DRMI LSC Tutorial

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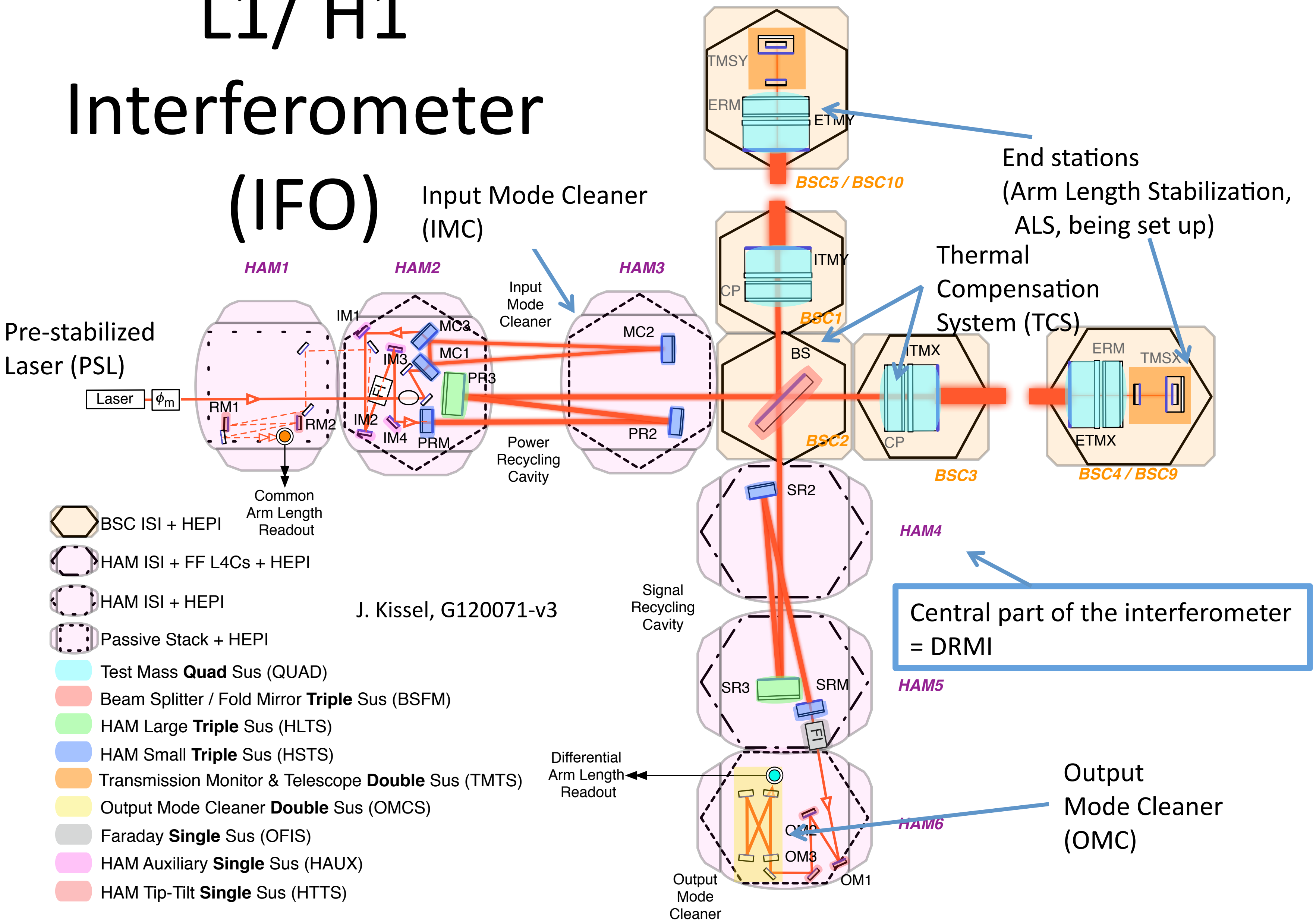
November 18th, 2013

DetChar weekly call

Contents

- DRMI (dual-recycled interferometer)
  Optical Configuration
- Basic Optics for preparation
- Length Sensing and Control (LSC) scheme
  - What is "3f locking" which is the official goal of the DRMI commissioning
  - What are PRMI carrier/ sideband lock?
  - How to find the locked segments?
  - Ch name conventions, important channels
- Alignment Sensing and Control scheme (ASC) Overview
- Reference, Contact people, Appendix for technical details

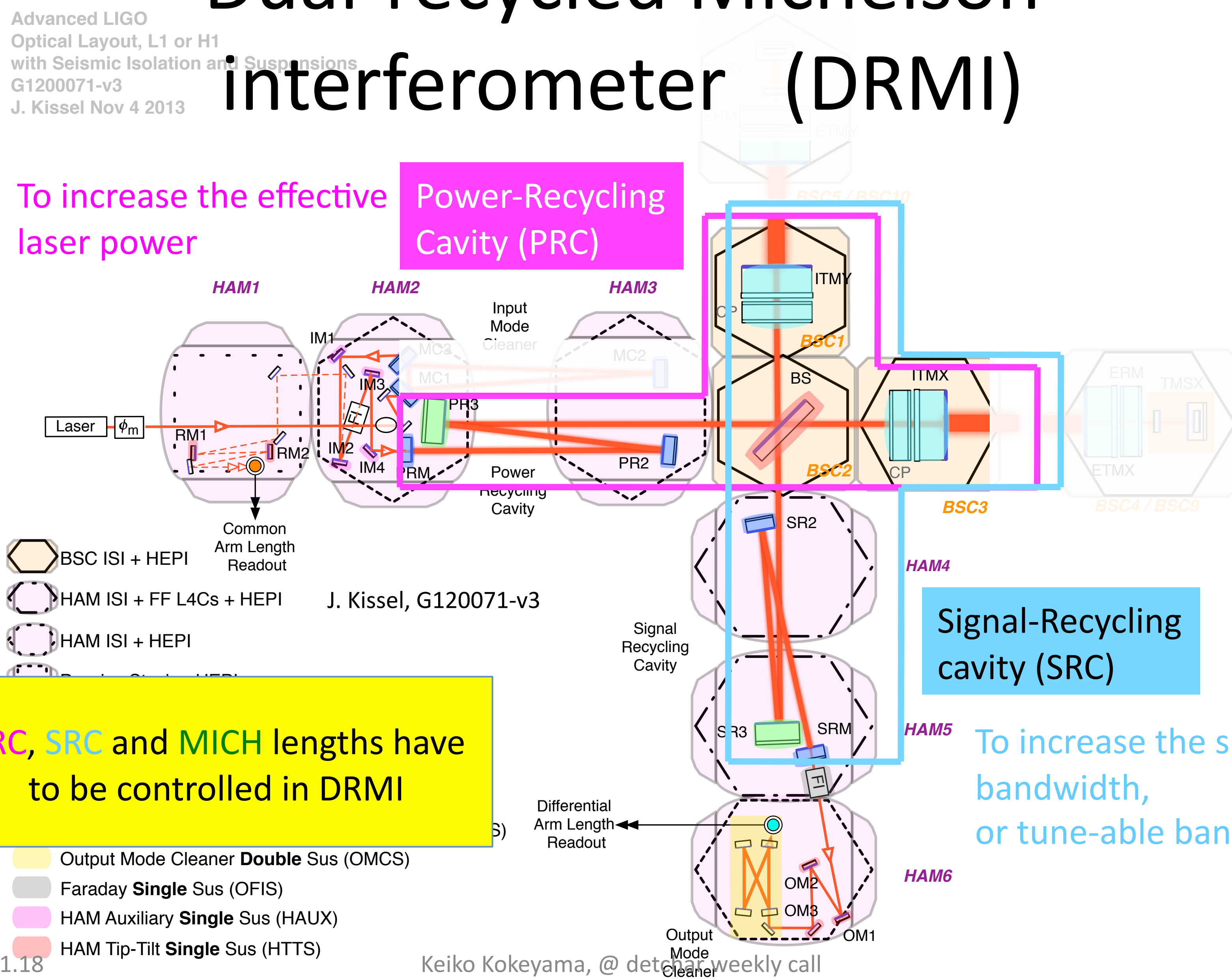
L1/ H1 Interferometer (IFO)



Dual-recycled Michelson interferometer (DRMI)

To increase the effective laser power

Power-Recycling Cavity (PRC)



Signal-Recycling cavity (SRC)

To increase the signal bandwidth,
or tune-able bandwidth

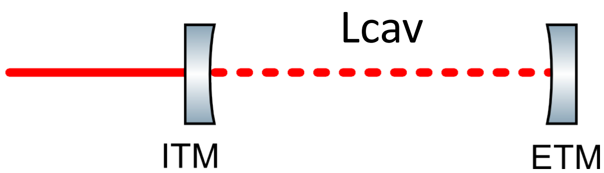
PRC, SRC and MICH lengths have to be controlled in DRMI

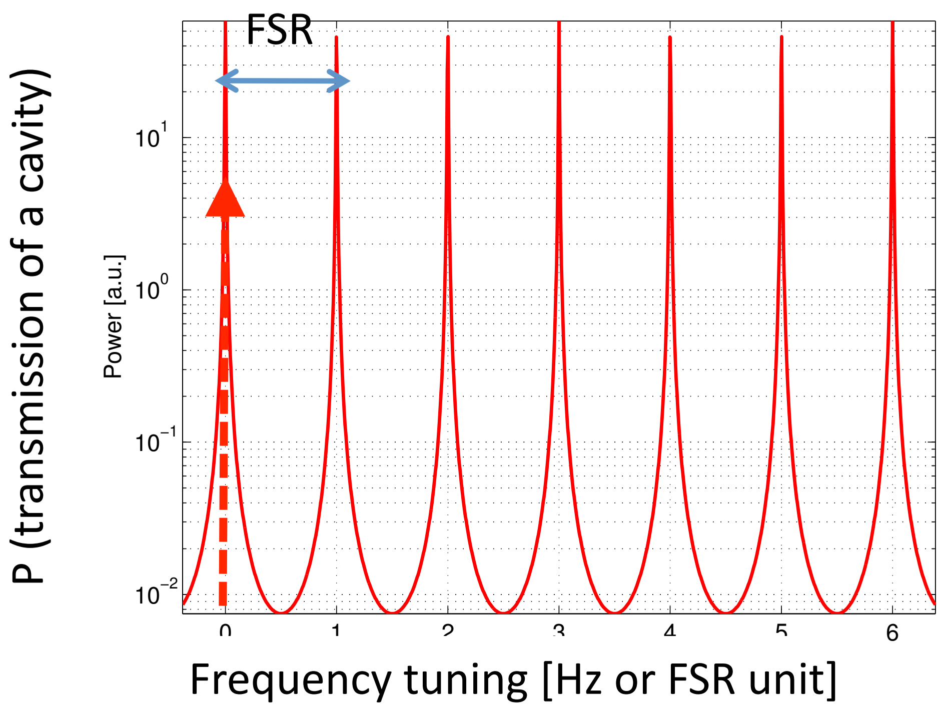
Why Control?

- Interferometer does not work as the gravitational wave detector, unless the mirrors are at proper operation points
- Interferometer has to be "locked" at its operation point by the feedback control
- Error signals which are linear to the control object (and GW!) are necessary – how to extract signals?
- DRMI commissioning goal is "3f locking." What is this scheme?

Simple Cavity and Free Spectral Range

Fabry-Perot (FP) Cavity



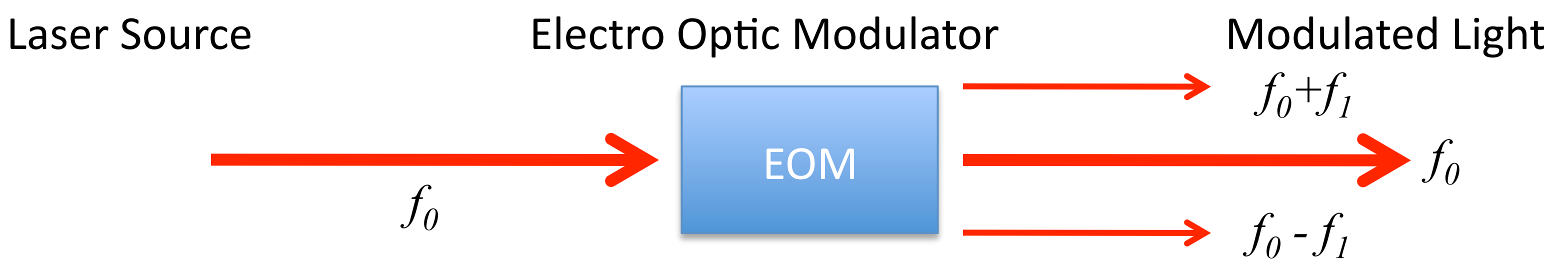


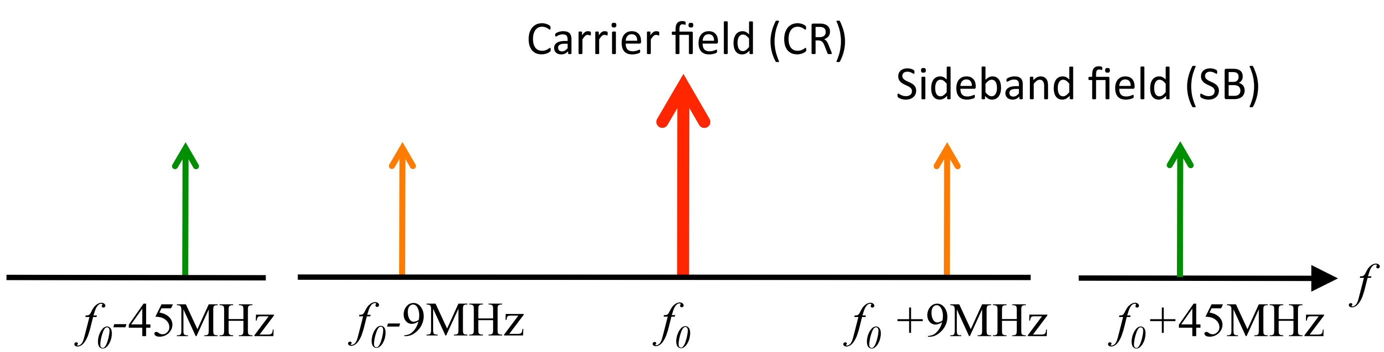
Free Spectral Range
FSR = c/2/Lcav [Hz]
frequency separation
from one resonant to the next

How to obtain the linear signal
(error signal) of Lcav
(or laser frequency)?

Basic of Optical Fields

Modulation

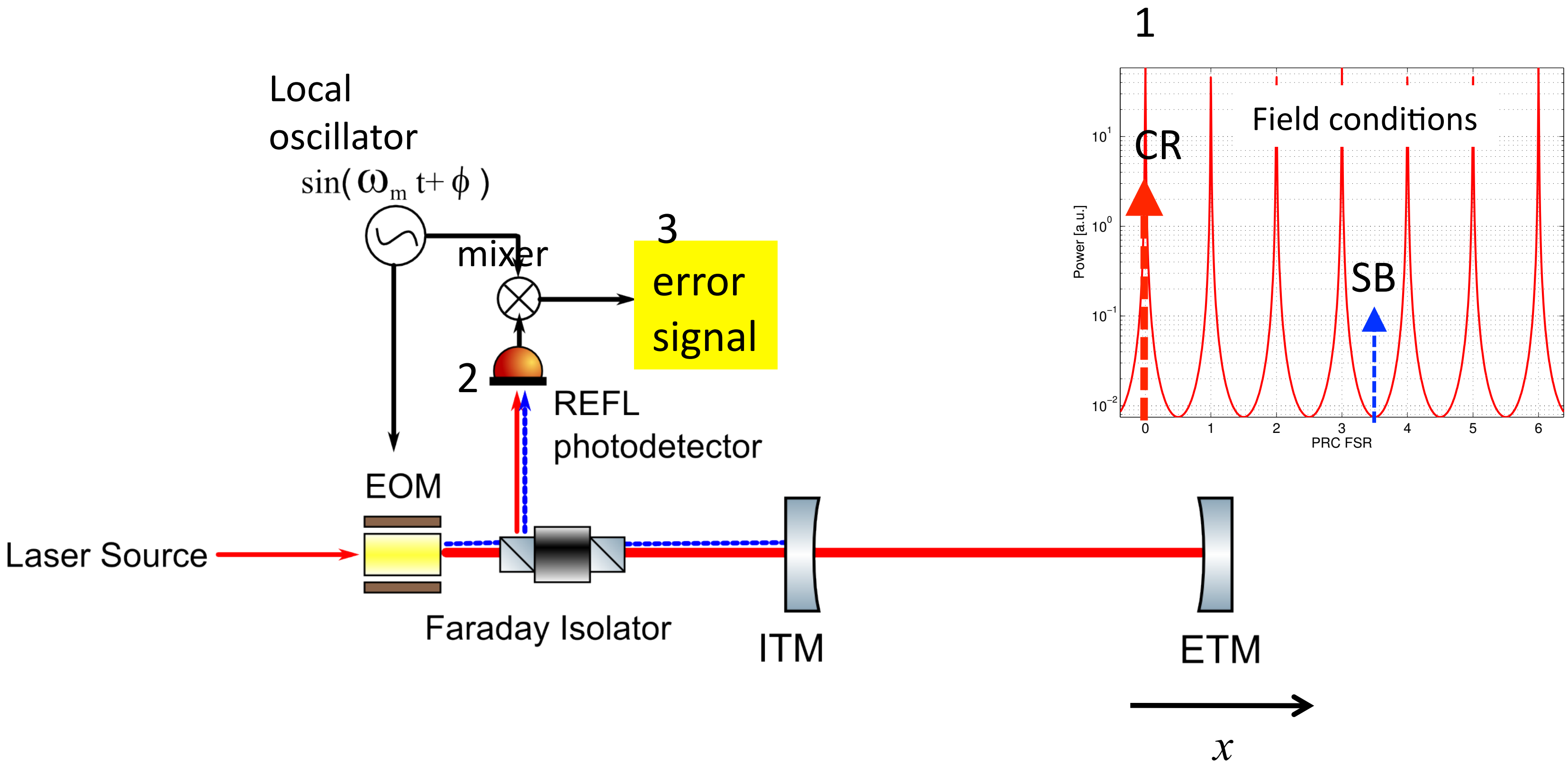




aLIGO has two sidebands (SBs), 9MHz and 45 MHz

Pound-Drever Hall Method

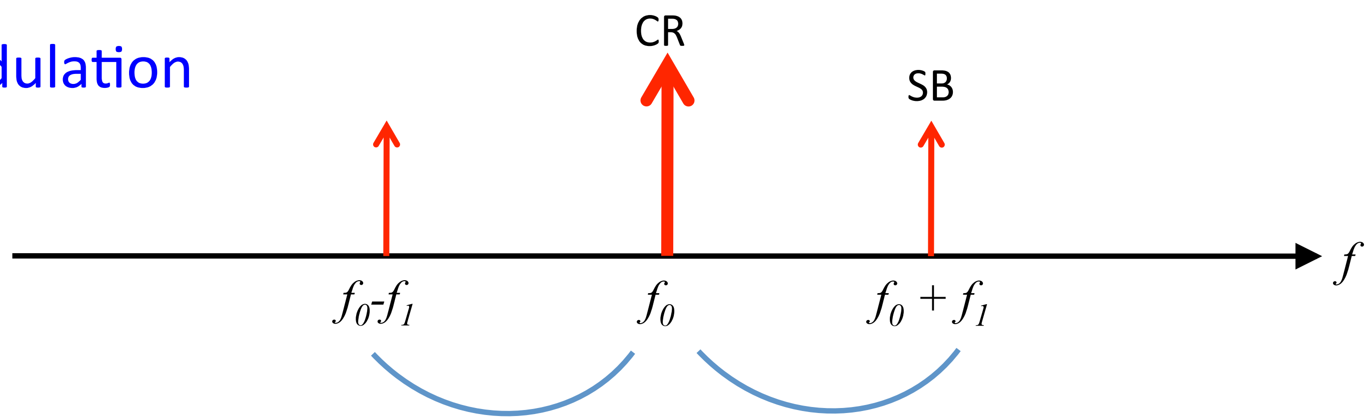
(Heterodyne detection)



1. Field condition
2. Detect the reflected field (REFL)
3. Demodulate to obtain error signal

Demodulation

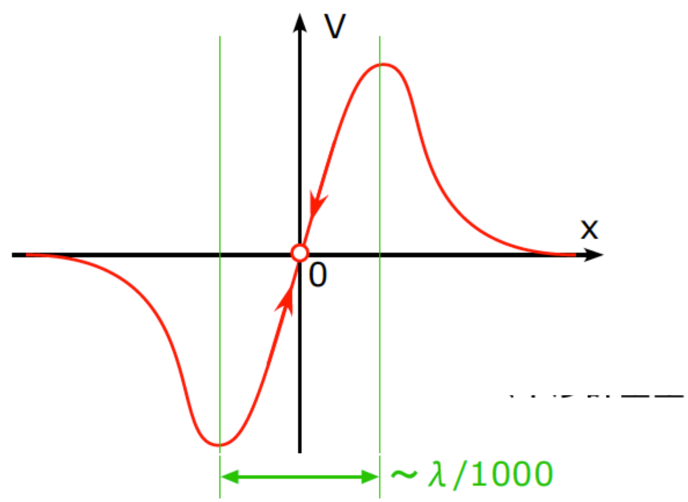
Demodulation



Take the beat between the carrier and two SB fields
→ error signals linear to the cavity length

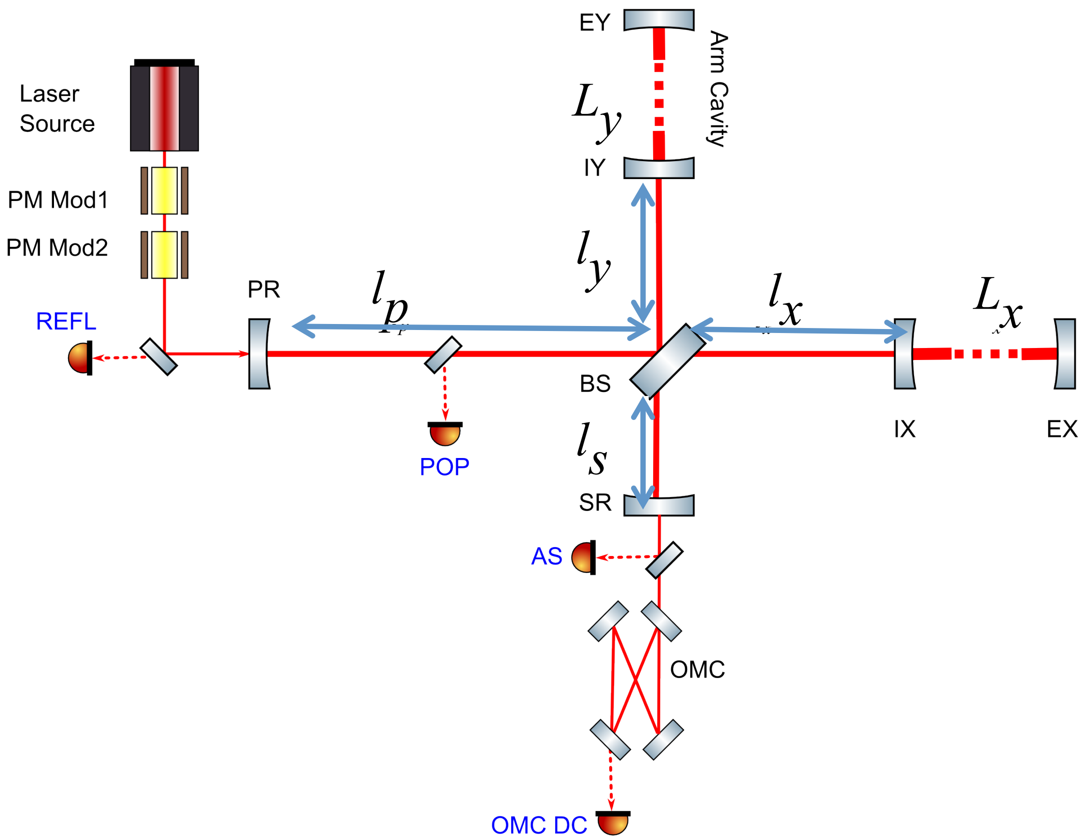
Error signal
linear to the cavity length in a range

We control the cavity length
so that the error signal is zero



5 DoF to Control in aLIGO

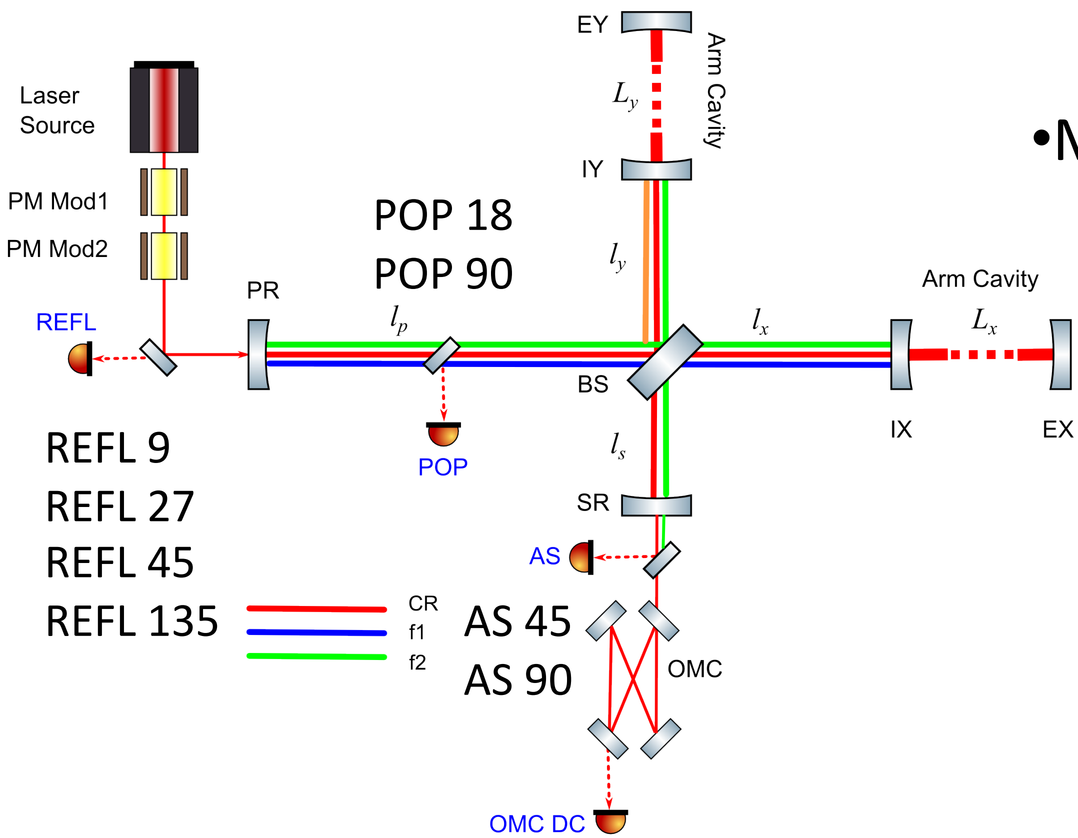
- Complex coupled cavity system
- Error signals for 5 DoF are necessary



DoF	Difinition
CARM	$(L_x+L_y)/2$
DARM	$(L_x-L_y)/2$
PRCL	$l_p+(l_x+l_y)/2$
MICH	l_x-l_y
SRCL	$l_s+(l_x+l_y)/2$

ALIGO (full) LSC method

- Two SB frequencies are used,
  - f1 ~ 9 MHz
  - f2 ~ 45 MHz
- Many sensors



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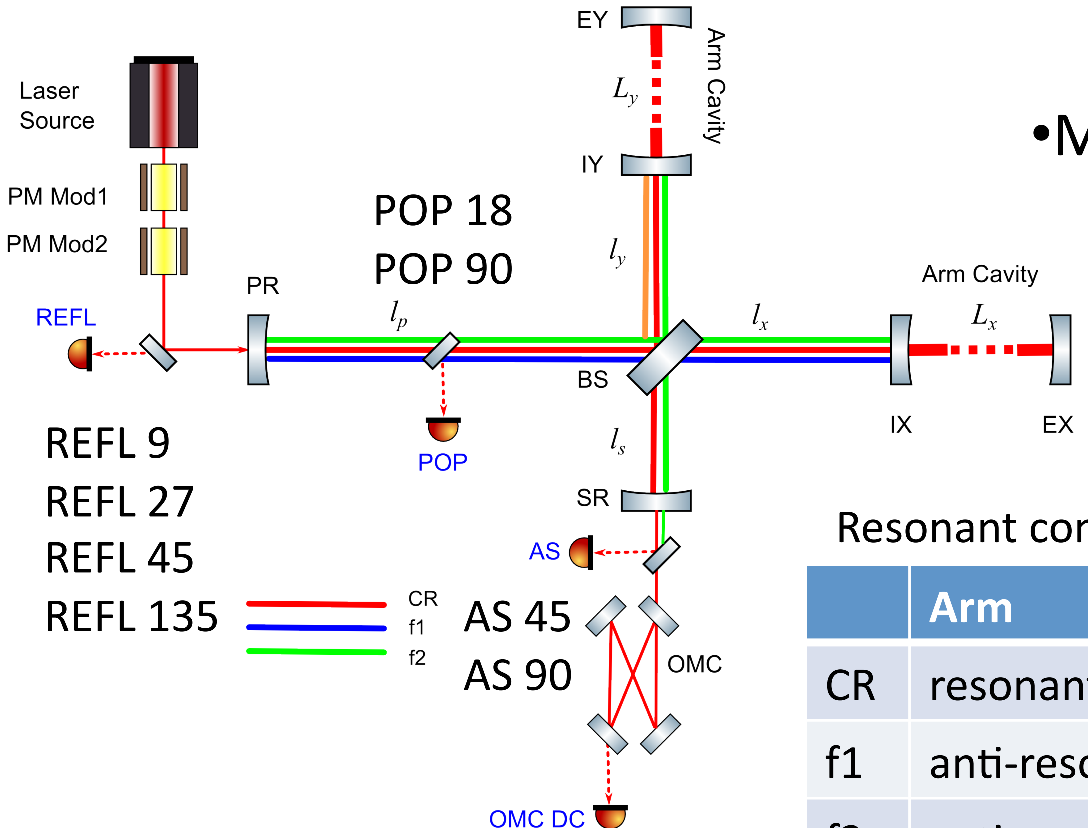


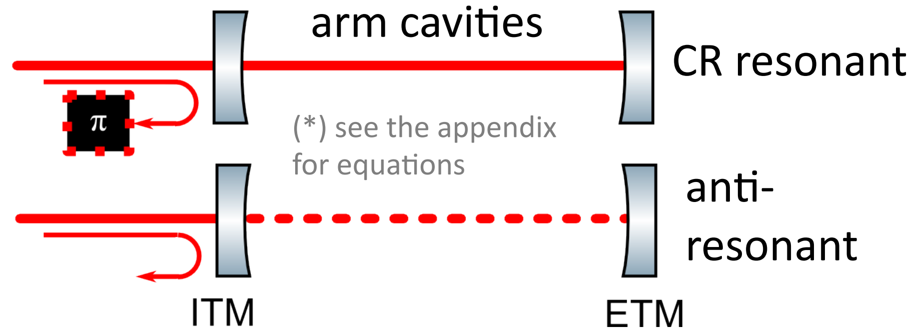
due to the relation between Shnupp asymmetry length (lx-ly) and f1

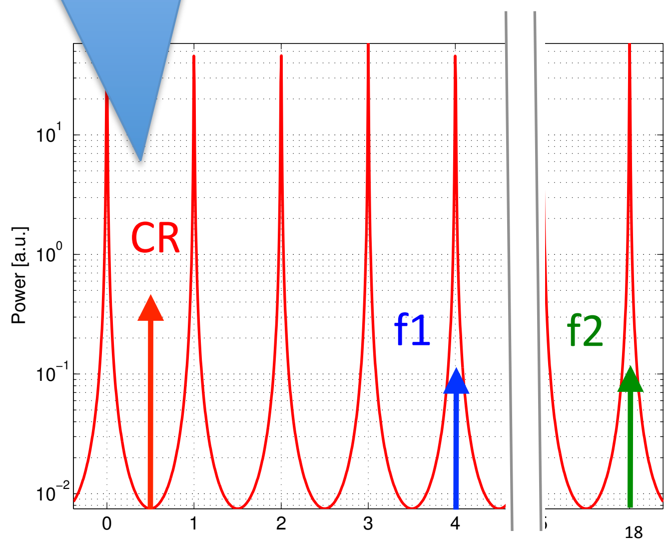
Resonant conditions

	Arm	PRC	SRC
CR	resonant	resonant	Dark at AS
f1	anti-reso	resonant	doesn't transmit MI
f2	anti-reso	resonant	resonant

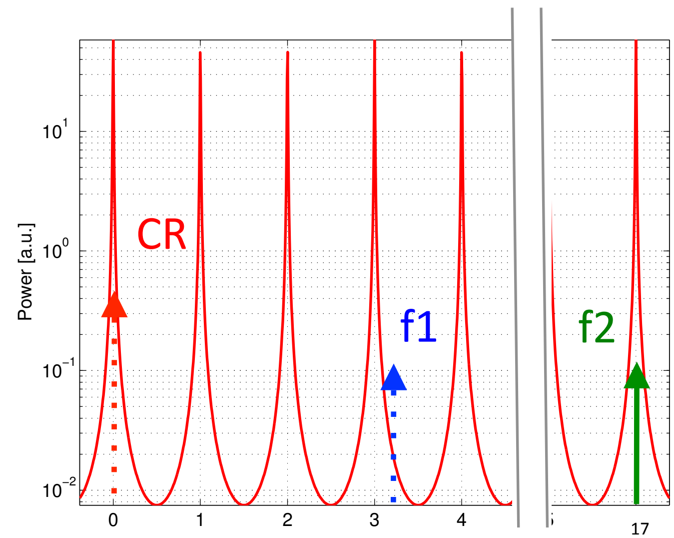
Field Conditions for the LSC

Reflectivity of the arm for resonant CR is π
→ resonant in PRC in overall





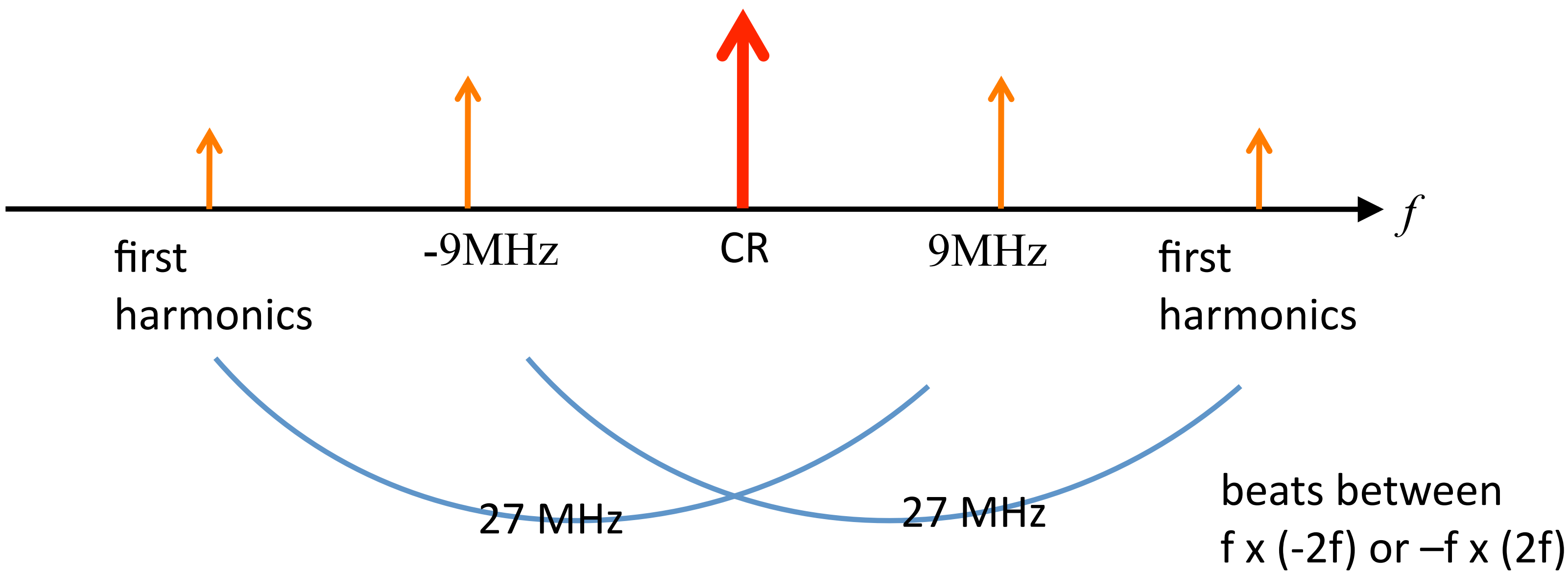
PRC (FSR 2.6 MHz)



SRC FSR = 2.68MHz

→ During the locking acquisition, error signal sings are flipped, if you use CR!

3f Locking Scheme is useful!



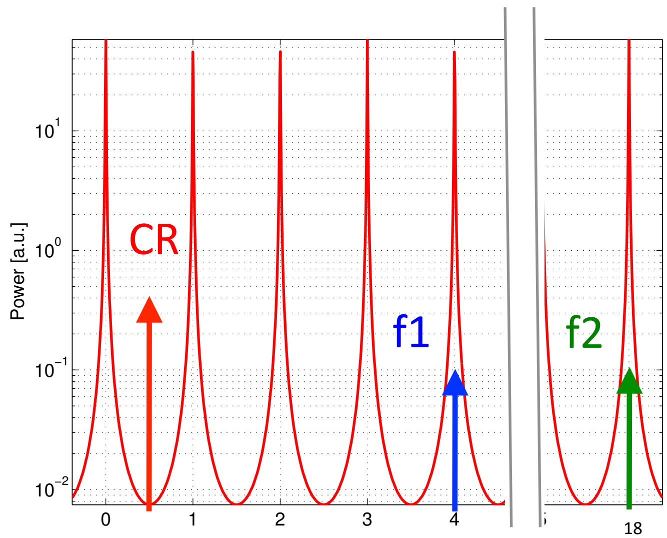
- Demodulate at 27 MHz or 135 MHz
- CR is not used for the demodulation process

→ Signal signs don't flip due to the CR condition in the arms
→ Robust signals during the lock acquisition
→ Smooth lock acquisition

Commissioning Done!

PRMI investigation:
What are PRMI CR and SB Lock?

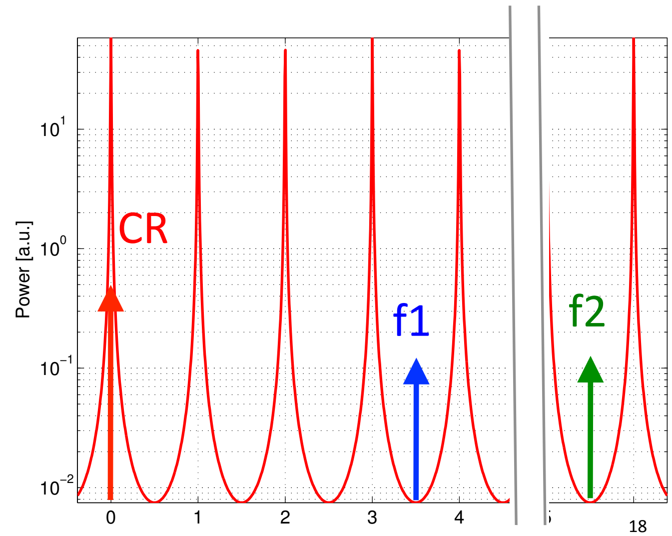
PRMI SB lock



PRC tuning

Same control condition as Full IFO
(without arms, CR is anti-resonant in PRC)

PRMI CR lock



PRC tuning

CR fields resonate in PRC
which is same when the full ifo

Investigation for thermal issues etc

When PRMI CR lock…

[Link to the AS port video](https://www.youtube.com/watch?v=HnlyOFnmMu4)

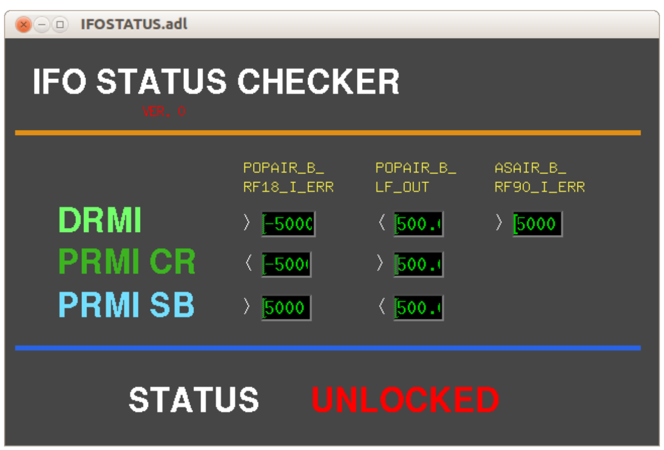
https://www.youtube.com/watch?v=HnlyOFnmMu4

REFL gets very dark (light is sucked by PRC)

Finding Locked Segments

- POP (Pick-Off of PRC) signals are useful
- CR build up ... L1:LSC-POPAIR_B_LF_OUT_DQ → CR buildup in PRC
- f1 build up ... L1:LSC-POPAIR_B_RF18_I_ERR_DQ → f1 buildup in PRC
- f2 build up at AS port ... L1:LSC-ASAIR_B_RF90_I_ERR_DQ → f2 buildup in SRC

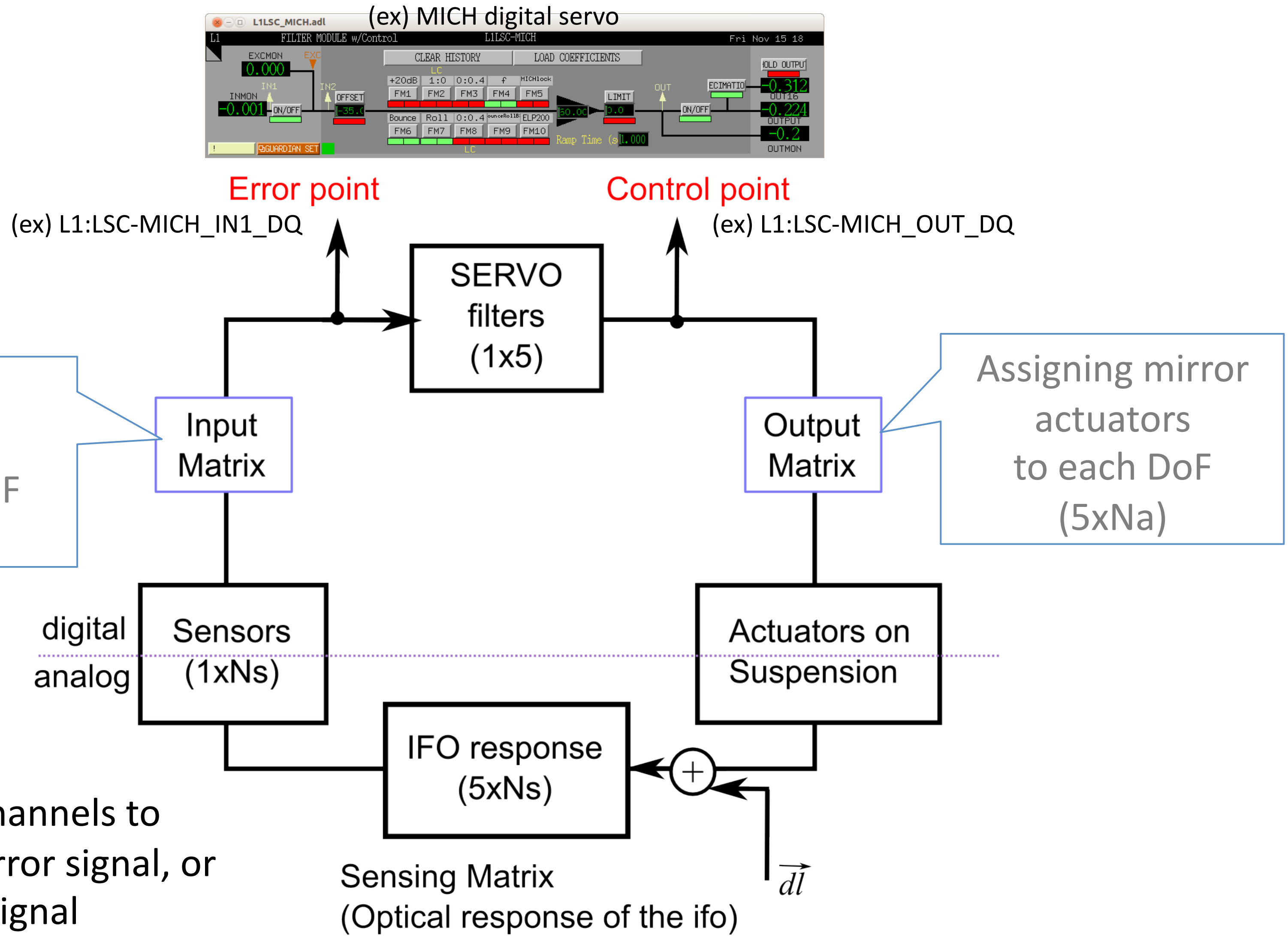
(IFO):LSC-(sensor name)_demodulation frequency_demodulation phase (I-phase or Q-phase)



STATUS channels (1 is locked, 0 is unlocked)
L1:LSC-DRMI_STATUS
L1:LSC-PRMICR_STATUS
L1:LSC-PRMISB_STATUS

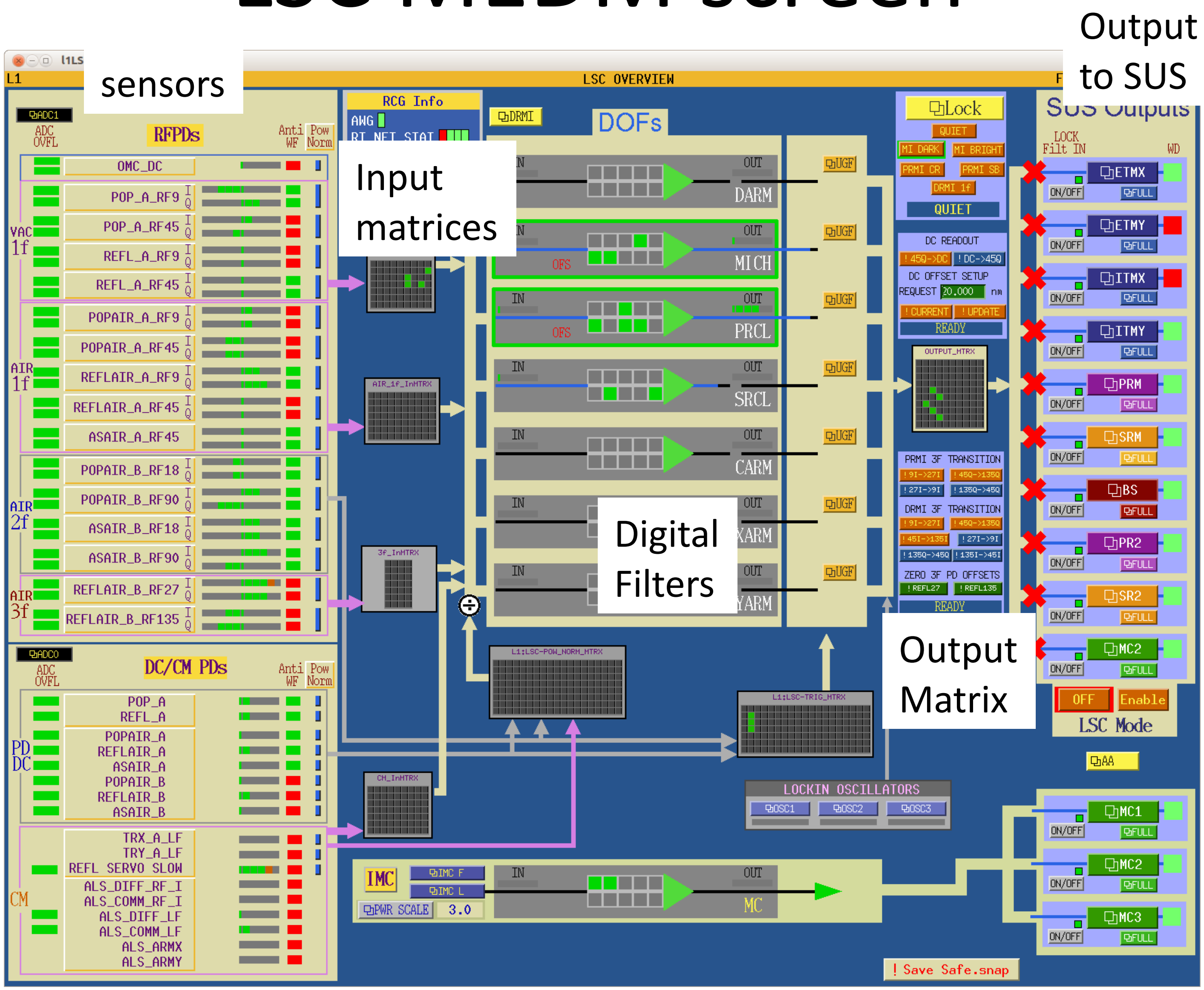
(*) LF means DC signal
(*) 2f SB condition details in appendix

MIMO control loop for LSC



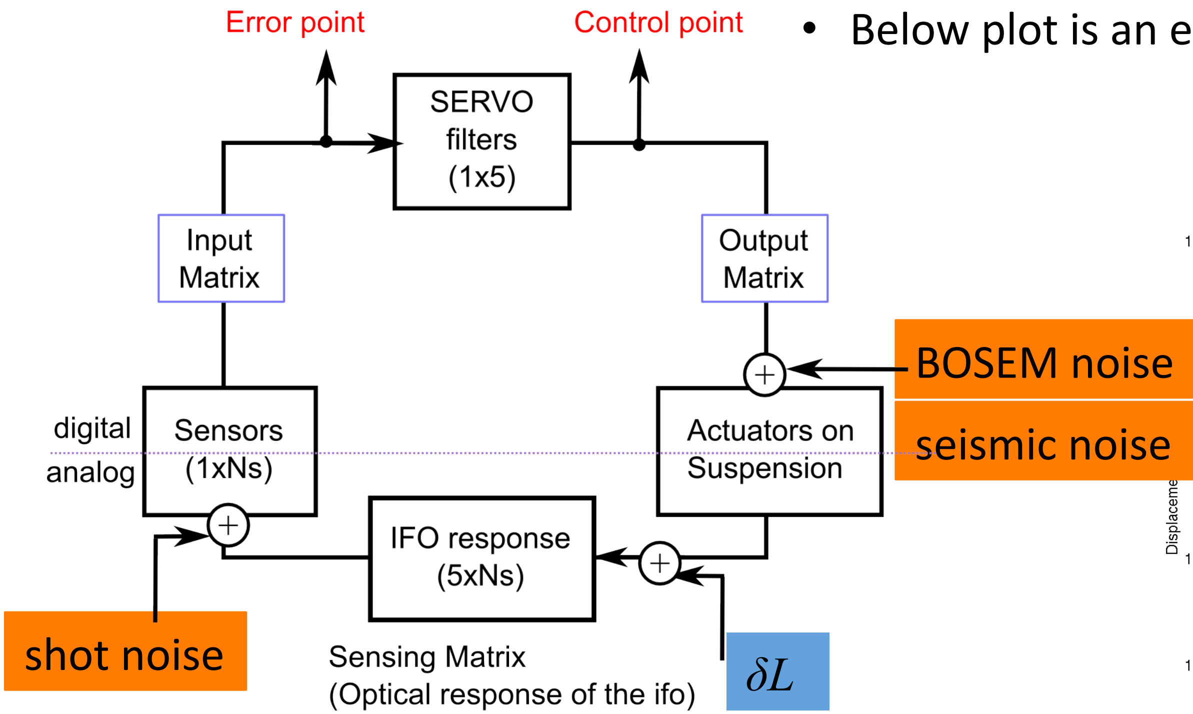
Important channels to look is the error signal, or the control signal

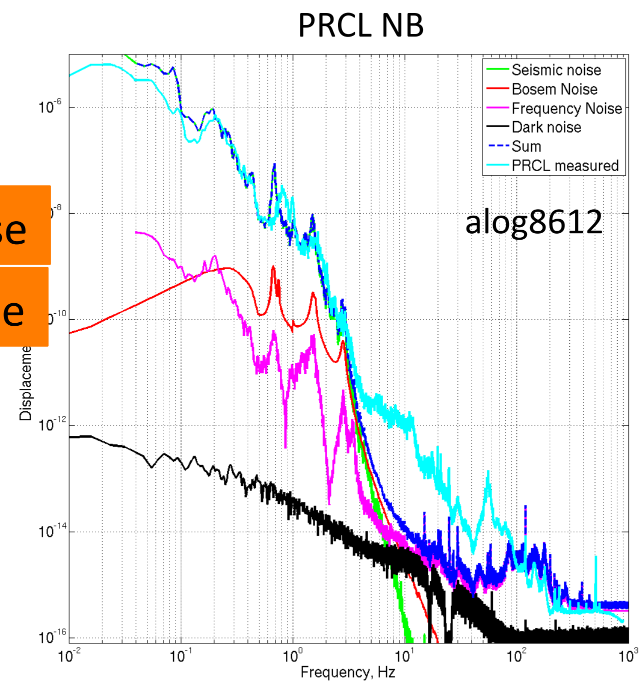
LSC MEDM screen



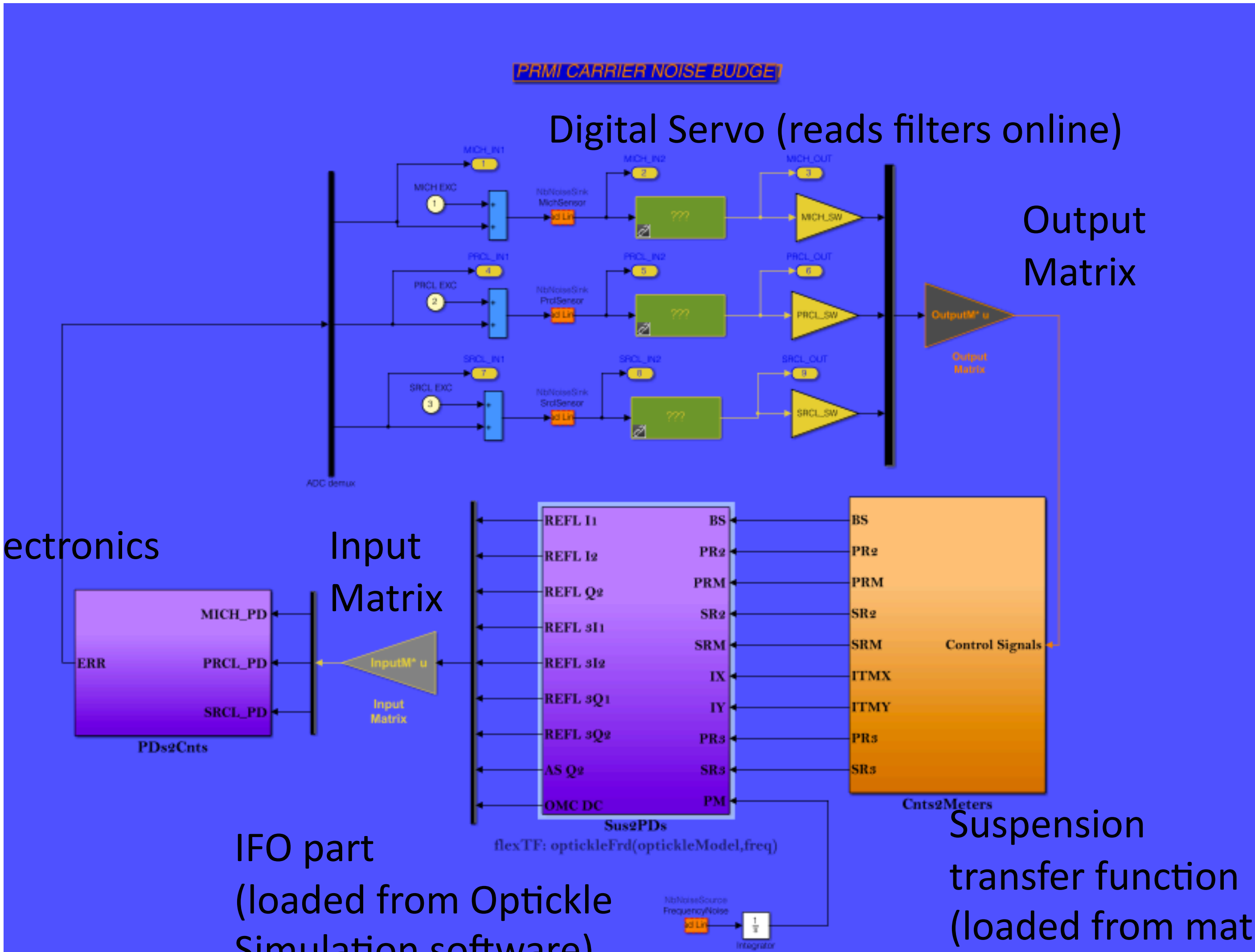
Noise Budget (NB)

- Model the brake down of the known noise sources
- Calibrate to the sensitivity
- DRMI NB is in progress
- Below plot is an example of PRMI CR on Sep





NB Simulink Model



Digital Servo (reads filters online)

Output Matrix

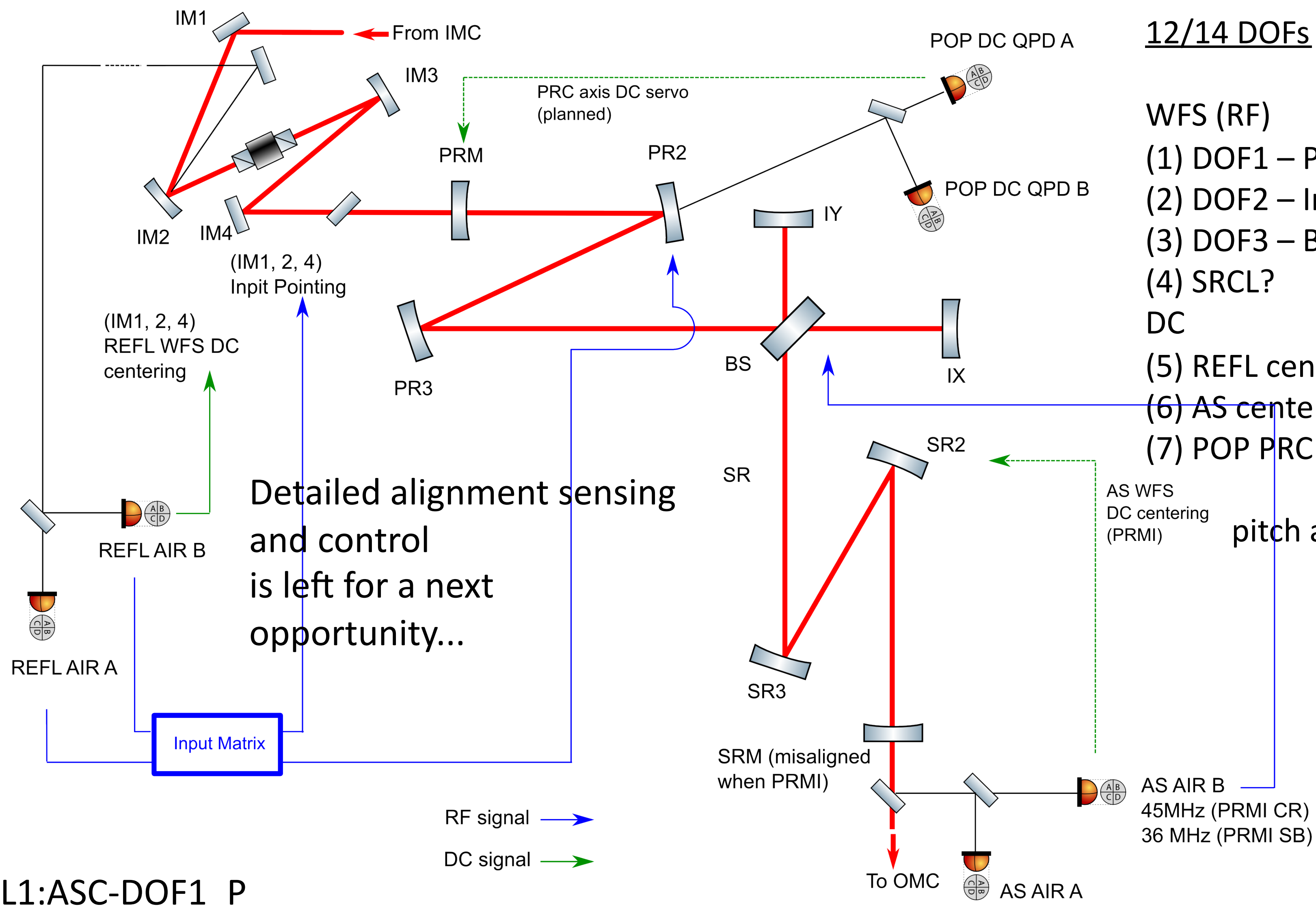
Sensor electronics Chain

Input Matrix

IFO part (loaded from Optickle Simulation software)

Suspension transfer function (loaded from matlab model)

Alignment Sensing and Control



Detailed alignment sensing
and control
is left for a next
opportunity...

<u>12/14 DOFs</u>

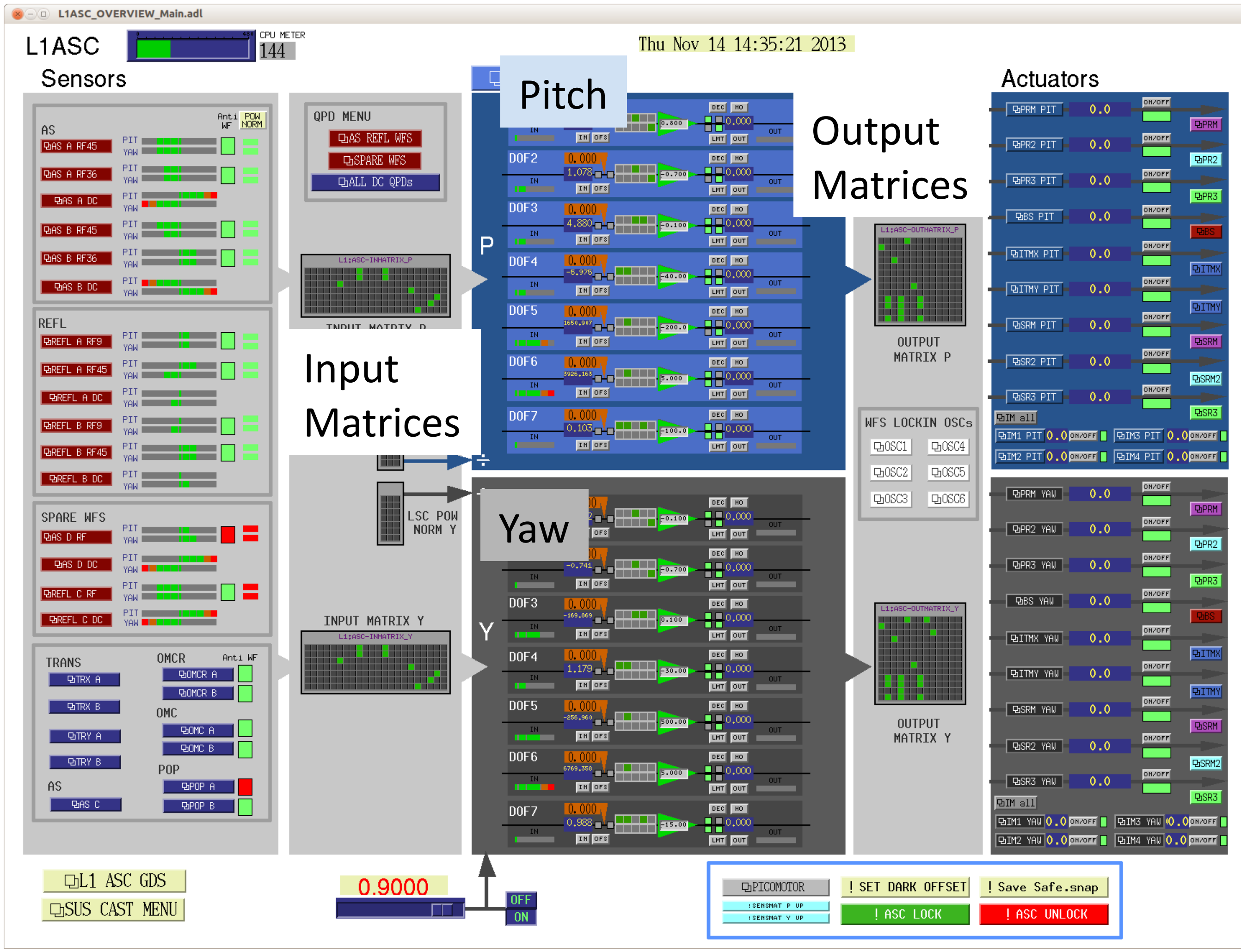
WFS (RF)
(1) DOF1 – PR2
(2) DOF2 – Input
(3) DOF3 – BS
(4) SRCL?
DC
(5) REFL centering
(6) AS centering
(7) POP PRC centering

pitch and yaw

L1:ASC-DOF1_P_

ASC MEDM screen

Sensors



Output to SUS

(ex error) L1:ASC-DOF1_P_IN1_DQ

(ex control) L1:ASC-DOF1_Y_OUT_DQ

Some Known Issues

(Possible Detchar Investigation?)

- ITMs violin modes are being excited for unknown reason.
- Force to angle (P, Y) couplings on BS M2 are very large. Simple Michelson cannot be locked without optical lever control. Optical lever will be turned off eventually for lower noise operation.
- PR3 and BS have µrad scale-drifts due to thermal effect/ thermal effect change wire lengths and occur pitch motions (PRMI CR)
- Keep eyes on the noise budget and noise hunting

Reading Materials

- aLIGO LSC
  - LIGO-T1000298-v2 (Final design document)
  - LIGO-T1200128-v4 (after SRM transitivity change)
- 3f locking scheme
  - Koji Arai's thesis (It is also a good textbook for the basic LSC)
- Wave front sensor principle
  - E. Morrison, B. J. Meers, D. R. & Ward, H., *APPLIED OPTICS*, **1994**, *33*, 22
- aLIGO ASC document
  - LIGO-T0900511-v4

Who to ask questions

- LSC
  - Jenne Driggers (Caltech, jenne@caltech.edu)
  - Anamaria Effler (LSU, aeffle2@lsu.edu)
  - Kiwamu Izumi (LHO, izumi_k@ligo-wa.caltech.edu)
  - Denis Martynov (Caltech, dmartyno@caltech.edu)
  - Nic Smith (Caltech, nicolas@ligo.caltech.edu)
- LSC NB
  - Chris Wipf (LHO, wipf@ligo.mit.edu)
  - Anamaria
- ASC
  - Keiko (LSU, keiko@lsu.edu)
  - Chris Mueller (UoF, cmueller@phys.ufl.edu)
  - Denis

References:

Koji Arai's presentation,

"Introduction of the interferometer experiment for data-analysts"

Koji Arai's PhD thesis, University of Tokyo (2001)

Masaki Ando's master thesis, University of Tokyo (1996)

Kiwamu Izumi's presentation, LIGO-G1200423

Please feel free to email me for questions!

Appendix

Basic of Optical Fields (1)

Light Field after a laser source

angular freq. $\Omega/2\pi \rightarrow f_0 = 281.76$ [THz]
$\rightarrow \lambda = 1064$ [nm]

$$E_1 = E_0 e^{i\Omega t} \qquad \text{... (1)}$$

Electro Optic Modulator (EOM) applies sideband (SB) fields

SB (angular) frequency

$$E_{\rm inc} = E_1 e^{i m_{\rm m} \cos \omega_{\rm m} t} = E_0 e^{i(\Omega t + m_{\rm m} \cos \omega_{\rm m} t)} \qquad \text{... (2)}$$

modulation index

Expand (approx) with Bessel Function

$$= \quad E_0 \left\{ J_0(m_{\rm m}) e^{i\Omega t} + i J_1(m_{\rm m}) e^{i(\Omega + \omega_{\rm m})t} + i J_1(m_{\rm m}) e^{i(\Omega - \omega_{\rm m})t} \right\} \qquad \text{... (3)}$$

Carrier Light Field

$\Omega+\omega_m$, $\Omega-\omega_m$ components are applied

M. Ando, master thesis

Basic of Optical Fields (2)

Detection of the Light Field

optical field at a certain port

$$
\begin{aligned}
P &= |E|^2 \\
&= |E_0|^2 + |E_1|^2 + |E_{-1}|^2 \\
&\quad + 2Re\left\{(E_0^* E_1 + E_0 E_{-1}^*) e^{i\omega_m t}\right\} \\
&\quad + 2Re\left\{E_1 E_{-1}^* e^{2i\omega_m t}\right\}
\end{aligned}
$$

DC component (offset)

ω_m component

$2\omega_m$ component (filtered by a low pass filter)

Demodulation

multiply $\cos(\omega_m t)$ to the detected field – signal is down converted to DC

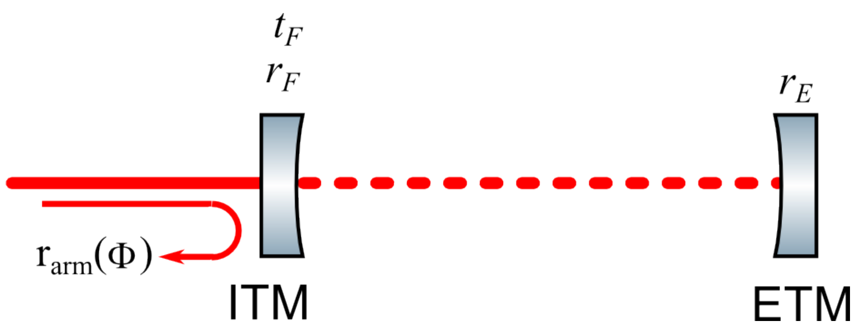
I-phase

$2Re\ \{(E_0{}^* E_1 + E_0 E_{-1}{}^*)\ \exp(i\ \omega_m t)\}\ \cos(\omega_m t) \rightarrow Re\ (E_0{}^* E_1 + E_0 E_{-1}{}^*)\ (1 + o(2\omega))$

Q-phase

$2Re\ \{(E_0{}^* E_1 + E_0 E_{-1}{}^*)\ \exp(i\ \omega_m t)\}\ \sin(\omega_m t) \rightarrow -Im\ (E_0{}^* E_1 + E_0 E_{-1}{}^*)\ (1 + o(2\omega))$

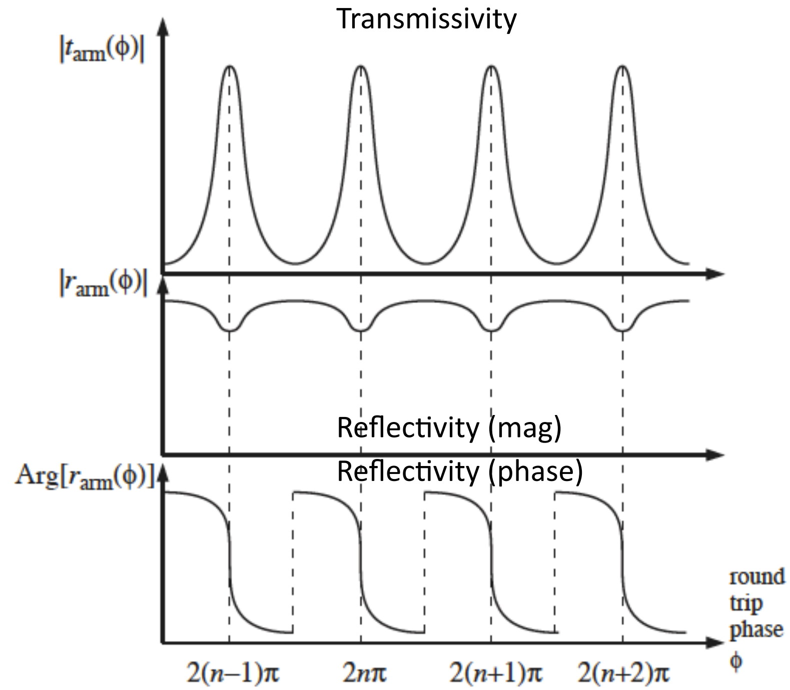
FP compound complex reflectivity



$$r_{\rm arm}(\Phi) = -r_{\rm F} + \frac{t_{\rm F}^2 r_{\rm E}\, e^{-{\rm i}\Phi}}{1 - r_{\rm F} r_{\rm E}\, e^{-{\rm i}\Phi}}$$

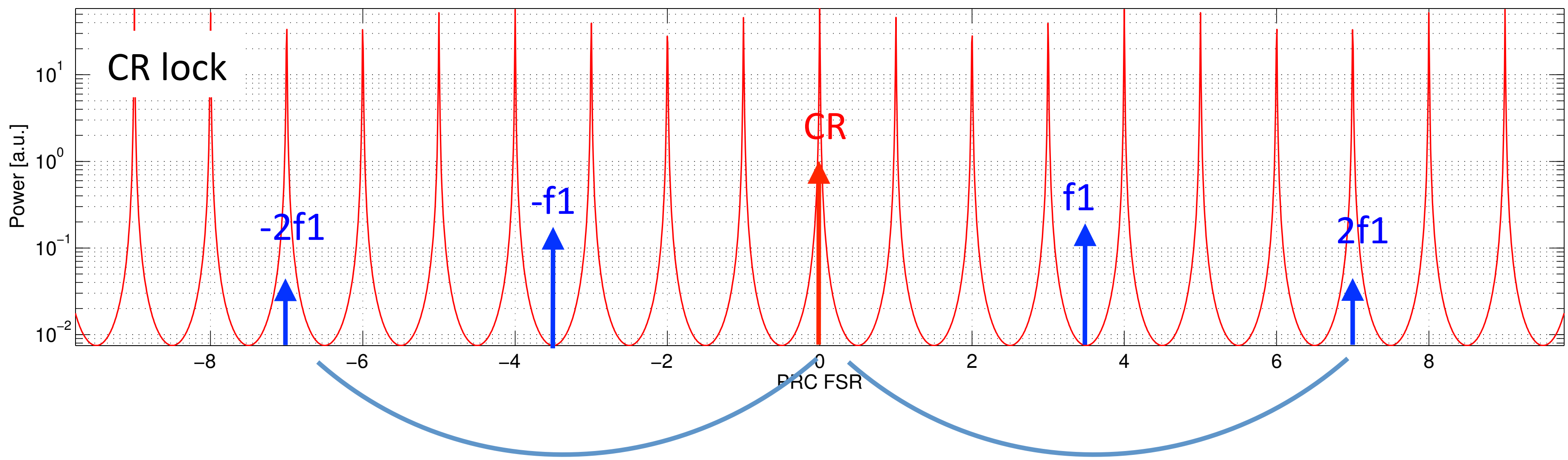
$$t_{\rm arm}(\Phi) = \frac{t_{\rm F} t_{\rm E}\, e^{-{\rm i}\Phi/2}}{1 - r_{\rm F} r_{\rm E}\, e^{-{\rm i}\Phi}}\ ,$$

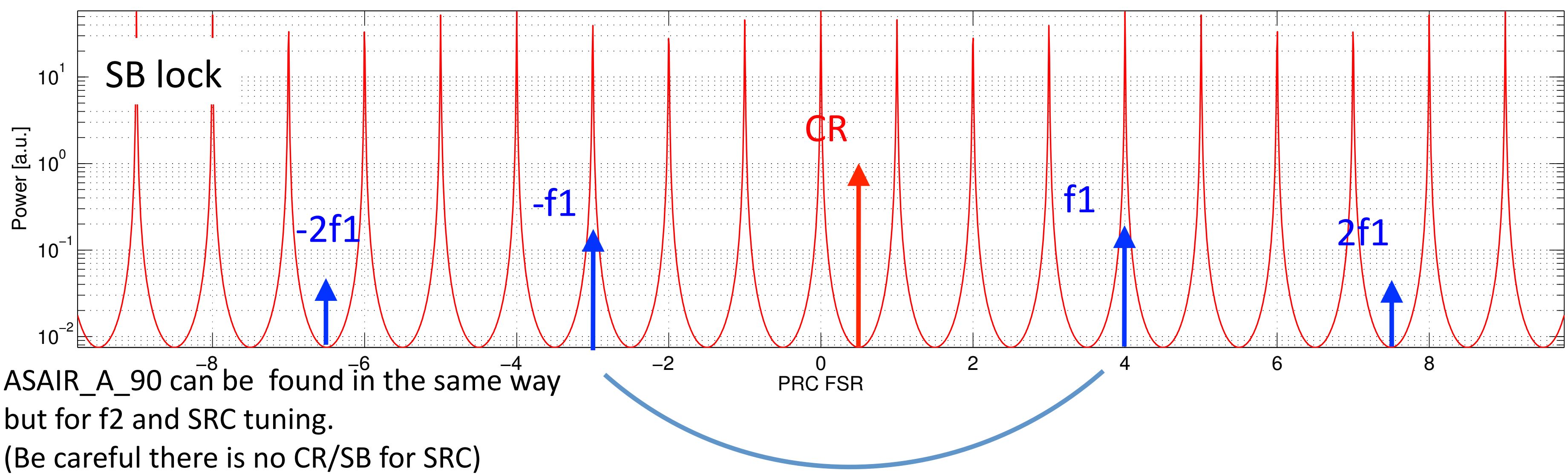
Φ: round trip phase
(2π: resonant, π: anti-reso)



K. Arai, Phd thesis

POPAIR_B_18 and ASAIR_A_90





ASAIR_A_90 can be found in the same way
but for f2 and SRC tuning.
(Be careful there is no CR/SB for SRC)

sensor assignment example when 3f DRMI

DoF	Sensor	UGF
PRCL	REFL 27 I	40Hz
MICH	REFL 135 Q	8Hz
SRCL	REFL 135 I	40Hz

Who to ask question:
Other LSC related Subsystems

OMC: Zach Korth (Caltech, korth@caltech.edu)
IMC: Chris Mueller
ALS: Kiwamu Izumi,
Adam Mullavey (LSU, amullavey@lsu.edu)

The SB transitivity to AS
in terms of the Schnupp Asymmetry Length Δl

$$t_{\mathrm{com}} = \sin(\Delta l\ \omega_m / c)$$