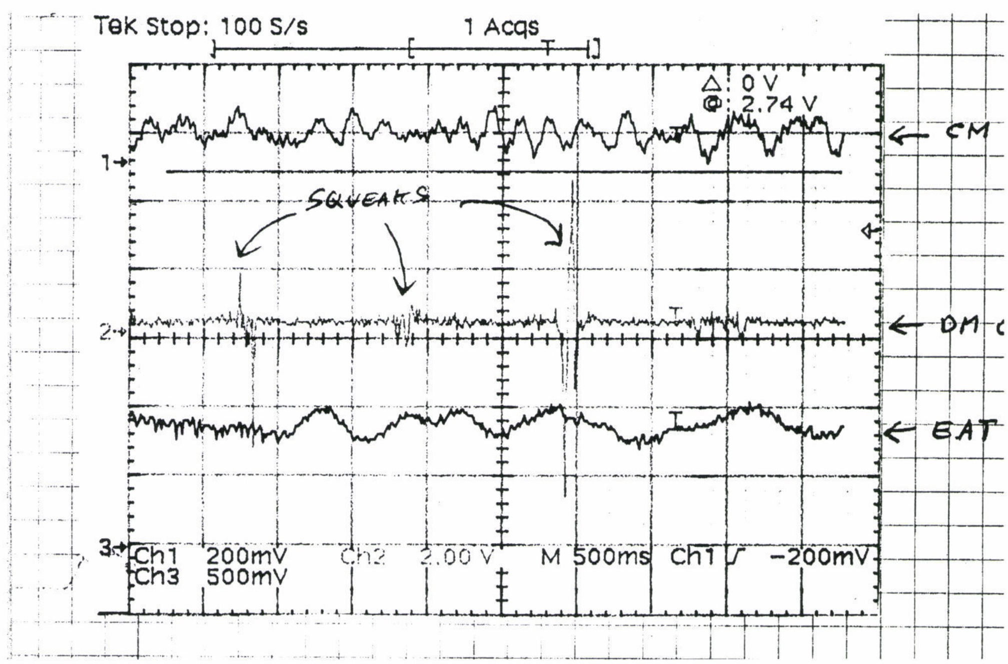
As alignment improves:

- Power in arm increases (bottom curve)
- Reflected power (inverse of top curve) decreases
- Power fluctuations grow
- Lock is lost

Why Can't We Align the IFO?

Is differential mode gain increasing too much?

- Measured gain margin $\approx$ 6 db
  (oscillation onset at 2.1 KHz)
- Intermittent squeaking audible on gravity wave signal when DM gain turned up: (middle curve)



- Evidence for saturation in APD RF response at high gain
- But IFO remarkably resilient to squeaking
- Reducing electronic gain cures squeakingΓ
  but not fundamental problem
- Photodiode saturation should helpΓnot hurt

$\Longrightarrow$ Differential Mode Unlikely Culprit

Why Can't We Align the IFO?

Common Mode servo has enormous bandwidth (≈MHz) and DC gain (≈10^8)

- Reducing electronic CM gain does not cure problem
- One worry: Crossover btw laser & arm feedback (≈3 Hz)
  - Designed to be robust
  - But hard to measure
  - Under investigation
- Jury still out

Recycling Mirror servo has received most attention

- If IFO critically coupledΓexpect optical gain to approach zero and perhaps flip sign
  - Positive feedback
  - Gross instability
- Orientation fluctuations could take IFO into overcoupled regime momentarily
- When lock is lostΓRM servo is almost always first to go

Why Can't We Align the IFO?

What is the full IFO coupling of carrier?

Originally expected overcoupling ($r_{\rm CR} < 0$) – Low arm losses

But evidence increased that $r_{\rm CR} > 0$:

- No need to flip sign on RM & BS servos to acquire full lock (SPD I & Q phases $\propto r_{\rm CR}$)
- DC visibility at SPD too low (Expected visibility near 100%; observe max visibility ≈60%)

Since IFO carrier coupling critically sensitive to arm lossesΓ we returned to individual arms for direct determinations

Why Can't We Align the IFO?

Arm Finesses and Losses

How do we measure arm parameters? (finesseΓlossΓcoupling)

- Ringdown measurement
  - Chop laser intensity
  - Look for characteristic decay time in transmitted light
  - Okay for measuring finesse ($\tau \propto$ F)
  - But high accuracy required to measure loss / coupling
  - Analysis complicated by two decay components: $e^{-t/\tau}$ and $e^{-t/2\tau}$
- Linewidth measurement
  - Tune f_{mod} so that $2f_{mod}$ sideband resonates in arm
  - Measure transmitted power *vs* f-f_{mod}
  - Cleaner measure of finesse - allows extraction of arm loss with smaller systematic uncertainty

Why Can't We Align the IFO?

- "DC Visibility" Measurement
  - Measure DC level of reflected light on and off resonance
  - Off resonance: $E_{Refl} \approx E_{In}$
  - On resonance: $E_{Refl} \approx E_{In} r_c$
  - Visibility $\equiv (P_{max} - P_{min})/P_{max} \approx 1 - r_c^2$
  - Advantage: Extremely simple measurement
  - Drawback: Affected by mode mismatch (of every kind)

- "RF Visibility" Measurement (developed by B. Kells)
  - Measure "2Ω" RF signal on / off arm resonance
  - Ratio: $P_{on}/P_{off} = (1 - r_c^2)/(1 + r_c) = 1 - r_c$
  - Extremely directΓbut sensitive to residual misalignment

Current best estimates of individual arm losses:

East: 380 ppm (intended = 230) $\Longrightarrow$ $r_c = -0.88$

South: 360 ppm (intended = 100) $\Longrightarrow$ $r_c = -0.88$

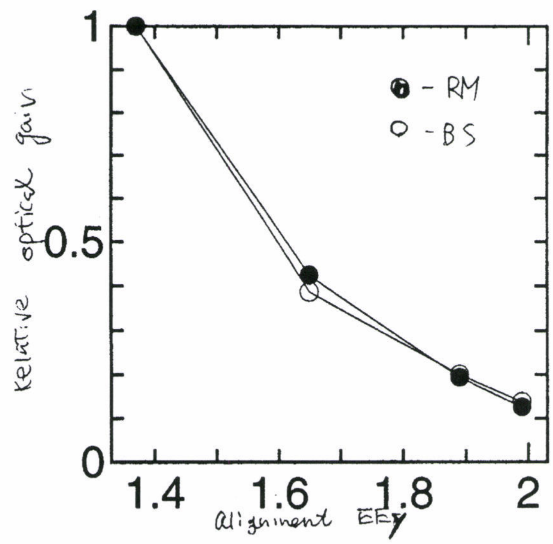
$\Longrightarrow$ Expect carrier IFO coupling $r_{\mathrm{CR}} > 0$ (undercoupled)

$\Longrightarrow$ Seems to confirm earlier suspicion

Why Can't We Align the IFO?

NowΓhoweverΓwe are not so sure...

From RM and BS power spectra (full IFO lock) taken *vs* end-mass misalignmentΓdeduce significant gain loss for RM and BS as maximum power approached
(Based on indirectΓout-of-band optical gain measurements)



$\Longrightarrow$ Gains approaching zero? (critical coupling)

Have also measured in-band RM and BS loop gains with swept sinesΓbut have been unable to complete clean measurements when very near best alignment

- Difficult to confirm directly the approach to zero (fluctuations would almost guarantee lock loss)
- Results qualitatively agree with power spectrum analysis *i.e.*Γgain plummets as best alignment approached

Why Can't We Align the IFO?

Will attempt a cleaner determination of RM optical gain (out-of-band)Γone fast enough to track correlations with IFO power fluctuations

What if we prove critical coupling is indeed the trouble?

What can we do?

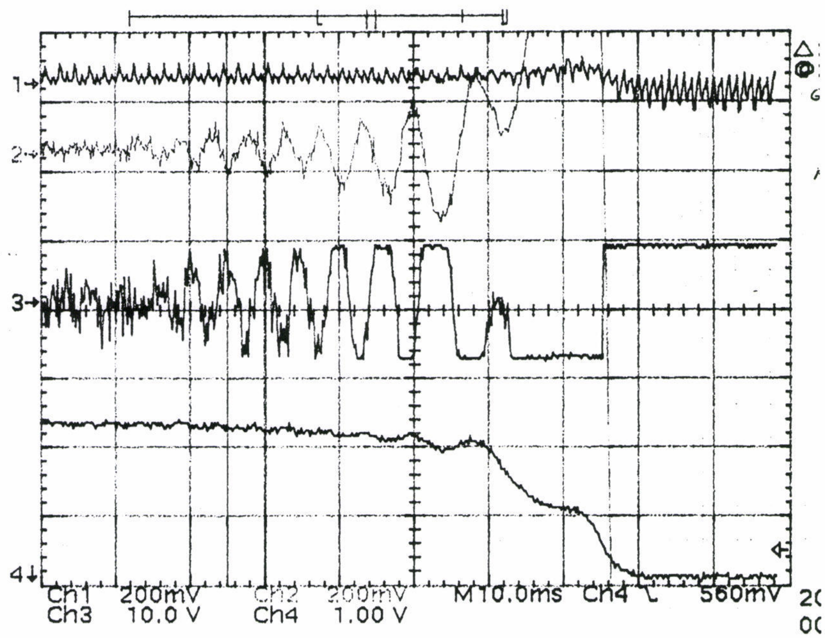
Simplest solution: Insert lossy flat optic into recycling cavity

$\Longrightarrow$ Additional loss forces undercoupling

$\Longrightarrow$ No sign flip

Why Can't We Align the IFO?

Example of lock-loss transient:



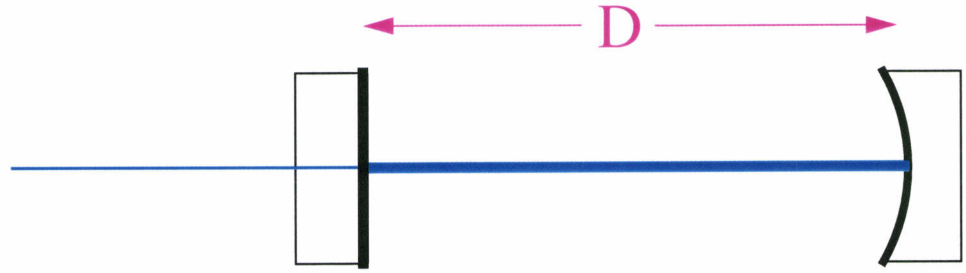
1 = Raw RM error signal (distorted by scope aliasing)
2 = Intermediate RM servo signal
3 = Final RM control signal
4 = Power in east arm

- Saturation in control signal (railing at supply voltages)
- Exponential growth
- Suggestive of servo instability
  - Flipped sign
  - Or inadequate gain margin
- ≈200 Hz oscillation not always present

Wave Front Sensing at the 40 Meter

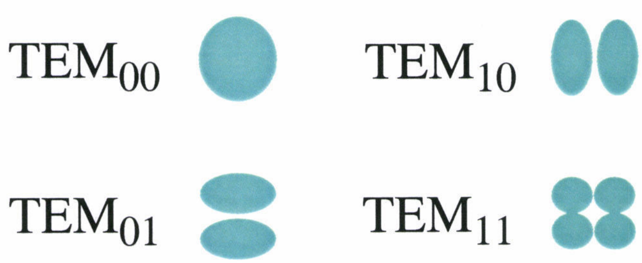
WFS Refresher

IFO arms are (essentially) flat-concave compounds:



Electric fields can be expanded in orthogonal basis of self-propagating TEM_{mn} modes: (Hermite-Gaussian)

Examples:



Resonance occurs for TEM_{mn} mode when

$$kD - (m+n+1)\phi_0^{\mathrm{Guoy}} \quad = \quad (N)\,\pi$$

where ϕ_0^{Guoy} is the Guoy Phase of the TEM_{00} mode:

$$\phi_0^{\mathrm{Guoy}} \quad = \quad \arctan\left(\frac{\lambda D}{\pi w_0^2}\right)$$

and w_0 is the beam waist size (at flat mirror):

$$w_0^2 \quad = \quad \frac{\lambda}{\pi}\sqrt{D(R-D)}$$

Wave Front Sensing at the 40 Meter

Some numbers:

	40 Meter	LIGO
D (m)	40	4000
R (m)	64	7400
w_0 (mm)	2.3	35
ϕ_0^{Guoy} (deg)	52	47

Sidenote

For flat-flat compoundΓ$R \to \infty$

$\Longrightarrow$ $w_0 \to \infty$ (plane wave)

$\Longrightarrow$ $\phi_0^{\text{Guoy}} \to 0$

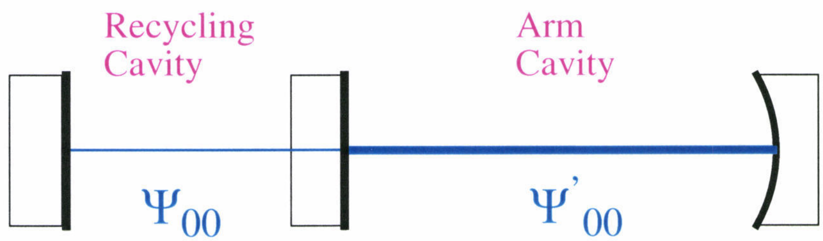
$\Longrightarrow$ All TEM modes resonate simultaneously

$\Longrightarrow$ Degenerate Cavity

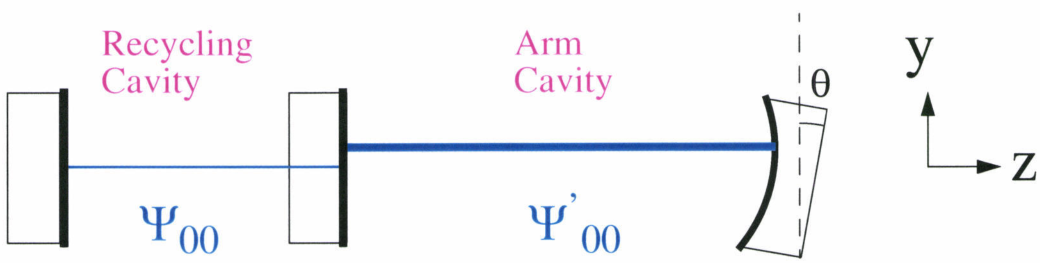
$\Longrightarrow$ Approximately true for recycling cavity

Wave Front Sensing at the 40 Meter

WFS exploits mismatch between recycling cavity TEM_{00} and arm cavity TEM'_{00} modes to measure relative misalignment



Consider effect of tilting end mirror by θ:



$\Longrightarrow$ Arm axis is displaced by $R\,\theta$ from input axis

Input field: (omitting x-dependence)

$$
\begin{aligned}
\Psi_{00}(y,z) &= A\,e^{-y^2/w_0^2}\,e^{i(kz-\omega t)} \\
\Psi_{01}(y,z) &= A\left(\frac{2y}{w_0}\right)\,e^{-y^2/w_0^2}e^{i(kz-\omega t)}
\end{aligned}
$$

Resonating arm field:

$$
\begin{aligned}
\Psi'_{00}(y,z) &= A\,e^{-(y-R\,\theta)^2/w_0^2}\,e^{i(kz-\omega t)} \\
&\approx A\,(1+\frac{2R\theta y}{w_0^2})\,e^{-y^2/w_0^2}\,e^{i(kz-\omega t)}
\end{aligned}
$$

Wave Front Sensing at the 40 Meter

To 2nd order in $\epsilon \equiv R\theta/w_0\Gamma$

$$\begin{aligned}
\Psi'_{00} &\approx \sqrt{1-\epsilon^2}\,\Psi_{00} + \epsilon\,\Psi_{01} \\
\Psi'_{01} &\approx \sqrt{1-\epsilon^2}\,\Psi_{01} - \epsilon\,\Psi_{00}
\end{aligned}$$

SimilarlyΓ

$$\begin{aligned}
\Psi_{00} &\approx \sqrt{1-\epsilon^2}\,\Psi'_{00} - \epsilon\,\Psi'_{01} \\
\Psi_{01} &\approx \sqrt{1-\epsilon^2}\,\Psi'_{01} + \epsilon\,\Psi'_{00}
\end{aligned}$$

Ψ'_{01} does not resonateΓbut coupling of input field to misaligned arm field induces Ψ_{01} component in reflection

$$\begin{aligned}
E_{In} &= \Psi_{00} \\
&= \sqrt{1-\epsilon^2}\,\Psi'_{00} - \epsilon\,\Psi'_{01}
\end{aligned}$$

ThereforeΓ

$$\begin{aligned}
E_{Refl} &= r_c\sqrt{1-\epsilon^2}\,\Psi'_{00} - \epsilon\,\Psi'_{01} \\
&= r_c\sqrt{1-\epsilon^2}\,(\sqrt{1-\epsilon^2}\,\Psi_{00} + \epsilon\,\Psi_{01}) \\
&\quad -\epsilon\,(\sqrt{1-\epsilon^2}\,\Psi_{01} - \epsilon\,\Psi_{00}) \\
&= (r_c(1-\epsilon^2) + \epsilon^2)\Psi_{00} + (r_c - 1)\epsilon\,\sqrt{1-\epsilon^2}\,\Psi_{01}
\end{aligned}$$

(Recall: $r_c \approx -1$ when arm resonating)

Wave Front Sensing at the 40 Meter

How Do We Detect the Signal?

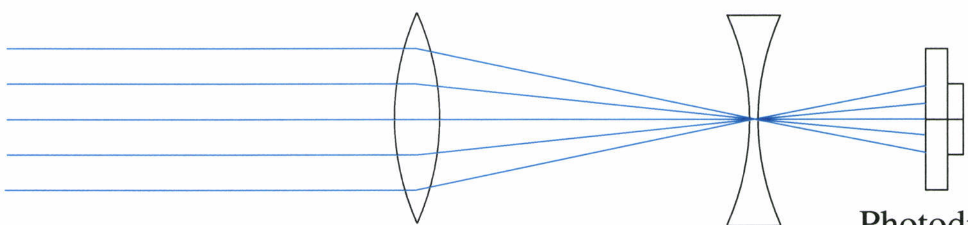
- Use segmented photodiode to pick out Ψ_{01} asymmetry
- Beat carrier TEM_{01} against sideband TEM_{00}

$$(-2\,\epsilon J_0)\Psi_{01} \quad \times \quad i\,J_1(e^{i\Omega t}+e^{-i\Omega t})\Psi_{00}$$

But we know this doesn't work! $\Longleftrightarrow$ Real J_0 $\times$ Imag J_1

$\Longrightarrow$ Need to change relative phase

$\Longrightarrow$ Use Guoy telescope



- Force light to converge at center of diverging lens

$\Longrightarrow$ Each TEM_{mn} mode undergoes phase shift:

$$\Delta\phi_{mn} \quad = \quad (m+n+1)\,(\pi/2)$$

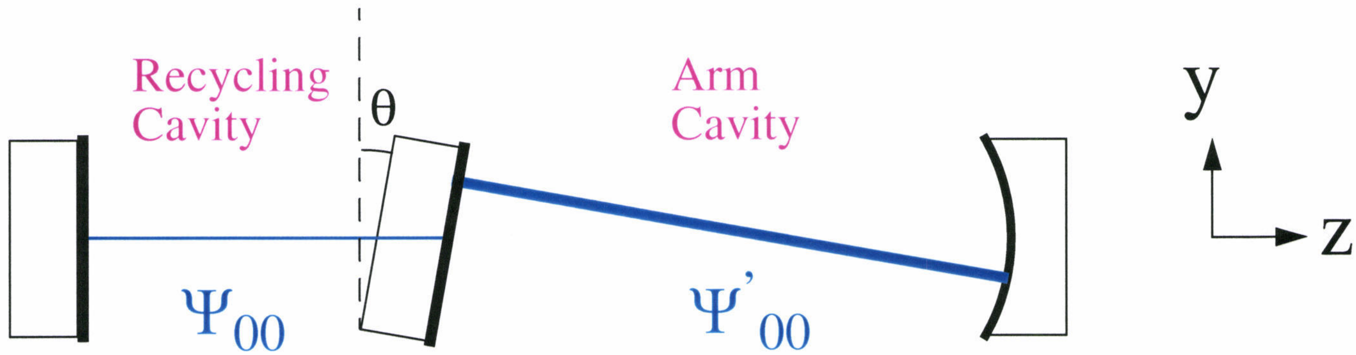
$\Longrightarrow$ Now beat carrier and sideband:

$$(i)^2(-2\,\epsilon J_0)\Psi_{01} \quad \times \quad (i)\,i\,J_1(e^{i\Omega t}+e^{-i\Omega t})\Psi_{00}$$

$\Longrightarrow$ Non-zero demod signal with sign(ϵ)

$\Longrightarrow$ Use in servo to zero out ϵ

What if the Input Mirror is Tilted?



$\Longrightarrow$ Axis tilted by θ

$\Longrightarrow$ Beam offset at input mirror $= (R - D)\theta$

$\Longrightarrow$ Also changes recycling cavity axis

Remarks:

- Inherently more complicated
- Tilt introduces imaginary Ψ_{01} admixture

$$\begin{aligned} e^{ikz'} &\approx e^{ik(z-\theta y)} \\ \Longrightarrow \quad \Psi'_{00} &\approx \Psi_{00} - i\,\epsilon'\Psi_{01} \\ \epsilon' &\equiv \frac{\pi w_0}{\lambda}\theta \end{aligned}$$

No need for Guoy telescope to extract just θ

Wave Front Sensing at the 40 Meter

- Sideband in cavity affected by tilt too
- Can disentangle effects via resonant sidebands (à la LIGO)
- At 40 Meter we now use only usual non-arm-resonant 32.7 MHz sidebands
- Full analysis of effects from different mirrors possible (c.f.ΓN. Mavalvala's thesis)
- But at 40 MeterΓwe control only two pairs of DOF and get by with diagonal matrix approximation:

APD WFS signal	$\rightarrow$	End mirrors (or beamsplitter)
SPD WFS signal	$\rightarrow$	Recycling mirror

Wave Front Sensing at the 40 Meter

What has been done so far at the 40 Meter?

- Demonstration of analog WFS control of RM & BS
  (SPDΓAPD WFS signals)
- Demonstration of simult. digital WFS control of RM & BS
- Demonstration of digital WFS control of
  East End (EE) Yaw
  (running in parallel or in place of global optical lever)
- In progress: Extension to EE pitch and SE pitch / yaw

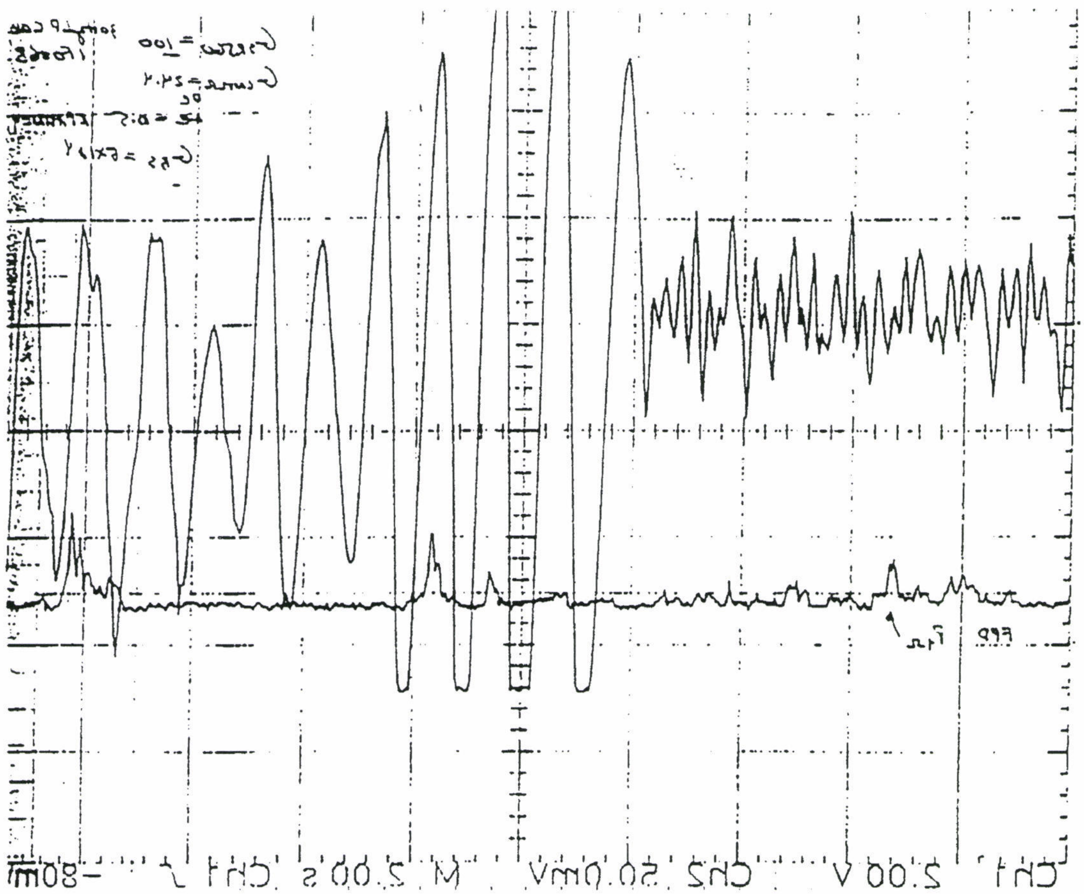
Wave Front Sensing at the 40 Meter

Problems in extending WFS control to end masses

- Fundamental pitch / yaw resonances somewhat high
  (1.3-1.4 Hz)
- Easy to excite secondary yaw resonances at 21 Hz:
  - Old suspensions are "double pendula"!
  - Solution – Insert tuned analog notch filters
- Side motion of mirror at 0.95 Hz completely undamped
  (small but non-zero coupling to orientation)
- Existing orientation servo loop (optical lever) has
  hard 6-pole 20-Hz rolloff
- WFS digital controller (old Motorola) limited to
  few hundred Hz sampling rate
  (restricts digital filter options)

Wave Front Sensing at the 40 Meter

“Before & After” effect of WFS Control (PRM)



Cheat: Time reversal of turning WFS off

Summary of Michigan contributions to 40 Meter:

- Diagnosis / elimination of various electronic noise sources*
- Modification of analog electronics modules for improved performance / sensitivity
- Shakedown of data acquisition system
- Enhancement of data display program
- Commissioning of digital control system for wave front sensing
- Implementation of wave front sensing of end masses (in progress)
- Investigation of Pockel cell failure
- Design / fabrication of beam shutter / locator devices*
- General support of recycling demonstration experiment (day-to-day operation / maintenanceΓmeasurements)

*To be discussed later in context of advancing LIGO

Michigan Gravity Wave Group

Enhancements to data display program (now running at Hanford)

- Trigger
- Two-channel correlation displays
- Real-time graphics manipulation
- Time frequency analysis (waterfallΓcarpet plots)

Commissioning of digital WFS control

- Rewrote MIT control software for 40 Meter configuration
- Investigated maximum sampling rate
- Implemented pole/zeroΓdouble pole/zeroΓ resonant gain filters
- Created EPICS-based control panel for setting pedestalsΓ gainsΓoffsetsΓfilter parametersΓetc. and for obtaining statusΓnumerical readingsΓetc.

Michigan Research at the 40 Meter

Implementation of wave front sensing

- Demonstrated simultaneous digital WFS control of pitch & yaw for beam splitter and recycling mirror
- Demonstrated digital WFS control of east end yaw
  - Complicated by old suspensionsΓ2nd yaw resonance
  - Can run WFS in place of optical lever control or in parallel
- Now implementing for pitch and for south end mass (at lower priority)
- Hope to substantially kill large intensity variations in arm light due to differential yaw / pitch fluctuations

Investigation of Pockel cell failures

- Strong suspicion: chronic failure due to heating in vacuum
- Heating caused by RF modulation
- Short-term solution:
  - Reduce modulation index when running
  - Turn off modulation at night
    $\Rightarrow$ degradation rate much reduced
- Long-term solution: heat-conducting substrates (prototype ready for testing at next venting)

Remarks

- We have attained hands-on familiarity with the 40 Meter
- We understand the interferometer and its control
- Improving interferometer performance is essential and is an appealing challenge we welcome
- But we are not primarily interferometer scientists

- We are driven by the astrophysics
- Our goal is discovery & investigation of gravity waves
- Our approach is flavored by our high energy experience:
  - Major contributions to instrumentation
  - Data analysis taking into account detailed instrumental idiosynchrasies

40 Meter Analysis Hopes / Plans

- Record one week of recycling-configuration data by end of 1998 with all ($\approx$130) DAQ channels active
- Characterize data – Identify:
  - Pathologies
  - Noise sources
  - Correlated channels
- Search in data for periodic gravity wave sources
  - Exercise in analyzing real data
  - Exercise in developing algorithms
  - No signal expected
  - But interesting broadband limits possible

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Plans for Long Term LIGO Research in Ann Arbor

- Wrap up 40 Meter analysis
- Search LIGO I data for periodic sources
- Develop advanced wave front sensing for advanced LIGO

Plans for Long Term LIGO Research at Sites

- Systemic Noise Studies
- Advanced Diagnostics and Controls

Addition of postdoc to group essential to these efforts

LIGO I Wave Front Sensing Plans

- WFS exploits interference pattern between lowest order (Gaussian) cavity mode and first-order transverse modes ($e.g.\Gamma\mathrm{TEM}_{10}$)
- LIGO I WFS based on "quadrant bullseye" segmented photodiodes
- Each DOF (pitchΓyawΓcurvature) effectively sensed by pair of photodiode segments
- Decoupling of effects from different mirrors accomplished via different modulation frequencies & Guoy telescopes
- Present scheme designed for 1st-order servo control of each DOF and should work fine

We want to extend this technique

Why?

- Better control / diagnosis of 1st-order transverse modes
- Attack higher order modes (diagnosticΓperhaps control)

How?

- Brute force: Increase photodiode segmentation (need more RF amplifiers & demodulators)
- More ambitious: True imaging system
  - Pre-sensor demodulation
  - Use CCD or active pixel sensor (APS) array for detector
- Work so far at the idea level – development needed
- But experience at the 40 Meter indicates the immense value of image information

Systemic Noise Studies

We plan to trace and analyze the NOISE of LIGO I (as implemented) for

Data AnalysisΓLIGO I ScienceΓand LIGO II

We will work backwards from the Gravity Wave Signal to isolate:

- 60 Hz and its Harmonics
- RF Leakage: out and in
- Accidental Couplings to High-Q Degrees of Freedom
- Non Stationary ProcessesΓ*e.g.*Γ
  - Out-of-Band Alignment or Servo Perturbations and Fluctuations leading to or driving upconversion of low Frequency noise

Advanced Diagnostics & Controls

- Light Shutter – Beam Locator
- Selective Attenuator
- IFO Coupling Diagnostic
- Independent Arm Lock Scheme
- Auxiliary Laser Lock Cavity – A Third Arm

Light Shutter - Beam Locator

We need to isolate one or both arms for tuningΓ testingΓor aligning:

- Power Recycled Michelson Configuration
- Individual Arms

Usually done by misaligning mirrorsΓbut problems arise:

- Hysteresis; you never get exactly back
- Insufficient range
- Incomplete light blockage

Light Shutter - Beam Locator

Our studentΓJ. RollinsΓhas fabricated and vacuum prepped four shutters for the 40 Meter

To be located:

- Just in front of the vertex test masses
- Just in front of the end masses (for beam location)

Consists of a vacuum-optics-compatible "Pico Motor" with a rotating vane

Vane has two stopped positions:

- Shutter
- Alignment hole

We propose to design and fabricate a similar system for LIGO

Selective Attenuator

We extend the Light Shutter to Selective Attenuator

Add another vane setting - highly transmitting optic

Purpose: Calibrated pertubation of recycling cavity

- Increase cavity loss
- Change contrast defect

Perhaps extend to arm cavities (higher quality optics)

Thermal lensing needs study

Coupling Diagnostic

Overall coupling of the input to the IFO is important and hard to measure

At the 40 Meter we step the input light and observe the transient response of the light and probe signals

The family of responses as a function of amplitude characterizes the couplingΓbut interpretation needs care / precision

This needs analysis and development

We will develop and test this diagnostic

Independent Arm Lock Scheme

Lock via arm Servo on transmitted light at End

Each arm is then semi independent

Study the "open loop" arm servo

DebugΓmeasure stuff

We have locked one arm of the 40 Meter this way

Two Schemes:

- Length Modulation
- Laser modulation

Requires modestly good laser frequency stabilization

Locking 40M laser to the mode cleaner is marginally adequate

Possible further uses:

- Establish beam for WFS startup
- Possible simple brute force path to lock
- Diagnostic replacement of CM Servo.

Auxiliary Laser Lock Cavity – A Third Arm

We propose a third Fabry-Perot arm-like Cavity

Purpose

Stabilize laser so well that either or both arms could be cleanly locked to it and studied with only a length servo

The recycled / recombined arms are inextricably coupled in the 40 Meter and LIGO

Decoupling was a convenient feature of the unrecombined 40 Meter IFO

Stability goal:

Intermediate between a full arm and mode cleaner lock

Auxiliary Laser Lock Cavity – A Third Arm

Possible implementation schemes:

- Mode cleaner derived – but you want test this too.
- Second FP cavity in 2K or 4k arm
- External system in vertex area *e.g.*Γbased on extension of the unused 40M 12-meter Mode Cleaner hardware

This system would stablilize the laser such that the arms could be independently locked with only length servo

Would enable stringent diagnostics of the main IFO-laser frequency control system

RESEARCH PLAN

Gustafson

At 40M and Hanford: ($> 50\%$)

- Data Runs and Analysis
- DiagnosticsΓControls
- Systemic Noise Study

At Michigan:

- Data Analysis
- Hardware Fabrication
- WFS Development
- Periodic Source Astrophysics and All Sky Problem

Riles

At Michigan:

- Data Analysis
- WFS Development
- Periodic Source Astrophysics and All Sky Problem

At 40M and Hanford (periodic visits):

- DAQ Tests and Improvements
- Advanced Alignment Issues

Michigan Gravity Wave Group

Postdoctoral Associate

At Michigan ($> 50\%$)

- Data Analysis
- WFS Development
- Periodic Source Astrophysics

At 40M and Hanford

- Data Runs
- DiagnosticsΓNoise Study

We are relative newcomers to Gravity Wave Physics

We've jumped in and made a strong contribution to 40 Meter R&D

We are now preparing to record and analyze LIGO-like data with the 40 Meter

We have substantially learned the LIGO/IFO trade

In the coming years we will:

- Carry out 40 Meter Gravity Wave Analysis
- Extend this to LIGO data
- Advance LIGO:
  - Contribute to Noise Study and Diagnostics
  - Develop Advanced Wavefront Sensing
  - Search for and Study Periodic Sources

Our Goals

Detect Gravity Waves

Study their Sources