LCGT Main Interferometer Subsystem

Type B Review

2011/3/1@ICRR

Y. Aso on behalf of the LCGT MIF Working Group

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Definition of the Subsystem

Main Interferometer

FP arms, PRC, SRC, Michelson, (OMC)

Length Control, Alignment Control, Lock Acquisition

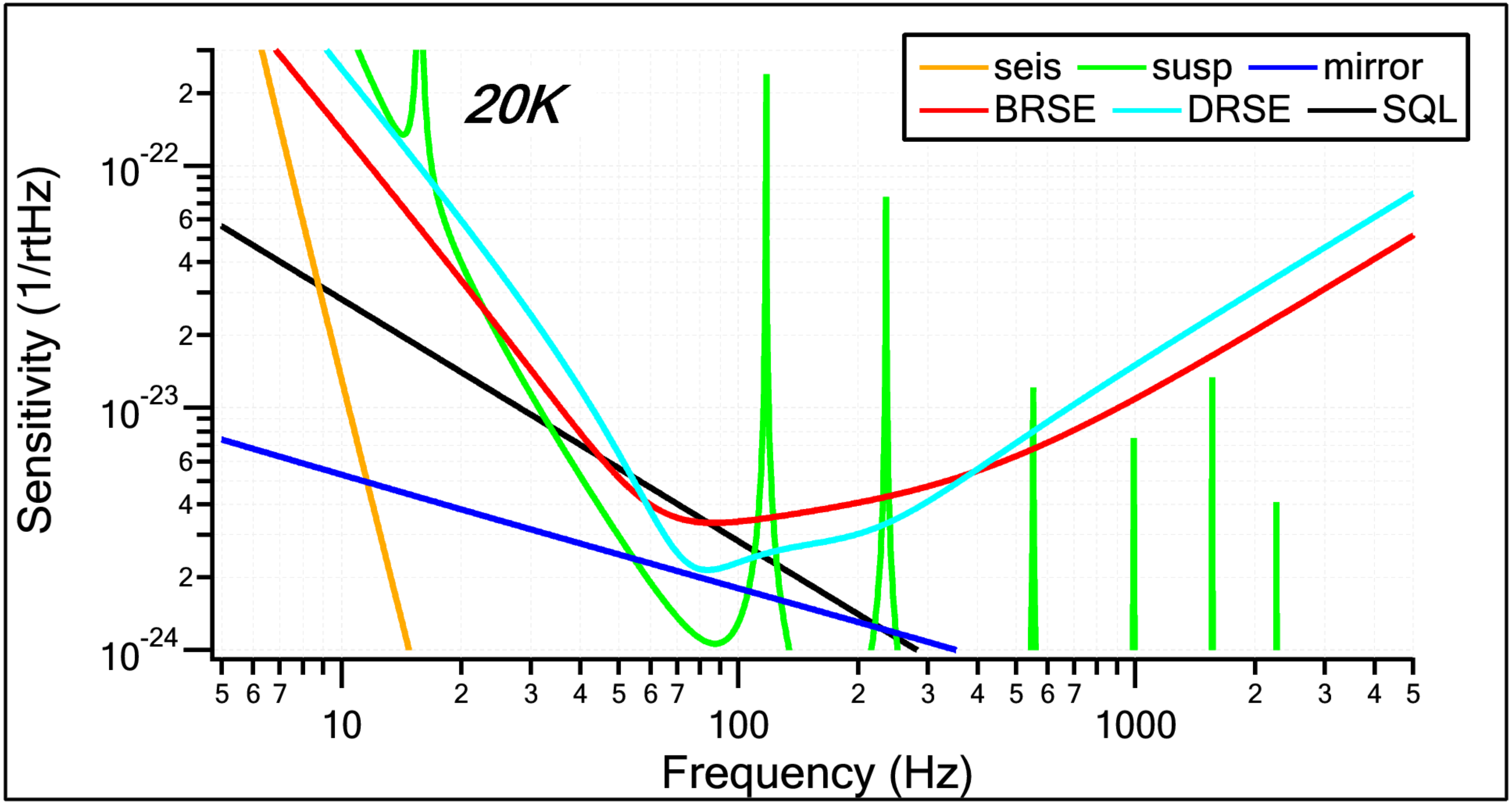
Commissioning

- No Hardware Manufacturing
- Design and Commissioning

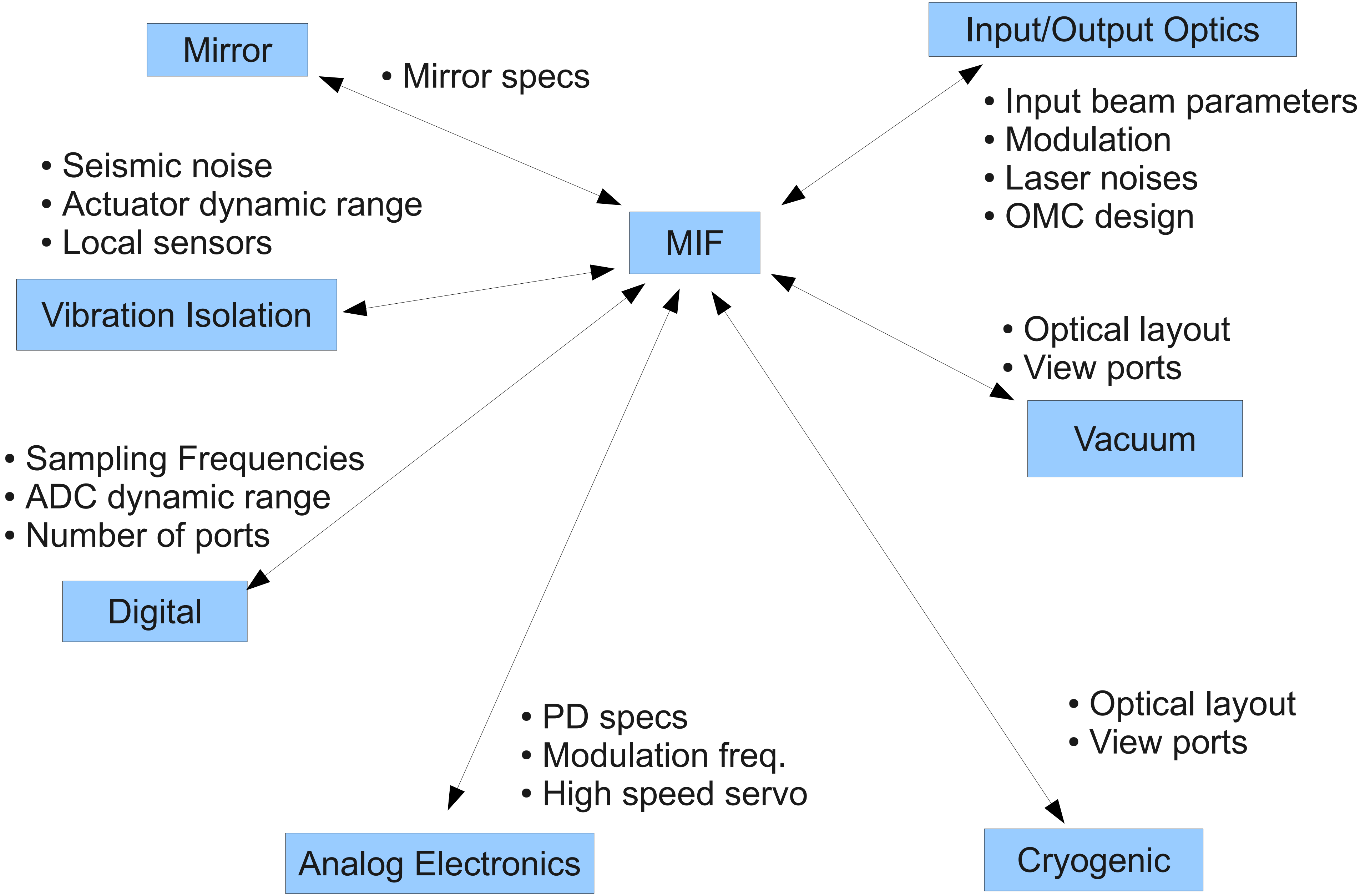
Requirements

- Design an interferometer which can achieve the target sensitivity of bLCGT
- Switchable between BRSE and DRSE
- Robust operation
- Efficient commissioning

bLCGT Target Sensitivity



Interfaces with Other Subsystems



- Mirror specs

- Input beam parameters
- Modulation
- Laser noises
- OMC design

- Seismic noise
- Actuator dynamic range
- Local sensors

- Optical layout
- View ports

- Sampling Frequencies
- ADC dynamic range
- Number of ports

- PD specs
- Modulation freq.
- High speed servo

- Optical layout
- View ports

Contents

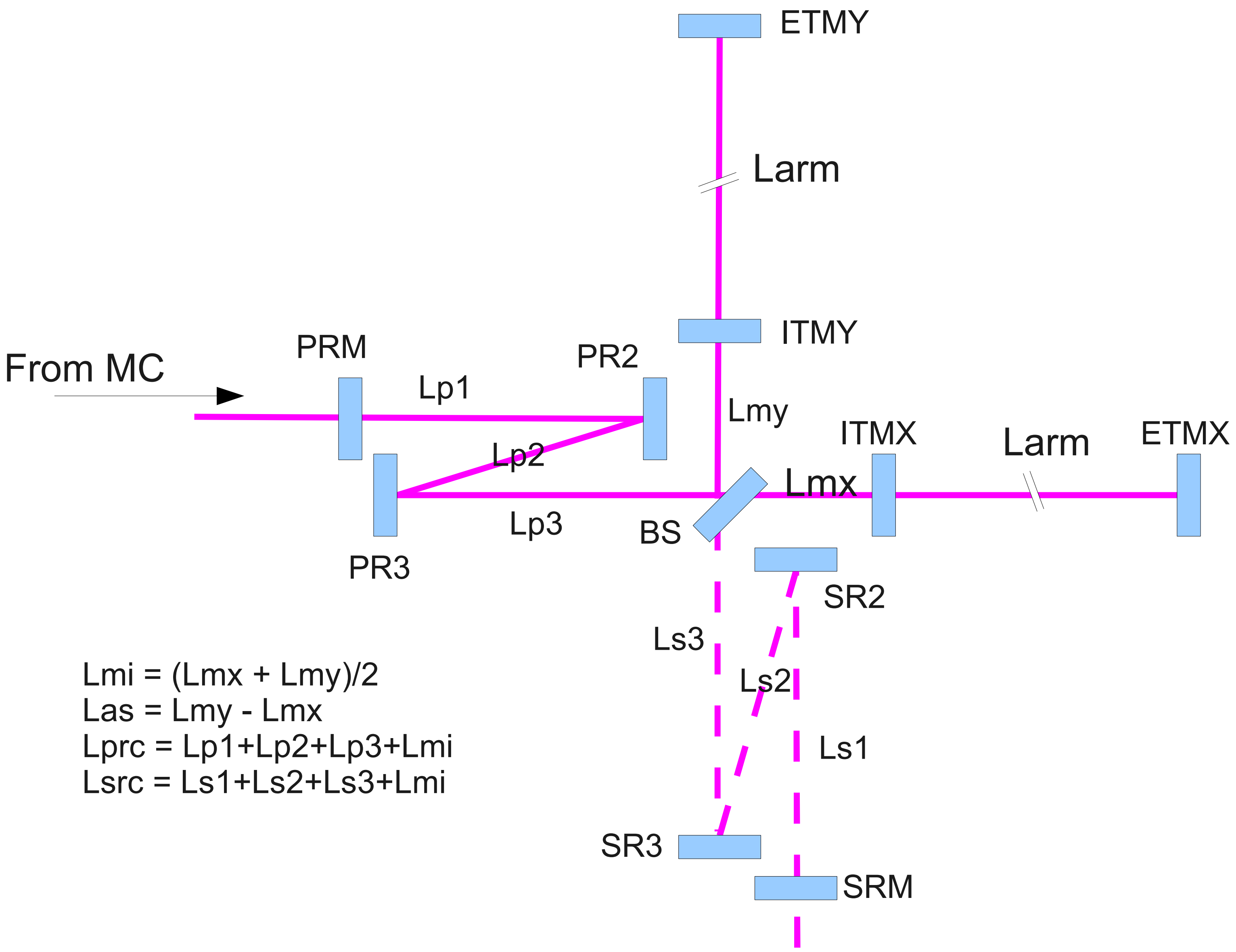
- Design of bLCGT Main Interferometer
- iLCGT design
- Activity plan during the tunnel excavation period
- Commissioning Schedule
- Risk Assessment

Main Interferometer Design

- Arm Cavity Design
  - Angular Instability
  - Parametric Instability
  - Higher Order Spatial Modes
- Recycling Cavities
  - Modulation Frequencies
    - Length Sensing Schemes
  - Folding
    - Alignment Sensing
- Lock Acquisition Strategy
  - Green laser pre-lock
  - 3rd Harmonics Demodulation
  - Non-Resonant Sideband
- Optical Layout

Overview

Dual Recycled Fabry-Perot Michelson Interferometer in RSE mode.



Lmi = (Lmx + Lmy)/2
Las = Lmy - Lmx
Lprc = Lp1+Lp2+Lp3+Lmi
Lsrc = Ls1+Ls2+Ls3+Lmi

Arm Cavity Design

Parameters

- Length: 3000.00m
- Finesse: 1546
- g-factor : g1=1, g2=0.572

Prefixed

Arm Cavity g-factor

- Spatial Mode Stability
- Beam Spot Size => Thermal Noise
- Angular Radiation Pressure Instability (Sidles-Sigg effect)
- Parametric Instability

Beam Spot Size

- Larger is Better for Thermal Noise
- 4.53cm@ETM => 0.6ppm diffraction loss
- 3.43cm@ITM
  - ITM coating is thinner than ETM
  - No problem for Thermal Noise

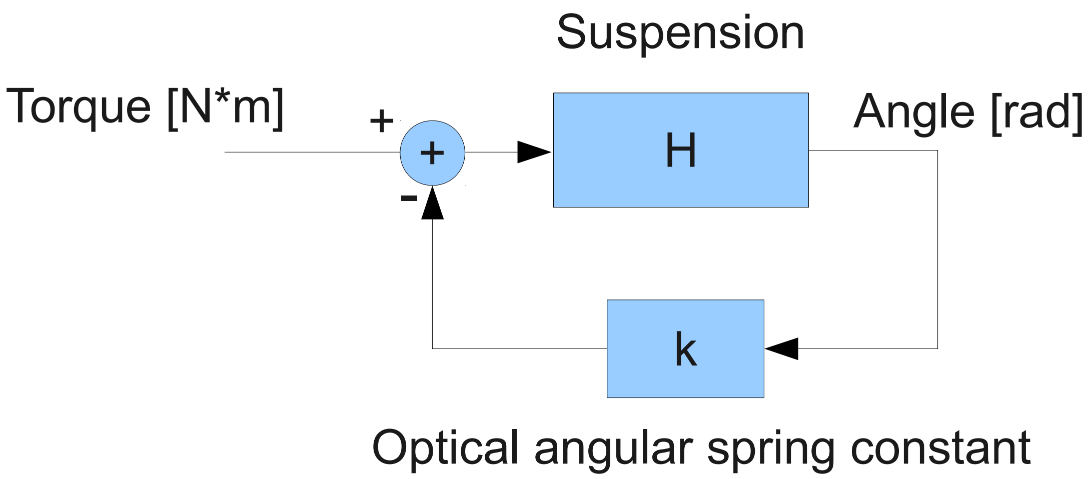
Angular Instability

Sidles-Sigg Stiffness Matrix

Angular Optical Spring Constant k [N*m/rad]

Large Beam (ITM=3.5cm, ETM=4.5 or 4.2cm)
4.4, -33.8 (g1 = 1, g2 = 0.572)
-4.6, 29.2 (g1 = -0.87, g2 = -0.6)

Small Beam (ITM=ETM=3.5cm)
5.0, -19.3 (g1 = g2 = 0.586)
-5.0, 19.3 (g1 = g2 = - 0.586)



Suspension

Torque [N*m]

Angle [rad]

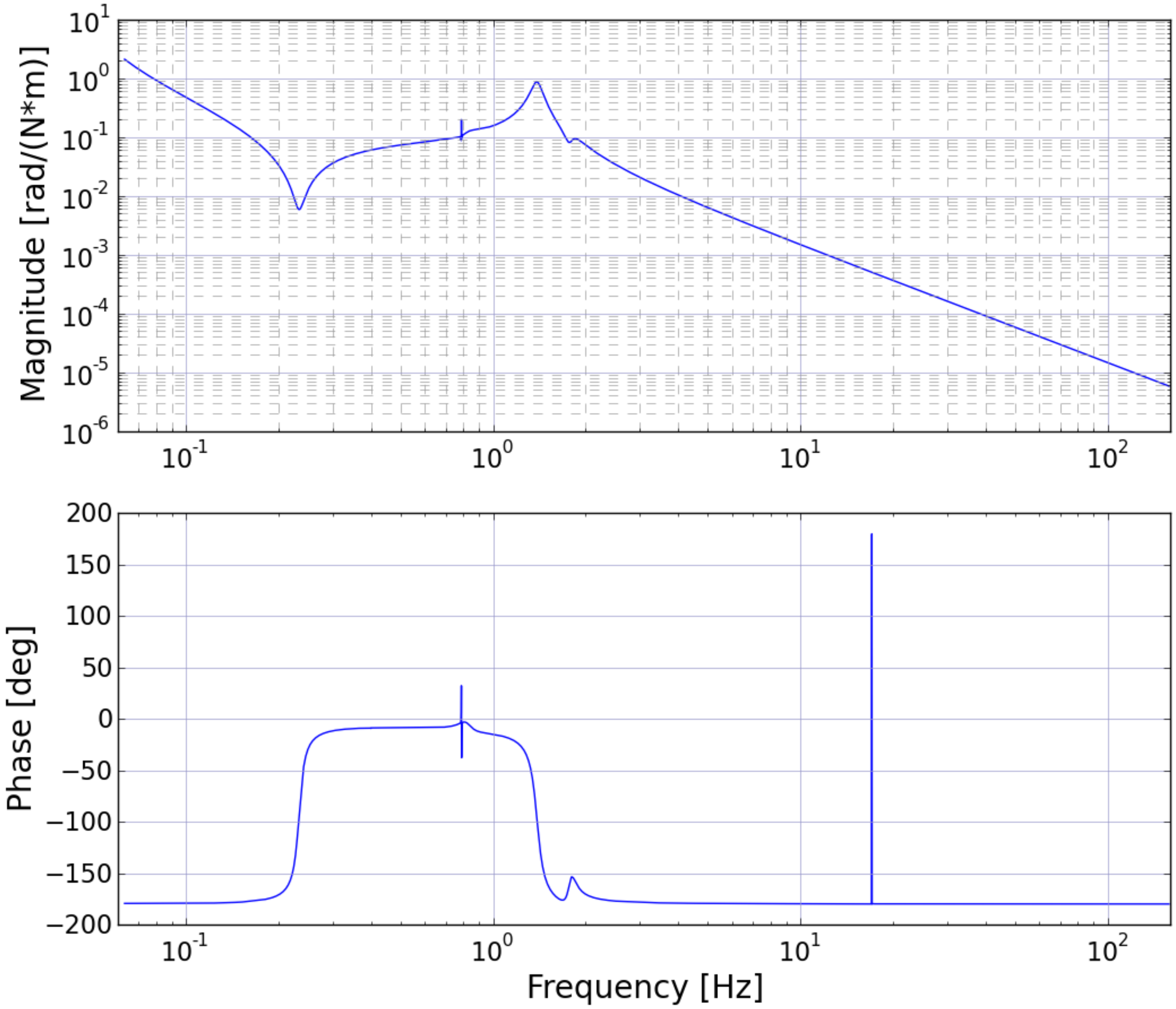
Optical angular spring constant

Open Loop Gain: G = k*H

Check Stability

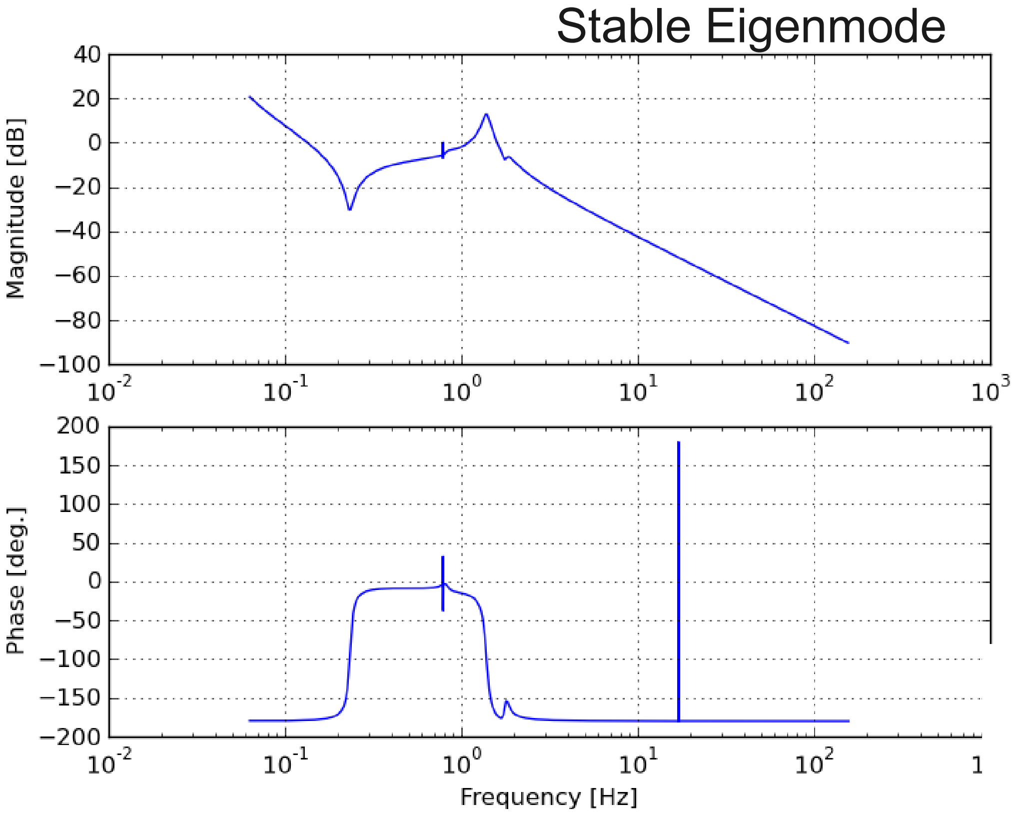
Suspension TF

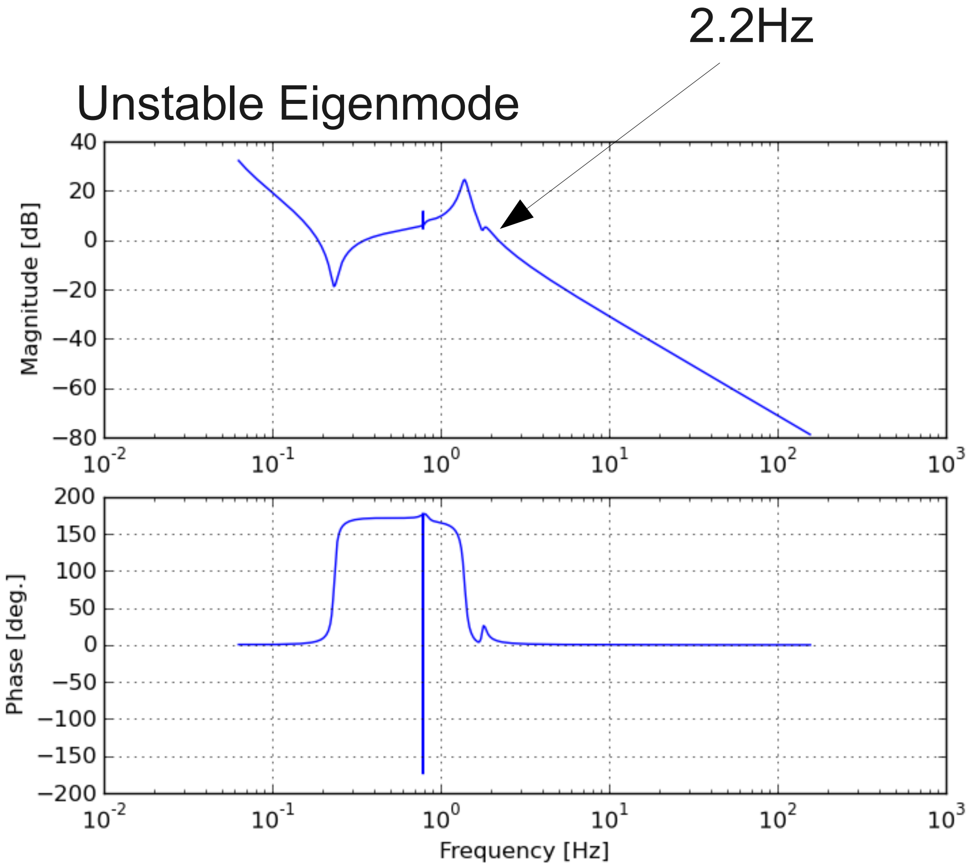
Yaw Torque -> Yaw Angle



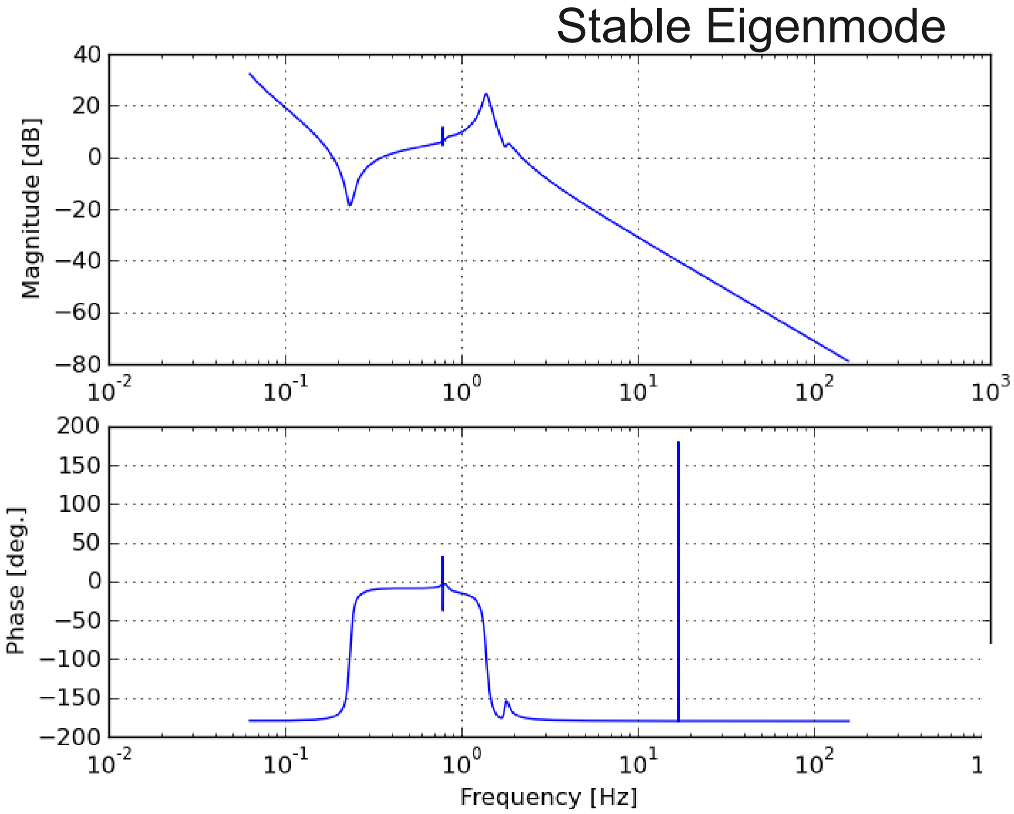
This is H

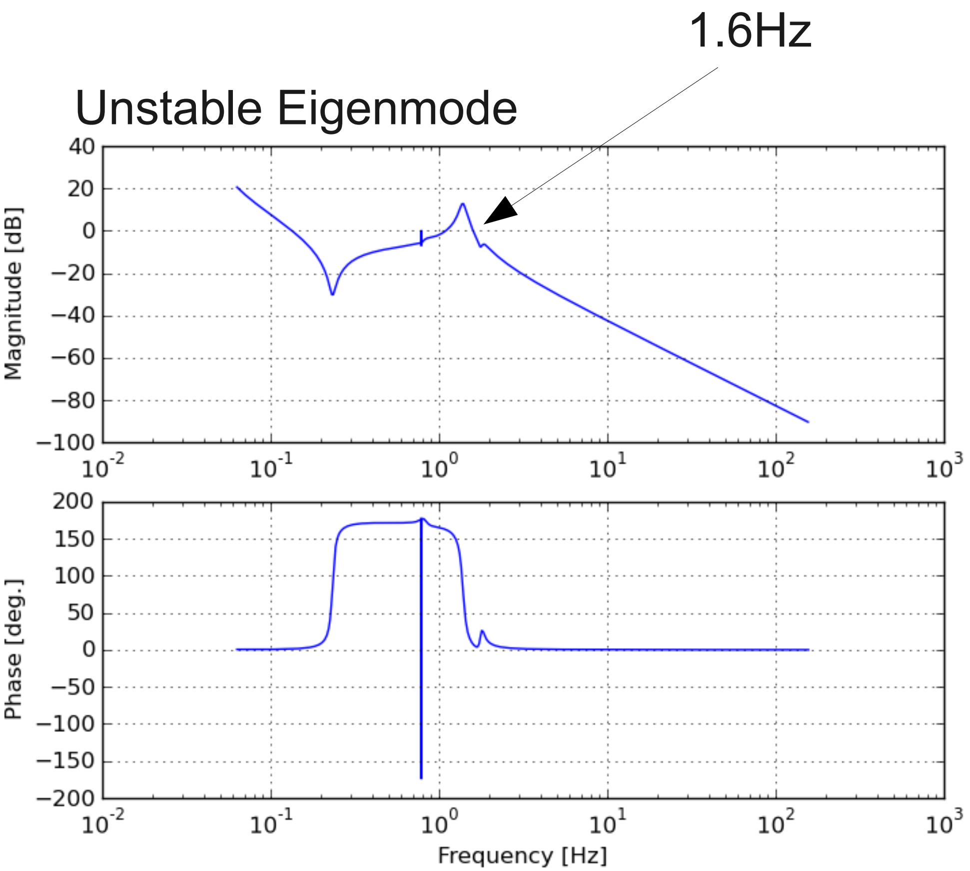
Small beam, positive (g1=g2=0.586)





Small beam, negative (g1=g2=-0.586)

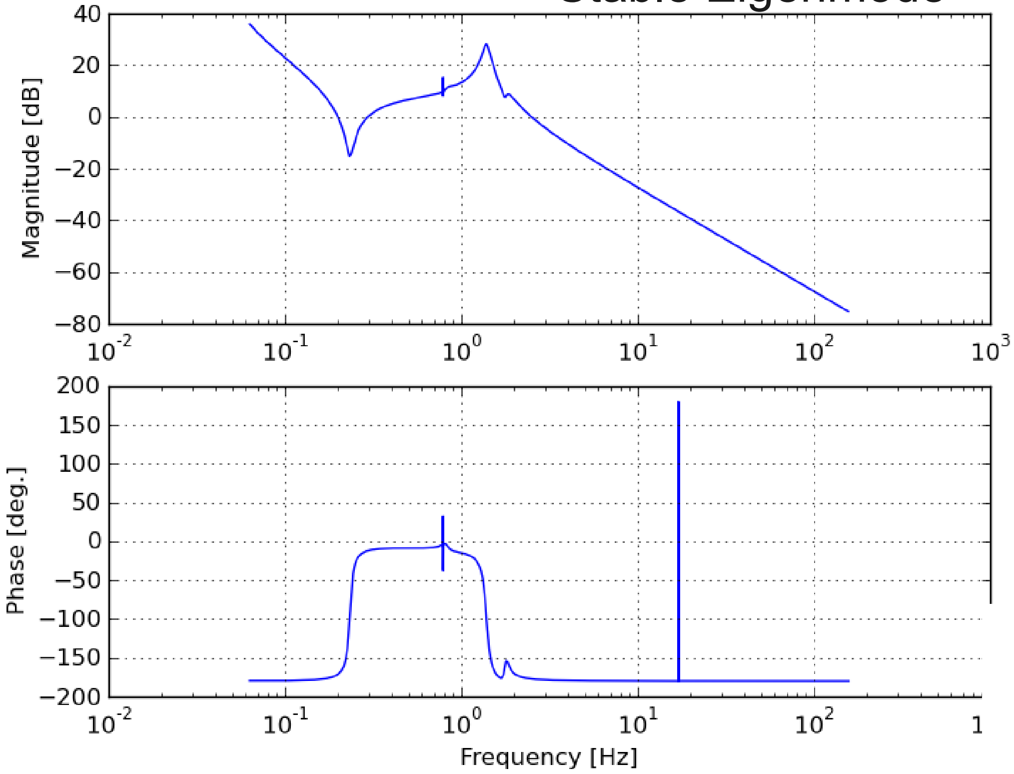

Stable Eigenmode


1.6Hz

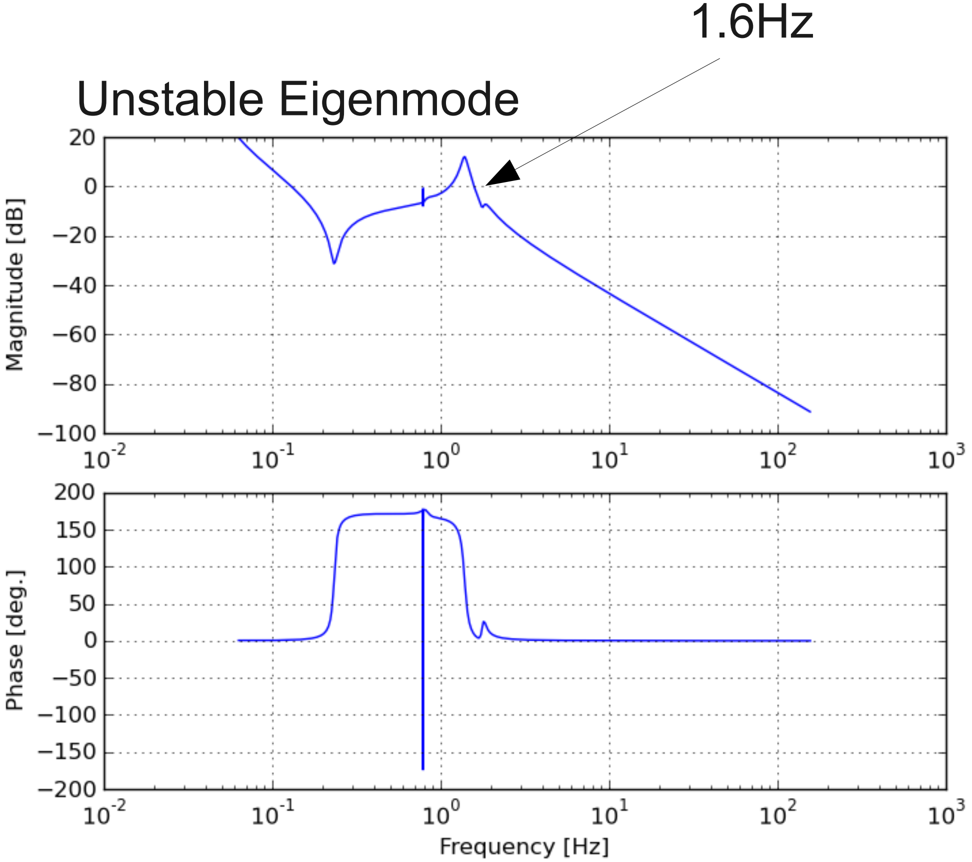
Unstable Eigenmode

Large beam, negative (g1=-0.87,g2=-0.6)

Stable Eigenmode

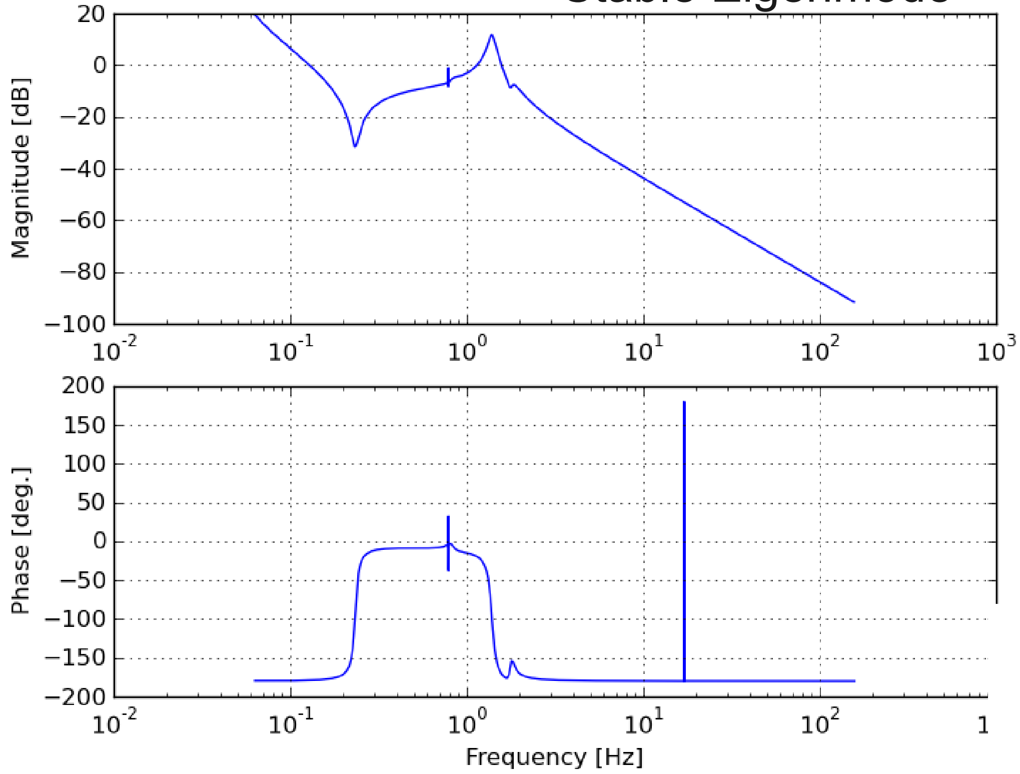


Unstable Eigenmode


1.6Hz

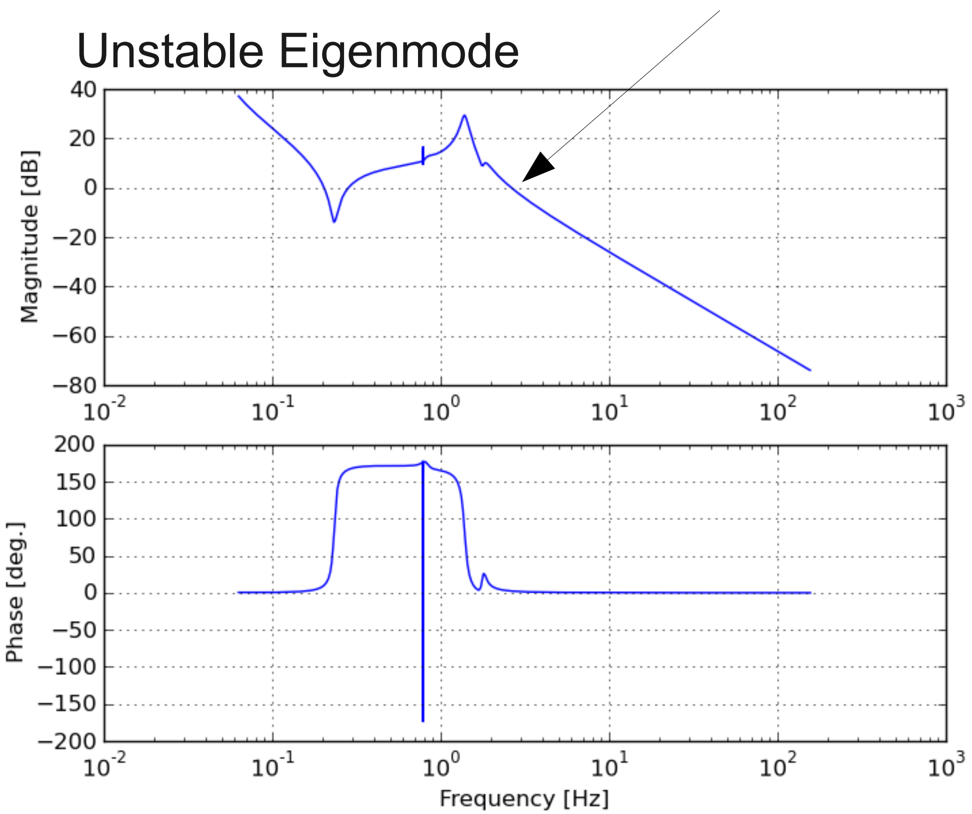
Large beam, positive (g1=1,g2=0.572)

Stable Eigenmode



2.65Hz

Unstable Eigenmode



Unstable Frequency

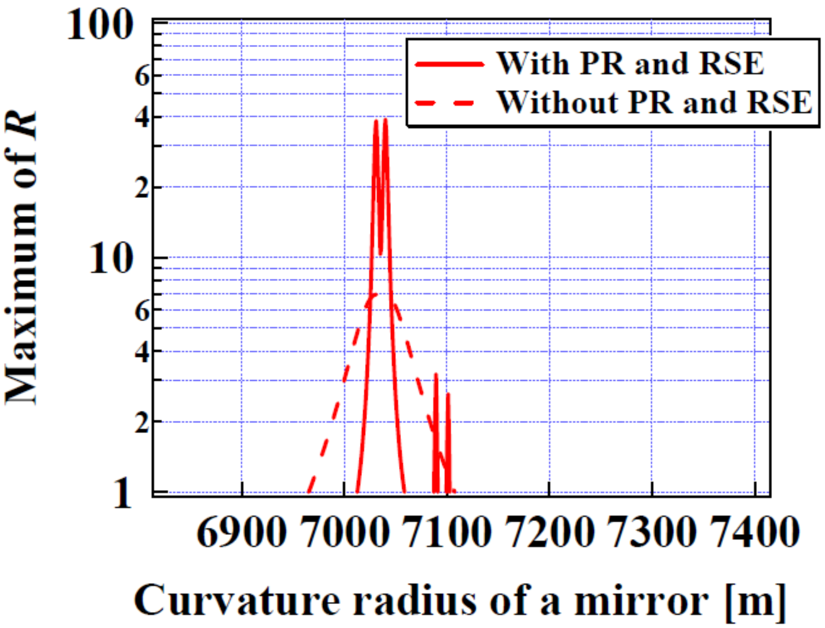
Large Beam
g1 = 1, g2 = 0.572: 2.65Hz
g1 = -0.87, g2 = -0.6: 1.6Hz

Small Beam
g1 = g2 = 0.586: 2.2Hz
g1 = g2 = - 0.586: 1.6Hz

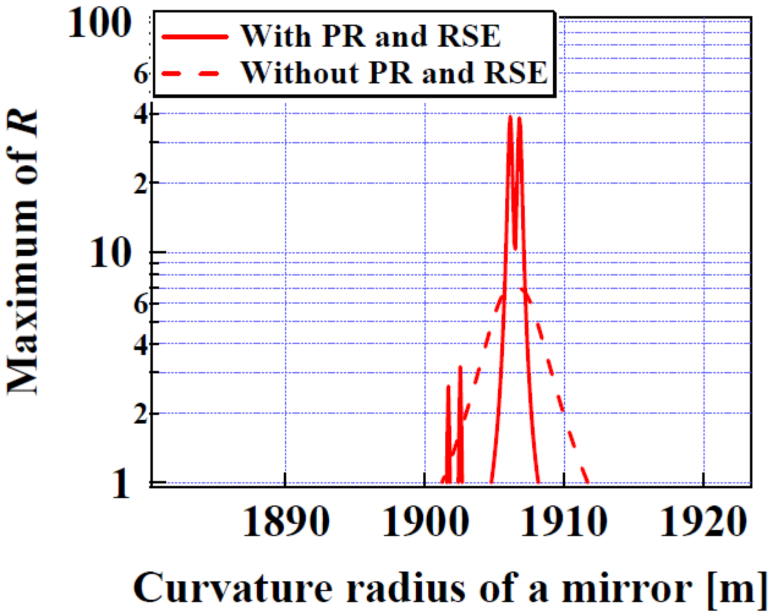
Parametric Instability

There are dangerous regions to avoid in the g-factor space

Positive g-factor



Negative g-factor



The error requirement on the mirror ROC is stricter for the negative g-factor.
by $\left(R_{\mathrm{p}}/R_{\mathrm{n}}\right)$

Negative g-factor: R ~ 1.9km
Positive g-factor: R > 7km

→ Negative g-factor is about 3.7 times more severe to ROC error in terms of PI

10m ROC errror for 1.9km mirror -> 0.5% error
100m ROC errror for 7km mirror -> 1.5% error

g-factor Comparison

		Thermal Noise (IR) DRSE/BRSE [Mpc]	Optical Spring Unstable Freq.	PI	ROC
(a)	g1=1 g2=0.572	275/246	2.6Hz	Easy	ITM: >100km ETM: 7000m
(b)	g1=-0.87 g2=-0.6	273/245	1.6Hz	Severe	ITM: 1604m ETM: 1875m
(c)	g1=0.586 g2=0.586	266/241	2.2Hz	Easy	ITM: 7246m ETM: 7246m
(d)	g1=-0.586 g2=-0.586	266/241	1.6Hz	Severe	ITM: 1892m ETM: 1892m

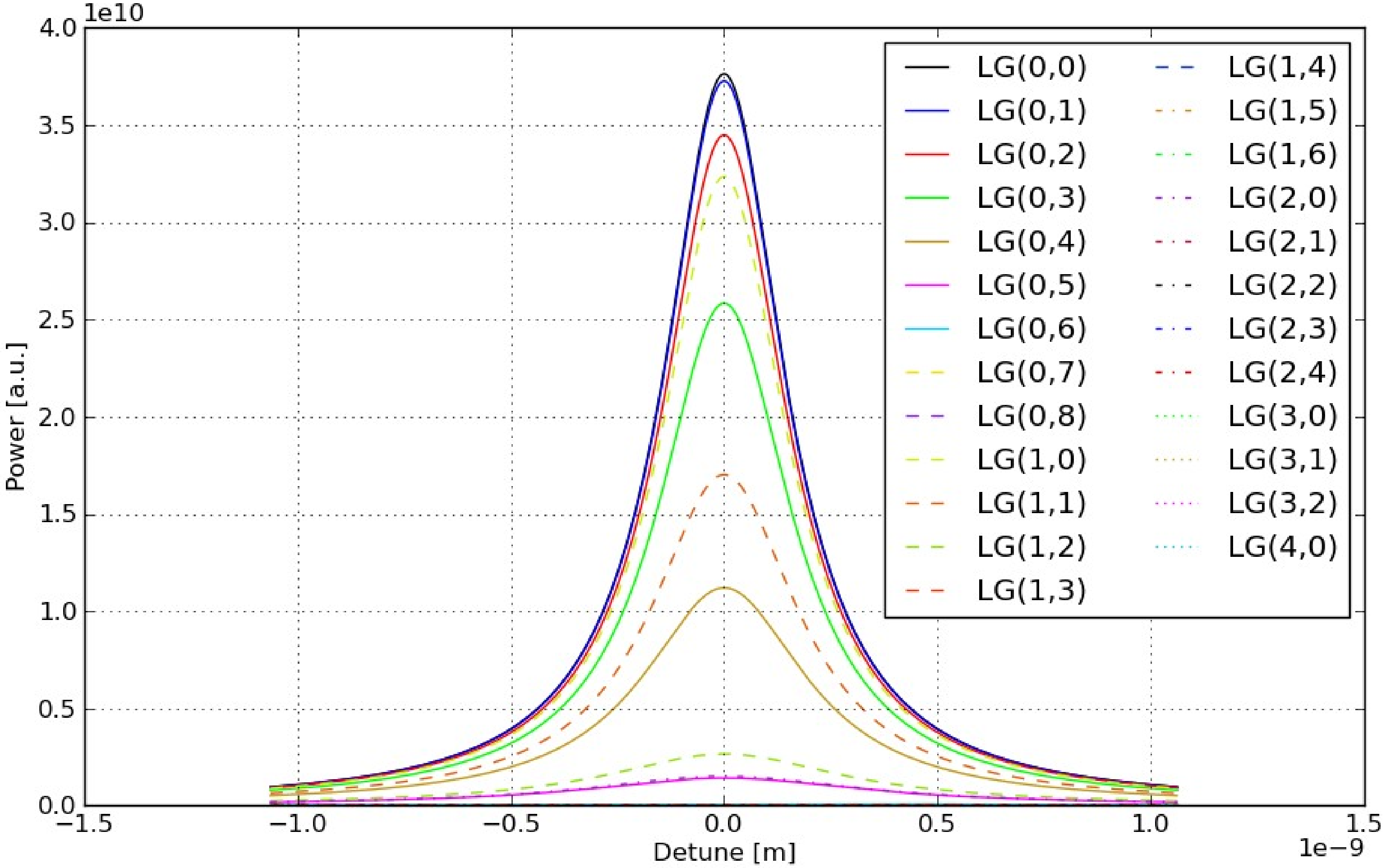
Arm Cavity Parameters

Length	3000.00m	ETM ROC	7000m
ITM Reflectivity	99.6%	ETM Beam Size	4.53cm
ITM ROC	flat	g-factor	0.572
ITM Beam Size	3.43cm	Round Trip Loss	<100ppm
ETM Reflectivity	>99.9945%	Finesse	1546

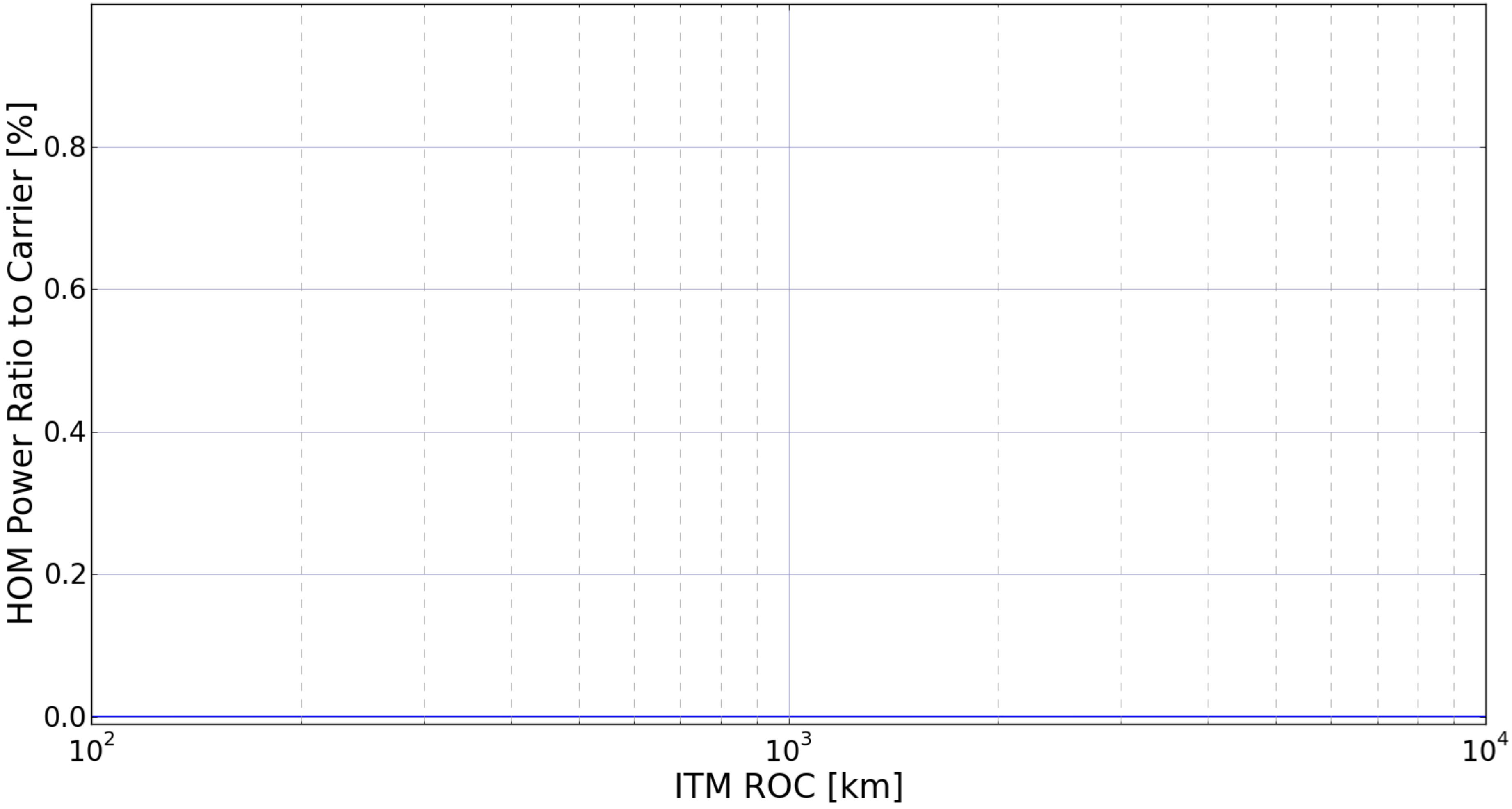
Higher Order Modes

- TEM00 resonance has to be isolated from higher order modes
- Higher order modes are large => Diffraction loss

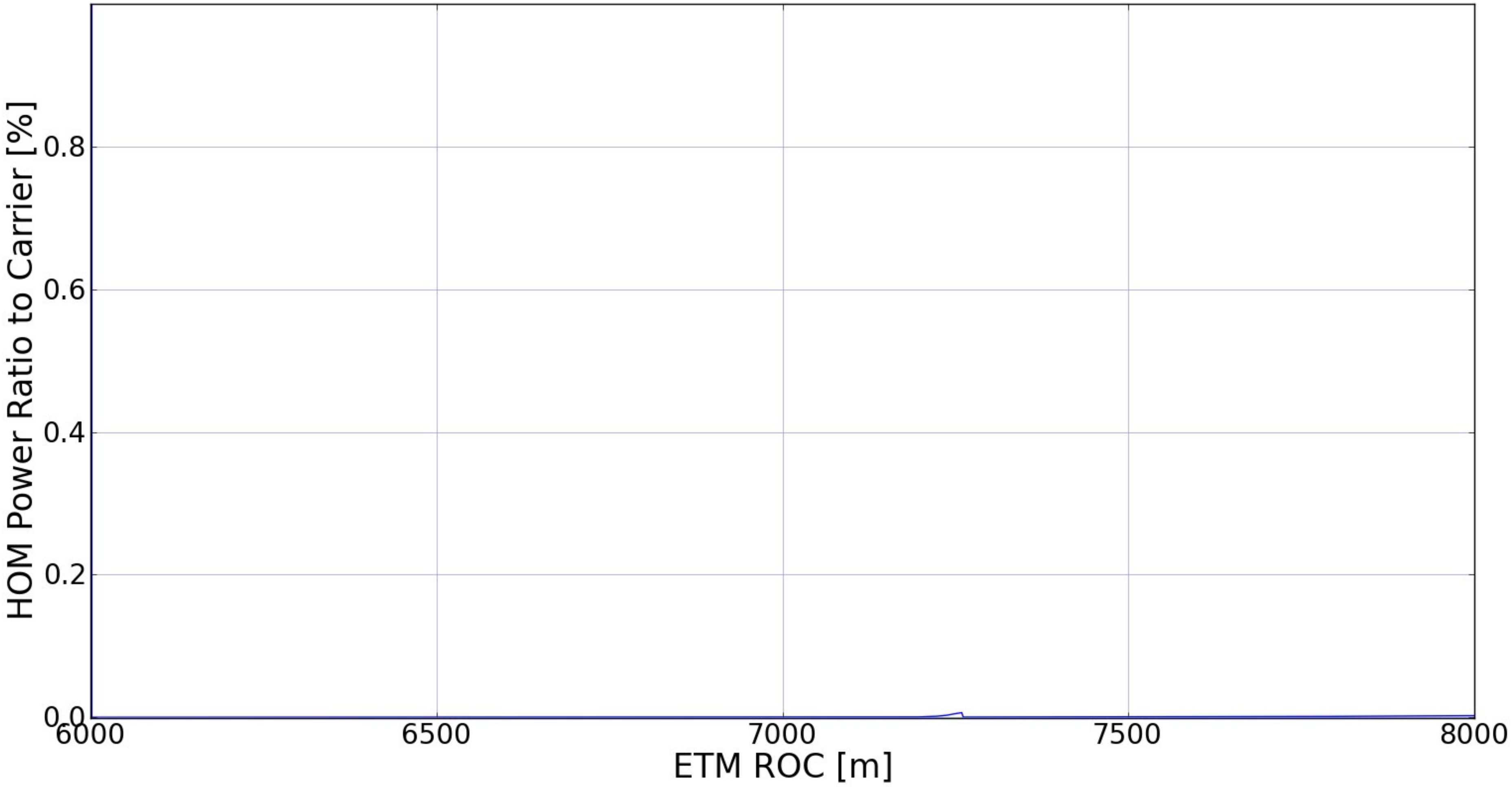
Resonant curves of LG(l,m) modes



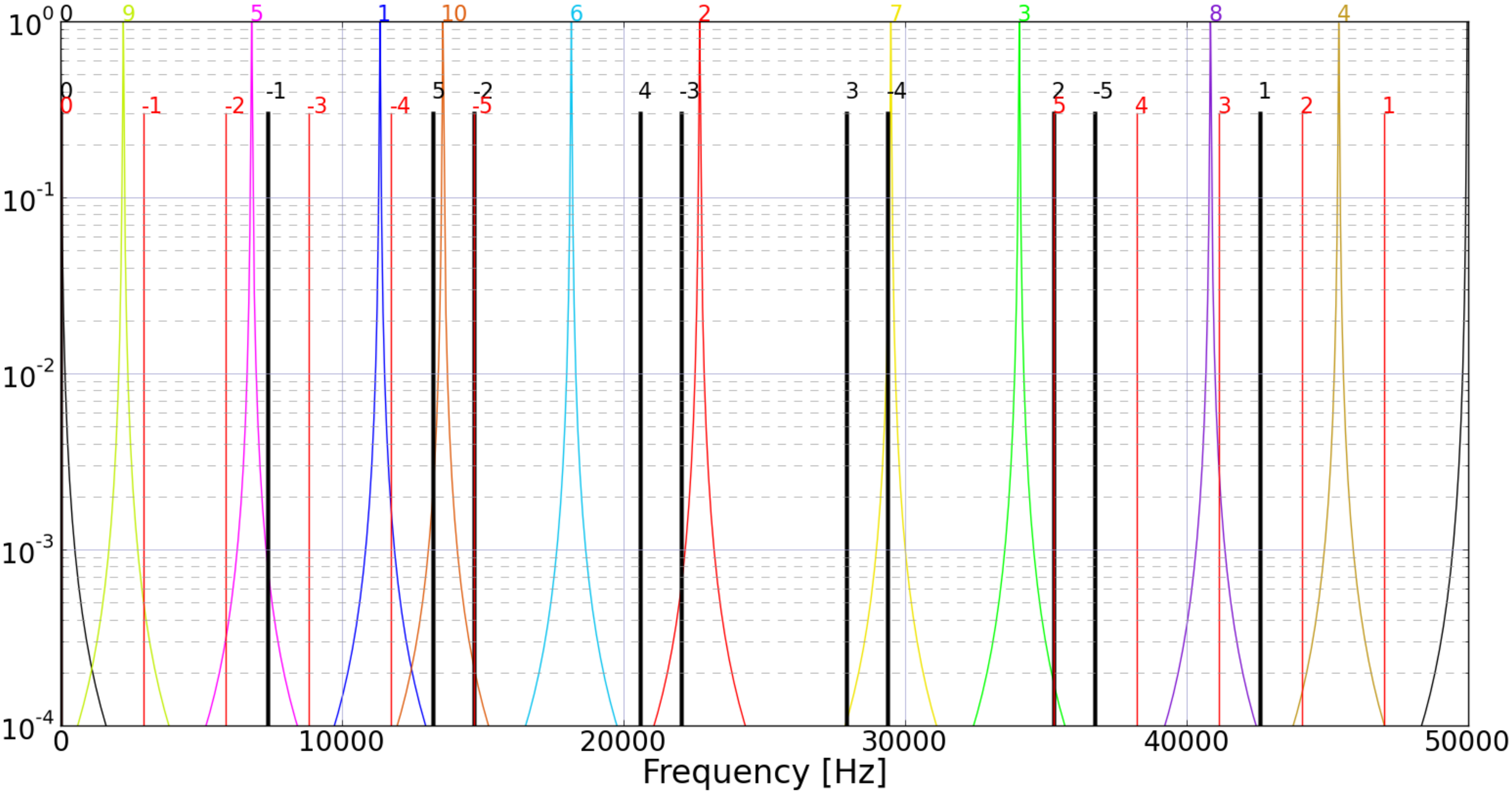
Maximum HOM Power, ITM ROC error



Maximum HOM Power, ETM ROC error



HOM RF Sideband Overlap



Recycling Cavity Lengths and Modulation Frequencies

Constraints

- Resonate RF sidebands in desired parts of the interferometer
  - f1 sees both PRC and SRC
  - f2 is only resonant in PRC

- MC length must not be too long (< 30m)

- Modulation frequencies should not be too high
  - PD and QPD response
- Modulation frequencies should not be too low
  - RF laser noise, CARM UGF

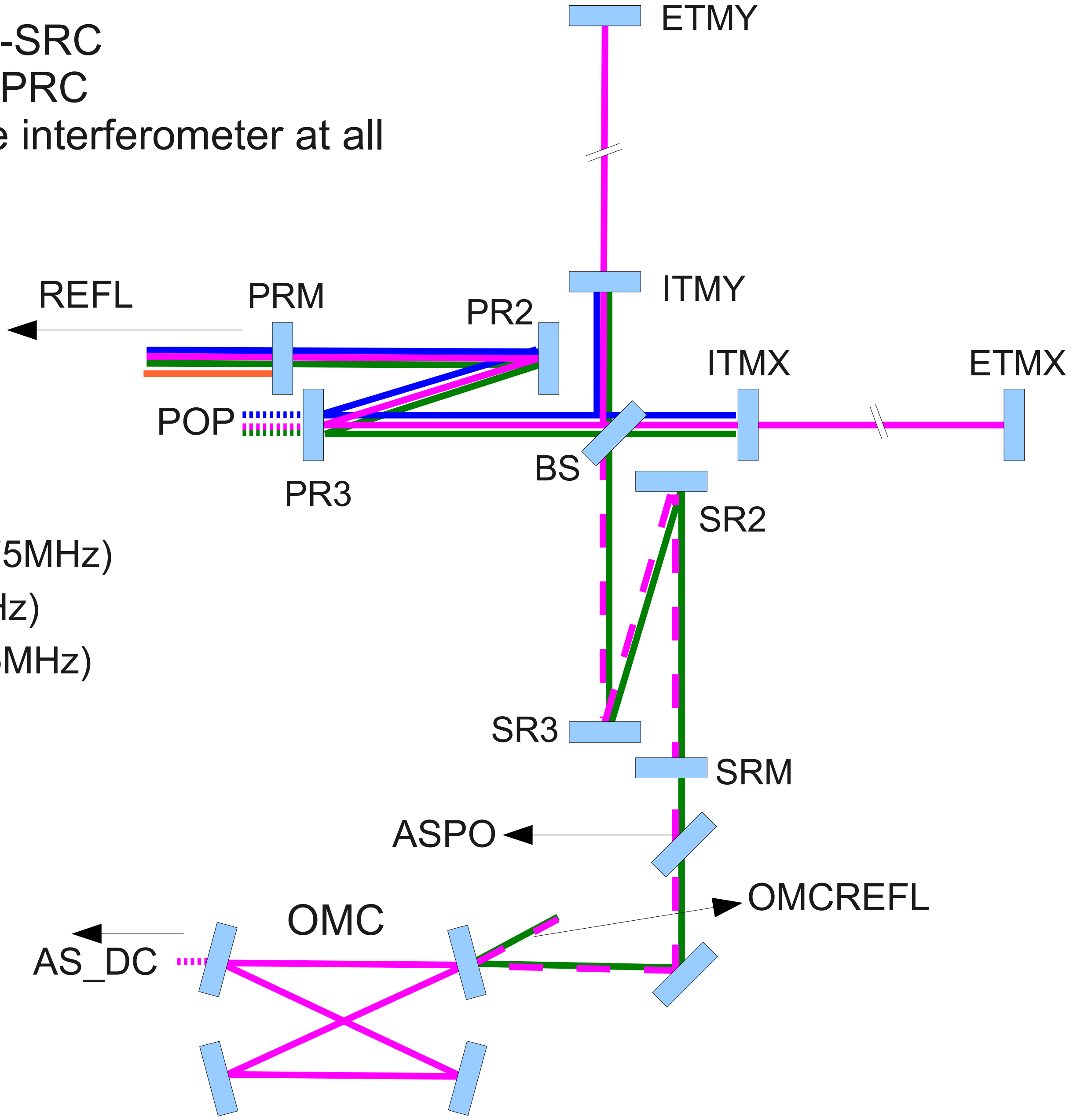
- Michelson Average Length ~ 25m
  - Cryogenic radiation shield = 20m (BS <-> ITM)
  - Schnupp asymmetry

- Not too large asymmetry

- Room for Folding

RF Sideband Resonant Conditions

- f1 sideband resonates in PRC-SRC
- f2 sideband resonates only in PRC
- f3 sideband does not enter the interferometer at all



Carrier
f1 sideband (PM 16.875MHz)
f2 sideband (PM 45MHz)
f3 sideband (AM 56.25MHz)

RC Length Parameter Scan

There are many candidates of Lprc, Lsrc, Las which satisfy the resonant conditions

Parameter selection procedure

- Fix f2 to be 45MHz
  - Not too high, not too low

- Choose Las
  - MICH reflectivity for f2 = 100%
  - Las = 3.3m or 6.6m

- Choose Lprc
  - Resonate f2
  - 65m< Lprc <85m

- Choose f1
  - Integral (or half integral) multiple of the FSR of PRC
  - MC length must not be too long (GCD of f1 and f2 is large enough)

- Choose Lsrc
  - f1 is resonant in SRC <= anti-resonant in PRC
  - f1 is anti-resonant in SRC <= resonant in PRC
  - 65m < Lsrc < 85m

Still there are many candidates

- Finesse of PRC-SRC for f1 varies depending on the MICH reflectivity to f1
- Choose one with wide enough resonance to allow detuning of SRC by offset

Parameter Candidates

It is basically a matter of choosing f1 frequency

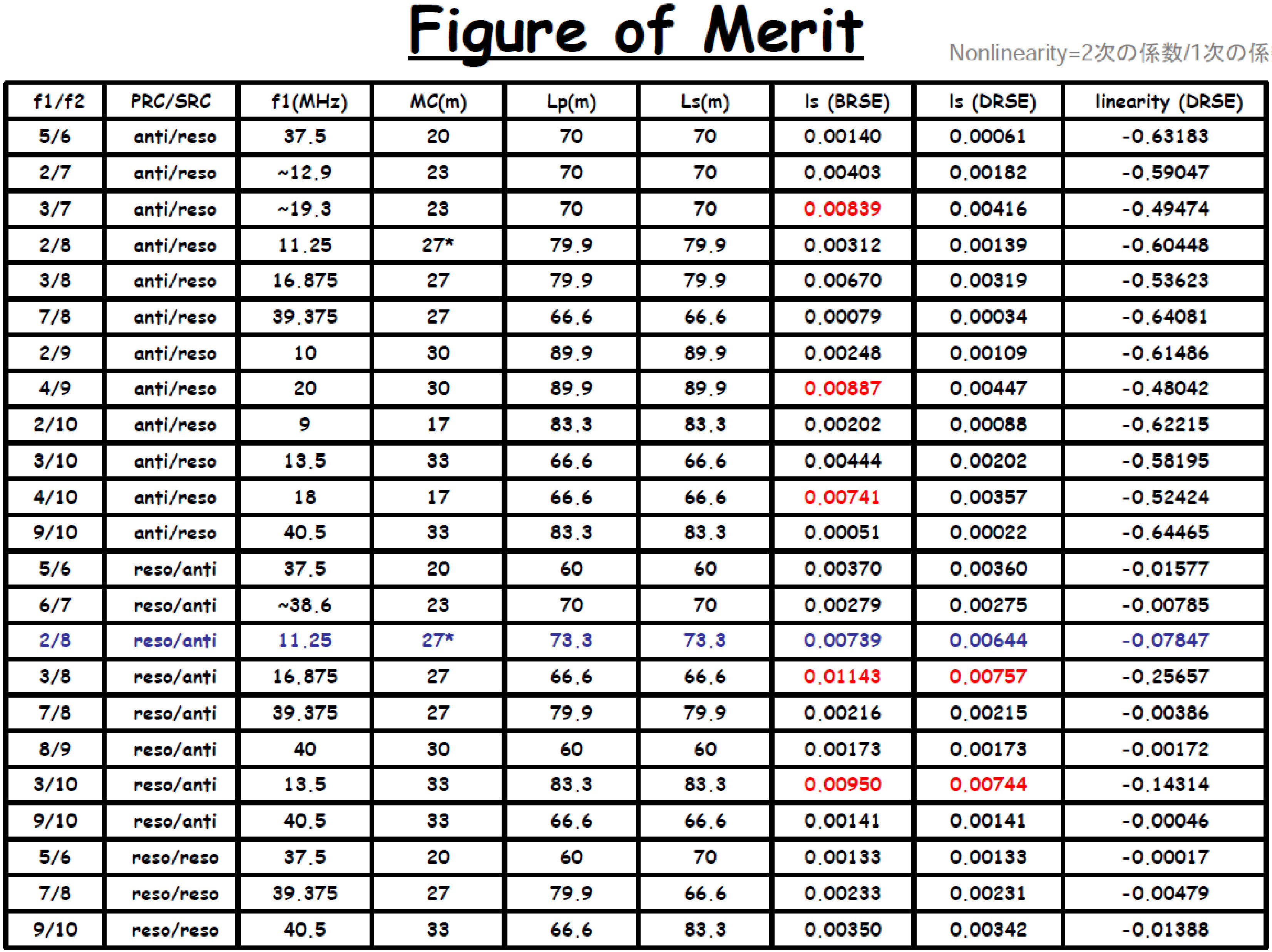


Figure of Merit

Nonlinearity=2次の係数/1次の係数

f1/f2	PRC/SRC	f1(MHz)	MC(m)	Lp(m)	Ls(m)	Is (BRSE)	Is (DRSE)	linearity (DRSE)
5/6	anti/reso	37.5	20	70	70	0.00140	0.00061	-0.63183
2/7	anti/reso	~12.9	23	70	70	0.00403	0.00182	-0.59047
3/7	anti/reso	~19.3	23	70	70	0.00839	0.00416	-0.49474
2/8	anti/reso	11.25	27*	79.9	79.9	0.00312	0.00139	-0.60448
3/8	anti/reso	16.875	27	79.9	79.9	0.00670	0.00319	-0.53623
7/8	anti/reso	39.375	27	66.6	66.6	0.00079	0.00034	-0.64081
2/9	anti/reso	10	30	89.9	89.9	0.00248	0.00109	-0.61486
4/9	anti/reso	20	30	89.9	89.9	0.00887	0.00447	-0.48042
2/10	anti/reso	9	17	83.3	83.3	0.00202	0.00088	-0.62215
3/10	anti/reso	13.5	33	66.6	66.6	0.00444	0.00202	-0.58195
4/10	anti/reso	18	17	66.6	66.6	0.00741	0.00357	-0.52424
9/10	anti/reso	40.5	33	83.3	83.3	0.00051	0.00022	-0.64465
5/6	reso/anti	37.5	20	60	60	0.00370	0.00360	-0.01577
6/7	reso/anti	~38.6	23	70	70	0.00279	0.00275	-0.00785
2/8	reso/anti	11.25	27*	73.3	73.3	0.00739	0.00644	-0.07847
3/8	reso/anti	16.875	27	66.6	66.6	0.01143	0.00757	-0.25657
7/8	reso/anti	39.375	27	79.9	79.9	0.00216	0.00215	-0.00386
8/9	reso/anti	40	30	60	60	0.00173	0.00173	-0.00172
3/10	reso/anti	13.5	33	83.3	83.3	0.00950	0.00744	-0.14314
9/10	reso/anti	40.5	33	66.6	66.6	0.00141	0.00141	-0.00046
5/6	reso/reso	37.5	20	60	70	0.00133	0.00133	-0.00017
7/8	reso/reso	39.375	27	79.9	66.6	0.00233	0.00231	-0.00479
9/10	reso/reso	40.5	33	66.6	83.3	0.00350	0.00342	-0.01388

Final Candidates

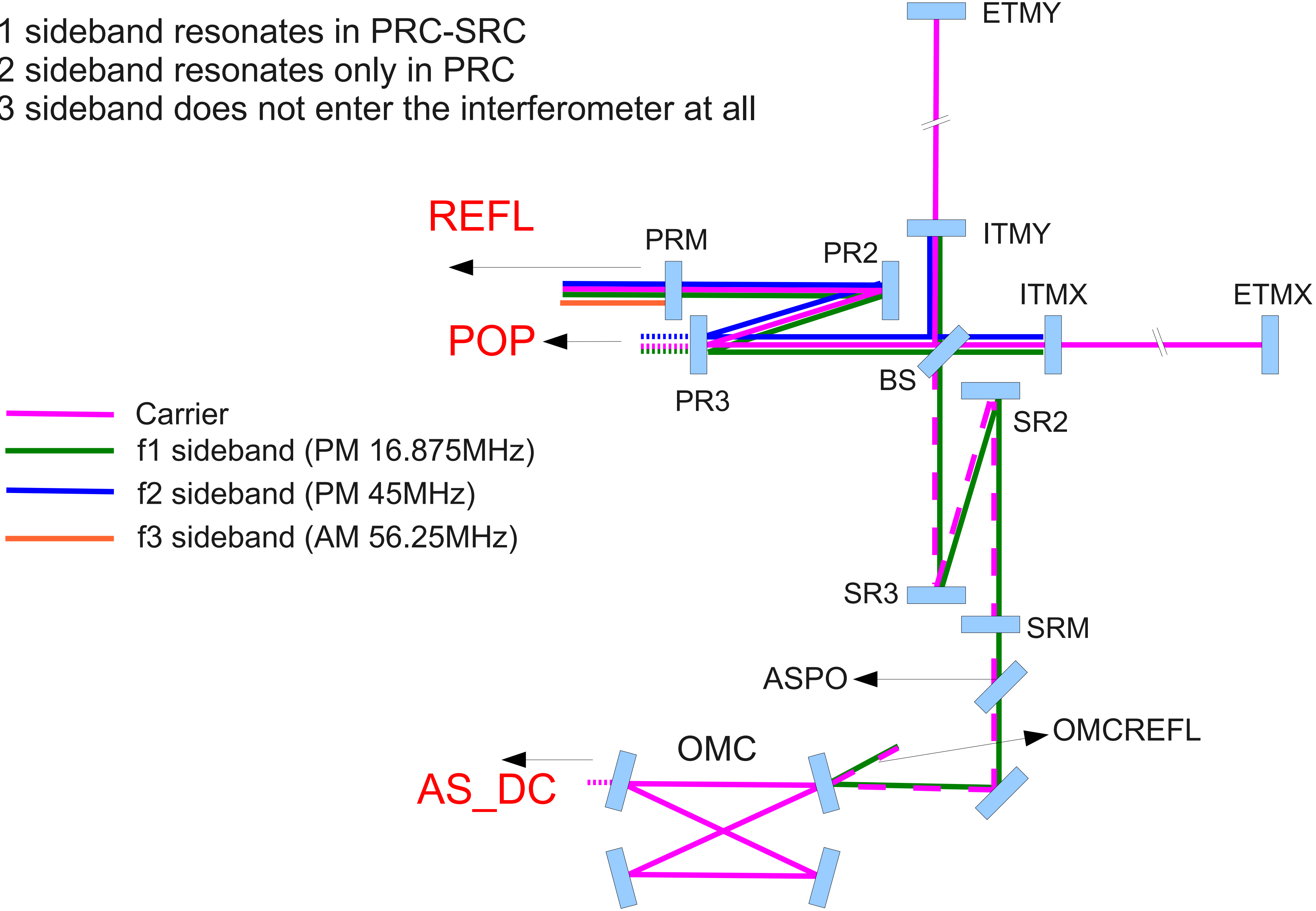
	9MHz	11.25MHz	16.875MHz
Lprc	74.95m	73.28m	66.62m
Lsrc	74.95m	73.28m	66.62m
Las	6.66m	3.33m	3.33m
Lmc	33.3m	26.65m	26.65m
f3	13.5MHz(f2*3/10)	61.9MHz(f2*11/8)	56.3MHz (f2*10/8)
DDM freq.	22.5MHz, 31.5MHz	16.9MHz, 50.6MHz	11.25MHz, 39.4MHz

Pros and Cons

- Loop noise 11.25MHz < 16.875MHz < 9MHz (worse < better)
- 9MHz needs a bit longer MC (33m not 27m)
- 9MHz has a longer asymmetry (6.6m compared to 3.3m)
- 11.25MHz is incompatible with 3rd harmonics demodulation
- 9MHz and 16.875MHz have larger SRCL non-linearity

Signal Extraction Ports

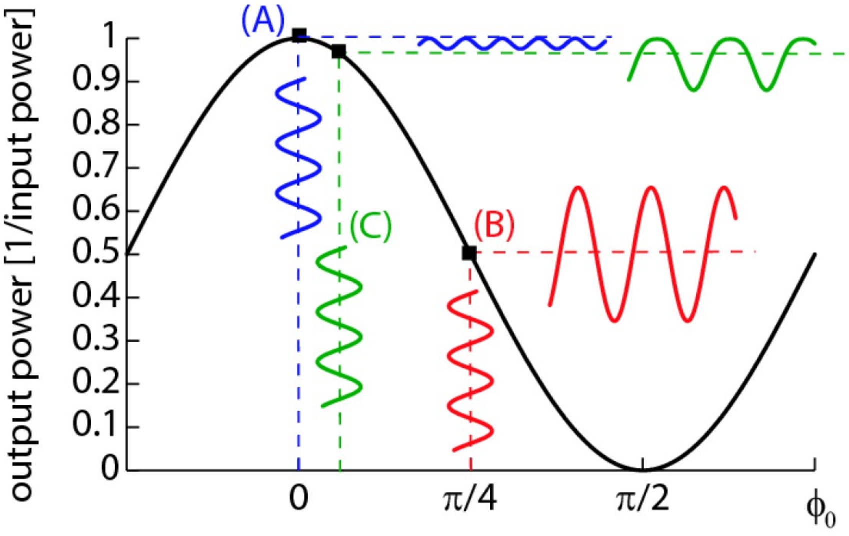
- f1 sideband resonates in PRC-SRC
- f2 sideband resonates only in PRC
- f3 sideband does not enter the interferometer at all



Modulation Types

PM or AM ?

- AM wastes laser power
  - Low loss method exist [N. Ohmae, Opt. Lett.] ---> complicated
- Mach-Zhender may introduce extra noise.



Conventional Scheme
f1:PM, f2:PM

- No MZ
- No AM

Conventional Scheme + NRS
f1:PM, f2:PM, f3:AM

- May need MZ
- Need AM
- AM can be weak if used only for lock acquisition

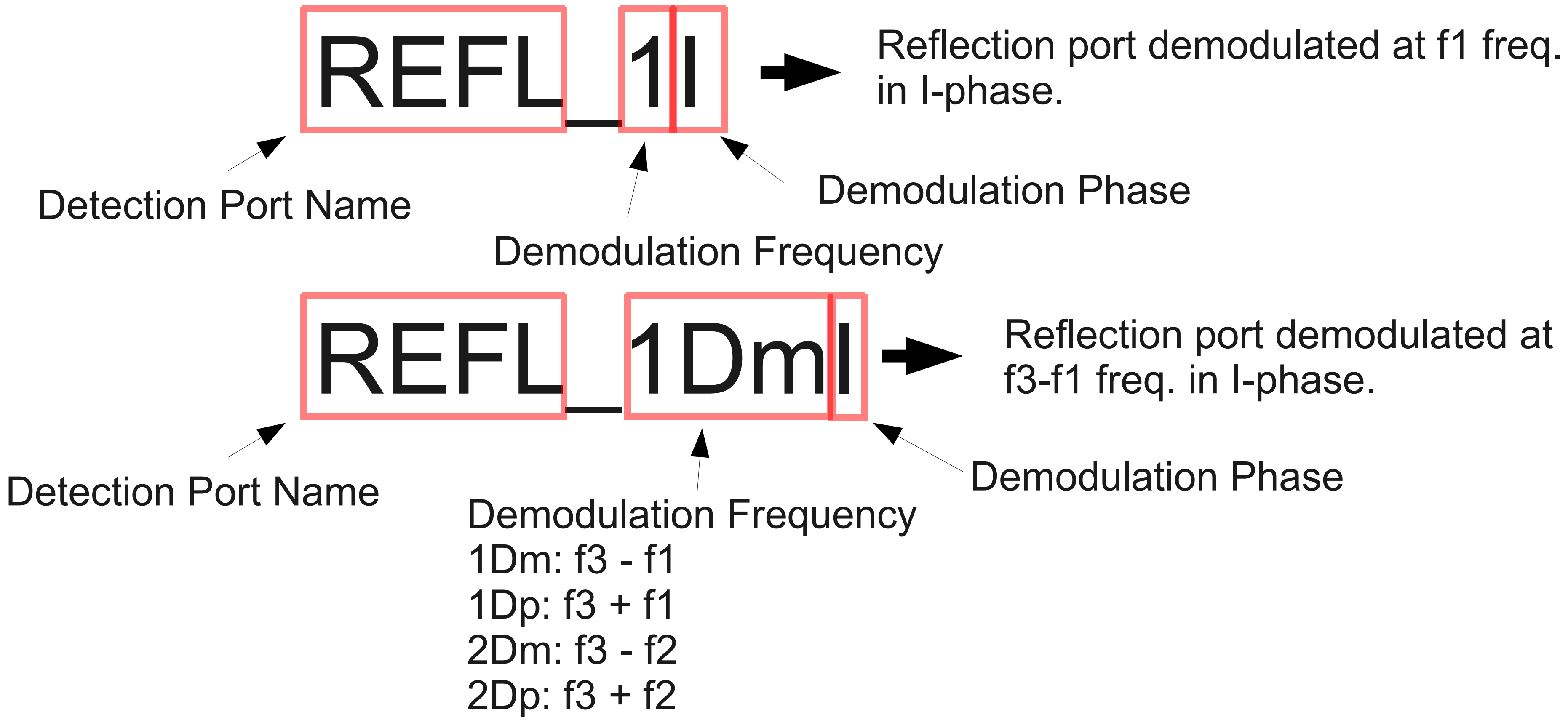
AM-PM Scheme
f1: AM, f2:PM

- Need MZ
- Need AM
- May have a problem with WFS at AS

Default:
Conventional Scheme + (NRS)

Signal Ports and Naming Convention

How to decipher a signal name ?



REFL_1I → Reflection port demodulated at f1 freq. in I-phase.

Detection Port Name

Demodulation Frequency

Demodulation Phase

REFL_1DmI → Reflection port demodulated at f3-f1 freq. in I-phase.

Detection Port Name

Demodulation Phase

Demodulation Frequency
1Dm: f3 - f1
1Dp: f3 + f1
2Dm: f3 - f2
2Dp: f3 + f2

DC Power at PDs

Attenuated to be less than 100mW on each PD

Sensing Matrix

BRSE: 16.875MHz - 45MHz

	DARM	CARM	MICH	PRCL	SRCL
AS_DC	1	4.2e-5	1.0e-3	4.8e-6	4.7e-6
REFL_1I	5.4e-3	1	4.3e-5	6.5e-3	4.3e-3
REFL_1Q	5.0e-3	1.3e-2	1	1.02	0.67
POP_2I	2.3e-2	4.3	1.0e-2	1	2.5e-4
POP_1I	8.7e-2	16.23	3.1e-2	2.1	1

- Large Coupling from CARM to PRCL & SRCL
- Gain hierarchy to suppress CARM
- PRCL, SRCL mixed to MICH

Sensing Matrix

Use of Non-Resonant Sideband (f3: 56.25MHz)

BRSE: 16.875MHz - 45MHz

	DARM	CARM	MICH	PRCL	SRCL
AS_DC	1	4.1e-5	1.0e-3	4.8e-6	4.7e-6
REFL_1I	5.4e-3	1	3.9e-5	5.4e-3	4.5e-3
REFL_1DmQ	4.8e-3	2.5e-3	1	0.7	1.3
REFL_2DmI	2.3e-2	8.3e-2	0.18	1	0.32
REFL_1DmI	8.7e-2	1.5e-2	2.4e-2	1.7	1

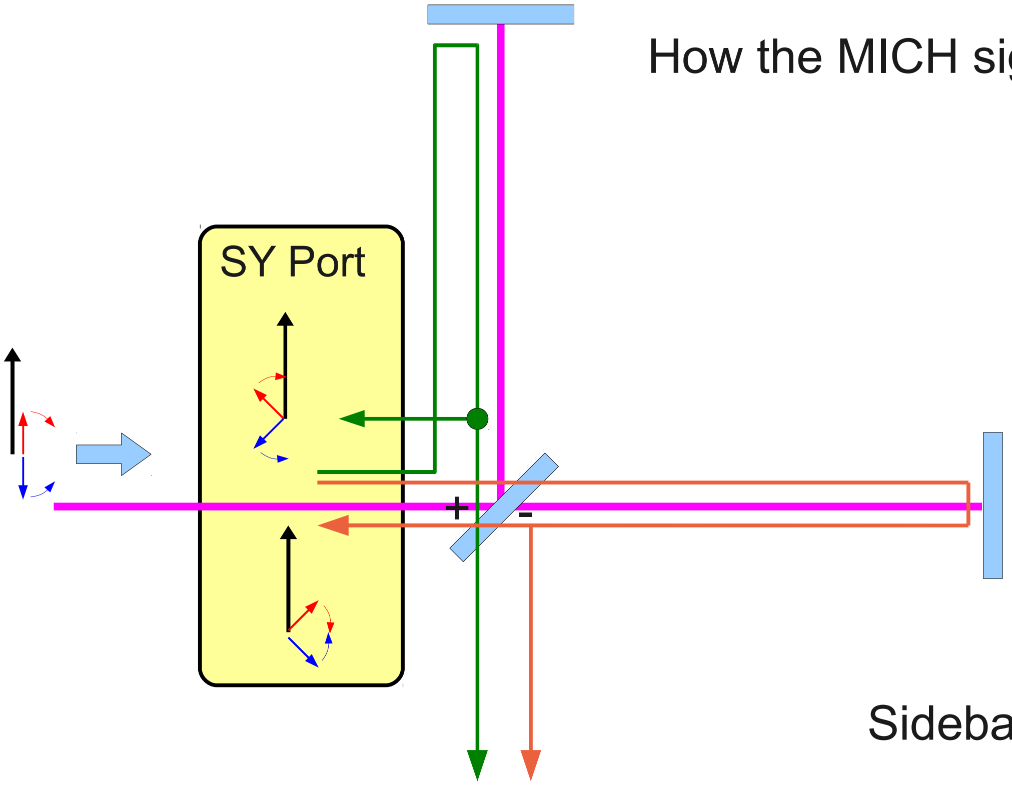
- CARM coupling is now small
- Shot noise may not be so good.

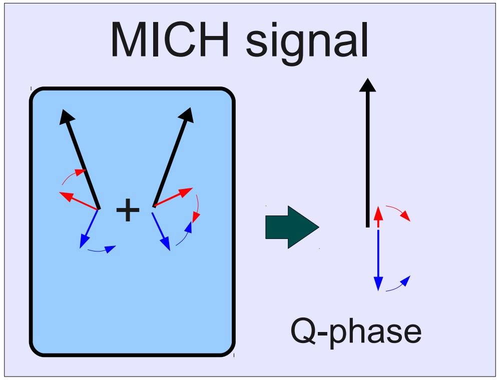
Loop Noise Coupling

Just looking at sensing matrices is not enough

- Auxiliary DOFs in general have worse shot noise than DARM
- MICH is particularly problematic one.
  - MICH unavoidably couples to DARM (1/finesse)
  - MICH signal is weak
  - Driving MICH with this bad signal ---> Noise coupling to DARM

How the MICH signal at REFL_Q is generated ?

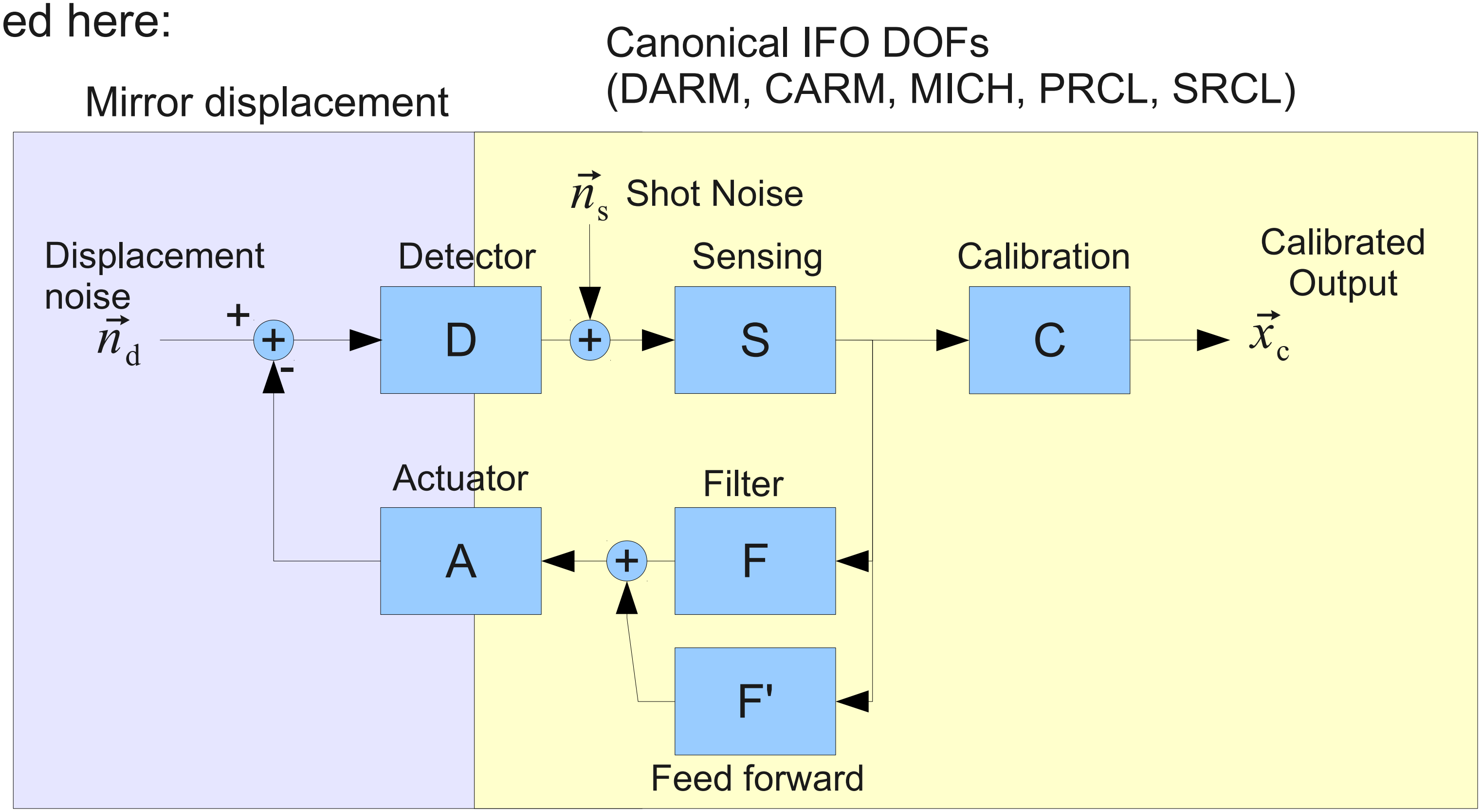




Sideband imbalance --> Weak signal

Loop Noise Coupling

Formulation used here:



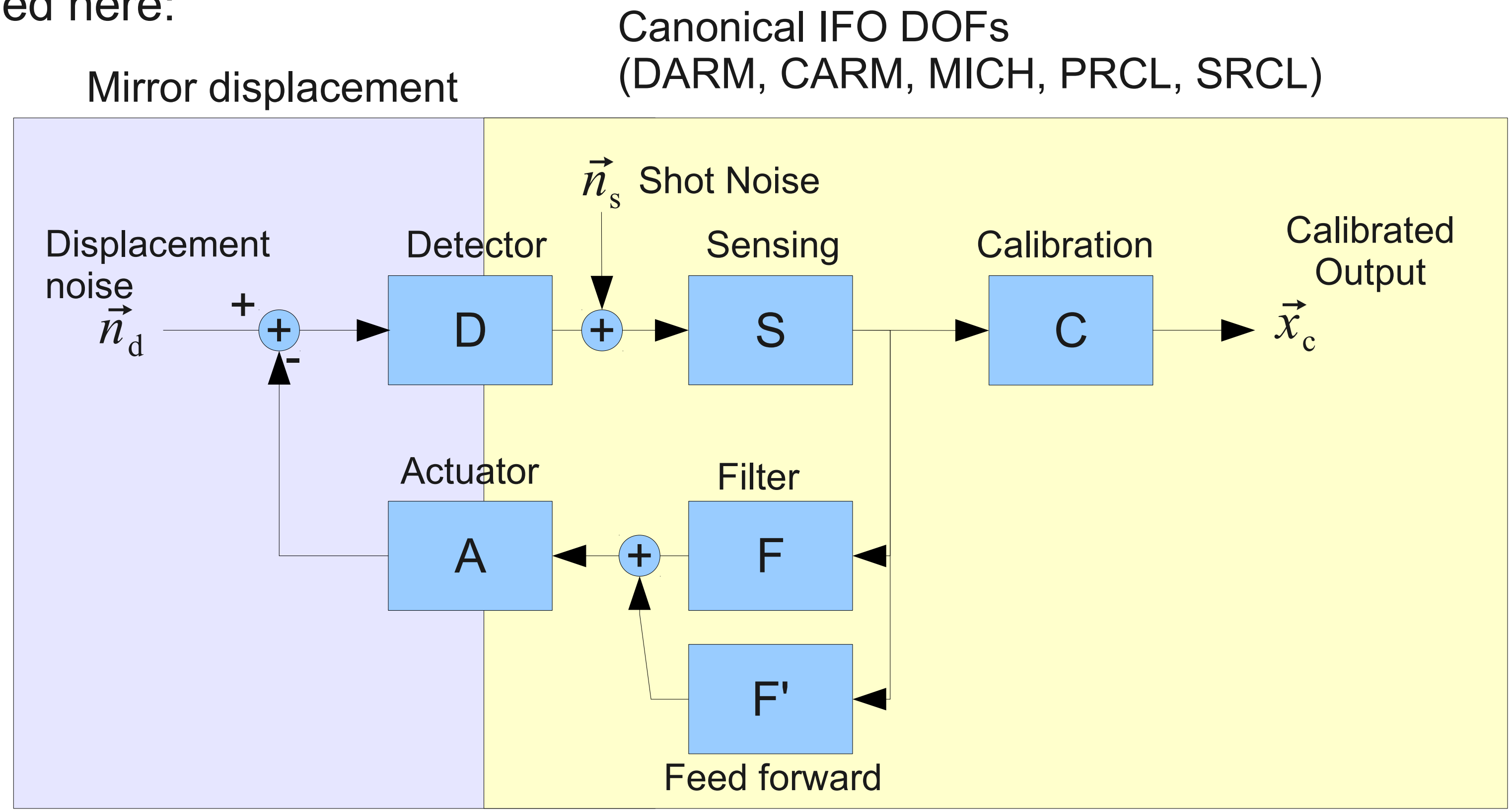
$$\vec{x}_c = (I+G)^{-1} \cdot S \cdot \vec{n}_s + (I+G)^{-1} \cdot SD \cdot \vec{n}_d$$

$$G \equiv S \cdot D \cdot A \cdot (F + F')$$

D: Optical Gain Transfer Function calculated by Optickle
A: Mechanical TFs of the mirror suspensions + optical spring stiffness
F: Feedback filters
F': Feed forward matrix
S: Sensing matrix (here I just used identity matrix)

Loop Noise Coupling

Formulation used here:



Mirror displacement

Canonical IFO DOFs
(DARM, CARM, MICH, PRCL, SRCL)

Displacement noise $\vec{n}_d$

$\vec{n}_s$ Shot Noise

Detector

Sensing

Calibration

Calibrated Output $\vec{x}_c$

D

S

C

Actuator

Filter

A

F

F'

Feed forward

+

-

$$\vec{x}_c = (I+G)^{-1} \cdot S \cdot \vec{n}_s + (I+G)^{-1} \cdot SD \cdot \vec{n}_d$$

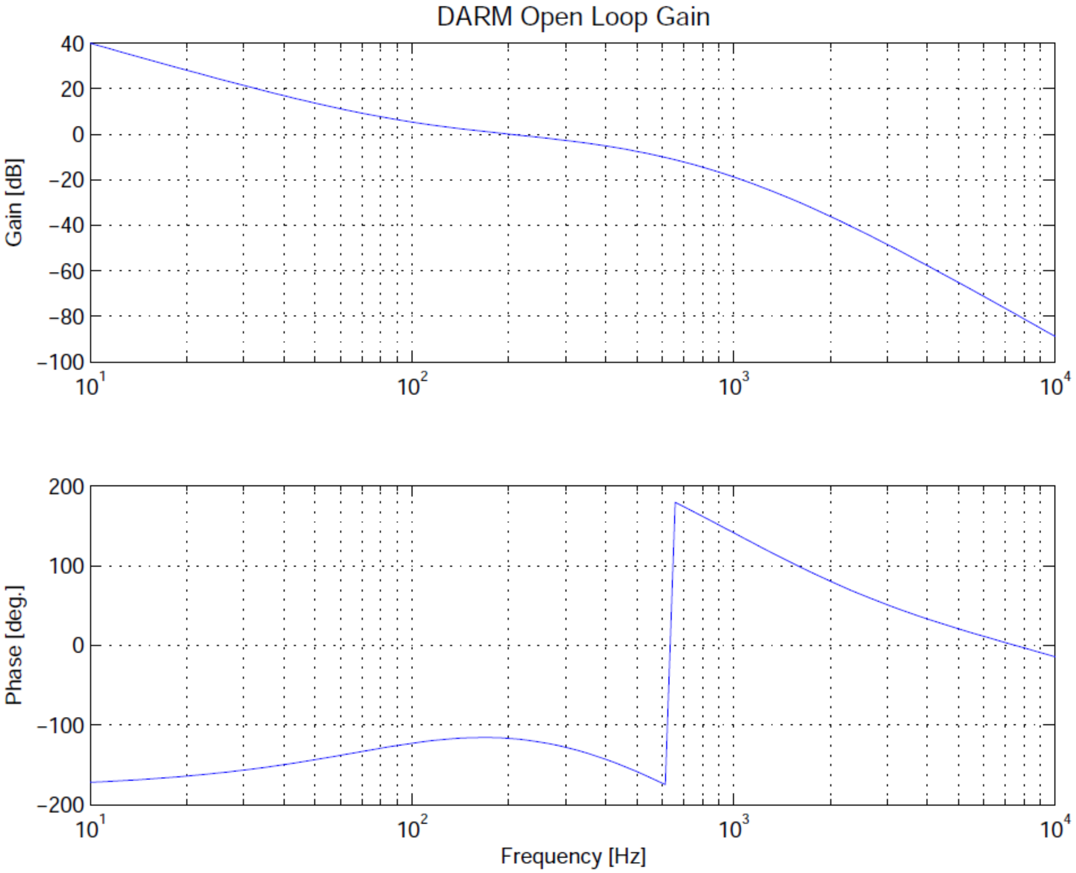
$$G \equiv S \cdot D \cdot A \cdot (F + F')$$

- Ideally, G is diagonal (D · A is diagonal), but in practice it is not.
- Off diagonal elements of G introduce the shot noise of auxiliary DOFs to DARM
- F' is added to diagonalize G (Feed forward)

Control Loop Gains

UGFs

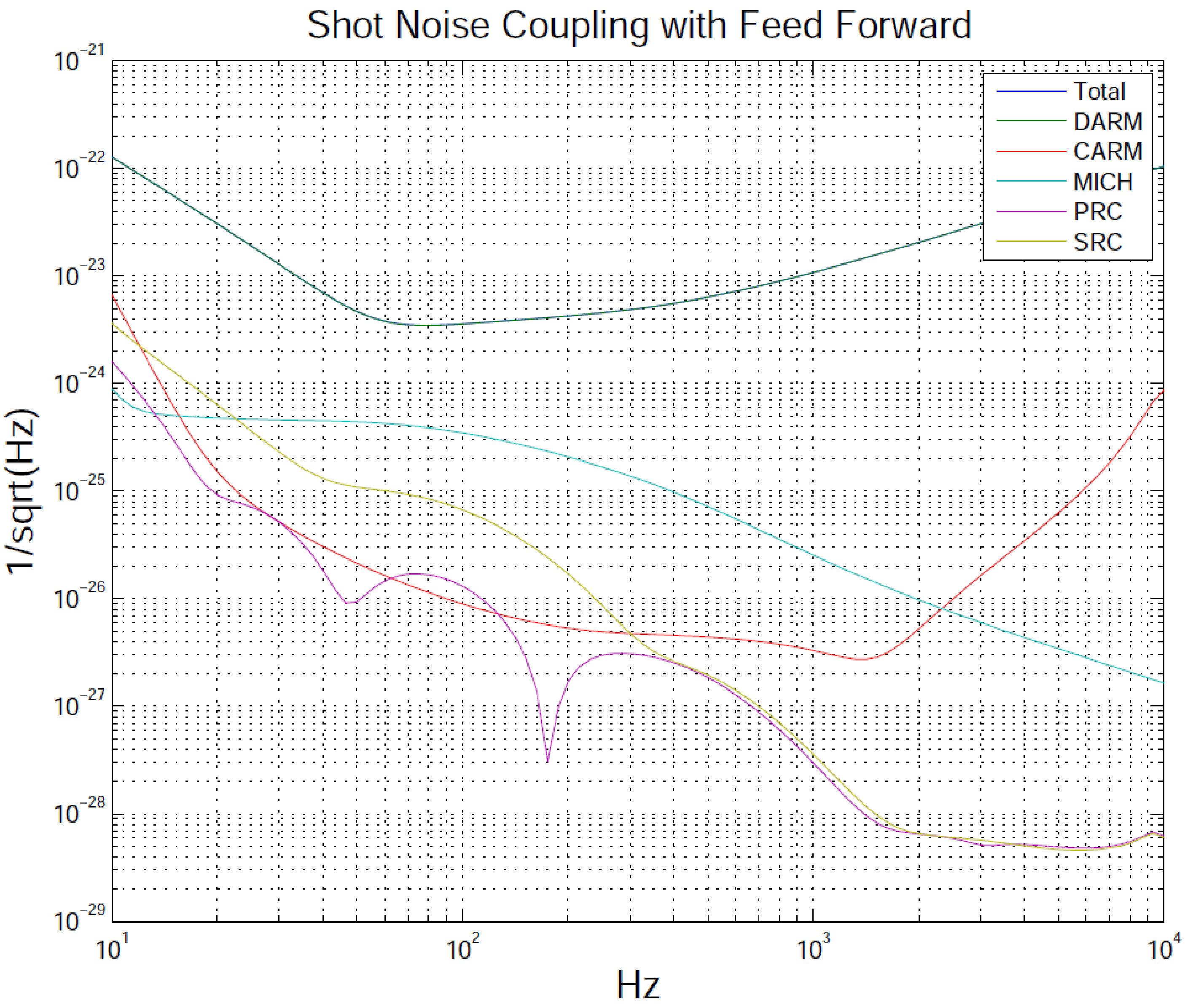
	BRSE	**DRSE**
DARM	200Hz	200Hz
CARM	10kHz	10kHz
MICH	50Hz	10Hz
PRCL	50Hz	50Hz
SRCL	50Hz	50Hz



9MHz-45MHz

DARM: ASDC
CARM: REFL 1I
MICH: REFL 1Q
PRCL: POP 2I
SRCL: POP 1I

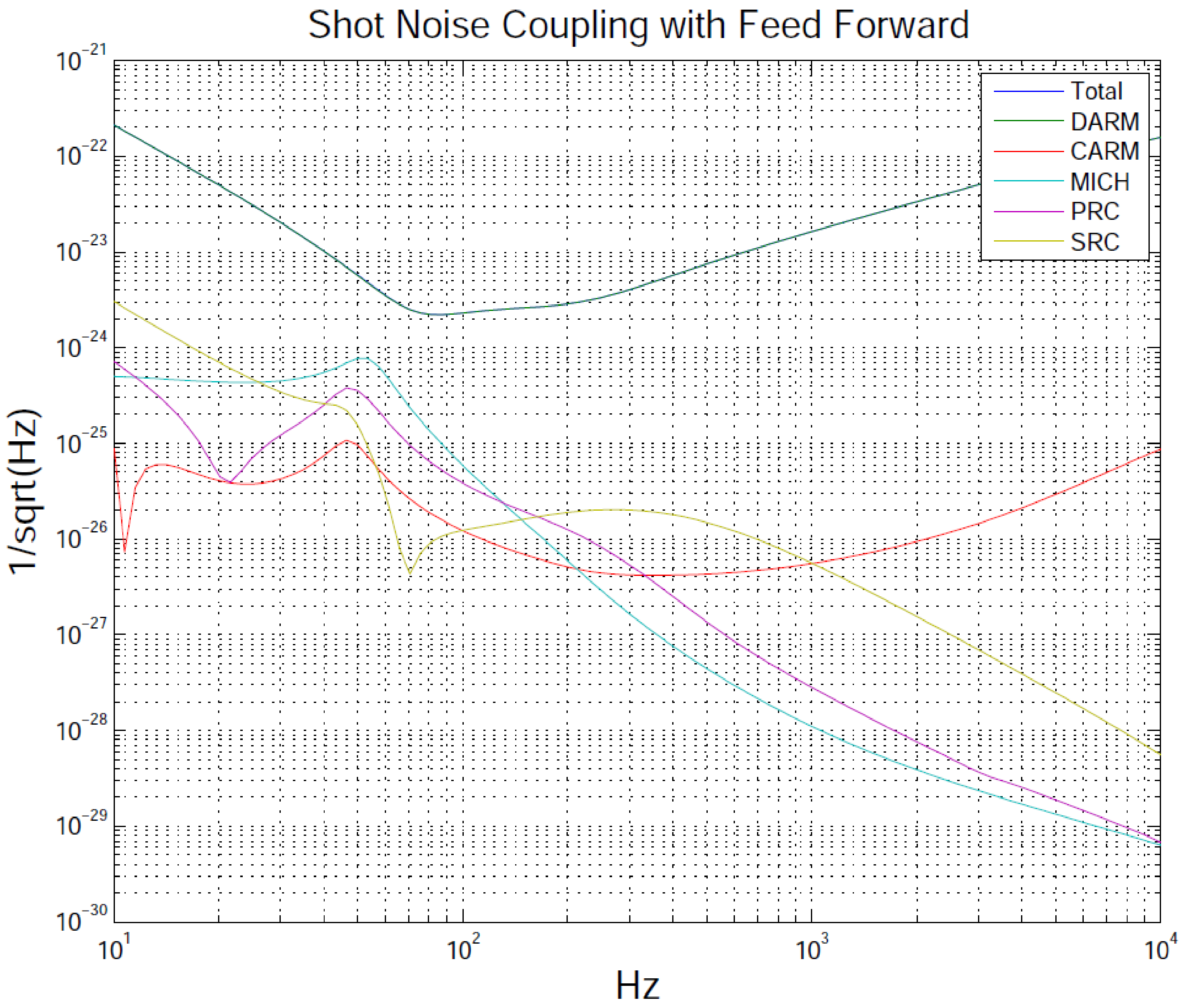
BRSE: f1=9MHz, Feed forward gain=100



9MHz-45MHz

DARM: ASDC
CARM: REFL 1I
MICH: REFL 1Q
PRCL: POP 2I
SRCL: POP 1I

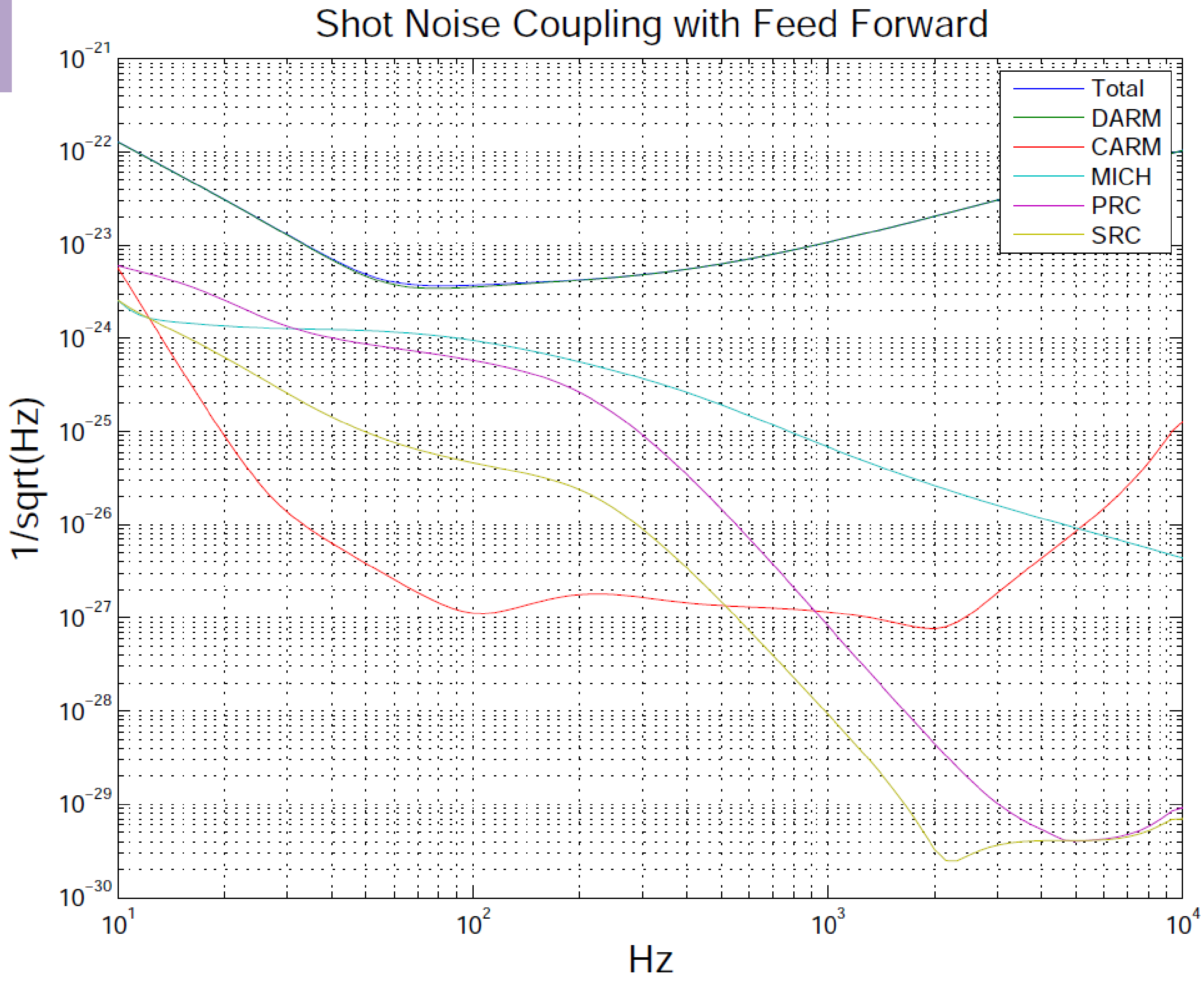
DRSE: f1=9MHz, Feed forward gain=100



11.25MHz-45MHz

DARM: ASDC
CARM: REFL 1I
MICH: REFL 1Q
PRCL: POP 2I
SRCL: POP 1I

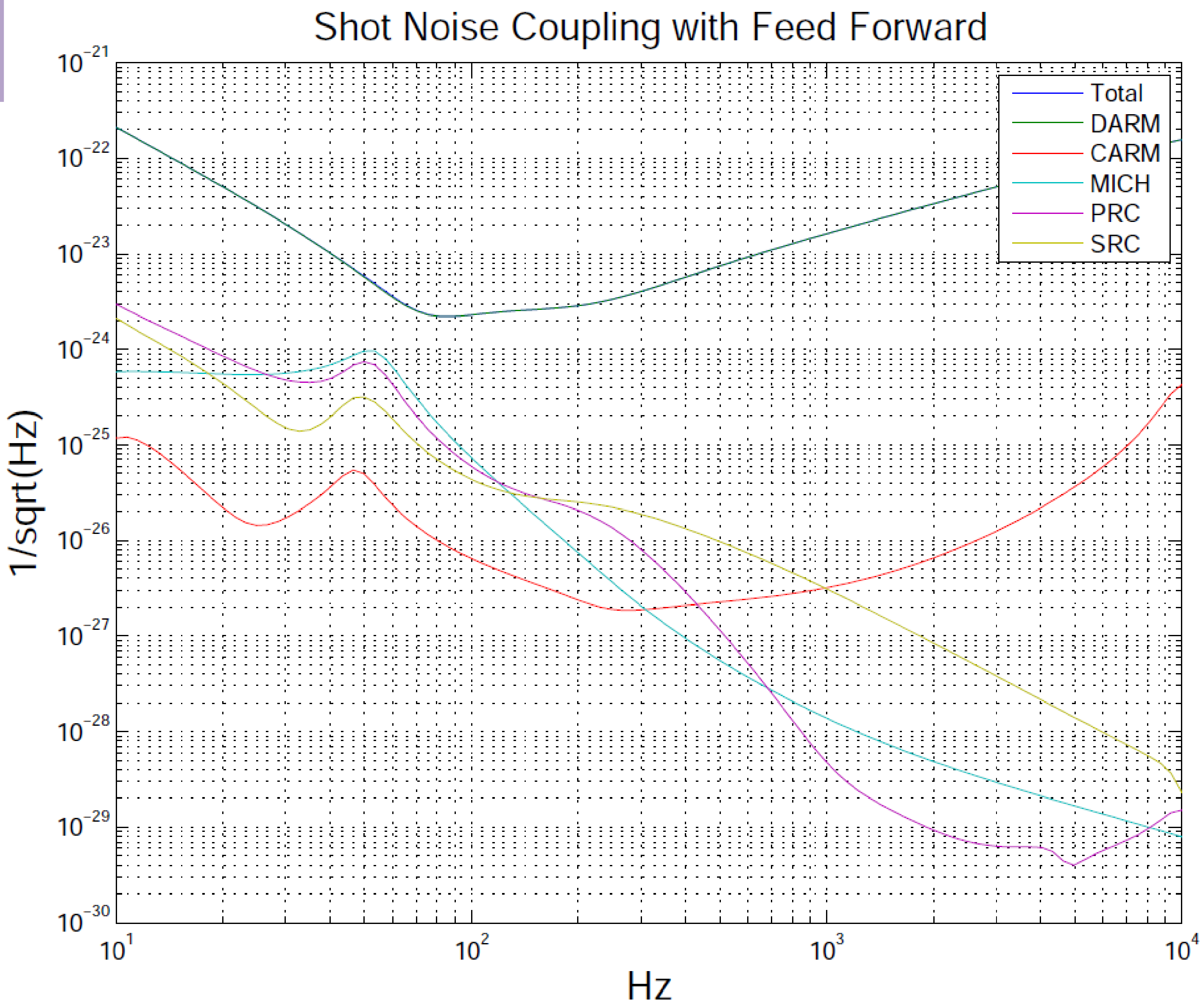
BRSE: f1=11.25MHz, Feed forward gain=100



11.25MHz-45MHz

DARM: ASDC
CARM: REFL 1I
MICH: REFL 1Q
PRCL: POP 2I
SRCL: POP 1I

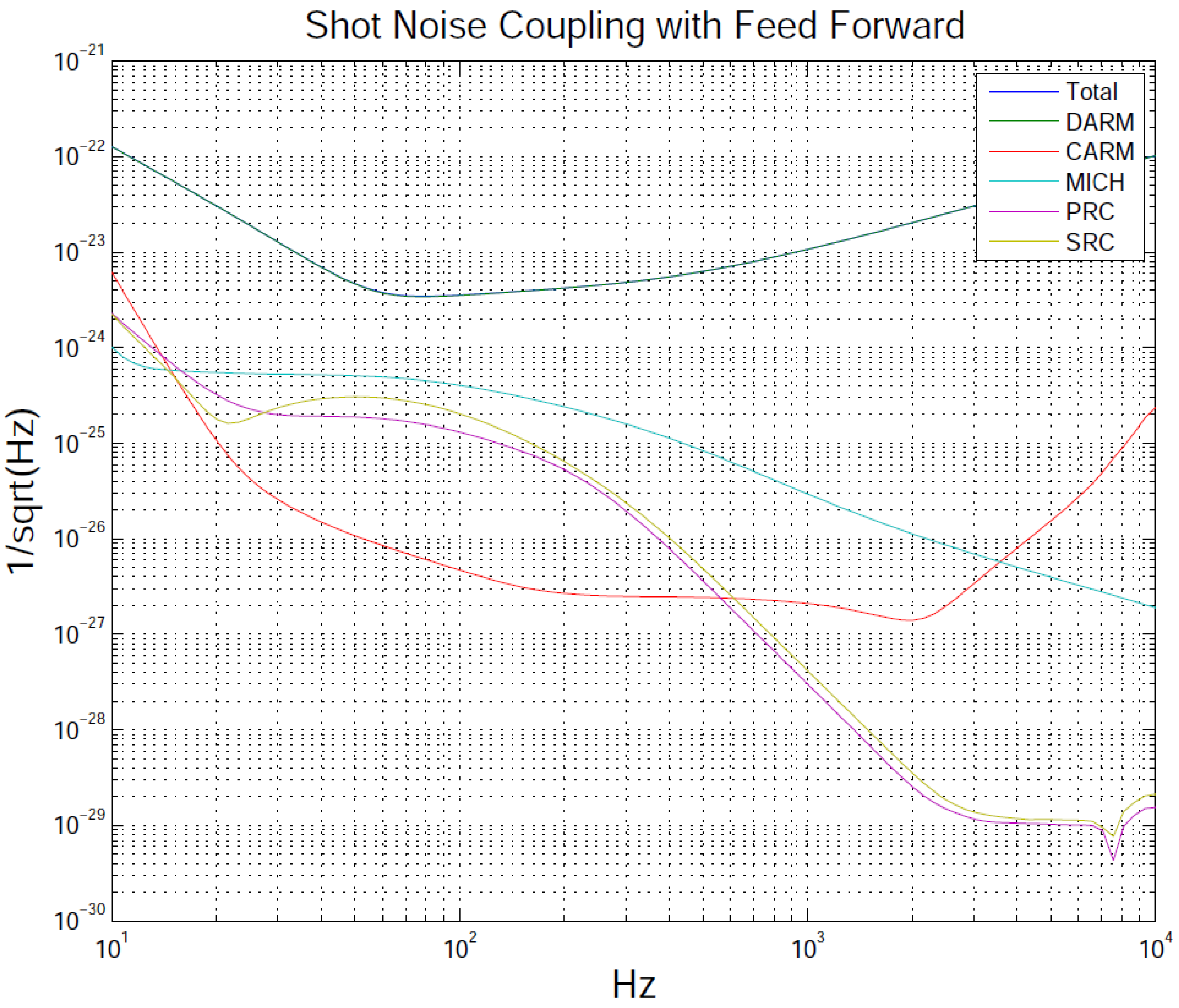
DRSE: f1=11.25MHz, Feed forward gain=100



16.875MHz-45MHz

DARM: ASDC
CARM: REFL 1I
MICH: REFL 1Q
PRCL: POP 2I
SRCL: POP 1I

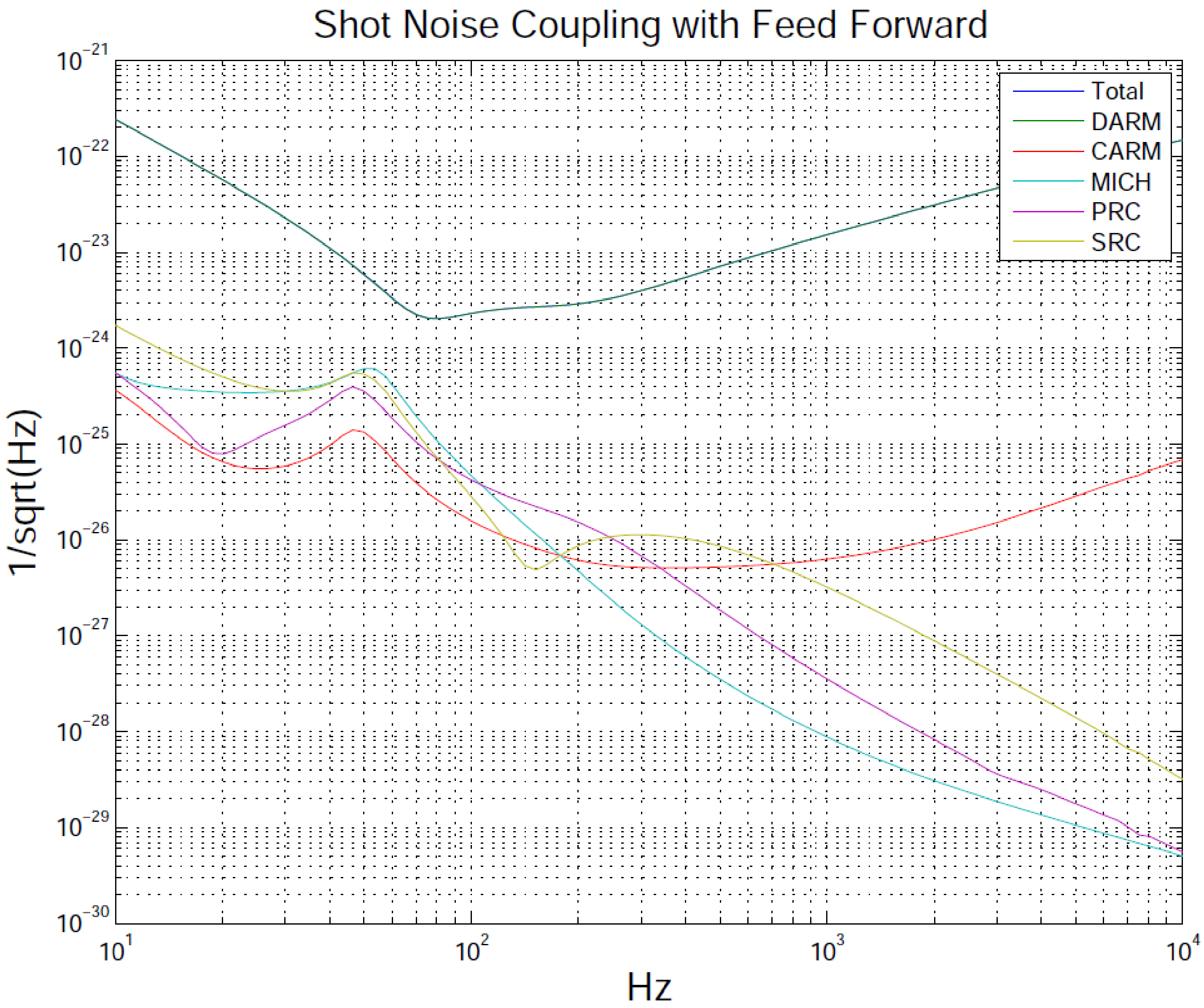
BRSE: f1=16.875MHz, Feed forward gain=100



16.875MHz-45MHz

DARM: ASDC
CARM: REFL 1I
MICH: REFL 1Q
PRCL: POP 2I
SRCL: POP 1I

DRSE: f1=16.875MHz, Feed forward gain=100

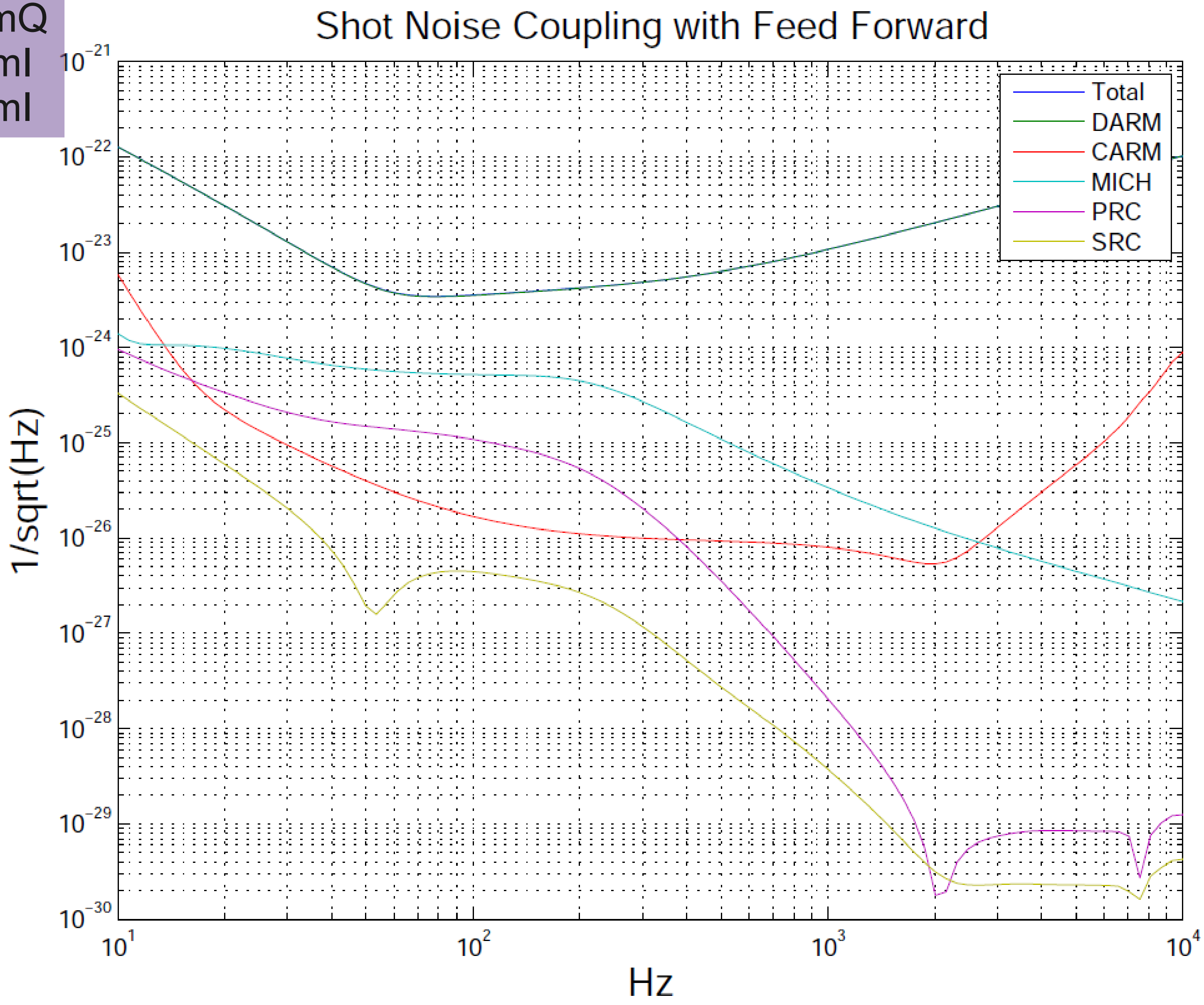


16.875MHz-45MHz

Double Demodulation with Non-Resonant Sideband

BRSE: f1=16.875MHz, Feed forward gain=100

DARM: ASDC
CARM: REFL 1I
MICH: REFL 1DmQ
PRCL: REFL 2DmI
SRCL: REFL 1DmI

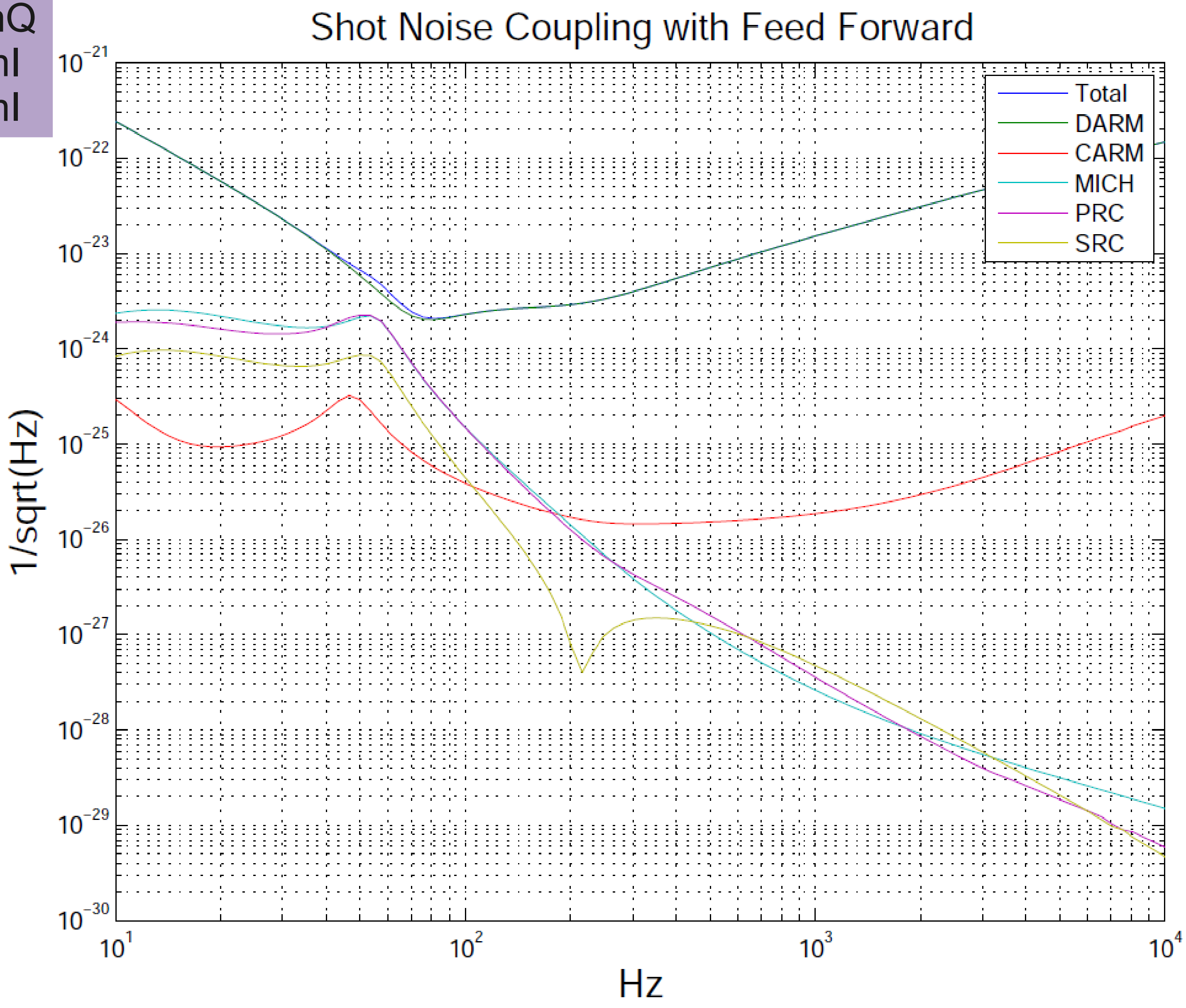


16.875MHz-45MHz

DARM: ASDC
CARM: REFL 1I
MICH: REFL 1DmQ
PRCL: REFL 2DmI
SRCL: REFL 1DmI

Double Demodulation with Non-Resonant Sideband

DRSE: f1=16.875MHz, Feed forward gain=100



SRCL Non-Linearity

- SRC detuning by offset => Error signal non-linearity
- Up conversion noise

Formalization

$$y(t)=a\,x(t)+b\,x^2(t)$$

x: mirror displacement [m]
y: error signal [W]

⇩ Calibration

$$x_e(t)=y(t)/a=x(t)+\underbrace{(b/a)\,x^2(t)}_{\text{Non-linear part}}$$

x_e: Displacement equivalent error signal [m]

b/a: dimension is 1/m

Total frequency conversion noise

[ref. Applied Electronics, Koichi Shimoda]

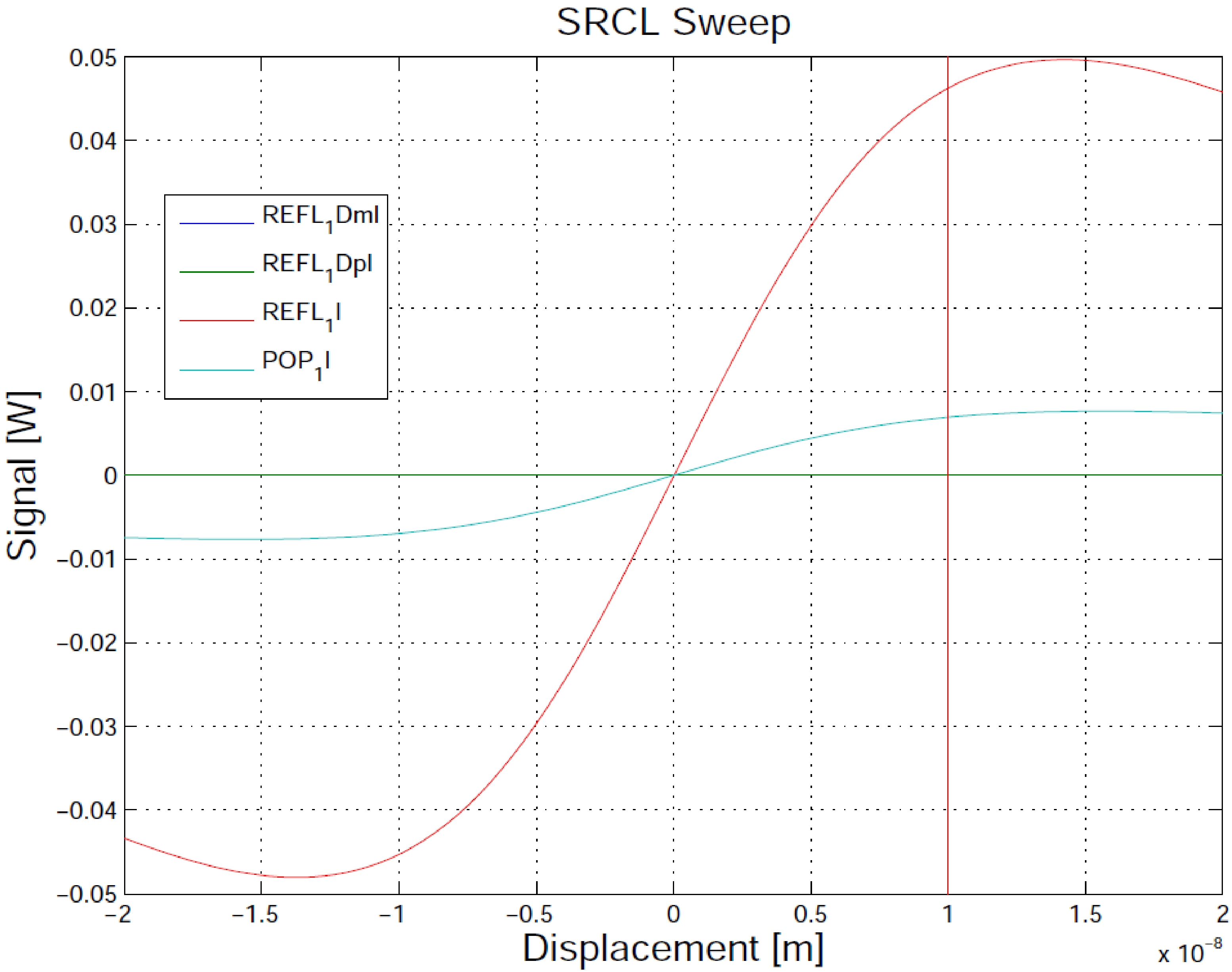
$$P_{\mathrm{conv}}(f)=\left(\frac{b}{a}\right)^2\left[\underbrace{\int_0^f P(f-f')P(f')\,df'}_{\text{Up Conversion}}+\underbrace{2\int_0^\infty P(f+f')P(f')\,df'}_{\text{Down Conversion}}\right]$$

P(f): Displacement equivalent noise spectrum [m^2/Hz], one sided.

SRCL error signal range, f1=9MHz

b/a = 1.3e8 m^{-1}

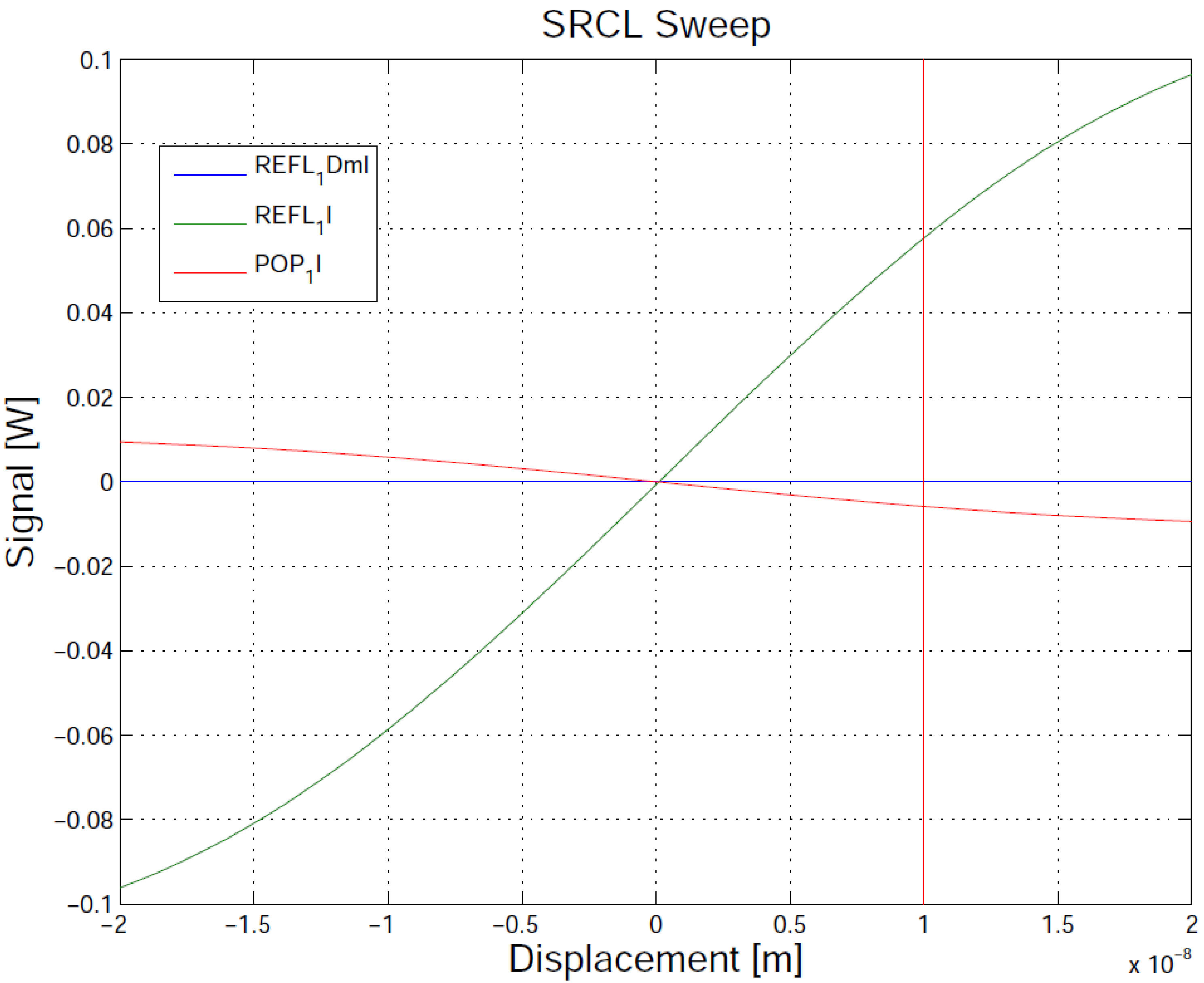
f1=9MHz



SRCL error signal range, f1=11.25MHz

b/a = 2.7e7 m^{-1}

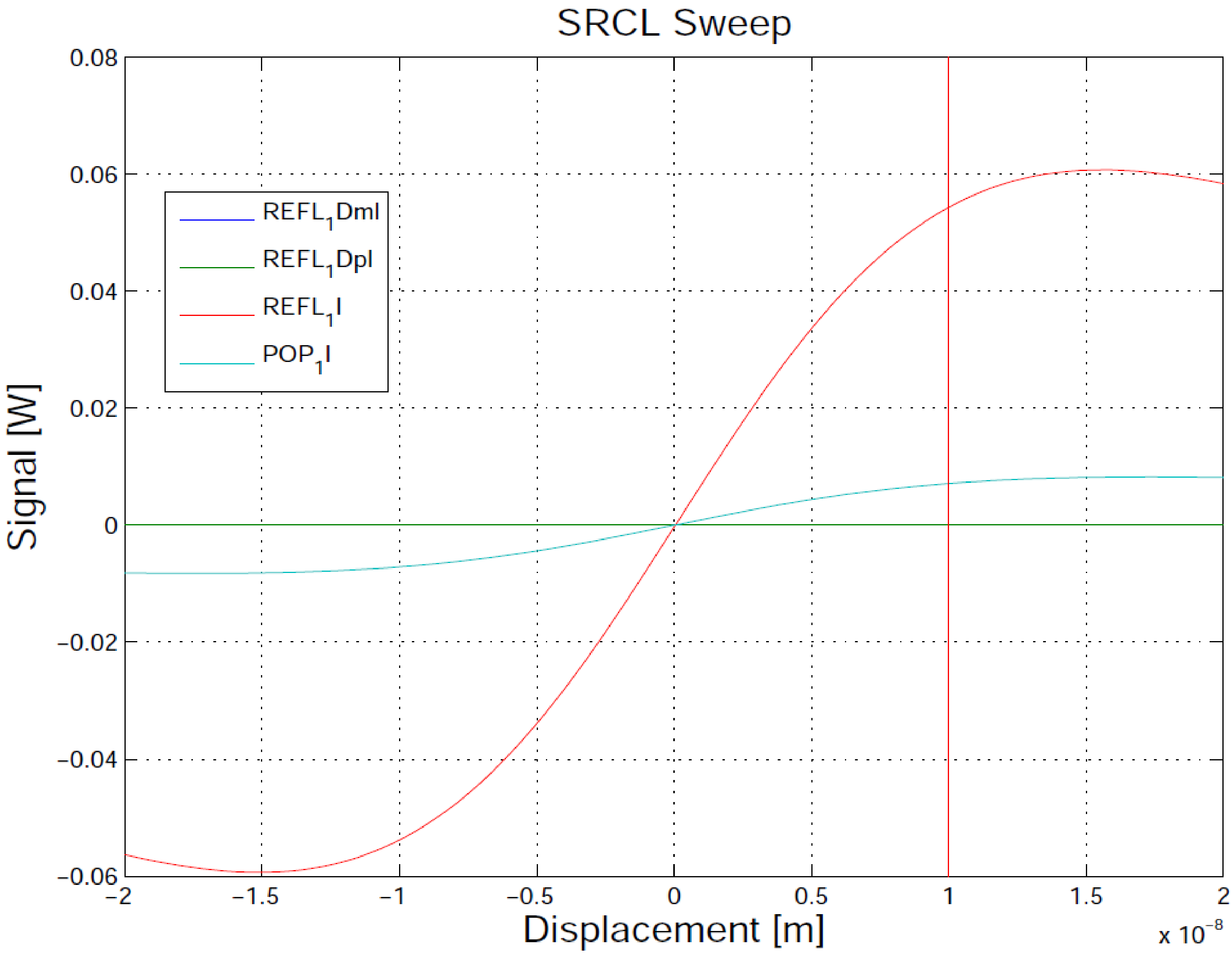
f1=11.25MHz



SRCL error signal range, f1=16.875MHz

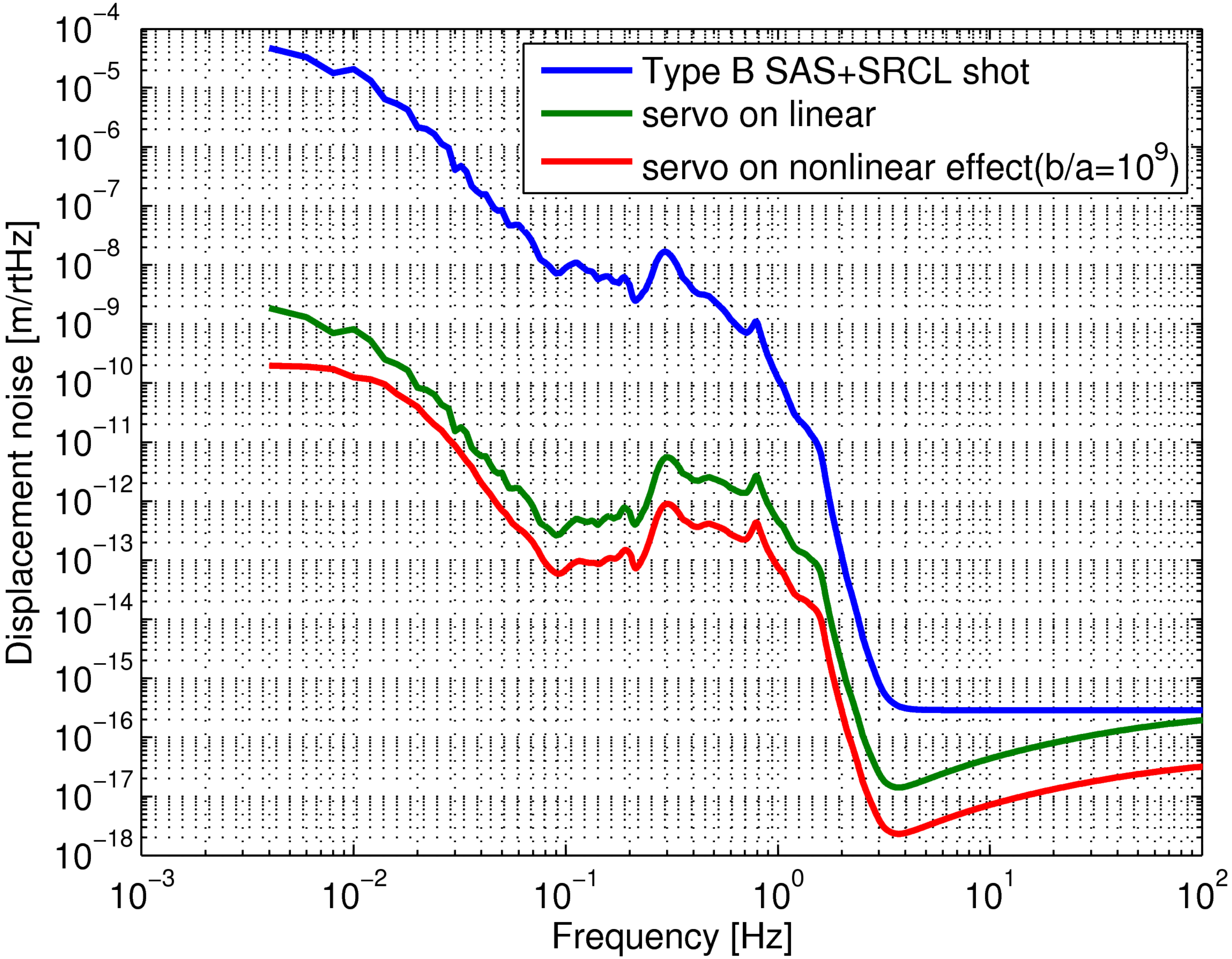
b/a = 1.05e8 m^{-1}

f1=16.875MHz



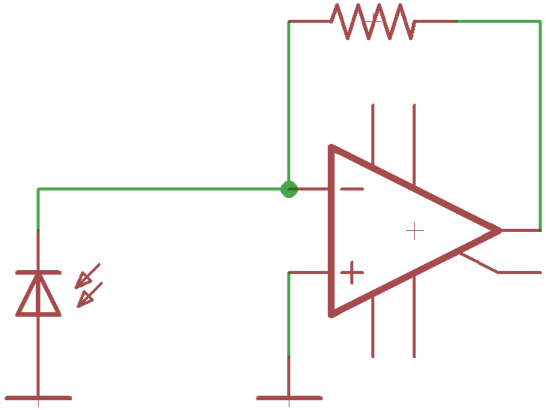
Up Conversion Noise

- Blue Curve: SAS displacement noise + SRCL shot noise
- Green Curve: Above noise suppressed by the servo
- Red Curve: Non-linear up conversion noise (b/a=1e9)



It does not seem to be a problem

PD Dynamic Range



Offsets in MICH and CARM --> Dynamic Range of RFPD circuit

SRC detuned: f1 SB is not at the peak of the resonance

→ f1 gets some phase rotation at REFL and POP

→ f1 is no longer pure PM for the carrier

→ Large offset at PDs for f1 SB

The buffer op-amp of the PD circuit has to handle this large RF signal

Max RF amplitude: ~ 0.1Vpp (?) Slew rate and linearity
Noise of the op-amp: >1nV/rtHz

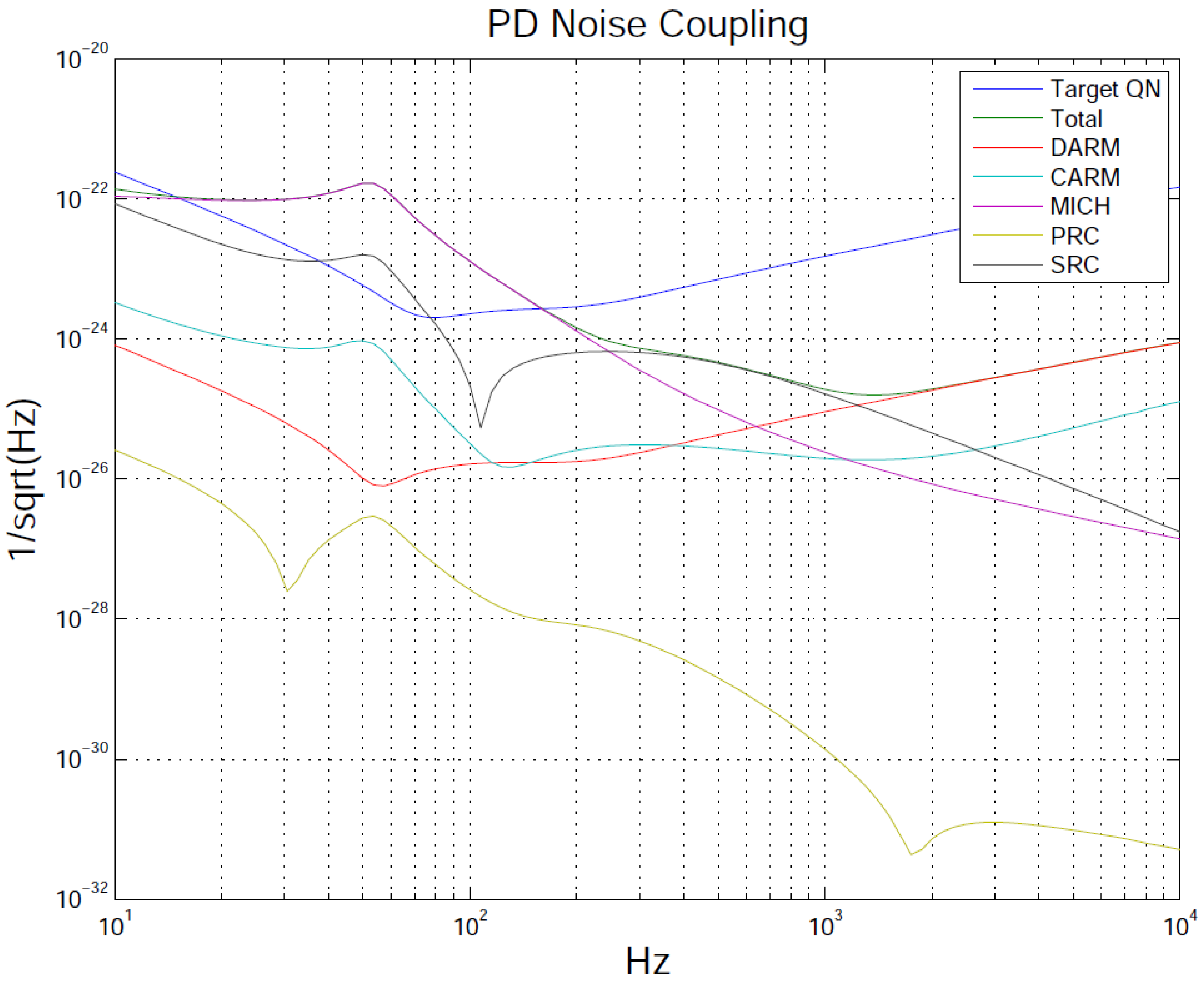
⇨ Dynamic Range ~ 160dB

Actual Numbers

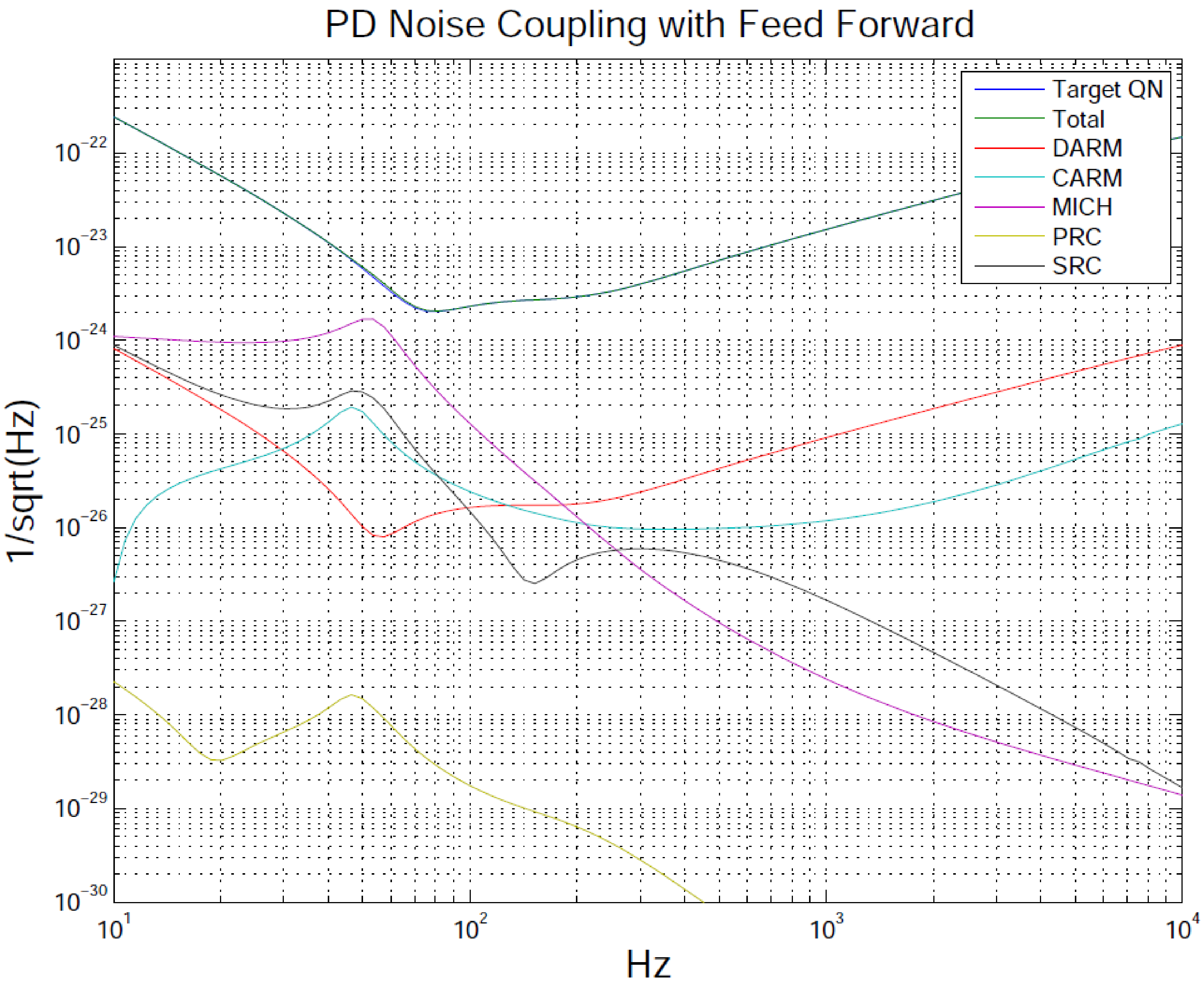
REFL_1 PD gets 55mW of offset RF signal@f1 frequency(16.875MHz) in DRSE
Input power equivalent noise of op-amp is 55mW/1e8/rtHz = 5.5e-10W/rtHz
Sensitivity is 1.64e9 W/m for CARM, 2.0e6 W/m for MICH
Displacement equivalent op-amp noise is 3.4e-19m/rtHz for CARM, 2.7e-16m/rtHz for MICH

POP_1 PD gets 7.2mW of offset RF signal@f1 frequency(16.875MHz) in DRSE
Input power equivalent noise of op-amp is 7.2mW/1e8/rtHz = 7.2e-11W/rtHz
Sensitivity is 3.3e5 W/m for SRCL
Displacement equivalent op-amp noise is 2.2e-16m/rtHz for SRCL

Risk: PD Noise Coupling



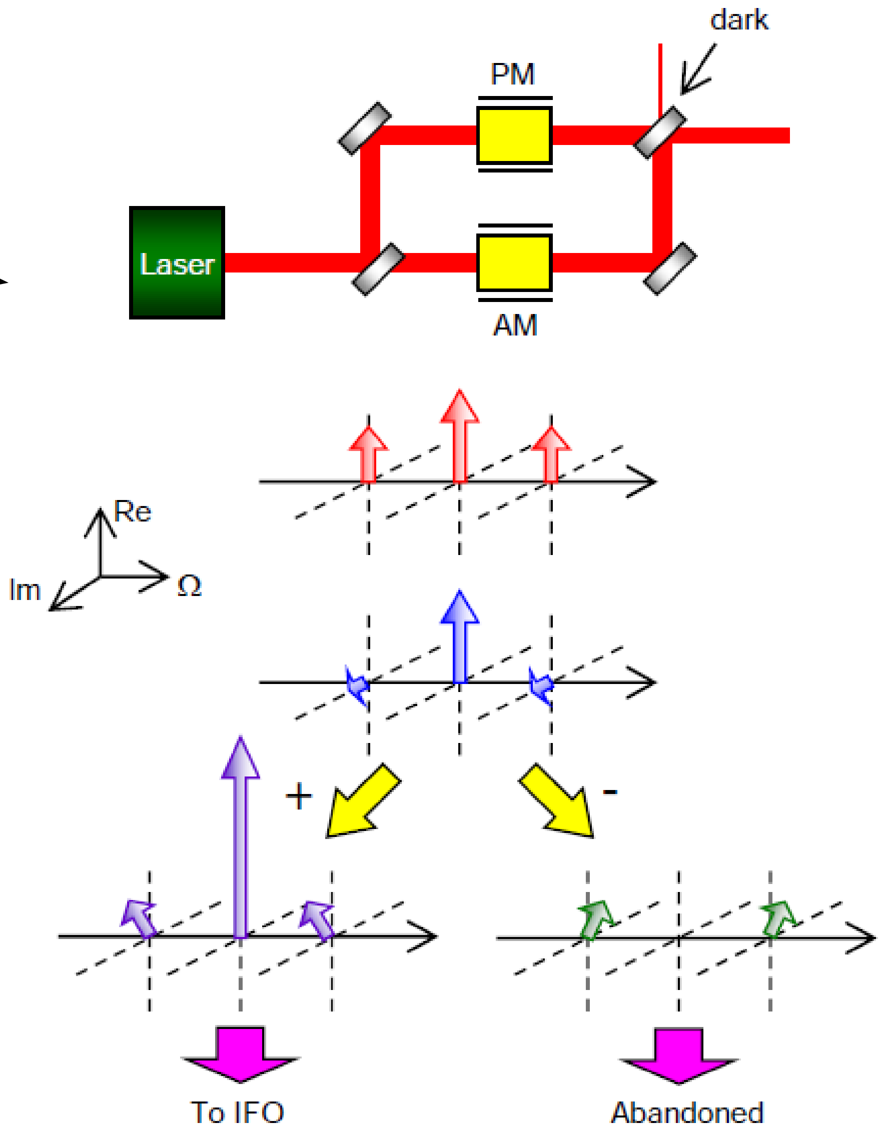
Risk: PD Noise Coupling with Feed Forward



Risk: SRCL detuning by Offset

How to deal with the PD dynamic range problem ?

- Find a good op-amp with larger dynamic range
- Increase the feed forward gain
- Current injection to PD to cancel the large RF signal (like AS_I servo in iLIGO)
- Pre-rotate f1 sidebands

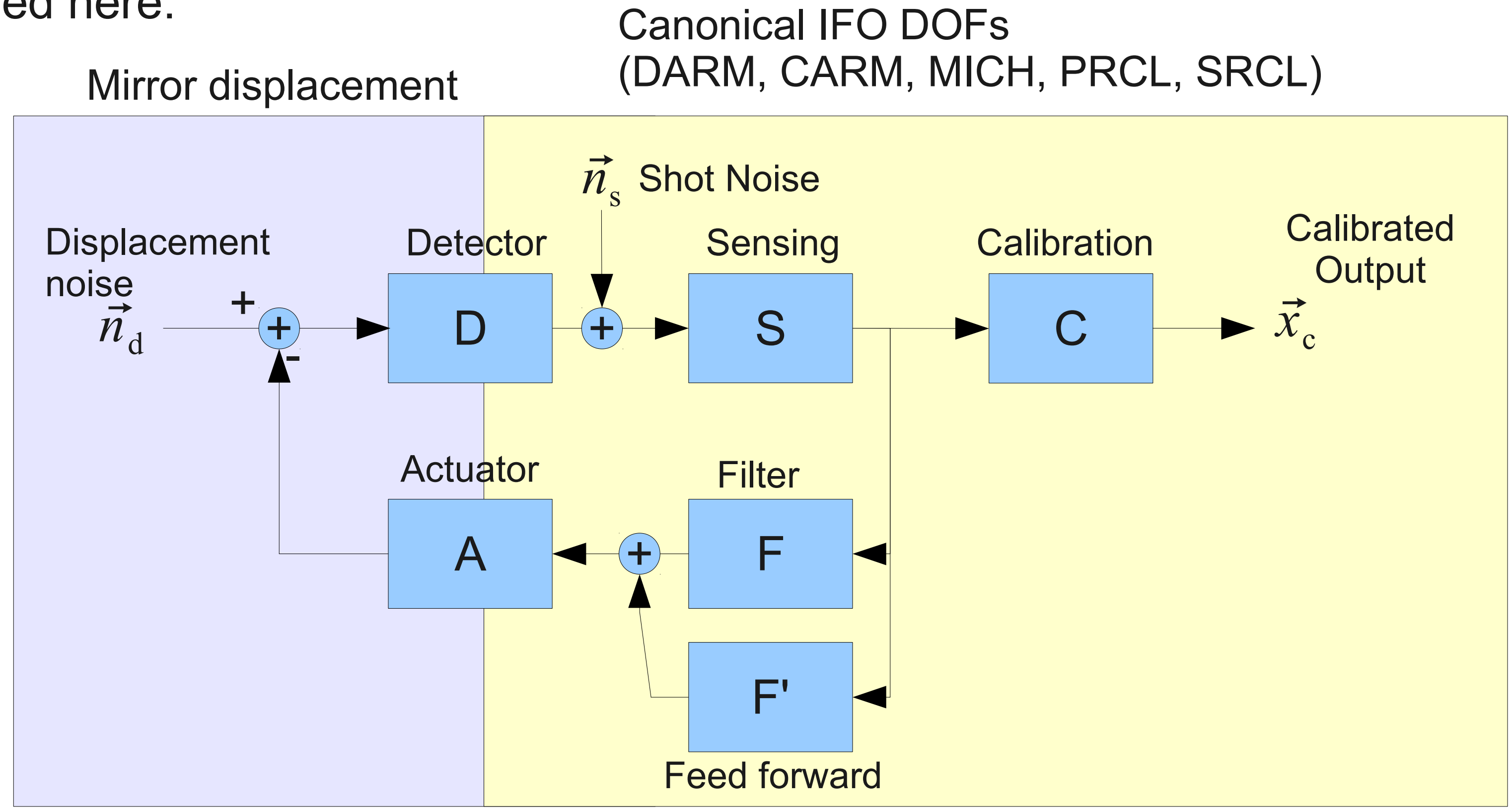


Conclusion on the Modulation Frequencies

	9MHz	11.25MHz	16.875MHz
Loop Noise	Good	OK	Good
SRCL Non-linearity	OK	OK	OK
3rd Harmonics Demodulation	OK	No	OK
Lprc,Lsrc	74.95m	73.28m	66.62m
Asymmetry	6.66m	3.33m	3.33m
Lmc	33.3m	26.65m	26.65m
f3	13.5MHz(f2*3/10)	61.9MHz(f2*11/8)	56.3MHz (f2*10/8)
DDM freq.	22.5MHz, 31.5MHz	16.9MHz, 50.6MHz	11.25MHz, 39.4MHz

Displacement Noise Requirements

Formulation used here:



$$\vec{x}_c = (I+G)^{-1} \cdot S \cdot \vec{n}_s + (I+G)^{-1} \cdot SD \cdot \vec{n}_d$$

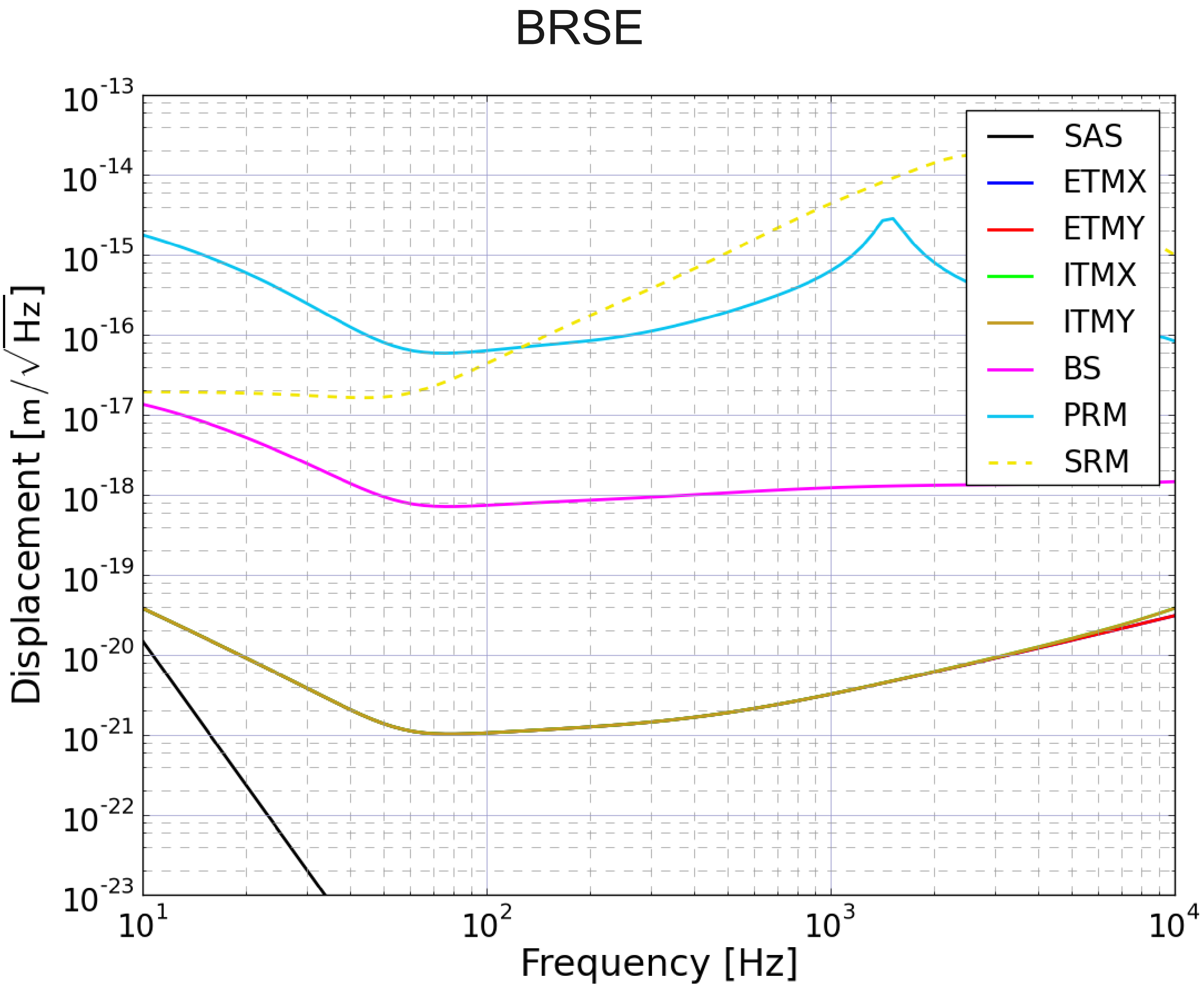
$$G \equiv S \cdot D \cdot A \cdot (F + F')$$

- $(I+G)^{-1}SD$: transfer function from n_d to x_c
- Require n_d's contribution to xc to be 1/10 of DARM shot noise

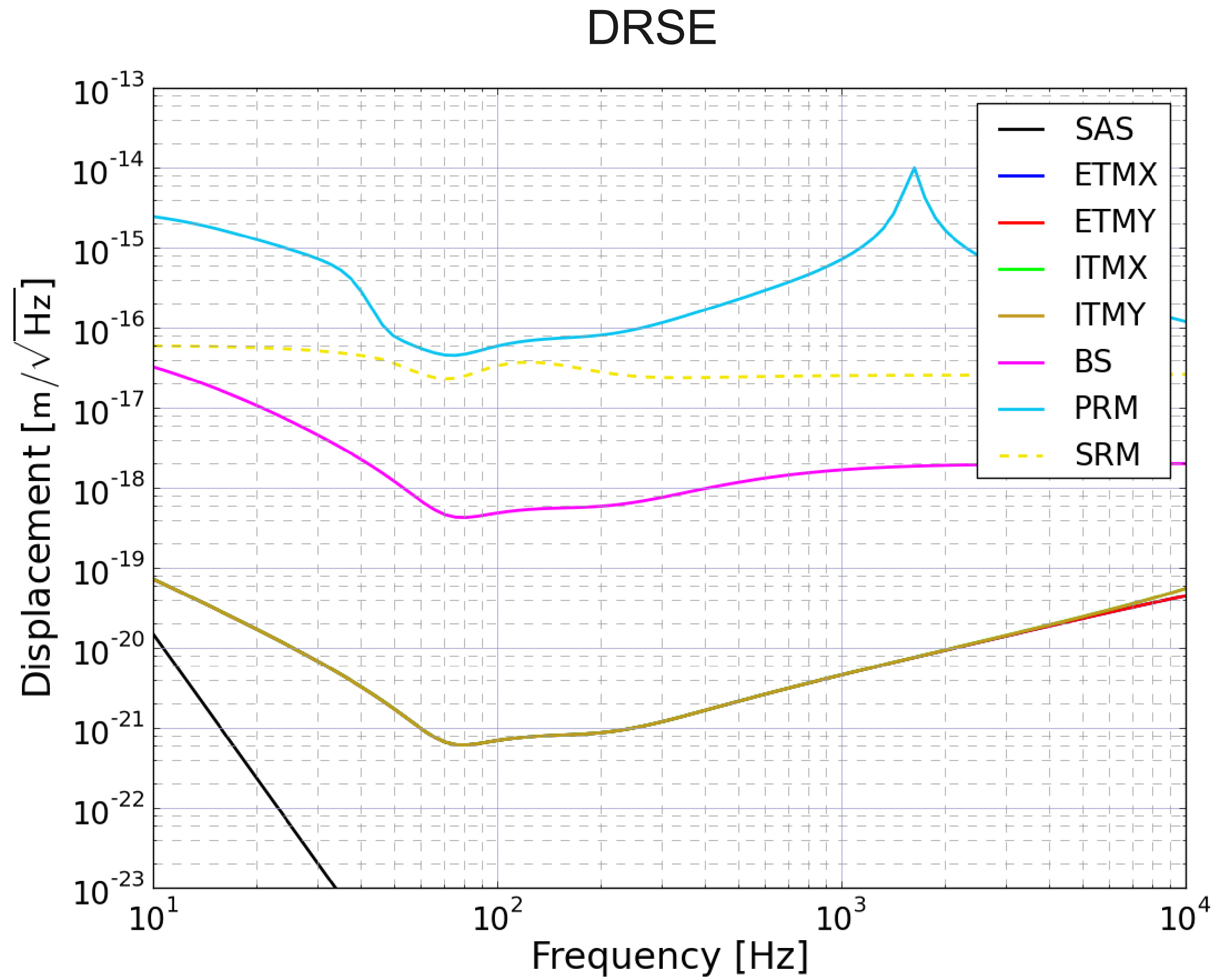
Safety factor

→ Requirement on each mirror's displacement noise
(seismic, thermal, etc)

Displacement Noise Requirements



Displacement Noise Requirements



Folding of Recycling Cavities

Straight Recycling Cavity ==> Nearly Degenerated

How badly degenerated ?

g-factor (g1*g2) = 0.9998
One-way Gouy Phase Shift = 0.7deg.
Transverse Mode Spacing = FSR/257
PRC Finesse = 57 (FWHM = FSR/57)
(PRCL = 42.5m, occupying the same tunnel space)

- HG(m,n) modes resonate up to m+n = 2
- LG(p,q) modes resonate up to 2*p+q = 2

The RFSB spatial modes are unstable (alignment fluctuation, thermal lensing)

Folding the PRC and focusing the beam inside ==> Stable PRC

How about SRC ?

- f1 SB resonates in PRC-SRC
- If PRC is stable, HOMs cannot resonate in PRC-SRC.
- No need to fold SRC ? -> Not so simple
- GW sidebands may be scattered to HOMs by mode mismatch between the arm cavities and SRC.
- The loss of GW sidebands is higher for degenerated SRC
(Kip Thorne & Yi Pan)

SRC Folding

Yi Pan's report (LIGO-T-060004): ITM ROC error of 0.25% ==> Up to 2% GW Signal Loss
Loss $\propto$ (ITM Error)^2 ==> 1% error -> 32% signal loss

The situation for LCGT should not be too different from aLIGO

But we should check it anyway

- HOM simulation using Finesse
- No definitive answer yet
- Large (1W) TEM00 leak at AS port if not folded
- Seems like non-folded SRC is bad

For the moment, the default design is to fold SRC

- Cost increase (two more vacuum tanks, suspensions, mirrors)
- Additional control of SR2, SR3 alignment (we have to control PR2, PR3 anyway)
- Folded SRC provides a convenient port for green laser injection
- The beam size at AS is smaller and easy to handle (4mm)
- If necessary, the tunnel can accommodate straight SRC (Lsrc=40m)

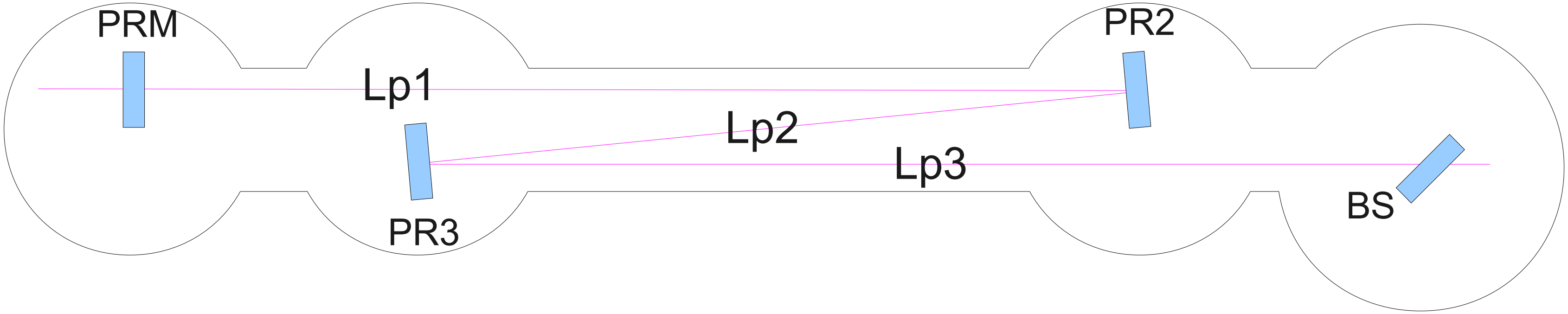
Folding Design

How Stable ?

- HOM isolation ==> Stable is better
- Too stable ==> Arm alignment signal is suppressed
- Compromise between HOM and ASC ==> One-way Gouy Phase Shift = 20deg.

Not Optimized Yet

How to fold the PRC/SRC ?



Constraints

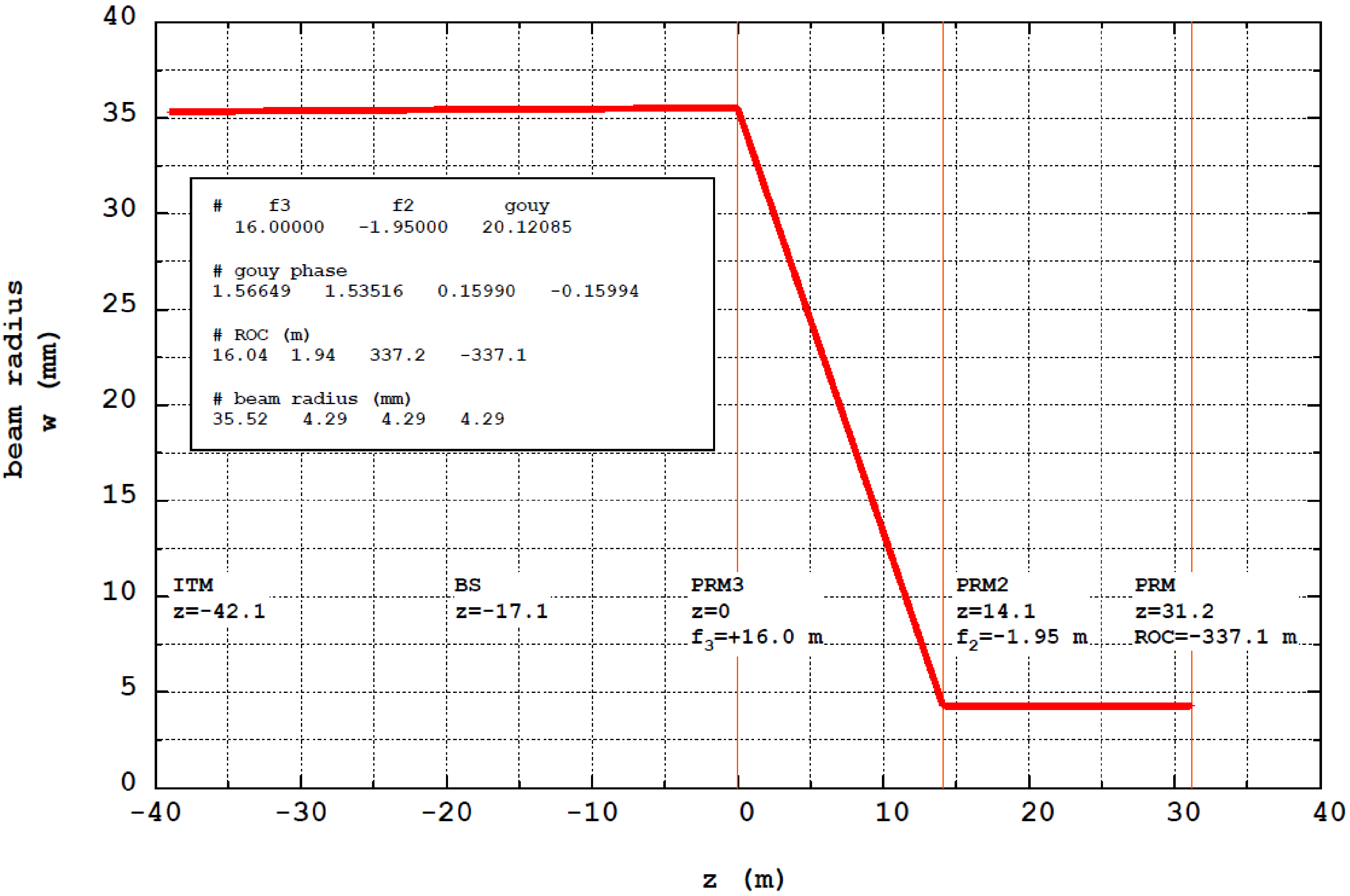
- Minimum vacuum chamber spacing: 2.7m
- Astigmatism: Smaller folding angle is better ==> Longer Lp2

➡ Mirror locations are almost uniquely determined

Play with ROCs of PR2 and PR3

Beam Propagation in PRC

Beam Width Change in PRC



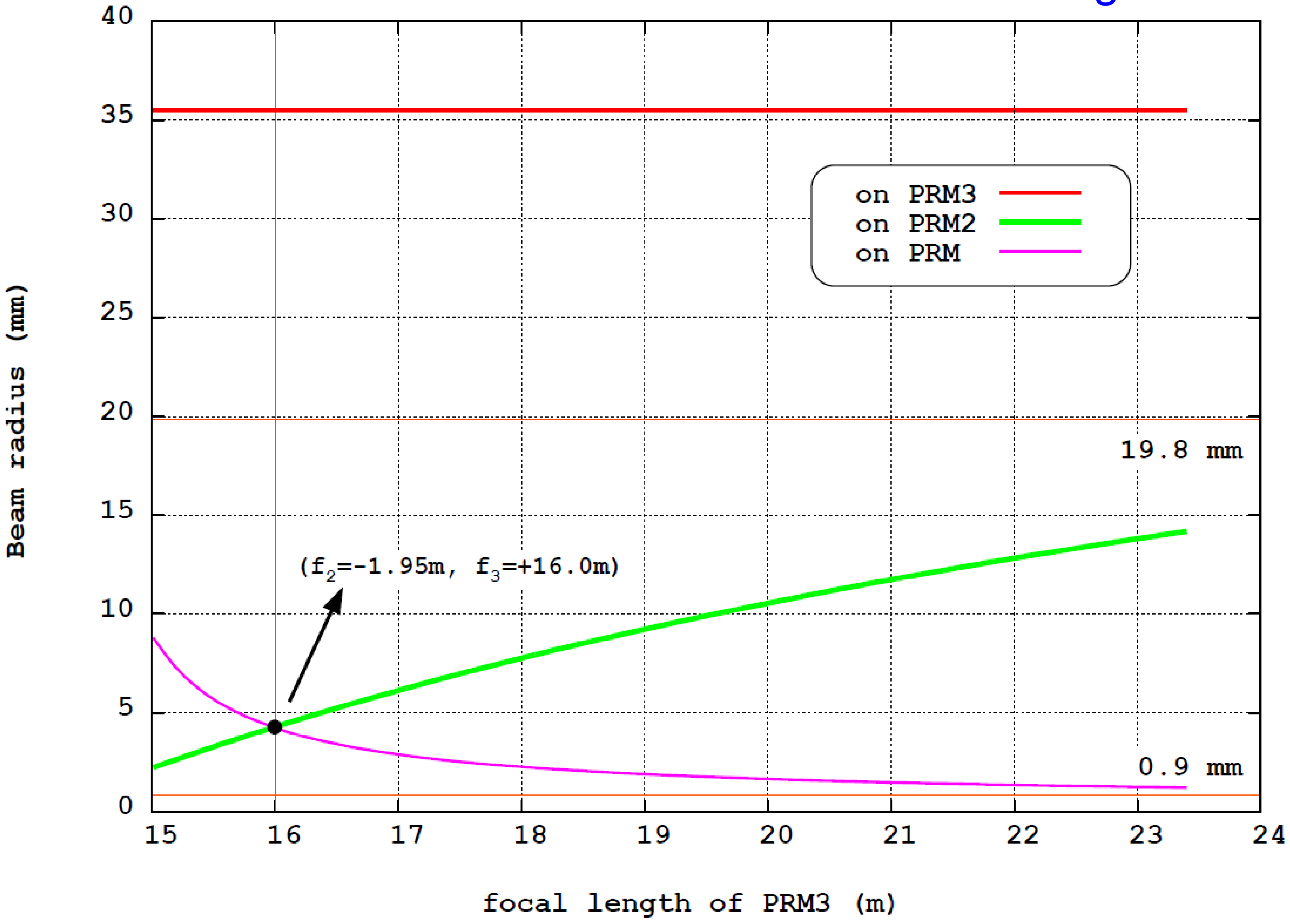
```
#    f3          f2         gouy
  16.00000    -1.95000    20.12085

# gouy phase
1.56649    1.53516    0.15990    -0.15994

# ROC (m)
16.04   1.94    337.2    -337.1

# beam radius (mm)
35.52    4.29    4.29    4.29
```

Folding Optimization

Mirror distances: fixed
One-way Gouy phase: 20deg

Small Beam Spot ==> Large Thermal Lensing

Beam Size on the Mirrors vs PR3 focal length



Thermal Lens

ITM Lensing

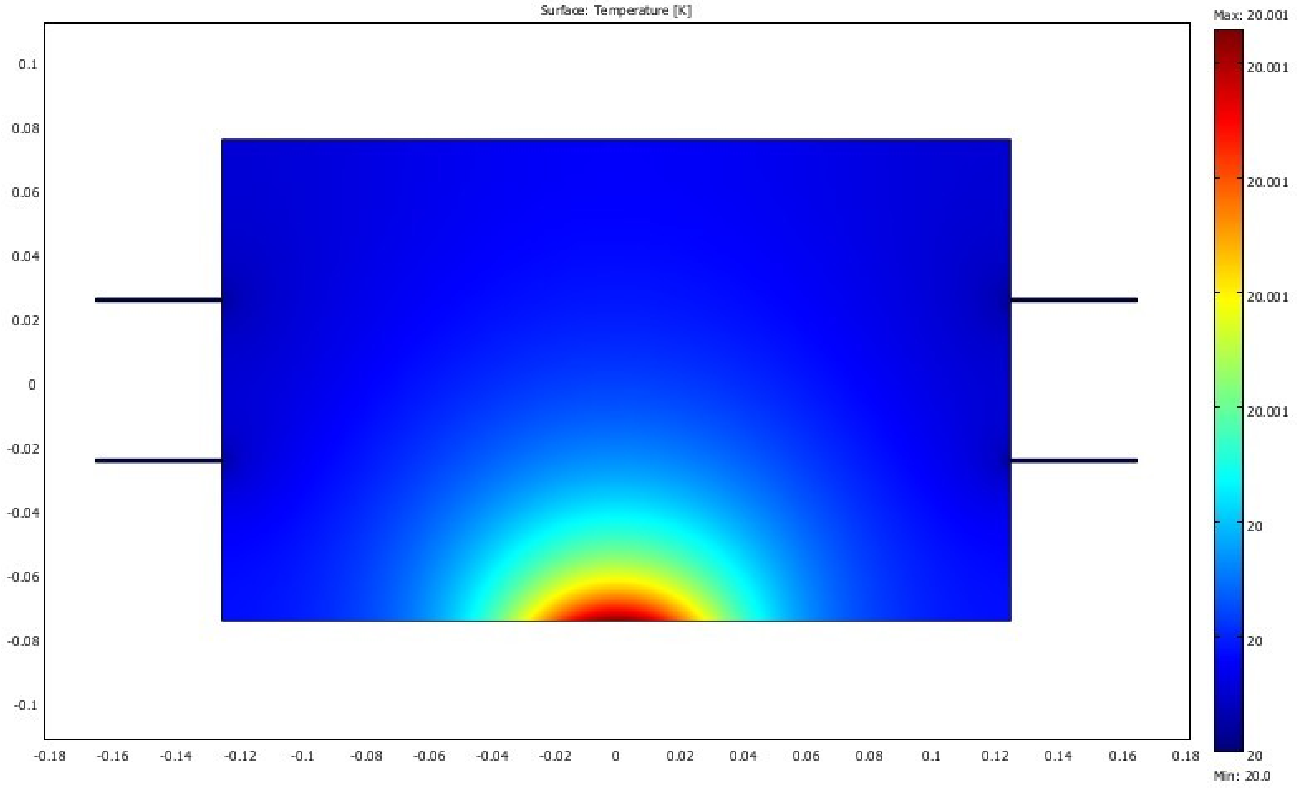
1W heat deposit
on the mirror

→

ROC=11661km, No Problem

Thanks to the high thermal conductivity of sapphire

1mK Temperature Raise



Calculation by Muzammil A. Arain (UFL)

Thermal Lens

PRM, PR2

Beam Spot Size: 4mm
Power on HR: 800W

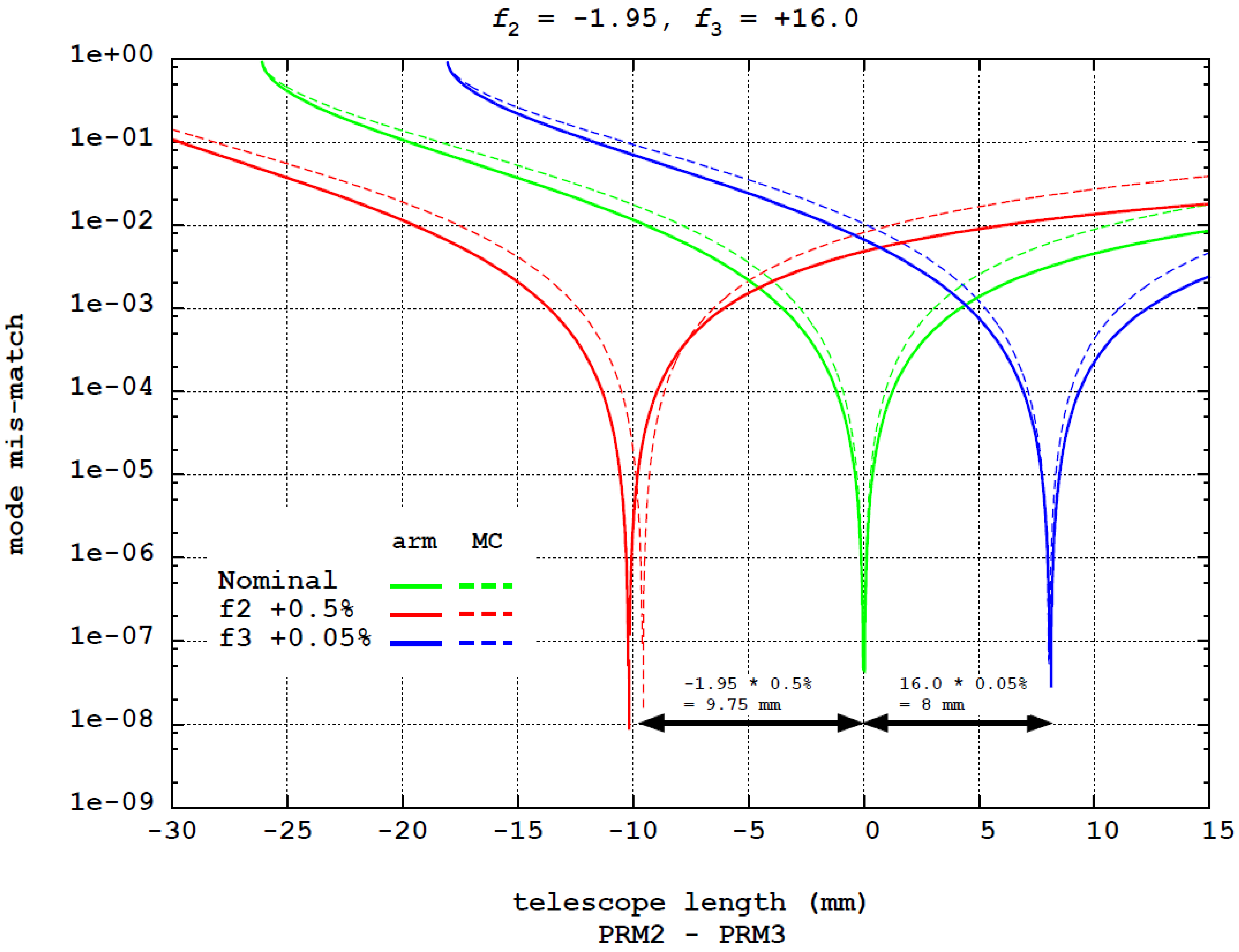
PR3, BS

Beam Spot Size: 35mm
Incident Power: 800W

	PRM	PR2	PR3	BS
10ppm absorption	18% ROC error	0.2% ROC error	0.3% ROC error	ROC 100km
1ppm absorption	2% ROC error	0.02% ROC error	0.03% ROC error	ROC 1000km

ROC Error of PR2, PR3

Very Sensitive to PR3 ROC Error



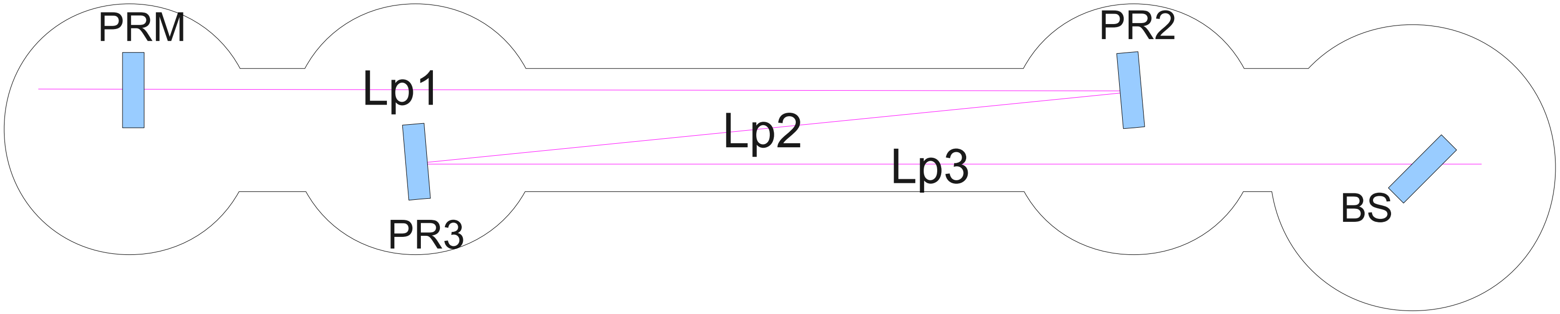
How to Handle PR3 ROC error ?

iLCGT
- No SAS. Suspensions can be easily moved by more than 10cm
- PR2 and PR3 for iLCGT will be used in bLCGT
- PRM is a blank with curvature

bLCGT
- PR2 and PR3 position can be changed by more than 10cm at the installation time
- After installation, it takes time to move them

Installation and Adjustment Plan

1. Make PR2 and PR3
2. Measure the ROCs of PR2 and PR3
3. Install them to iLCGT
4. Adjust the location of PR2 and PR3 to form the desired telescope
5. Remember the optimal location of PR2 and PR3
6. Measure the ROC of PRM, which match the actually formed PRC.
7. Order a PRM according to the measured ROC.
8. Install PR2 and PR3 at the remembered positions for bLCGT
9. Install the PRM



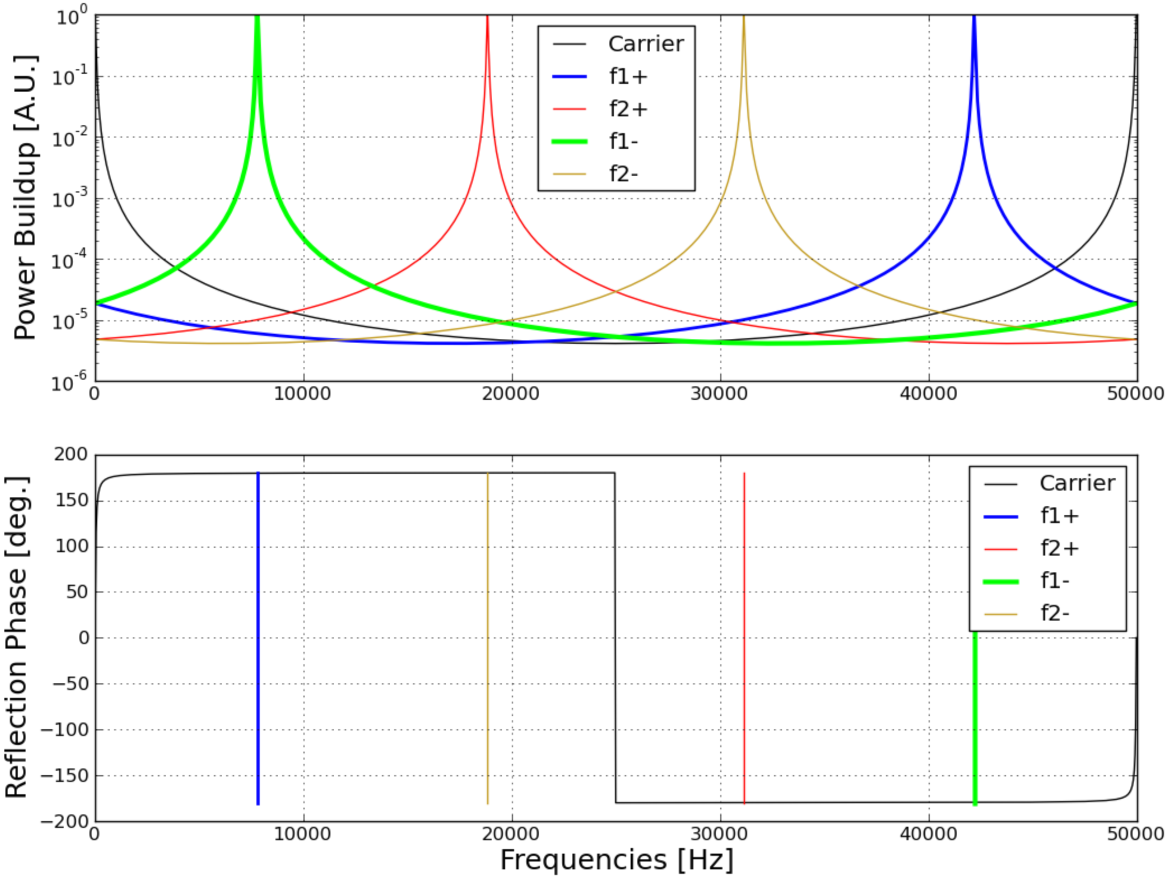
Modulation frequency Fine adjustment

f1 and f2 SBs are not exactly anti-resonant to the arm cavities

- f1 and f2 get finite phase shifts from the arm cavities
  - In general, f1 and f2 cannot fully resonate in the PRC at the same time
- Fine adjust the MC length (thus f1, f2 frequencies) to achieve

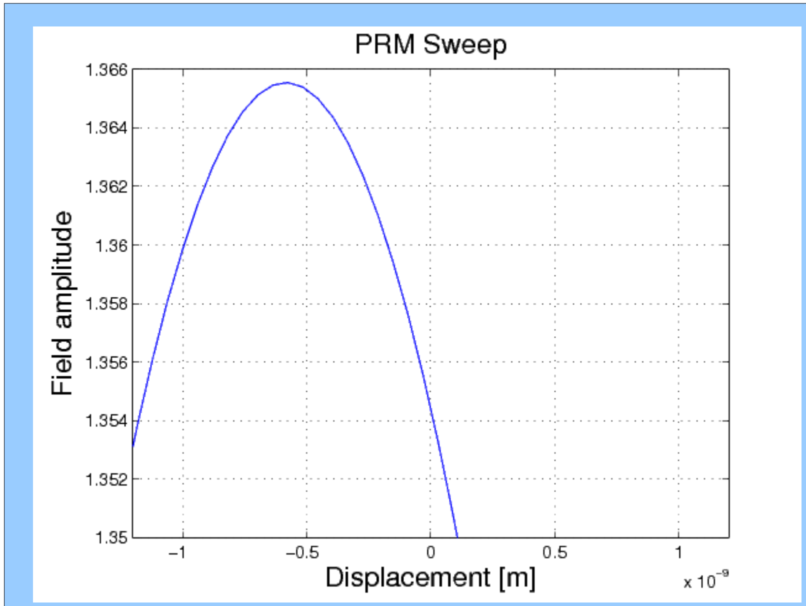
  $\Phi1:\Phi2 = f1:f2$ ($\Phi1$: phase shift of f1 by the arm, $\Phi2$: phase shift of f2 by arm)
- Lprc and Lsrc are adjusted accordingly

Locations of RF SBs in the FSR of AC

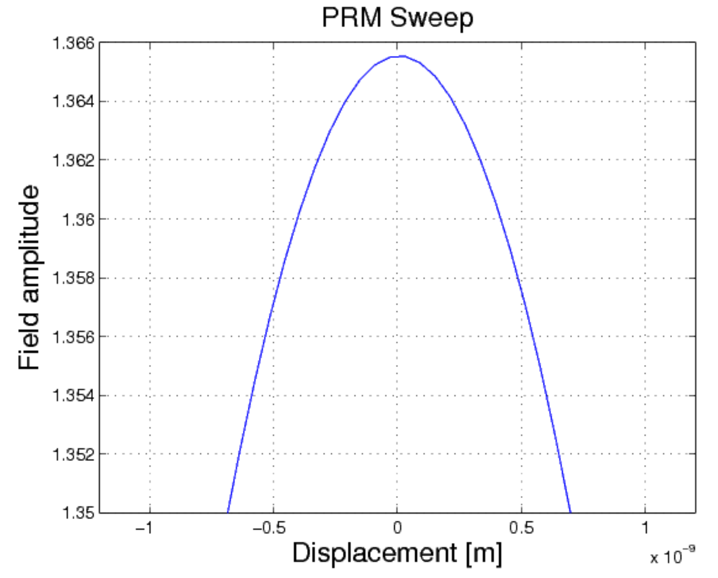


Lmc adjustment = -1.37cm

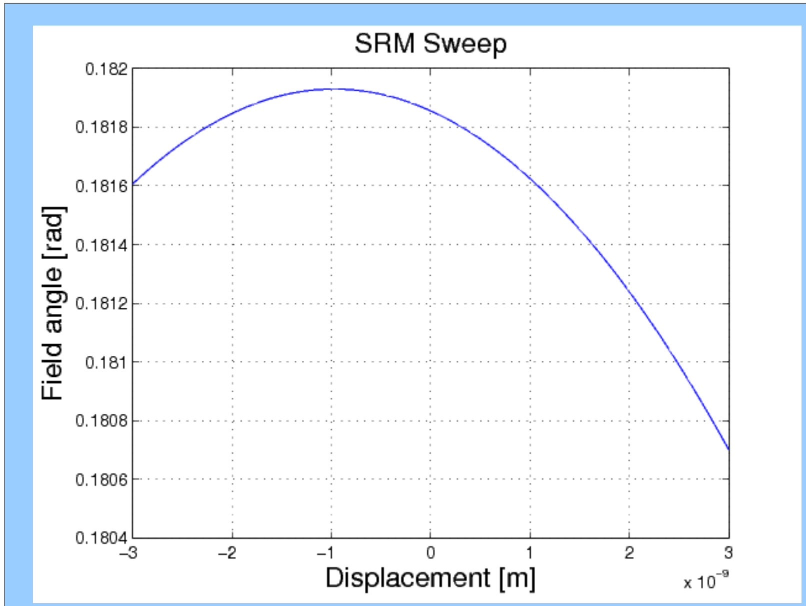
f2 resonance



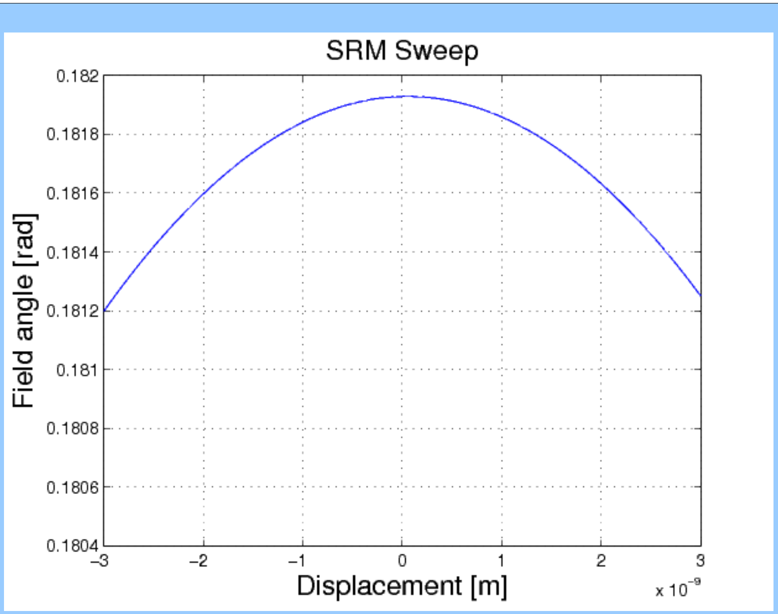
Adjust Lprc
by 3.7mm



f1 resonance



Adjust Lsrc
by 7.4mm



Alignment Sensing and Control

Basic Strategy

Combination of Wave Front Sensing (WFS) and Optical Levers

Arm Cavity Misalignment Modes

Combinations of the ITM, ETM rotation to diagonalize the angular stiffness matrix

→ Hard - Soft basis

[Common Hard (CH), Common Soft (CS), Differential Hard (DH), Differential Soft (DS)]

Folding and ASC

- RCs are very stable --> TEM01 and TEM10 modes are suppressed
  - No ASC signal of TMs
- One-way Gouy phase shift in RCs --> about 20 deg.
- Needs optimization
- What to do with the alignment of folding mirrors ?
  - Not enough DOF from WFS
  - Control a linear combination of PRM,PR2,PR3 angles ?
  - Is it stable ?

Simulations with Optickle (Pickle), work in progress

bLCGT ASC Sensing Matrix

Angle Sensing Matrix [W/rad]

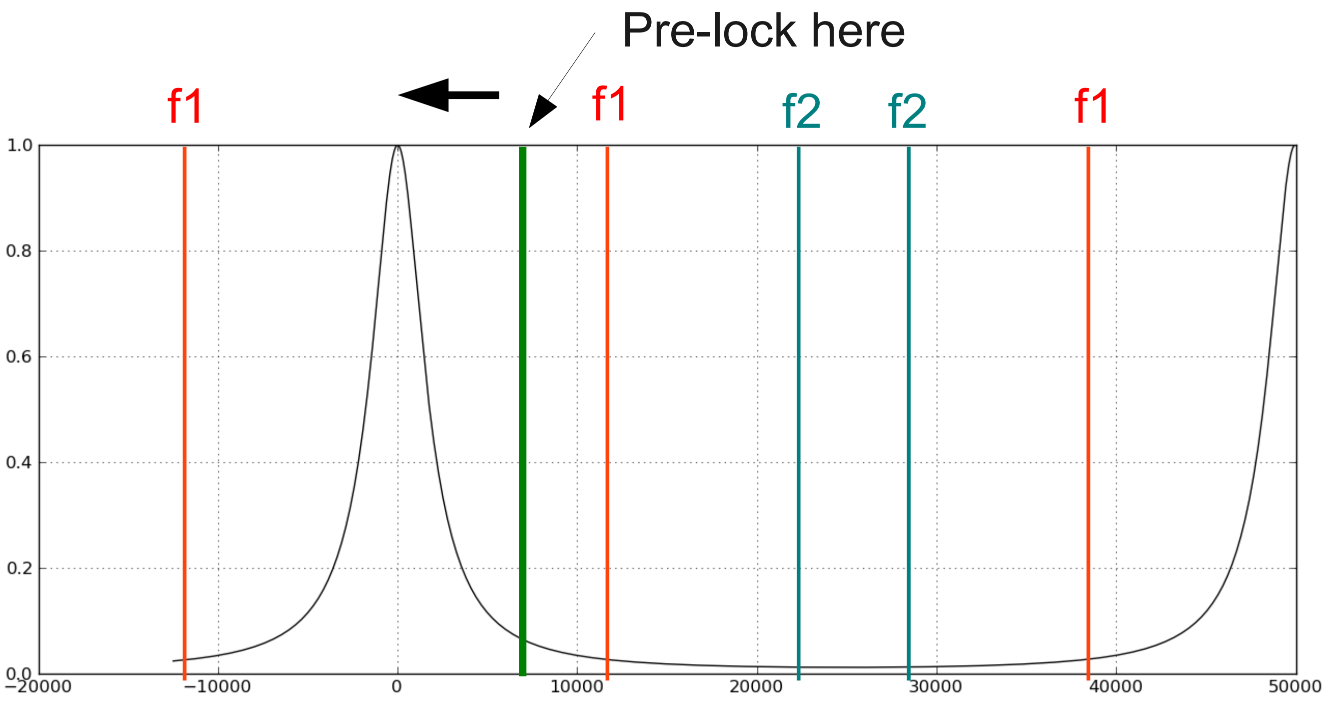
	CS	CH	DS	DH	PRM	PR2	PR3	SRM	SR2	SR3	BS
POY_B Q2	-5.54	-4.5	-132	155	0.392	0.363	0.443	-0.00311	-0.00591	-0.0496	-372
POY_B I2	1e+003	-1.17e+003	856	-1.22e+003	-84.6	-935	-7.9e+003	-0.0162	-0.0309	-0.259	-68.3
POY_A Q2	97	98.2	-1.15e+003	1.23e+003	-5.64	-1.35	39.5	-0.0131	-0.025	-0.209	-3.05e+003
POY_A I2	-145	-23	1.06e+003	-1.15e+003	9.92	54.2	412	0.00955	0.0182	0.152	3e+003
POY_B Q1	-76.9	33	42.8	48.3	2.66	36.2	310	-0.143	-0.271	-2.27	67.1
POY_B I1	-58.1	61.4	54.9	-50.7	3.31	49.3	426	-1.59	-3.03	-25.4	283
POY_A Q1	-135	155	135	-155	11.6	127	1.07e+003	-0.00453	-0.00862	-0.0723	758
POY_A I1	184	-20.2	-190	40.7	-7.69	-83.8	-705	7.85	14.9	125	-536
POX_B Q2	675	-851	-1.07e+003	1.37e+003	-57.9	-658	-5.58e+003	0.00518	0.00985	0.0825	-5.16e+003
POX_B I2	-591	761	810	-1.06e+003	50.8	583	4.94e+003	-0.00955	-0.0182	-0.152	4.2e+003
POX_A Q2	54.1	-57.8	87	-111	-4.48	-48.1	-406	-4.26e-005	-8.09e-005	-0.000678	115
POX_A I2	459	-267	1.21e+003	-1.21e+003	-35.3	-313	-2.58e+003	0.0202	0.0384	0.322	2.21e+003
POX_B Q1	-16.4	31.1	17.2	-52.7	0.0136	10.4	95.9	2.01	3.82	32	125
POX_B I1	-1.75	3.3	5.88	-11	1.09	2.02	8.96	1.93	3.66	30.7	24.2
POX_A Q1	223	-62.1	219	-57	-10.3	-116	-976	7.51	14.3	120	-3.85
POX_A I1	-102	156	-103	157	10.1	114	966	0.998	1.9	15.9	5.74
POP_B Q2	5.91	4.14	-0.136	0.165	-0.436	-0.812	-4.21	1.4e-006	2.65e-006	2.22e-005	-1.74
POP_B I2	-1e+003	1.17e+003	-1.77	2.36	84.8	938	7.93e+003	-0.000147	-0.000279	-0.00234	2.8e+003
POP_A Q2	18.9	-135	0.569	-0.589	-3.01	-65.6	-582	1.24e-005	2.36e-005	0.000197	-206
POP_A I2	63.4	188	-0.585	0.451	-2.09	52.7	509	-1.01e-005	-1.92e-005	-0.000161	182
POP_B Q1	-43.4	4.25	7.14	-9.18	0.965	11.4	96.3	0.579	1.1	9.23	41.3
POP_B I1	9.22	-1.14	34.8	-43.7	-0.208	-2.51	-21.3	-0.116	-0.22	-1.85	97.3
POP_A Q1	-0.796	0.931	-155	195	0.055	0.594	5.01	0.000227	0.000432	0.00362	-452
POP_A I1	-82.2	-64	-0.395	-0.193	0.423	4.12	33.7	-6.81	-12.9	-109	12.7
AS_B Q1	-0.628	2.78	-922	-491	-0.0259	-4.5	-41.5	-0.000256	5.91	53.6	-166
AS_B I1	85.6	-125	6.65e+003	3.81e+003	-4.38	-45.2	-378	3.76	-36.5	-336	535
AS_A Q1	-42.5	53.1	0.98	-34.7	3.75	41.8	354	-0.103	-0.19	-1.59	176
AS_A I1	51.6	-18	-1.95e+004	-1.5e+004	-2.56	-34.6	-296	-1.3	5.64	51.2	-2.02e+003
REFL_B Q2	-445	97.4	-1.51	2.35	5.28	236	1.9e+003	-4.01e-005	-7.62e-005	-0.000639	660
REFL_B I2	-1.08e+004	-9.77e+003	8.28	14.8	-871	571	-570	0.000124	0.000235	0.00197	-490
REFL_A Q2	-9.58e+003	-4.22e+003	-3.41	22.5	-356	2.27e+003	1.55e+004	-0.000239	-0.000455	-0.00381	5.27e+003
REFL_A I2	-1.08e+004	-5.39e+003	-1	22.6	-448	2.3e+003	1.51e+004	-0.000219	-0.000416	-0.00349	5.1e+003
REFL_B Q1	-26.4	-11	-943	1.19e+003	0.0786	4.98	39.8	-1.43	-2.71	-22.7	-2.75e+003
REFL_B I1	-1.84e+003	-1.46e+003	21.1	-27.6	-110	158	685	-40.6	-77.2	-647	279
REFL_A Q1	-1.23	10.9	-978	1.23e+003	1.57	3.41	36.1	-0.787	-1.5	-12.5	-2.85e+003
REFL_A I1	-2.05e+003	-1.47e+003	7.32	-10.2	-99.4	194	955	-36.5	-69.5	-582	294

Lock Acquisition

Principle: Lock acquisition has to be a deterministic process

Lock acquisition steps

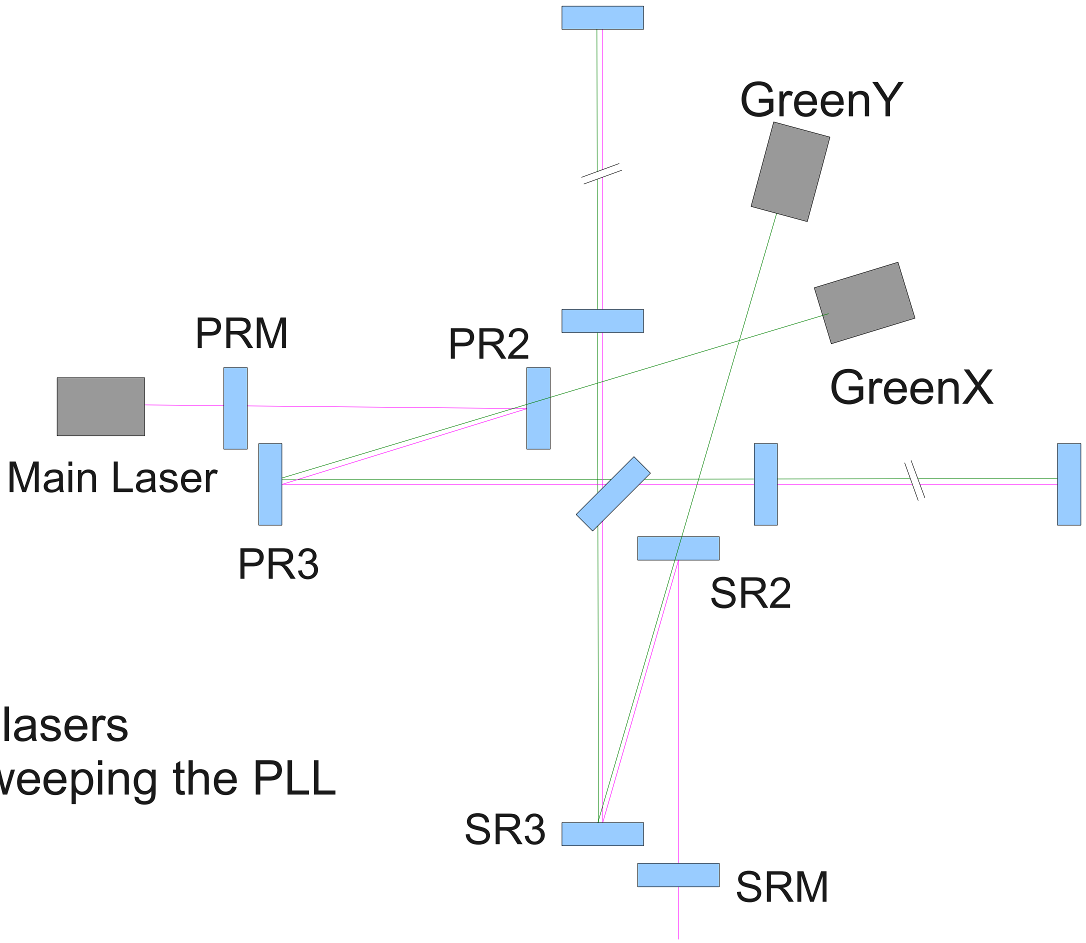
1. Pre-lock the arms at off-resonant positions (Green laser pre-lock)
2. Lock the central part using the third harmonics demodulation or non-resonant sideband
3. Reduce the arm offset to the full resonance
4. The error signals to low noise ones



Green Laser Pre-Lock

Basic ideas for green laser lock

- Two green lasers (Frequency doubled from 1064nm)
- Green lasers are phase locked to the main laser by PLL
- Green Lasers are injected from PR2 for X-arm, and SR2 for Y-arm
- PR3 and SR3: High reflectivity for green (>90%)
- BS is transparent to green
- Arm finesse for green is low (~10)
- Two green lasers are frequency shifted by ~ 100MHz



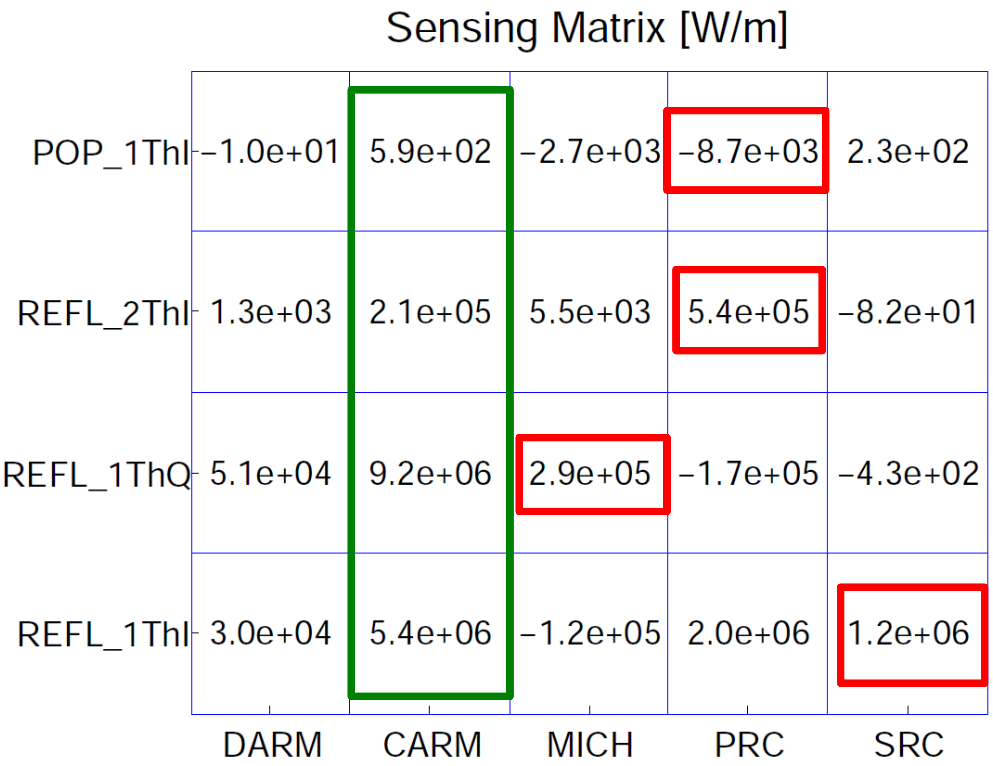
- Lock the arms independently by the green lasers
- Arm cavity length can be finely tuned by sweeping the PLL

Third Harmonics Demodulation

- Beat between 2*f1 and f1 (Insensitive to the arms)
- Useful for lock acquisition.
- Substitutes for NRS. No MZ, no AM necessary -> simple.

Unfortunately, all the f1 candidates cannot use this method in the usual sense, because 2*f1 resonates in the PRC-SRC.
(f1 frequencies tested: 9MHz, 11.25MHz, 13.5MHz, 16.875MHz, 19.3MHz)

Actually, 3rd harmonics demodulation produces some signal due to difference in the response of 2*f1 and f1.
However, strong interference from the carrier is present (carrier-3*f1 beat).

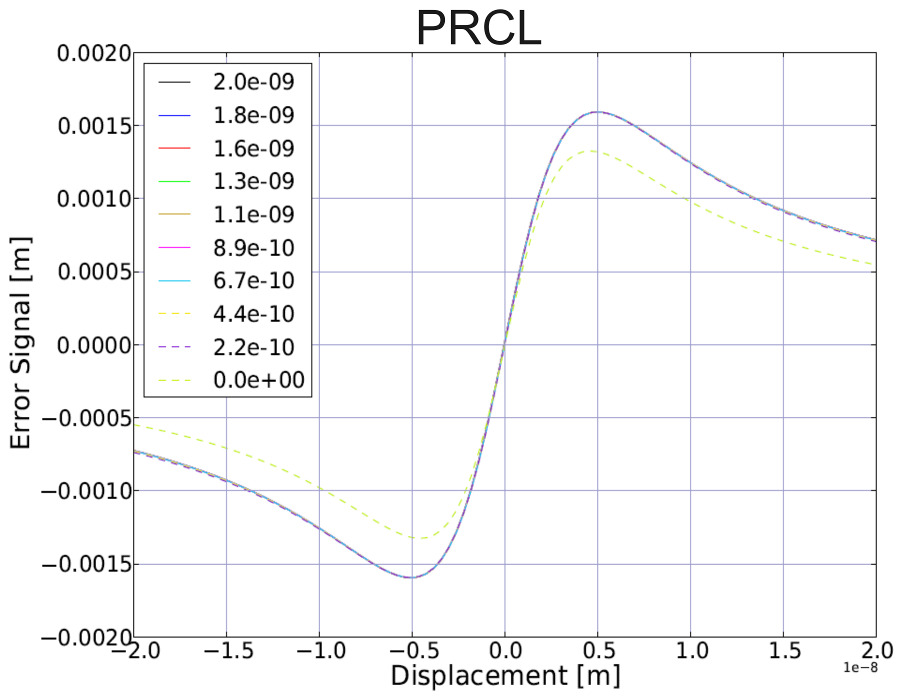


Sensing Matrix [W/m]

	DARM	CARM	MICH	PRC	SRC
POP_1ThI	−1.0e+01	5.9e+02	−2.7e+03	−8.7e+03	2.3e+02
REFL_2ThI	1.3e+03	2.1e+05	5.5e+03	5.4e+05	−8.2e+01
REFL_1ThQ	5.1e+04	9.2e+06	2.9e+05	−1.7e+05	−4.3e+02
REFL_1ThI	3.0e+04	5.4e+06	−1.2e+05	2.0e+06	1.2e+06

@100Hz

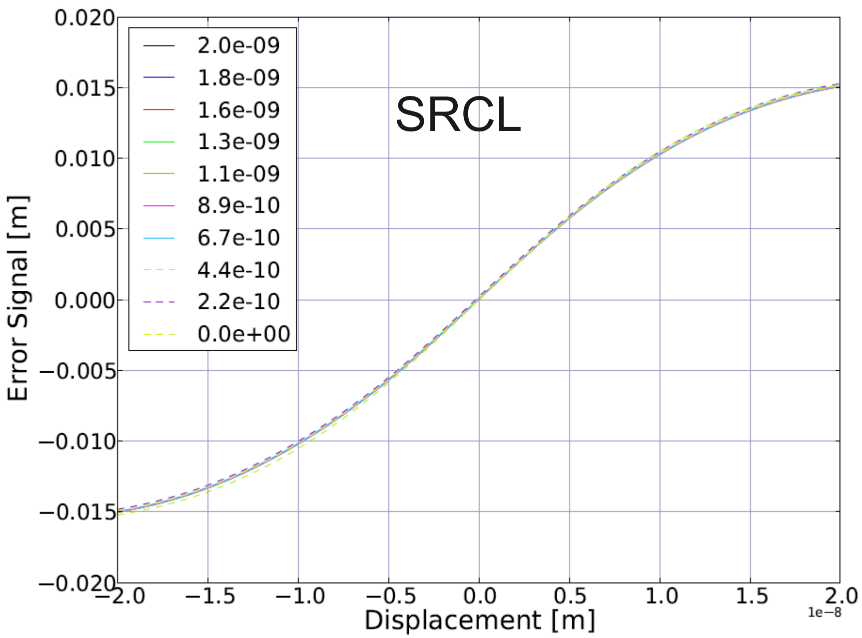
Third Harmonics Demodulation

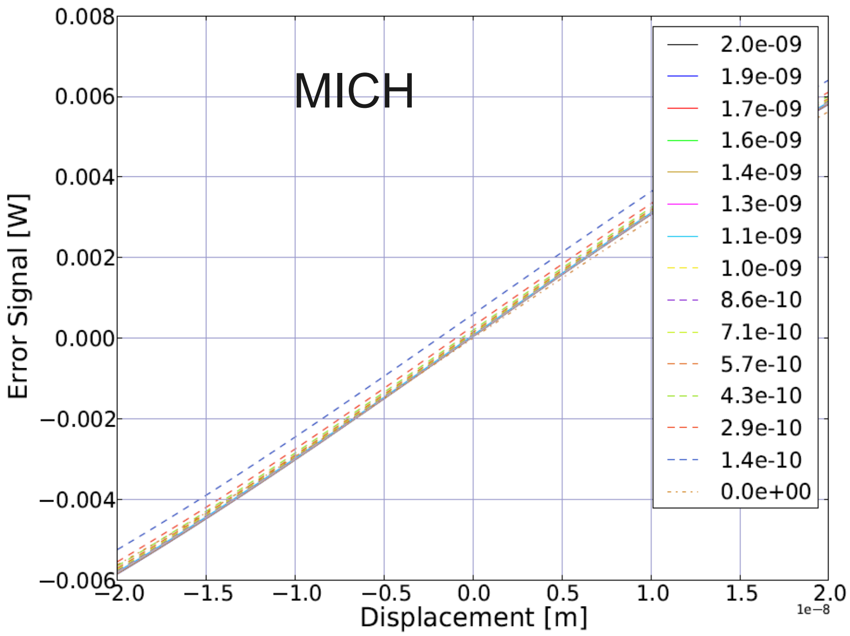


3rd Harmonics signal during lock acquisition

CARM offset: 2nm -> 0

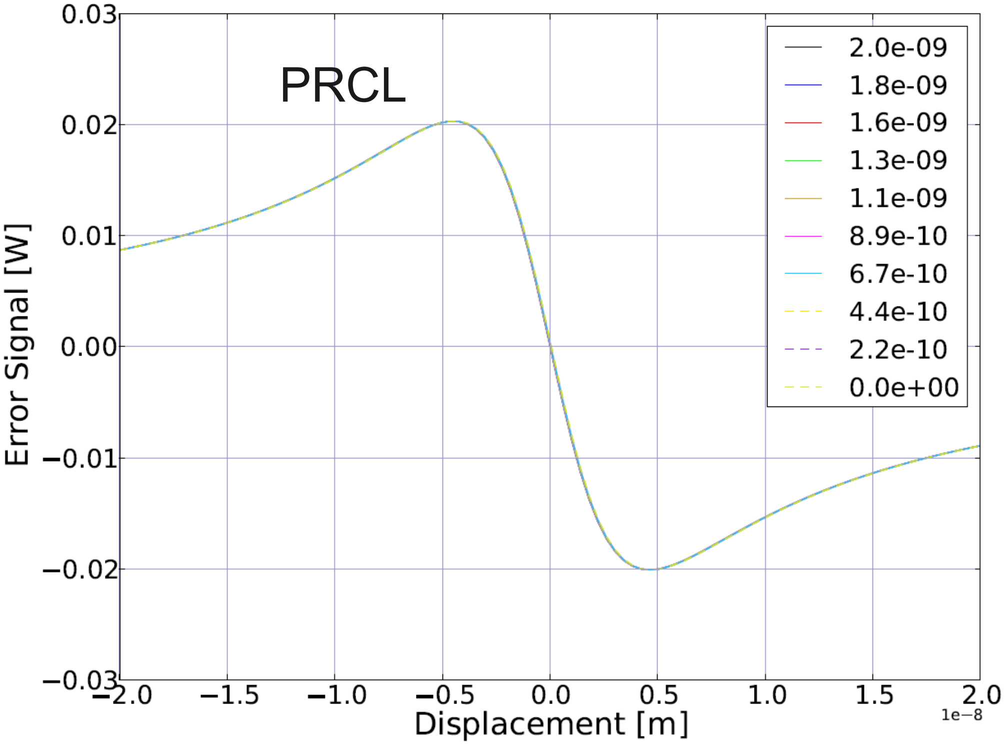
MICH is affected by CARM





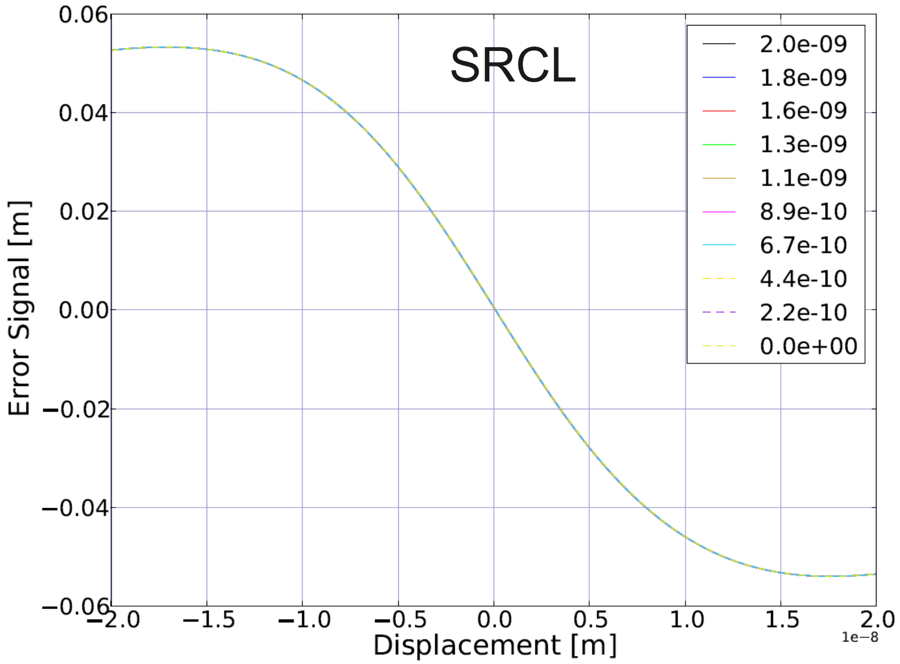
Non-Resonant Sideband for Lock Acquisition

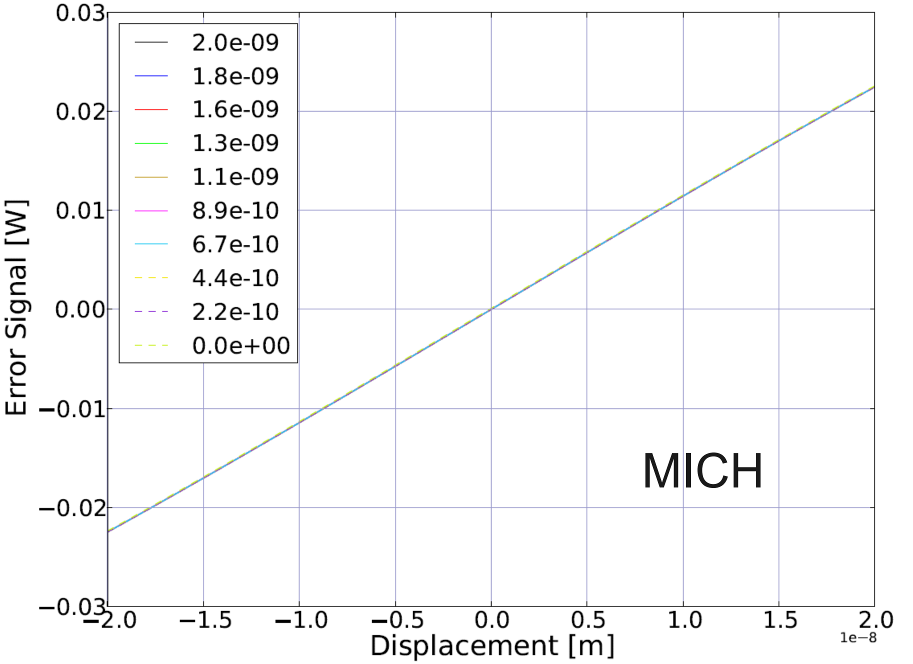
NRS serves as a local oscillator insensitive to the arms



NRS signals during the lock acquisition

CARM offset: 2nm -> 0





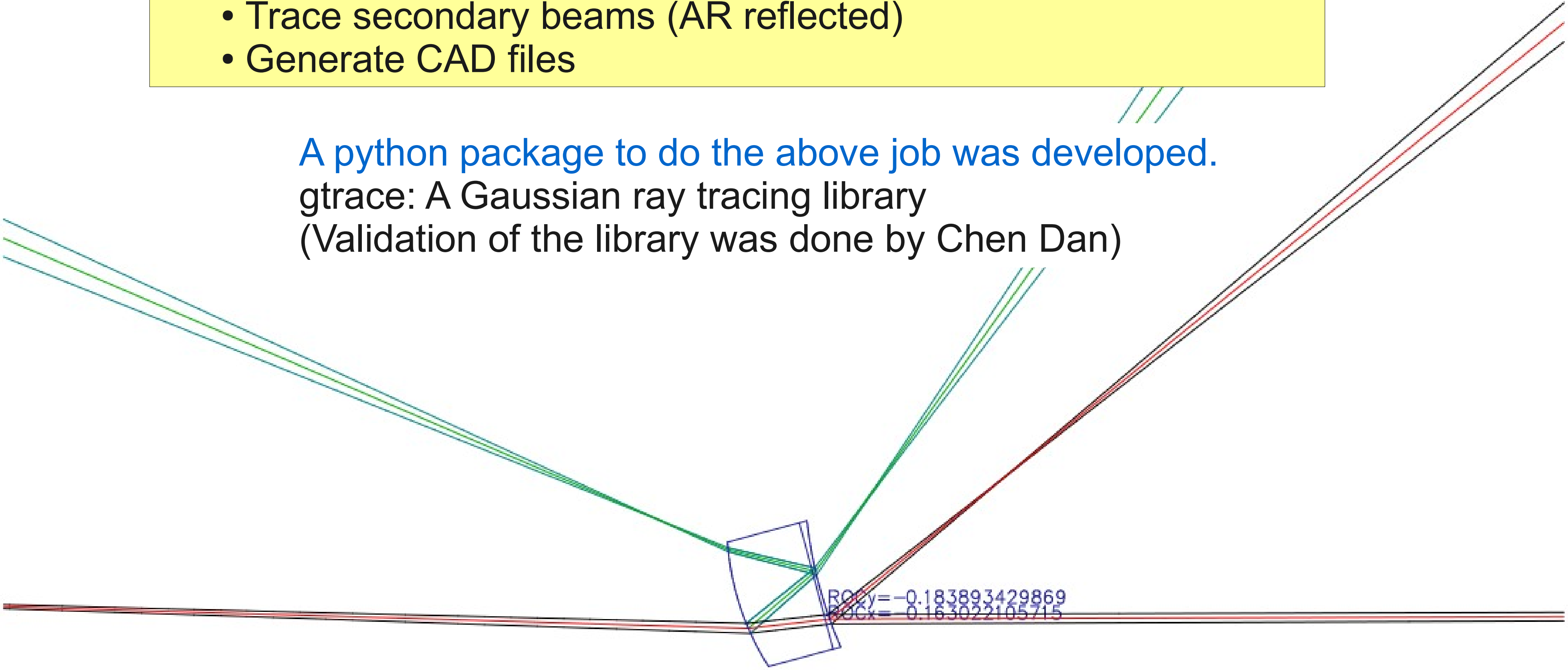
Detailed Optical Layout

Detailed optical layout design is a non-trivial task !

We have to ...

- Take into account wedge deflection
- Make the two arms at the right angle
- Track the optical path length (for SB resonant conditions)
- Track the Gaussian mode evolution
- Track the Gouy phase evolution
- Take into account the dispersion effect for the green beams
- Trace secondary beams (AR reflected)
- Generate CAD files

A python package to do the above job was developed.
gtrace: A Gaussian ray tracing library
(Validation of the library was done by Chen Dan)



iLCGT

- iLCGT has to be on the way to bLCGT
- Minimum detour from the straight path to bLCGT
- Most parameters are the same as bLCGT

Interferometer Configuration

- Fabry-Perot Michelson Interferometer (no recycling)
- Arm cavity finesse is the same as bLCGT

Mirrors

- Test masses are fused silica
- All the other mirrors are to be used in bLCGT (BS and the folding mirrors)
- PRM is a blank with curvature (for mode matching)
- No SRM installed.

LSC

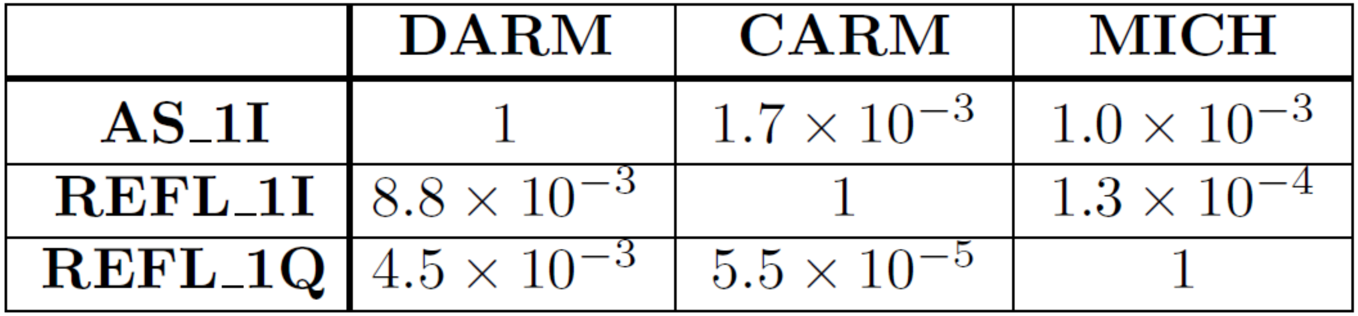
- A simple frontal modulation scheme using f1 SB only

ASC

- Wave front sensing at REFL and AS

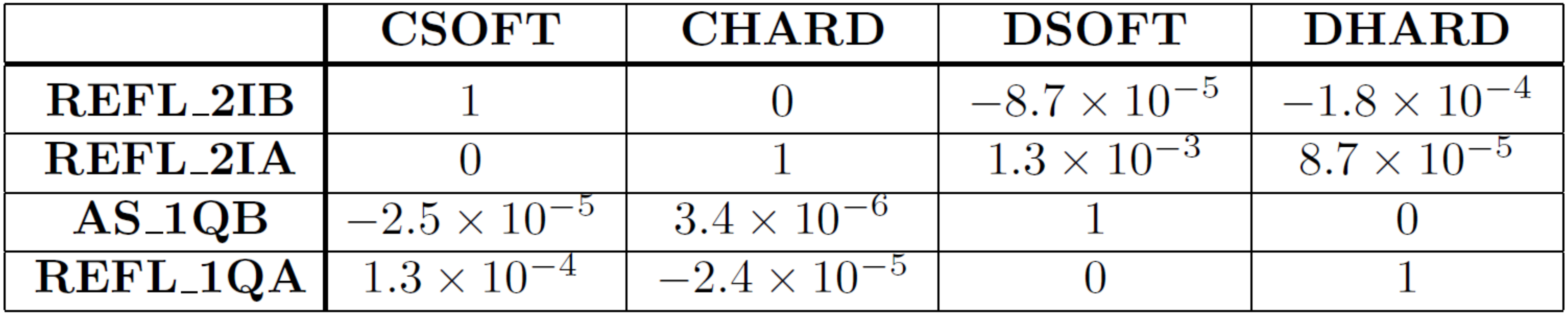
iLCGT Sensing Matrices

LSC



	DARM	CARM	MICH
AS_1I	1	1.7×10^{-3}	1.0×10^{-3}
REFL_1I	8.8×10^{-3}	1	1.3×10^{-4}
REFL_1Q	4.5×10^{-3}	5.5×10^{-5}	1

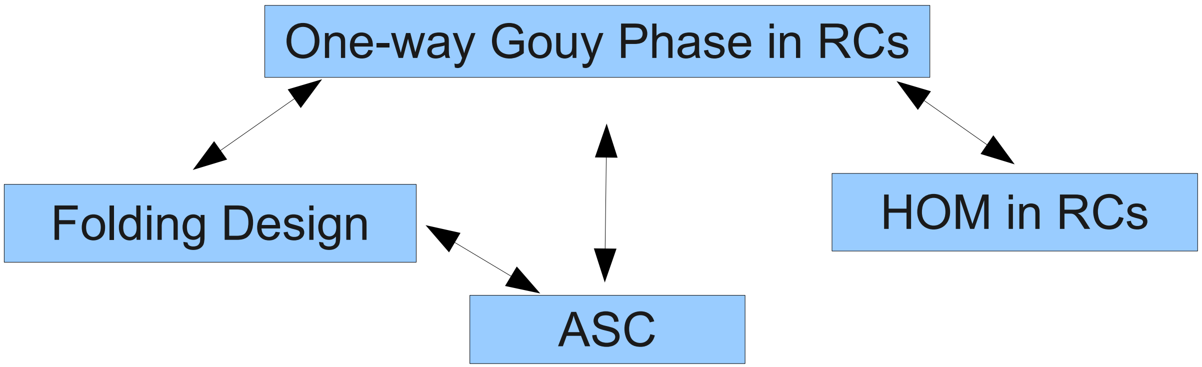
ASC (Diagonalized)



	CSOFT	CHARD	DSOFT	DHARD
REFL_2IB	1	0	-8.7×10^{-5}	-1.8×10^{-4}
REFL_2IA	0	1	1.3×10^{-3}	8.7×10^{-5}
AS_1QB	-2.5×10^{-5}	3.4×10^{-6}	1	0
REFL_1QA	1.3×10^{-4}	-2.4×10^{-5}	0	1

What to do next ?

ASC and Folding Optimization


One-way Gouy Phase in RCs

Folding Design

HOM in RCs

ASC

Technical Noise Couplings

- Laser Noise (frequency, intensity)
- Modulator phase noise
- Actuator noise (hierarchical control)
- PD noise
- etc ....

→ Requirements to other subsystems

OMC Design (together with the IOO group)

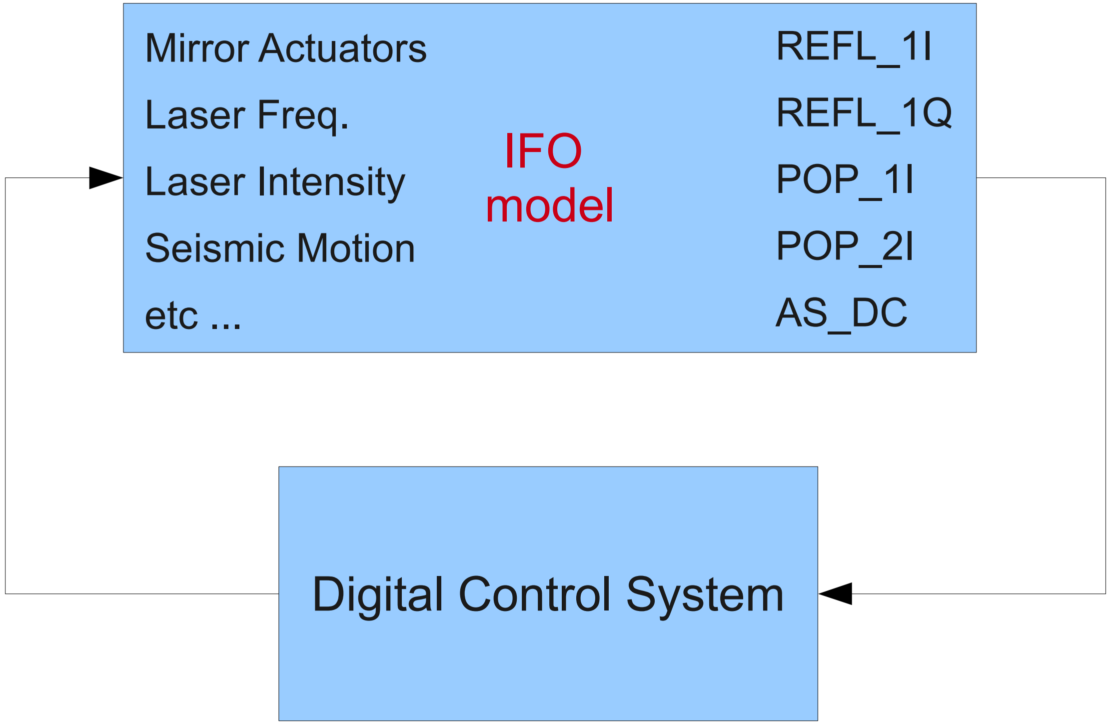
- Requirements (HOM reduction ratio)
- Control Schemes
- Prototype test

Simulated IFO plant

- Expedite the commissioning
- Make effective use of tunnel excavation & vacuum installation period (2 years)

Develop a computer model of the IFO

- Connected to the digital control system
- Develop the LSC & ASC digital servo system before actual interferometer is available
- Once real interferometer is installed, use the pre-developed servo system



Linear Model

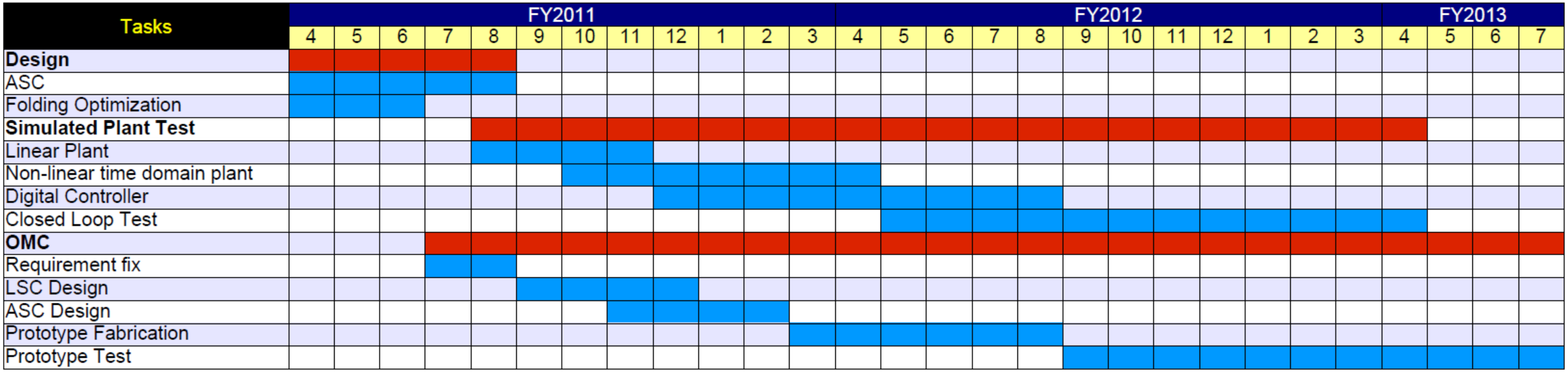
Model Generation: Optickle
Implementation: Digital System

Non-Linear Model

Time-domain simulation: e2e
Non-realtime
Simulate lock acquisition etc..

Schedule

During the construction period



Tasks	FY2011												FY2012												FY2013			
	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
Design	🟥	🟥	🟥	🟥	🟥																							
ASC	🟦	🟦	🟦	🟦	🟦																							
Folding Optimization	🟦	🟦	🟦																									
Simulated Plant Test					🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
Linear Plant					🟦	🟦	🟦	🟦																				
Non-linear time domain plant							🟦	🟦	🟦	🟦	🟦	🟦	🟦															
Digital Controller									🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦											
Closed Loop Test														🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
OMC				🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Requirement fix				🟦	🟦																							
LSC Design						🟦	🟦	🟦	🟦																			
ASC Design								🟦	🟦	🟦	🟦																	
Prototype Fabrication												🟦	🟦	🟦	🟦	🟦	🟦											
Prototype Test																		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

Schedule

Commissioning Period

Tasks	FY2013								FY2014												FY2015											
	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
FPMI	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥																		
X-arm	🟦	🟦	🟦	🟦	🟦																											
Y-arm				🟦	🟦	🟦	🟦																									
MI							🟦	🟦	🟦																							
FPMI										🟦	🟦	🟦	🟦																			
Noise hunting												🟦	🟦																			
Observation														🟦																		
RSE1															🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥									
Preparation															🟦	🟦	🟦															
DRMI																		🟦	🟦													
PRFPMI																				🟦	🟦											
RSE																					🟦	🟦										
Observation																							🟦									
RSE2																								🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
VIS Upgrade																								🟦	🟦	🟦	🟦	🟦	🟦			
RSE																														🟦	🟦	
Observation																																🟦

Tasks	FY2016												FY2017											
	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
CRSE	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥												
Installation of Cryogenic System	🟦	🟦	🟦	🟦	🟦	🟦	🟦																	
Single Arm Tests								🟦	🟦															
FPMI										🟦														
RSE											🟦													
Noise hunting												🟦												
Observation													🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Noise Hunting														🟦			🟦				🟦			

Risks

- Arm loss may be higher --> PRC becomes under coupled
  - Prepare several PRMs with slightly different reflecvitities

- Arm loss may be smaller
  - Shot noise increase of the DDM signals

- HD phase depends on the amount of reflectivity mismatch between the arms
  - DARM offset may have to be very large
  - HD phase may be almost 90 deg.

- SRC detuning by offset

- PR3 ROC error
  - Leave room for moving PRM, PR2, PR3, SRM, SR2 and SR3

- ASC design
  - How to control the folded PRC/SRC ?

- OMC design
  - Control Schemes

Summary

Interferometer Design (bLCGT)

- RSE interferometer
- Variable BRSE/DRSE
- 66m folded recycling cavities

Interferometer Design (iLCGT)

- Fabry-Perot Michelson
- No Recycling

Length Control Scheme

- 16.875MHz-45MHz PM, Single demodulation
- Optional Non-Resonant Sideband

Alignment Sensing Scheme

- WFS & Optical Lever
- Needs more study

Lock Acquisition

- Green laser pre-lock
- Third harmonics demodulation or NRS

TO DO

- Alignment Sensing Schemes
- Folding design optimization
- OMC design
- Technical noise couplings
- Simulated IFO plant