LCGT LSC Design
and other practical interferometer details

Yoichi Aso
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Basic Ideas behind the LSC scheme of LCGT

DOFs to be controlled: DARM, CARM, MICH, PRCL, SRCL

- Signals are extracted using the beat between the carrier and RF sidebands except for DARM (DC readout).

- CARM is sensed at REFL by the beat between the carrier, which sees the arm cavity and one of the RF sidebands, which are insensitive to the arms. This signal is usually huge.

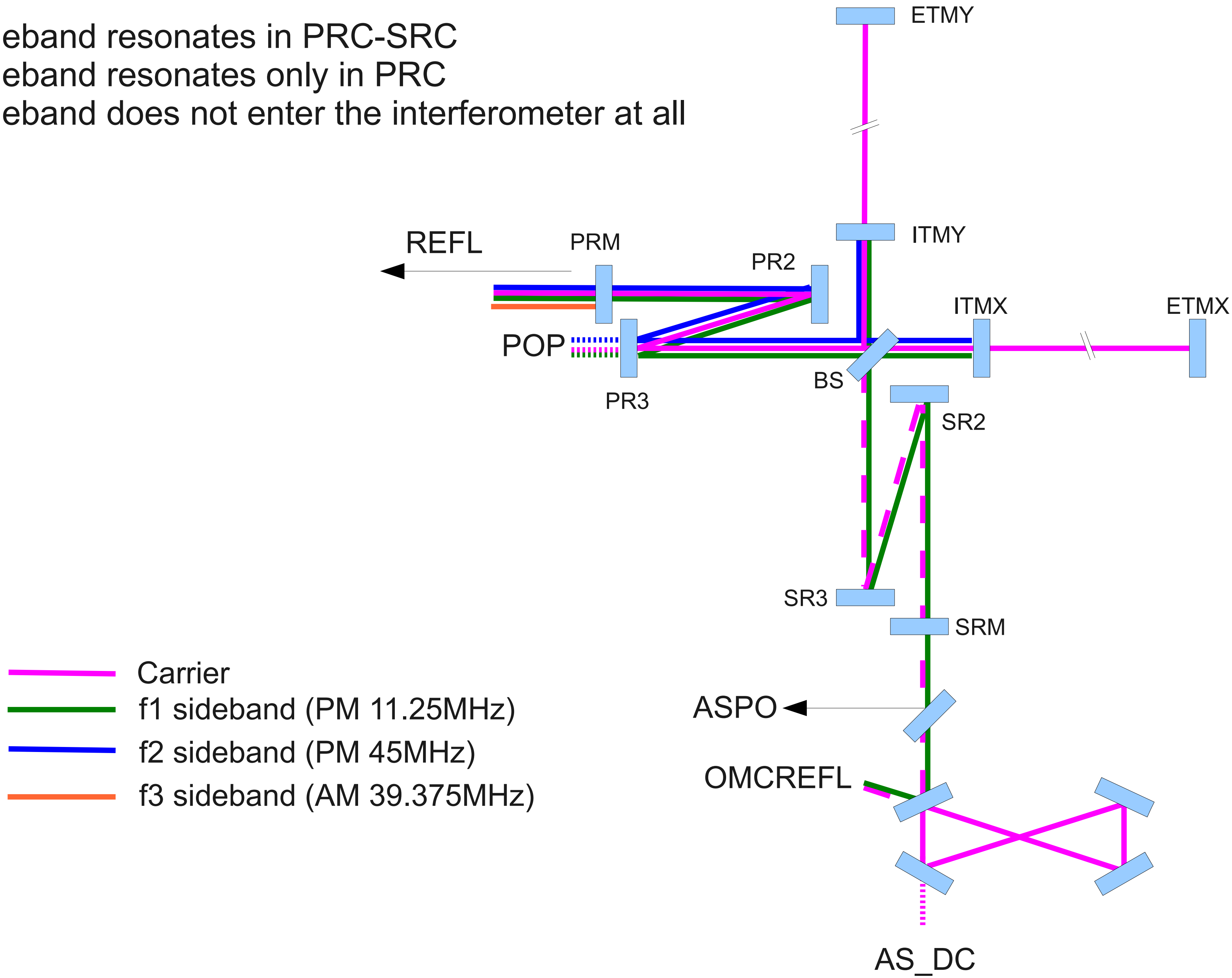
- Two RF sidebands are resonated in the PRC and SRC in different ways:
  - One sideband, called f2, is perfectly reflected by the MICH so that it sees only PRC.
  - The other sideband (f1) resonates in the coupled PRC-SRC cavity. So it carries both the information of PRC and SRC.
  - These two sidebands are PM so that these can be used for WFS.

- Additional sideband, which is non-resonant to the PRC, can be used to provide a local oscillator for the PRC, SRC, MICH sensing. This sideband is AM.

- MICH signal is generated in the Q-phase by the imbalance of the upper and lower sidebands of f1 beating against the carrier or the non-resonant sideband.

Sideband Resonant Conditions and Signal Ports

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



Macroscopic Length and modulation frequencies

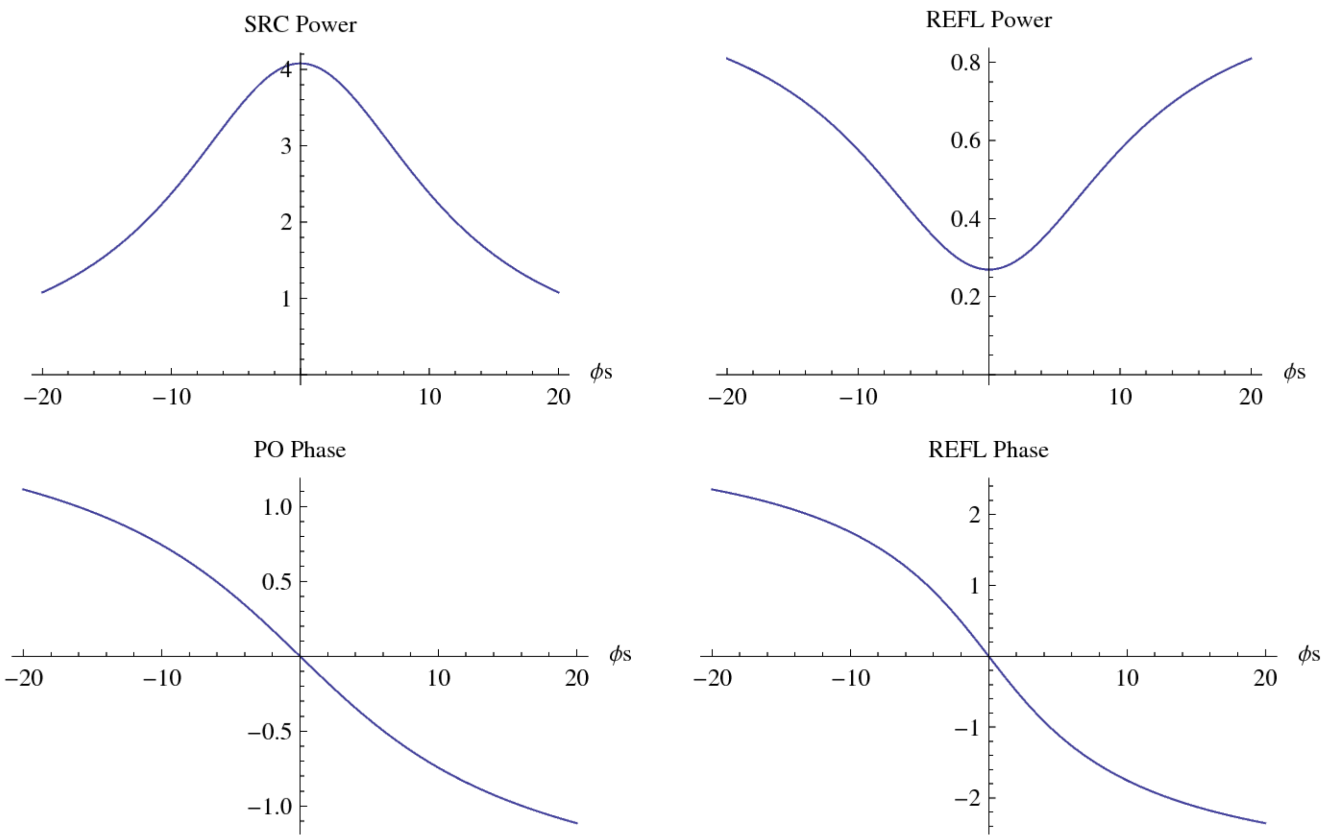
Important requirement: The SRC finesse for f1 has to be moderate.
--> Allow 3.5deg detuning of SRC.

The MICH reflectivity for f1 has to be close to PRM reflectivity to make the combined mirror of PRM+MICH has a low reflectivity.

- f2 frequency was chosen to be not too high but not too low.
  --> 45MHz
- MICH asymmetry (Las) was set to perfectly reflect the f2 sidebands.
  --> 3.33m (smallest possible)
- PRC length (Lp) is chosen to make f2 resonant in the PRC.
  - There are actually many choices for Lp. We preferred to make it about 80m.
  - 25m is taken by the cold pipe for radiation shield between BS and ITMs.
  - The rest is for folding.

  --> 73.2826m
- f1 frequency is chosen to be resonant in the PRC and also to have an appropriate MICH reflectivity. Also, the MC FSR has to be small enough to make the MC length practical.
  --> 11.25MHz (f2/4).
- SRC length (Ls) is chosen to make f1 resonant in the PRC-SRC coupled cavity.
  - We also want to make this about 80m for the same reasons for Lp.
    --> 73.2826m

Resonance curves of f1 sideband to the SRC



Signal Extraction Scheme

Optickle Simulation

Optickle: A frequency domain simulation tool for interferometers (by M. Evans)

It can ...
- Generate optical gain transfer functions from optics to signal ports.
- DC offset at each port.
- Quantum noise (shot noise and radiation pressure noise).
- Incorporate mechanical TFs of optics.

A New Optickle Model of LCGT

- Full LCGT IFO including MZ, folding mirrors and OMC
- New version of Optickle
  - Vacuum fluctuations are injected automatically at every open or lossy port.
- Loop noise calculation.
- Displacement noise coupling

All Optickle simulations are done with ...
- Up to 3rd order harmonics of RF sidebands included.
- 1% mirror reflectivity imbalance between the two arms.
- +/-10ppm arm loss imbalance.

Move from AM-PM to PM-PM scheme

Original Scheme:
f1: AM, f2: PM

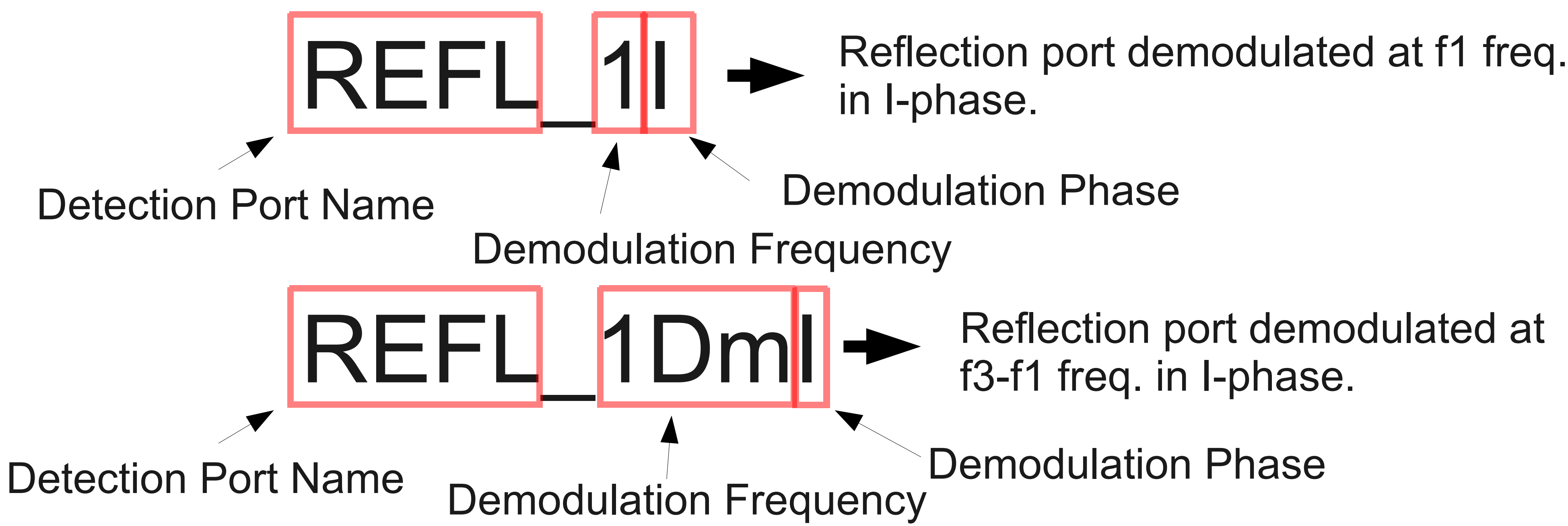
- f1 is the only available sideband at the AS port
- However, it is AM. Not good for WFS.
- No RF DARM available.

WFS and AM

- WFS signal can be obtained using AM sidebands
  - Gouy phase difference between TEM00(f1) and TEM01(carrier) transforms AM sidebands to PM at certain locations.
- However, residual TEM00 carrier creates strong beat against f1 TEM00.
- Any QPD mis-centering would see this residual beat.
- Using OMC REFL, we could in principle eliminate carrier TEM00
- This has a potential of contaminating the WFS signal with the OMC alignment noise

Signal Ports and Naming Convention

How to decipher a signal name ?



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

DC Power at each port

REFL: ~ 200mW
AS: ~ 10mW
POP: ~ 400mW

CARM, PRCL, SRCL

These signals are mixed

- CARM signal can be extracted from the beat between the carrier and the f1 or f2 sidebands at the REFL port.
- PRCL and SRCL information is also embedded in the same signal.
  - PRCL is obtained from f2 demodulation, which contains no SRCL information.
  - f1 demodulation is a mixture of SRCL, PRCL and CARM

How do we solve the signal mixing problem ?

Gain Hierarchy: iLIGO and aLIGO way

- CARM feedback is much faster than any other DOFs because we can use the laser frequency actuators. (UGF ~ 50kHz).
- Therefore, we can expect a good suppression of CARM signal at UGFs of PRCL and SRCL (~100Hz).

Examples of signal extraction ports

CARM: REFL_2I
PRCL: POP_2I
SRCL: POP_1I

Sensing Matrix with Single Demodulation
(BRSE, measured at 100Hz)

Sensing Matrix [W/m]

	DARM	CARM	MICH	PRC	SRC
REFL_2DmQ	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00
REFL_2DmI	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00
REFL_1DmQ	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00
REFL_1DmI	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00
POP_2Q	6.1e+03	1.1e+06	7.6e+01	2.5e+03	1.6e+01
POP_2I	3.9e+05	7.0e+07	1.7e+05	1.6e+07	5.0e+03
POP_1Q	2.1e+03	3.3e+03	4.3e+05	6.4e+05	1.0e+05
POP_1I	3.0e+05	5.6e+07	7.8e+04	1.0e+07	1.8e+06
REFL_1Q	1.4e+03	4.9e+03	3.4e+05	1.7e+06	3.5e+05
REFL_1I	1.2e+07	2.1e+09	2.0e+05	7.2e+06	2.8e+06
REFL_2Q	1.0e+02	2.0e+03	2.1e+03	2.9e+05	2.6e+04
REFL_2I	2.1e+07	3.7e+09	2.6e+05	5.1e+06	1.0e+06
ASPO_1Q	2.2e+00	5.5e+01	1.2e+02	7.7e+03	3.5e+03
ASPO_1I	4.7e+08	1.1e+05	4.8e+05	2.1e+04	1.3e+04
AS_DC	1.3e+10	5.6e+05	1.4e+07	6.3e+04	3.0e+05

Alternative: Non-Resonant Sidebands (NRS)

- CARM signal is mixed with PRCL and SRCL because we used the carrier for signal generation.
- If we use a sideband which does not enter the interferometer at all as a local oscillator for f1 and f2, PRCL and SRCL can be

Now MC length is doubled. FSR is 11.25/2.
We can use,
f3: AM at 39.375MHz

This should in principle be insensitive to any arm motion.

No it is not unless we use Mach Zehnder.

Serial Modulation

Generates sidebands of sidebands (sub-sidebands)

For example, (f3-f2) sub-sidebands beating against the carrier create some signal of CARM at the (f3 - f2) frequency.

Sensing Matrix with NRS
(BRSE, no MZ, measured at 100Hz)

Signals are still mixed
(but a bit less)

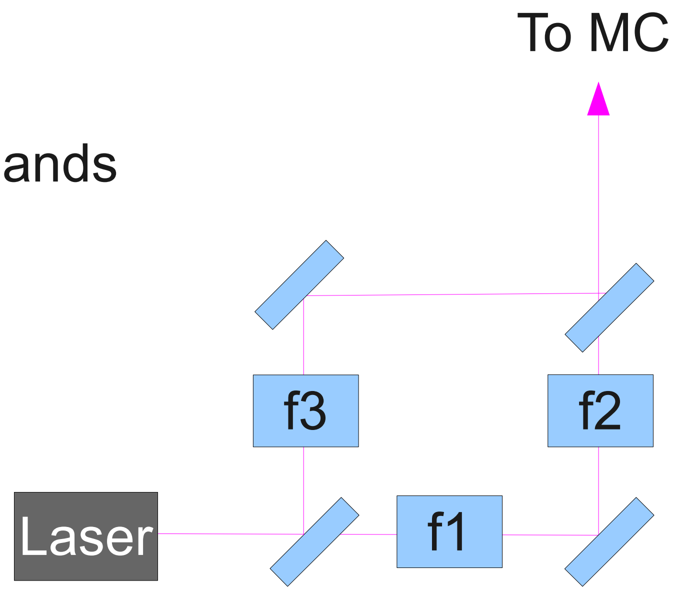
Sensing Matrix [W/m]

	DARM	CARM	MICH	PRC	SRC
REFL_2DmQ	1.3e+05	2.4e+07	7.9e+03	2.0e+05	5.9e+03
REFL_2DmI	1.0e+06	1.9e+08	9.3e+05	8.6e+07	2.7e+04
REFL_1DmQ	2.0e+05	3.5e+07	2.2e+06	5.3e+05	5.2e+03
REFL_1DmI	1.0e+06	1.9e+08	5.7e+05	5.3e+07	9.3e+06
POP_2Q	6.1e+03	1.1e+06	7.7e+01	2.5e+03	1.6e+01
POP_2I	3.8e+05	7.0e+07	1.7e+05	1.6e+07	4.9e+03
POP_1Q	2.1e+03	3.3e+03	4.3e+05	6.4e+05	1.0e+05
POP_1I	3.0e+05	5.5e+07	7.8e+04	1.0e+07	1.8e+06
REFL_1Q	1.4e+03	4.8e+03	3.3e+05	1.7e+06	3.5e+05
REFL_1I	1.2e+07	2.1e+09	2.0e+05	7.2e+06	2.8e+06
REFL_2Q	1.0e+02	2.0e+03	2.3e+03	2.9e+05	2.6e+04
REFL_2I	2.0e+07	3.7e+09	2.6e+05	5.1e+06	1.0e+06
ASPO_1Q	2.2e+00	5.5e+01	1.2e+02	7.7e+03	3.5e+03
ASPO_1I	4.7e+08	1.1e+05	4.8e+05	2.1e+04	1.3e+04
AS_DC	1.3e+10	5.5e+05	1.3e+07	6.3e+04	3.0e+05

Mach Zehnder

Pros:
- Able to avoid generation of sub-sidebands
- Cleaner signal separation

Cons:
- Waste half of the sideband power
- Additional phase noise



Sensing Matrix with NRS
(BRSE, with MZ, measured at 100Hz)

Clean signal separation

Sensing Matrix [W/m]

	DARM	CARM	MICH	PRC	SRC
REFL_2DmQ	1.0e+02	1.1e+01	1.8e+03	4.0e+03	1.3e+03
REFL_2DmI	5.5e+03	4.8e+04	4.7e+05	4.4e+07	4.2e+03
REFL_1DmQ	5.0e+03	1.8e+03	1.1e+06	1.9e+04	1.7e+03
REFL_1DmI	1.2e+04	1.4e+05	2.9e+05	2.7e+07	4.7e+06
POP_2Q	3.1e+03	5.6e+05	3.8e+01	1.3e+03	4.1e+00
POP_2I	1.9e+05	3.5e+07	8.5e+04	8.2e+06	1.2e+03
POP_1Q	1.1e+03	1.7e+03	2.2e+05	3.2e+05	5.3e+04
POP_1I	1.5e+05	2.8e+07	3.9e+04	5.0e+06	9.0e+05
REFL_1Q	1.7e+03	3.9e+03	4.2e+05	1.2e+06	2.3e+05
REFL_1I	1.2e+07	2.1e+09	1.8e+05	3.7e+06	2.5e+06
REFL_2Q	5.3e+01	1.3e+03	1.1e+03	1.5e+05	1.3e+04
REFL_2I	2.1e+07	3.7e+09	2.5e+05	3.4e+06	5.0e+05
ASPO_1Q	1.1e+02	1.6e+01	2.7e+02	2.2e+03	8.4e+02
ASPO_1I	2.4e+08	5.7e+04	2.4e+05	1.0e+04	6.9e+03
AS_DC	1.3e+10	5.6e+05	1.4e+07	6.3e+04	3.0e+05

Loop Noise

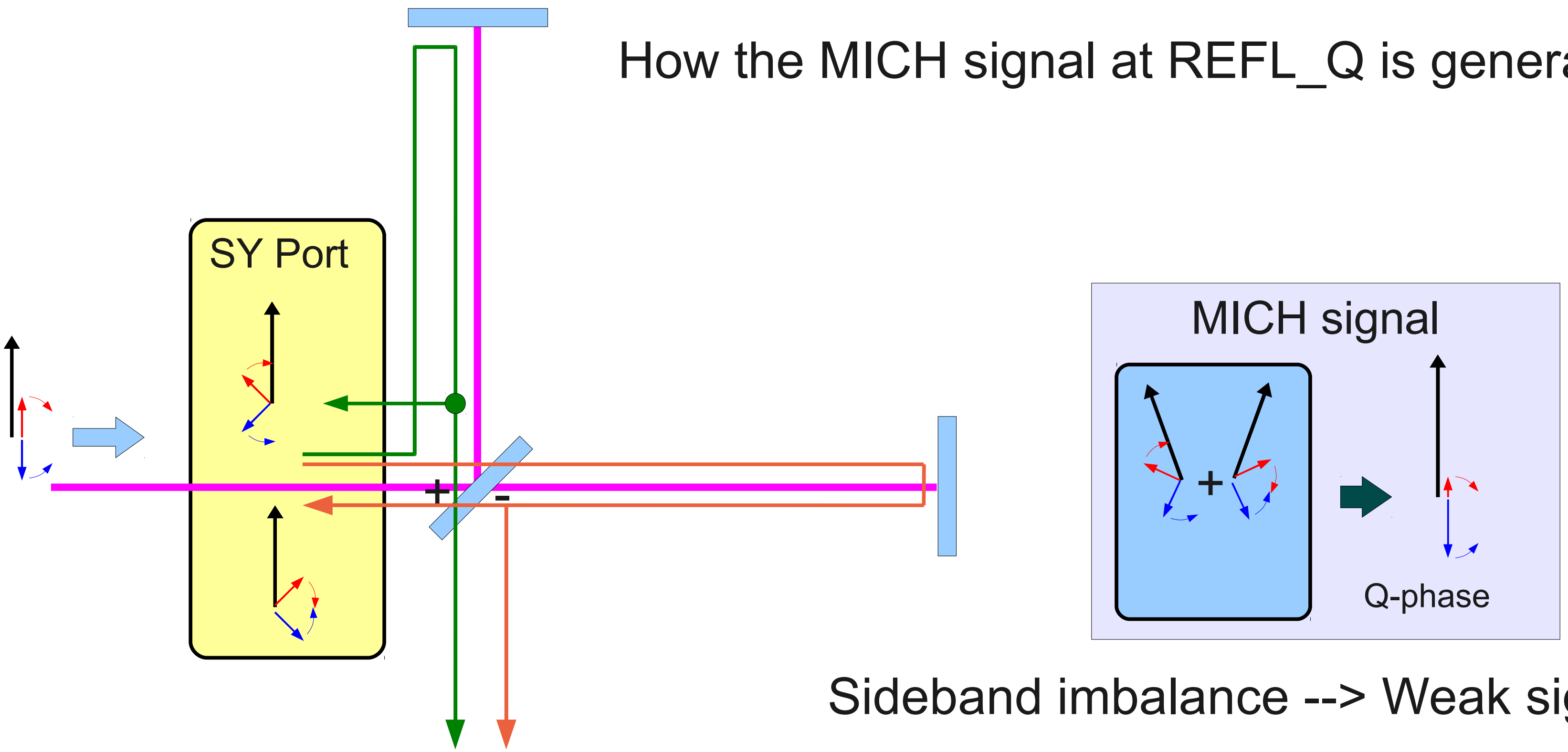
Shot Noise Coupling

So far, we've been concerned only with the signal separation ...

This is by no means sufficient.

- 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

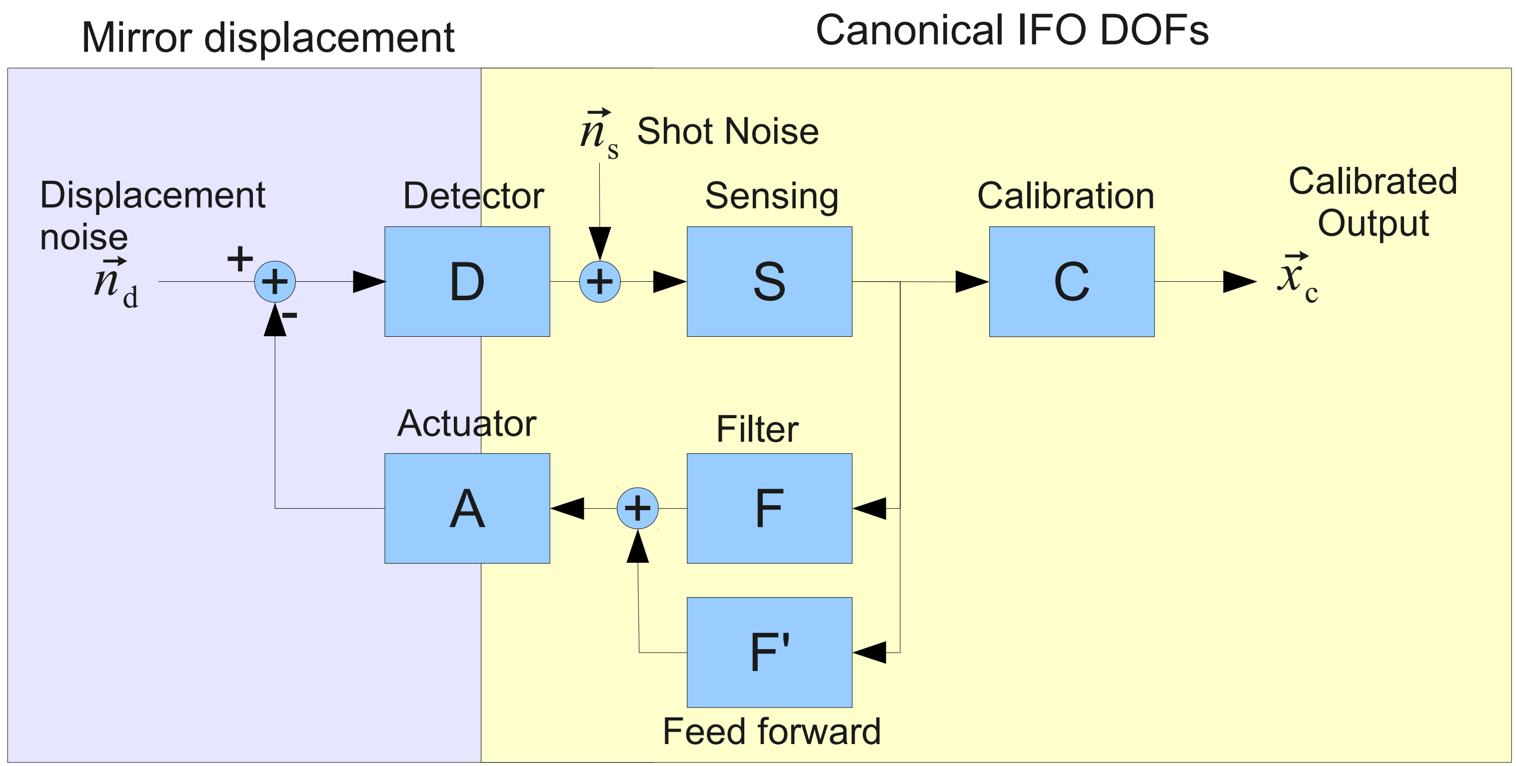
How the MICH signal at REFL_Q is generated ?



Sideband imbalance --> Weak signal

Loop Noise

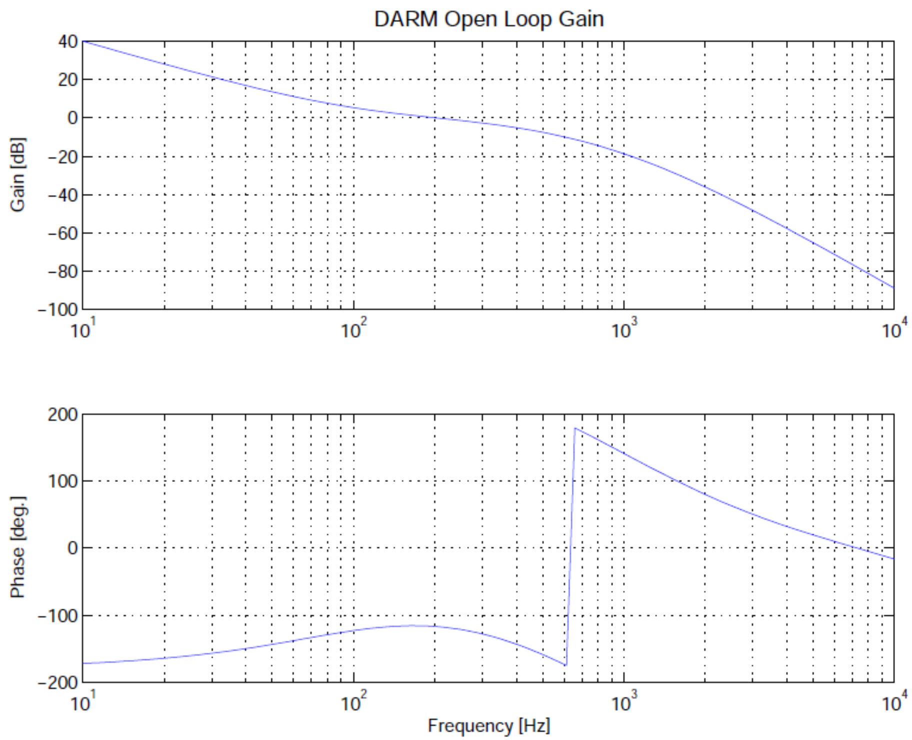
Formulation used here:

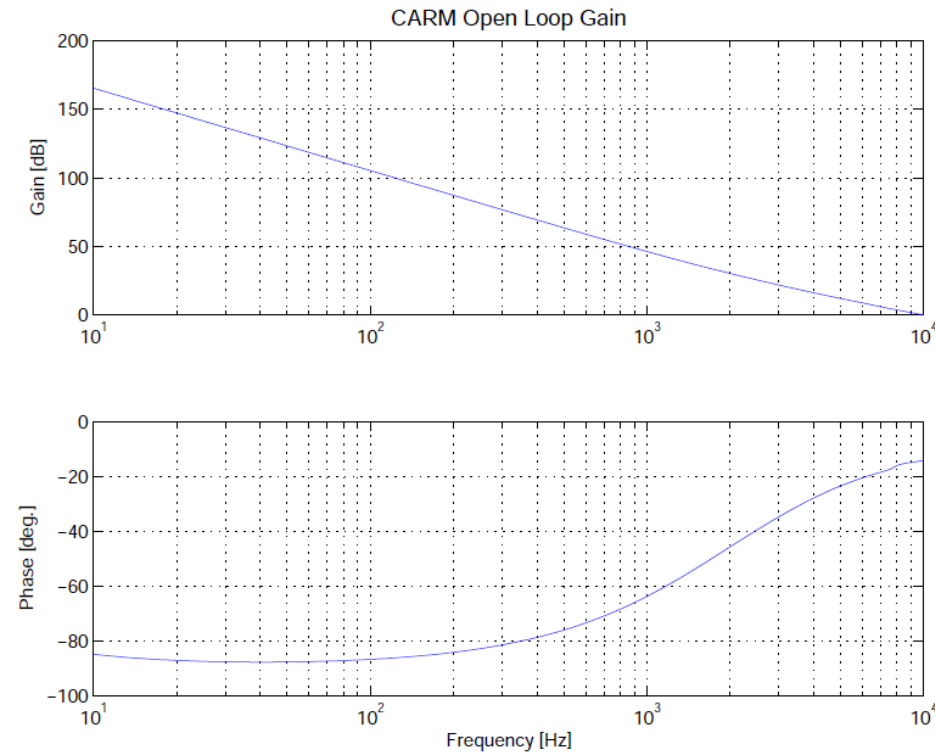


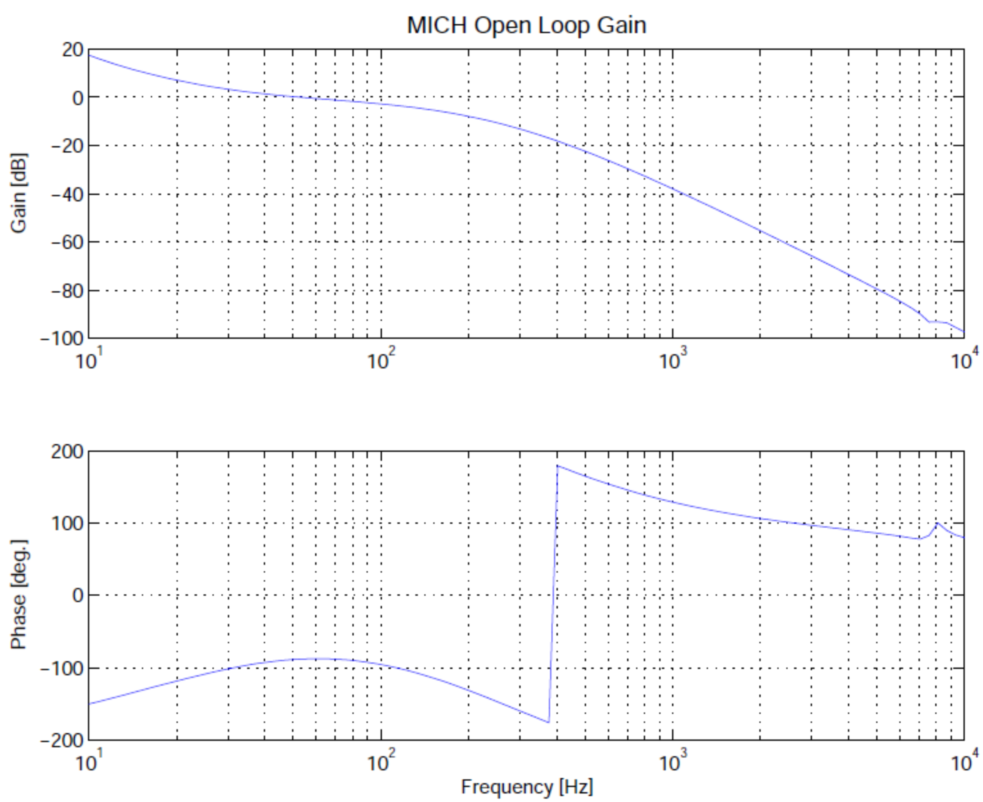
$$\vec{x}_c = (I+G)^{-1} \cdot S \cdot \vec{n}_s + (I+G)^{-1} \cdot SD \cdot \vec{n}_d$$

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

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)







Default UGFs

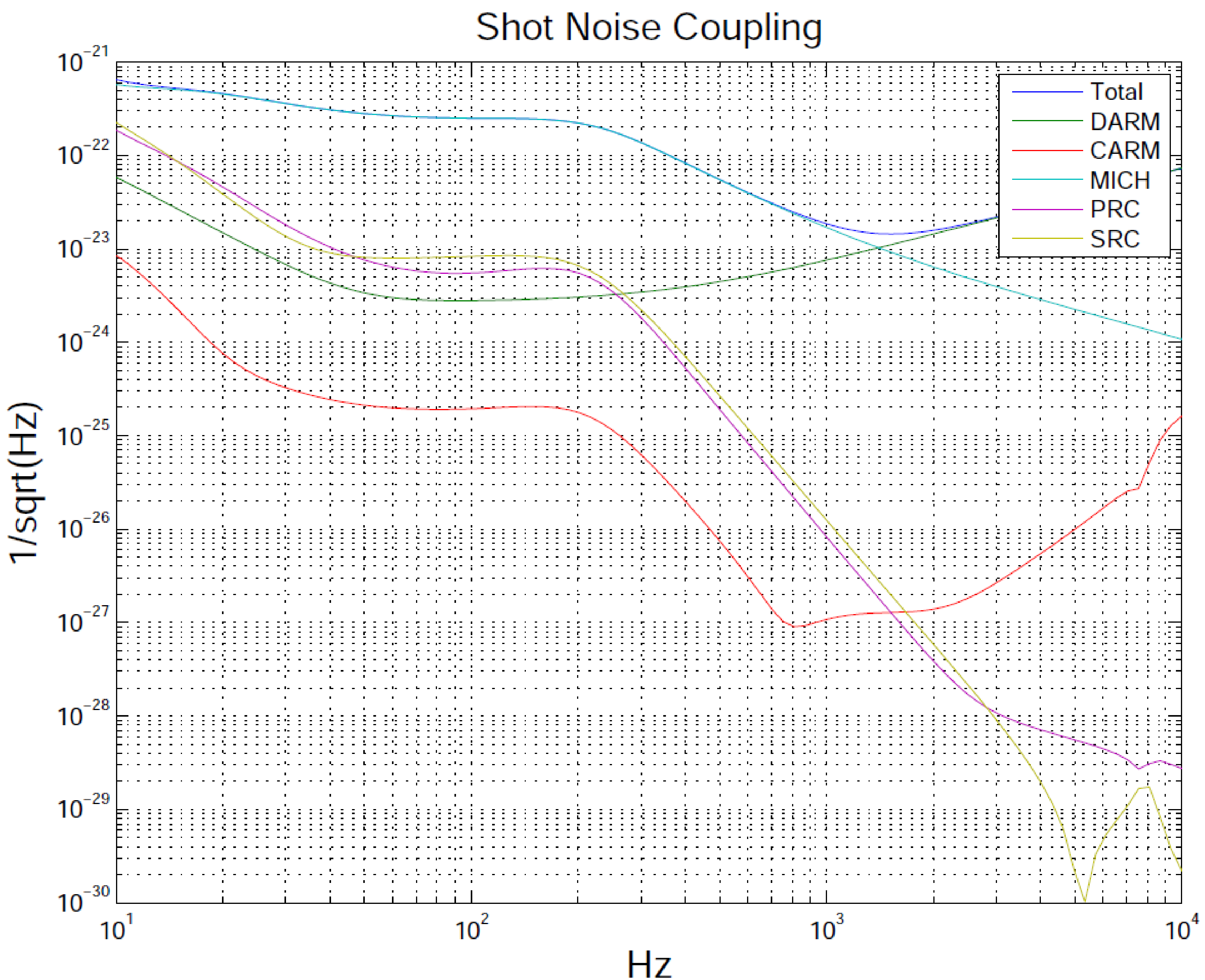
DARM: 200Hz
CARM: 10kHz
MICH: 50Hz
PRCL: 50Hz
SRCL: 50Hz

At Kamioka, we may be able to reduce them further (~10Hz ?)

Feed forward used for MICH and SRCL

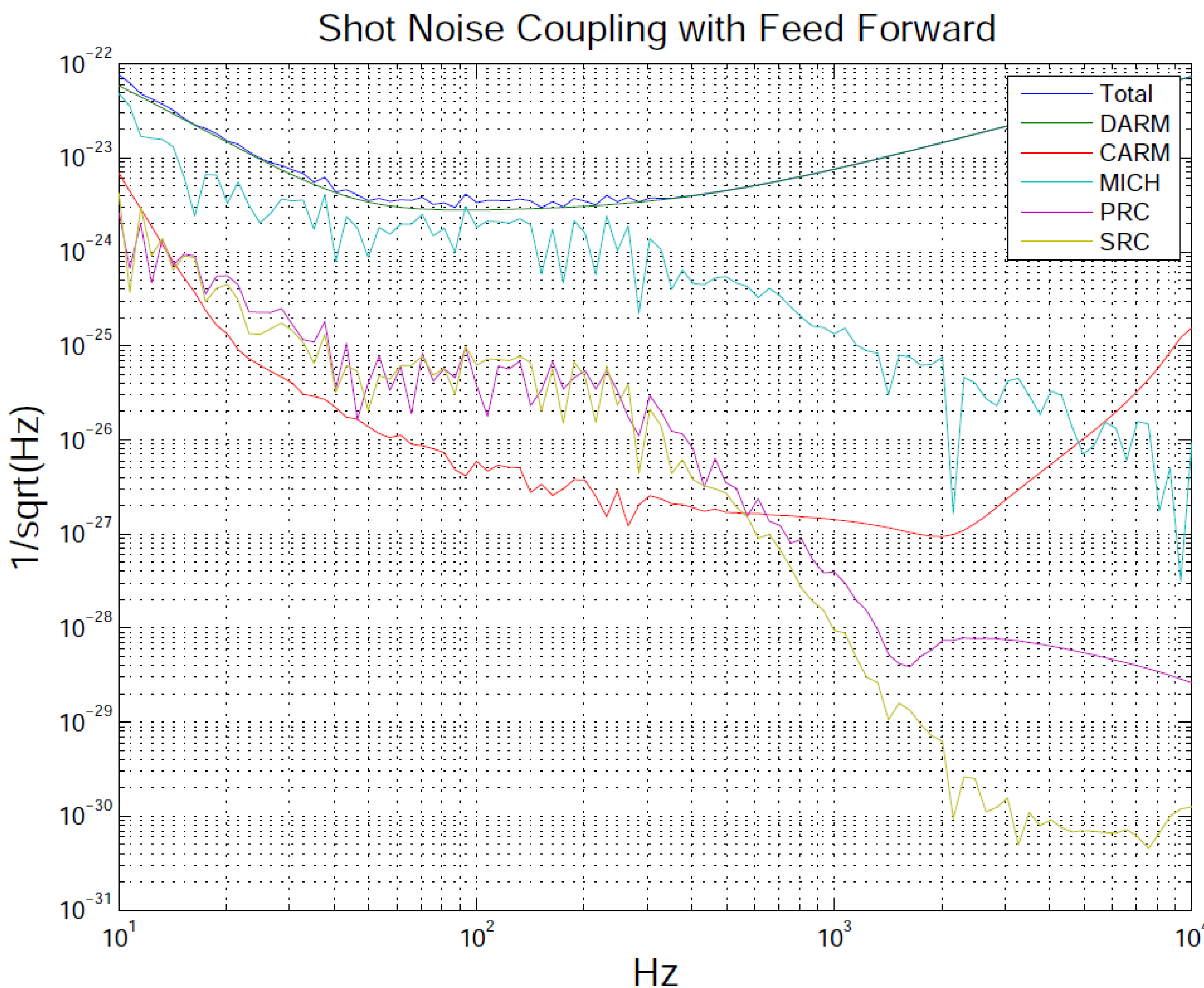
So, the shot noise coupling kills the sensitivity

BRSE, SDM, no feed forward



With the Feed Forward

Feed Forward TF error = 1% (random error added)



Other Configurations

BRSE DDM no MZ
MICH: REFL_1DmQ
PRCL: REFL_2DmI
SRCL: REFL_1DmI

BRSE DDM with MZ

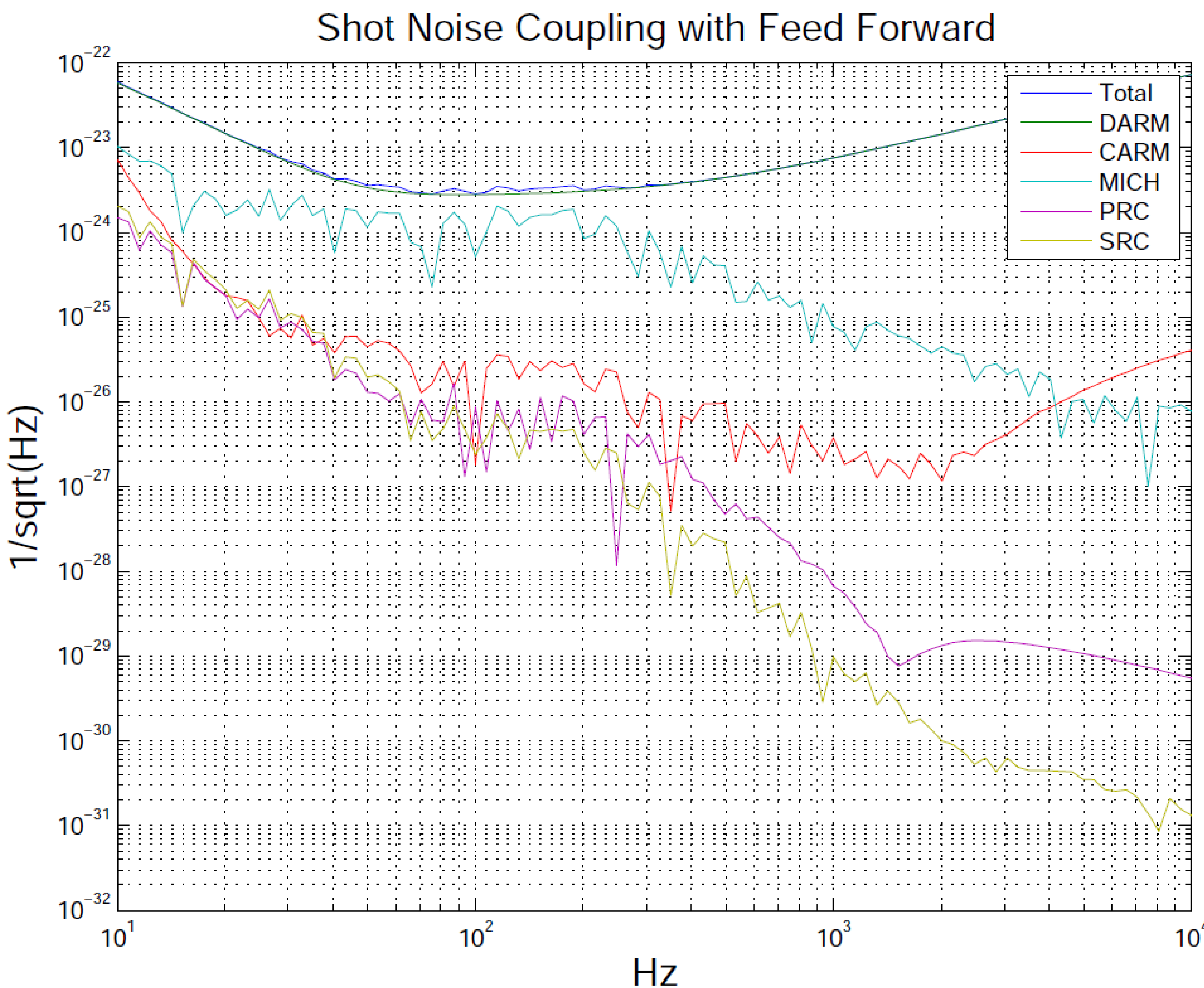
DRSE SDM

DRSE DDM no MZ

DRSE DDM with MZ

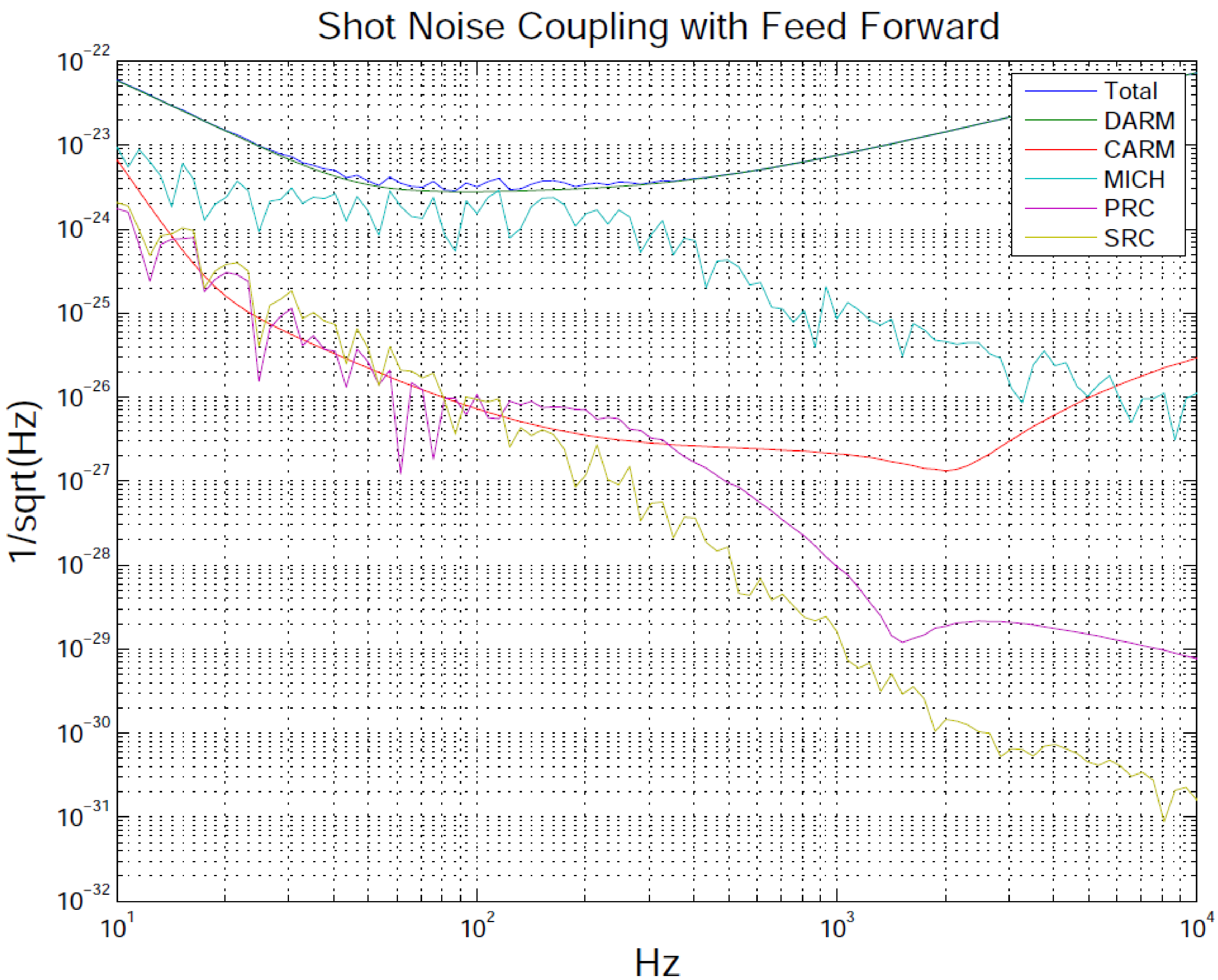
BRSE DDM no MZ

Feed forward accuracy = 3%



BRSE DDM with MZ

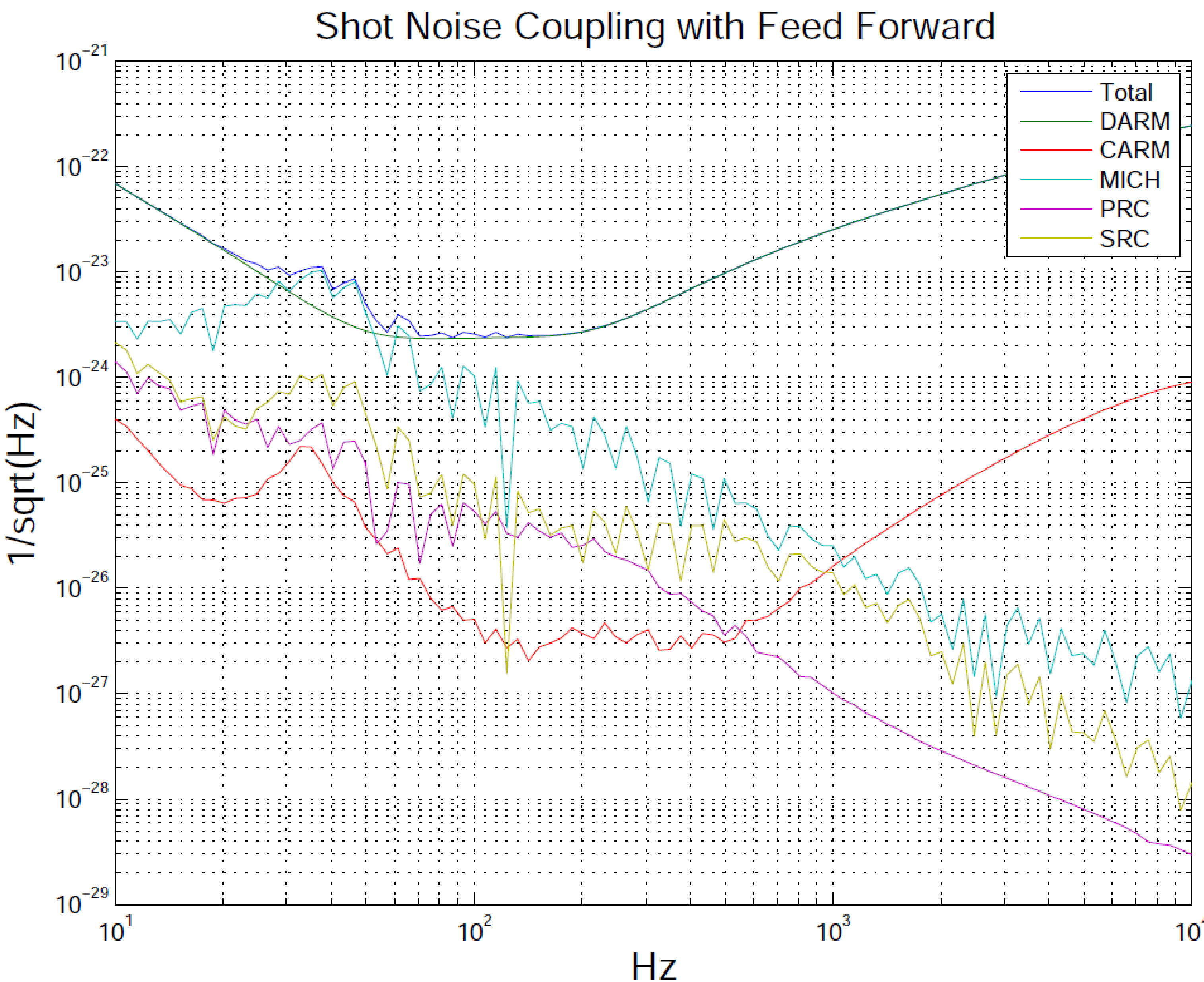
Feed forward accuracy = 3%



DRSE SDM

Feed forward accuracy = 1%

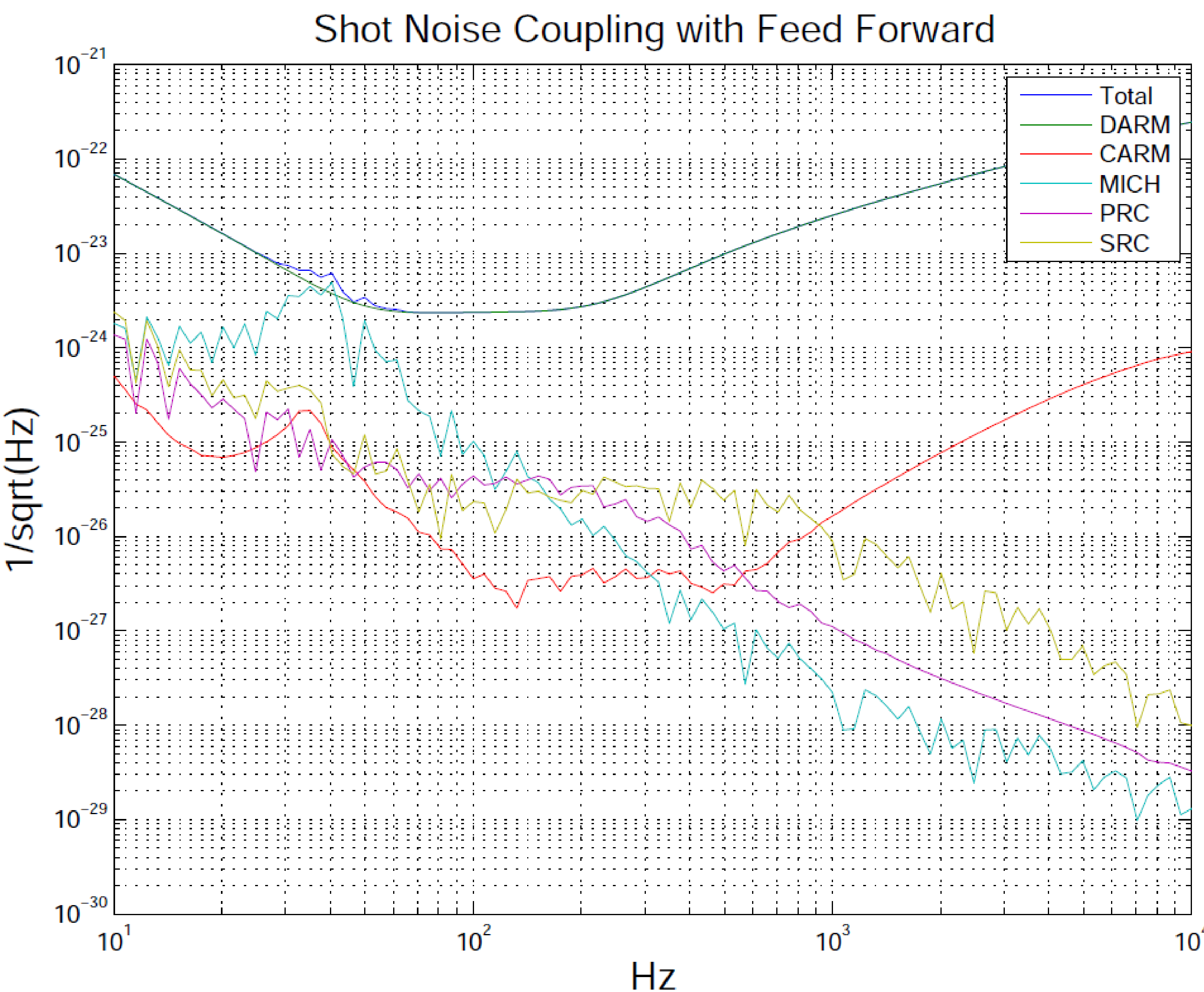
A large optical spring peak around 40Hz ruins the sensitivity



DRSE SDM

Feed forward accuracy = 1%

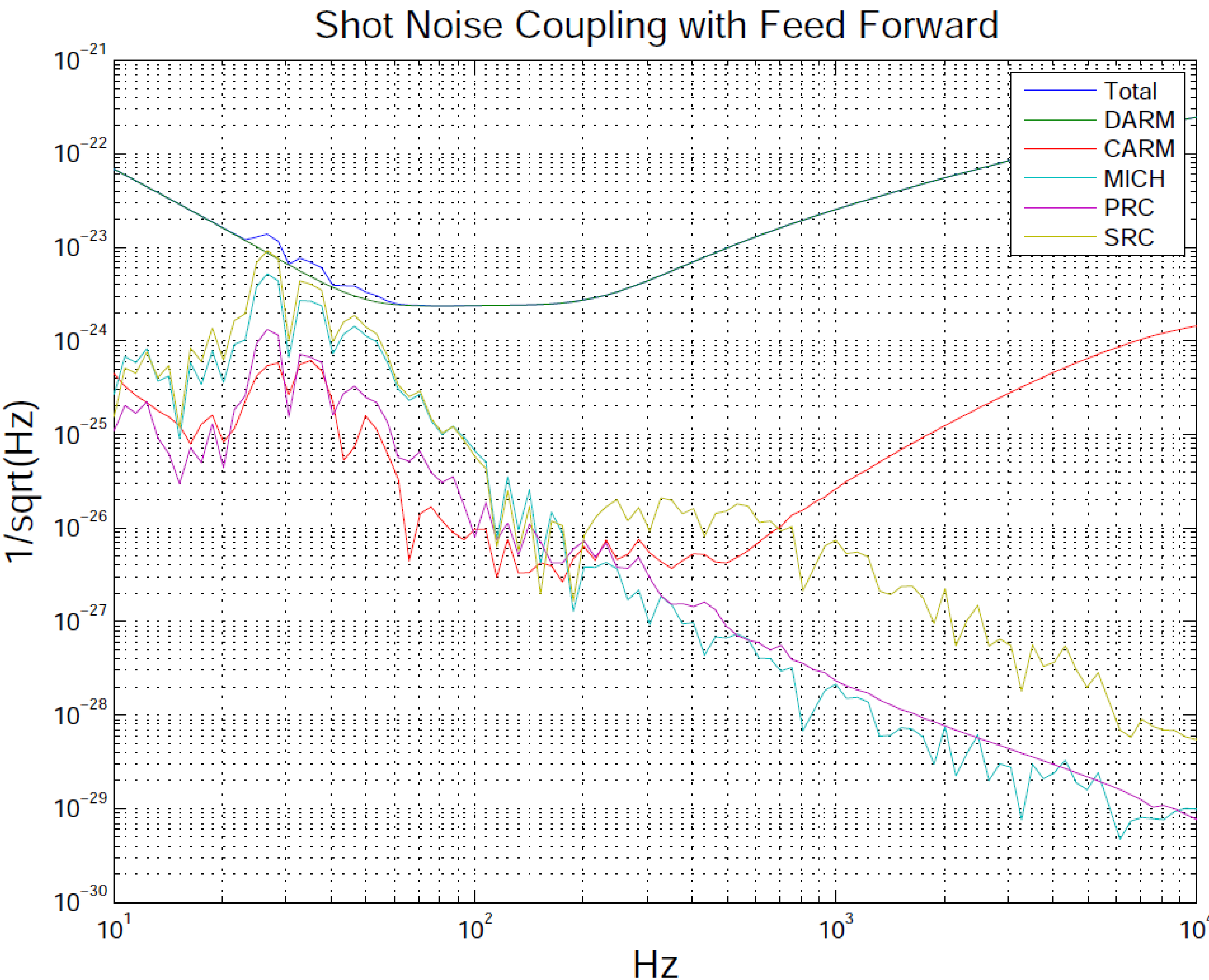
Reduced MICH UGF to 10Hz



DRSE DDM no MZ

Feed forward accuracy = 1%

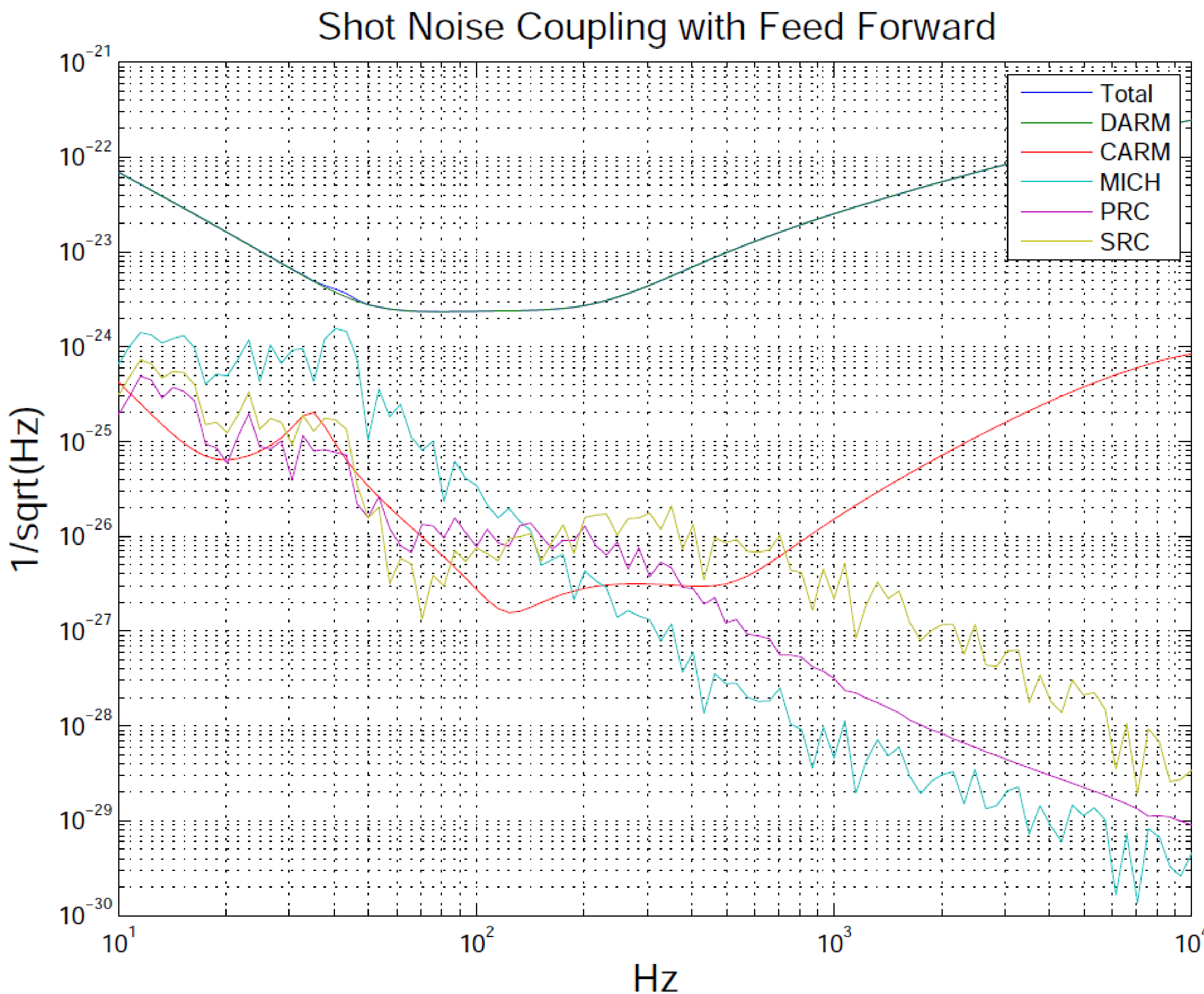
MICH UGF = 10Hz



DRSE DDM with MZ

Feed forward accuracy = 1%

MICH UGF = 10Hz



Check DC Offset

Offset amount in meters

	DARM	CARM	MICH	PRCL	SRCL
BRSE SDM	7.64e-13	7.17e-15	4.04e-12	7.49e-12	2.8e-11
BRSE DDM no MZ	7.64e-13	6.99e-15	3.74e-11	4.19e-11	1.9e-11
BRSE DDM with MZ	7.64e-13	7.28e-15	6.12e-13	7.17e-11	7.99e-14
DRSE SDM	7.64e-13	1.15e-14	4.96e-09	8.23e-12	1.22e-08
DRSE DDM no MZ	7.64e-13	1.15e-14	1.72e-09	3.48e-11	1.23e-08
DRSE with MZ	7.64e-13	1.08e-13	1.75e-09	8.01e-11	1.23e-08

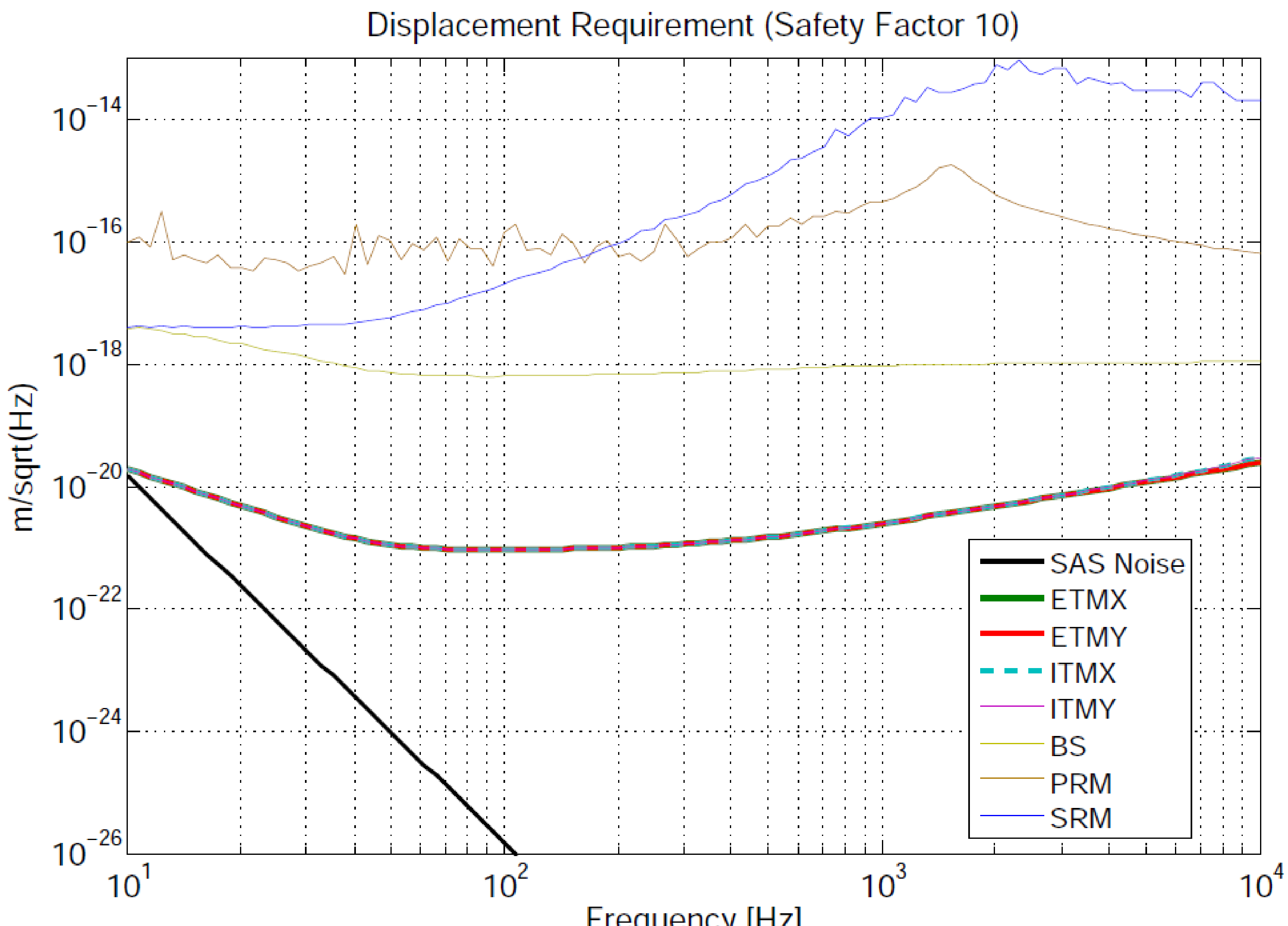
Problem ?

Caused by the f1 sideband rotation by the SRC detuning
(f1 no longer acts as pure PM but somewhere between AM and PM)

Displacement Noise Requirement

Feed forward increases displacement noise coupling from aux. mirrors to DARM

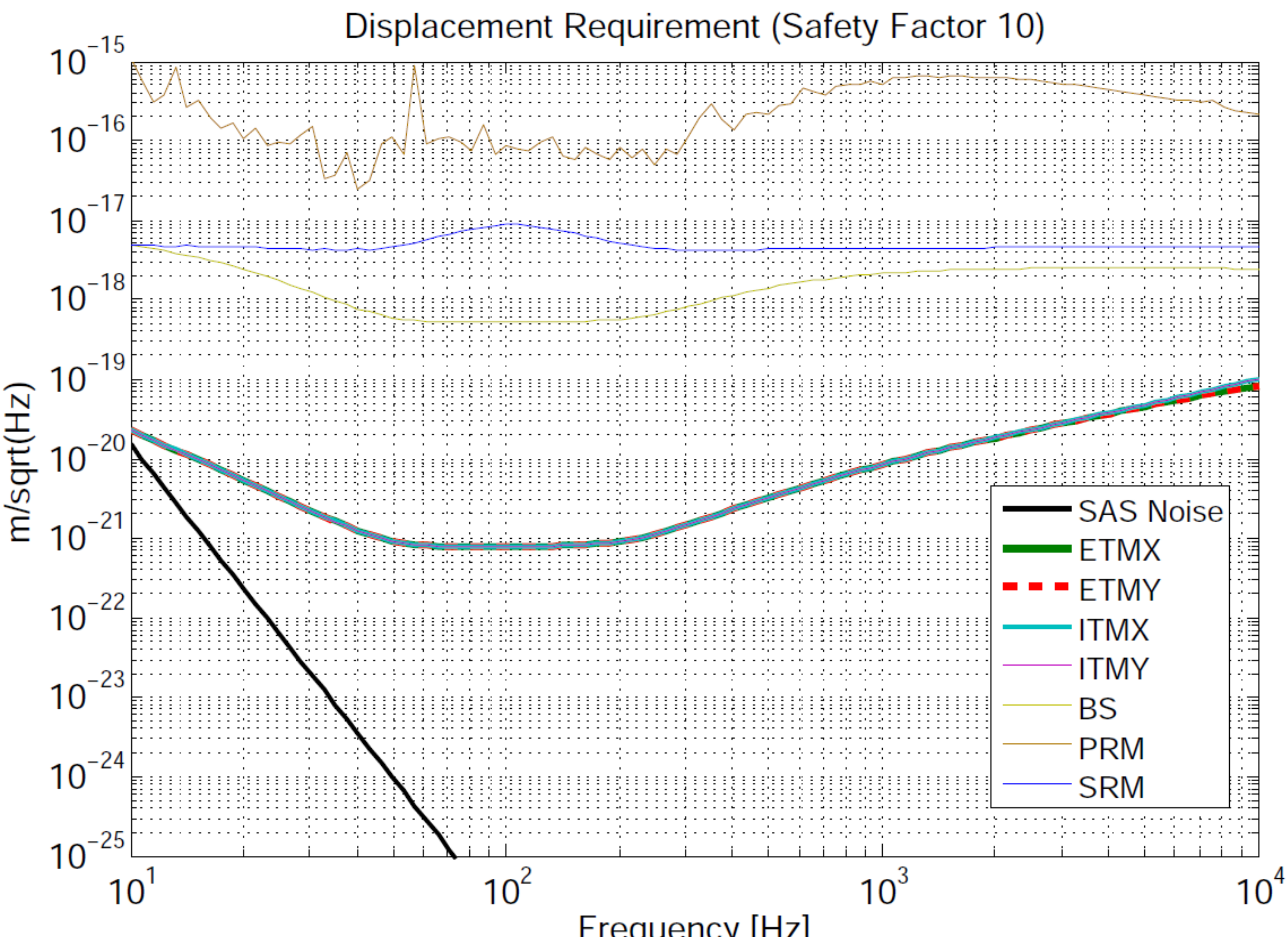
BRSE, no MZ, Feed Forward 3%



Displacement Noise Requirement

Feed forward increases displacement noise coupling from aux. mirrors to DARM

DRSE, no MZ, Feed Forward 1%, MICH UGF=10Hz



Summary of the Length Sensing Schemes

For BRSE, Non-Resonant Sideband Method without MZ seems OK.

- No MZ makes the setup simple and robust
- Moderate feed forward gain (30) is enough.
- MICH UGF can be as high as 50Hz.

For DRSE, Non-Resonant Sideband Method with MZ seems the best choice.

- MZ noise could be a problem.
- High feed forward gain (100) is required.
- MICH UGF has to be below 10Hz.
- A large MICH offset can be a problem.

We don't have to make a choice now !

- These sensing schemes can be switchable at a later time.
- No in vacuum work necessary to switch
- MZ <--> no-MZ change may require some work,
  but still doable on an optical bench.

Important thing is: There are schemes which seem to work.

Lock Acquisition

Lock Acquisition Procedure

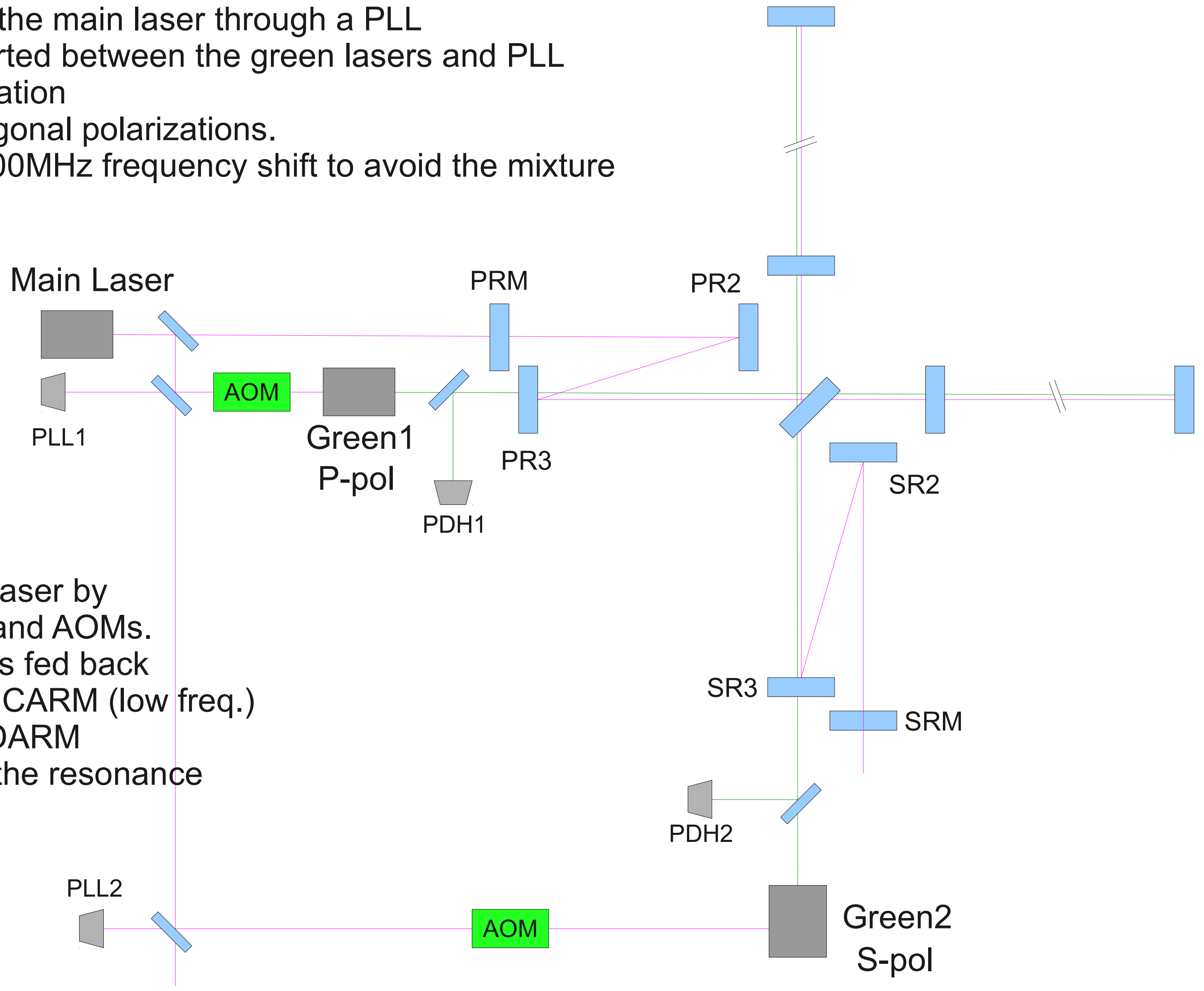
- First, lock the central part then lock the arms
- When the central part is locked, this lock should not be disturbed by the arms
- It is desirable to use signals insensitive to the arms
  - e.g. 3^{rd} Harmonics demodulation
- NRS DDM with MZ is insensitive to the arms
- Alternatively, the arms can be pre-locked to an aux. laser

The Default Plan for LCGT Lock Acquisition is Green Pre-Lock

Green Pre-Lock

Basic ideas for green laser lock

- Green Lasers are injected from PR3 for X-arm, and SR3 for Y-arm
- PR3, SR3 and BS are transparent to green.
- ITMs and ETMs are dichroic mirrors
- Each green laser is locked to the main laser through a PLL
- Additional AOM could be inserted between the green lasers and PLL to provide fast frequency actuation
- Two green beams have orthogonal polarizations.
- Optionally, they can have ~ 100MHz frequency shift to avoid the mixture of the signals from the arms.



Lock procedure

- Each arm is locked to the green laser by frequency feedback to the PLLs and AOMs.
- Common signal of the two arms is fed back to the main laser (high freq.) and CARM (low freq.)
- Differential signal is fed back to DARM
- Scan the PLL1 and PLL2 to find the resonance of the main laser

Mirror Requirements for Green

Several Dichroic Mirrors are necessary

Specs for 532nm

PR3: T>99%, Polarization: P
SR3: T>99%, Polarization: S
BS: T>99% for both Polarization
ITMX: R=80%, Polarization: P
ITMY: R=80%, Polarization: S
ETMX: R=90%, Polarization: P
ETMY: R=90%, Polarization: S

Arm finesse = 20

Injection Port Considerations

- At PR3, the beam size is large (3.5cm)
  - Requires either a large optical window or an in-vacuum telescope
- At PR2, the beam size is small. Much easier to handle.
- Probably we want to separate the output port for POP (large 1064nm leak) and the injection port for green.
- Dispersion between 1064nm and 532nm separates 1064nm and 532nm beams by 2mm on PR3. Not enough to separate beams.
- PR2 injection seems better because PR3 POP won't be contaminated by green.

Alignment Sensing and Control (ASC)

There are several ways to reduce alignment fluctuation

- Passive attenuation by the suspension system @ detection band.
- Optical Lever @ Resonant frequencies
- WFS @ DC and Resonant frequencies

- WFS senses the mismatch between the incident beam and the cavity axis.
- This is why WFS is used for DC.
- WFS does not guarantee beam centering. We may need something else.

WFS signals

Possible Detection Ports

DARM: AS
CARM: REFL
PRC: REFL_2D
SRC: REFL_1D

Optickle Simulation is needed.
We are working on it now...

Folding Cavity and Alignment Control

Straight RCs: Almost degenerated →
- Sideband Modes are Unstable
- GW sidebands can be reduced
- WFS signals may not make sense

↓

Increase the Gouy phase shift in the RCs → Focus the beam in the RCs

↓

Folding the RCs

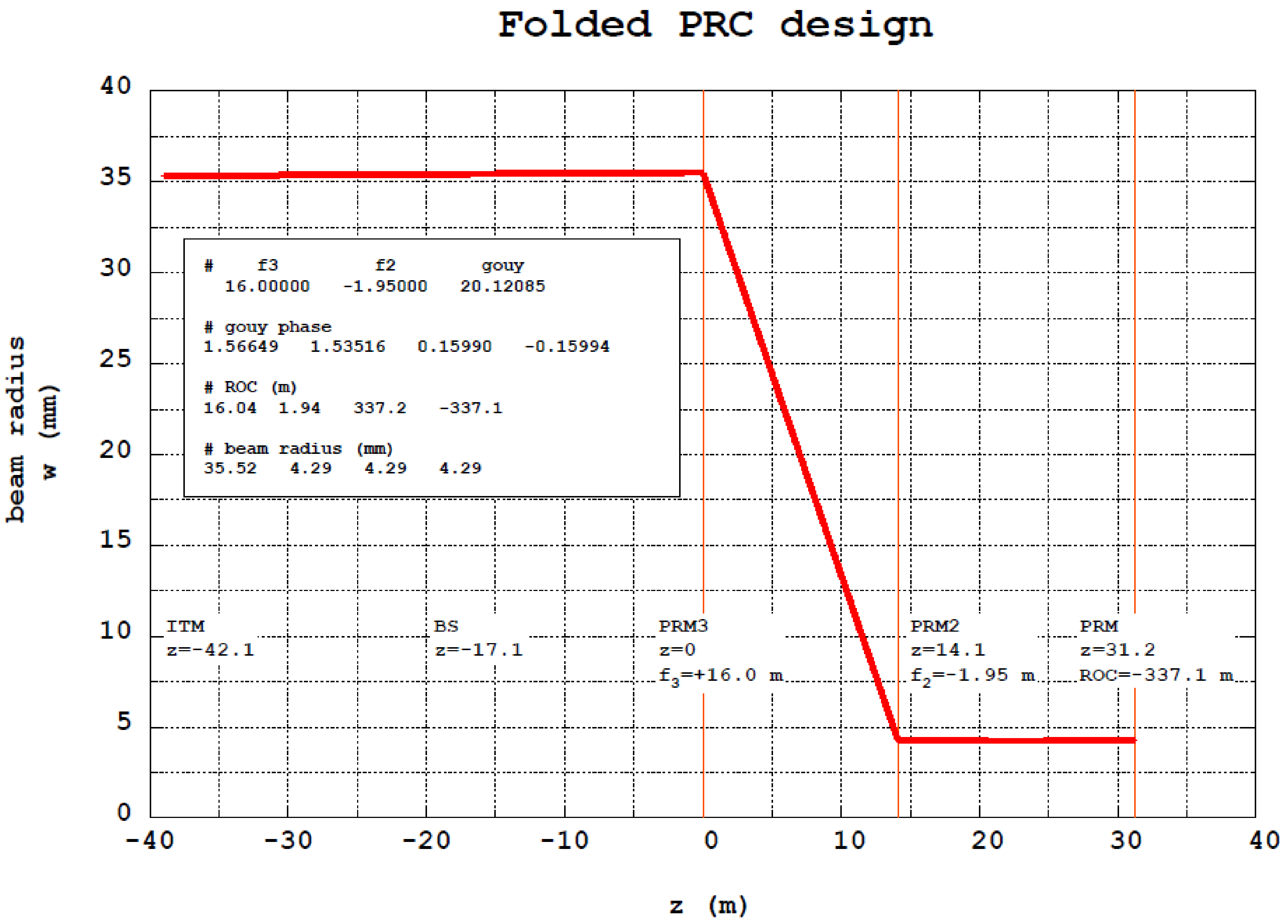
If the Cavity is Too Stable

- Arm misalignment scatter the TEM00 carrier to TEM01 or TEM10
- TEM01 or TEM10 are suppressed in the RCs --> No WFS signal.

A Compromise between the Stability and he WFS signal

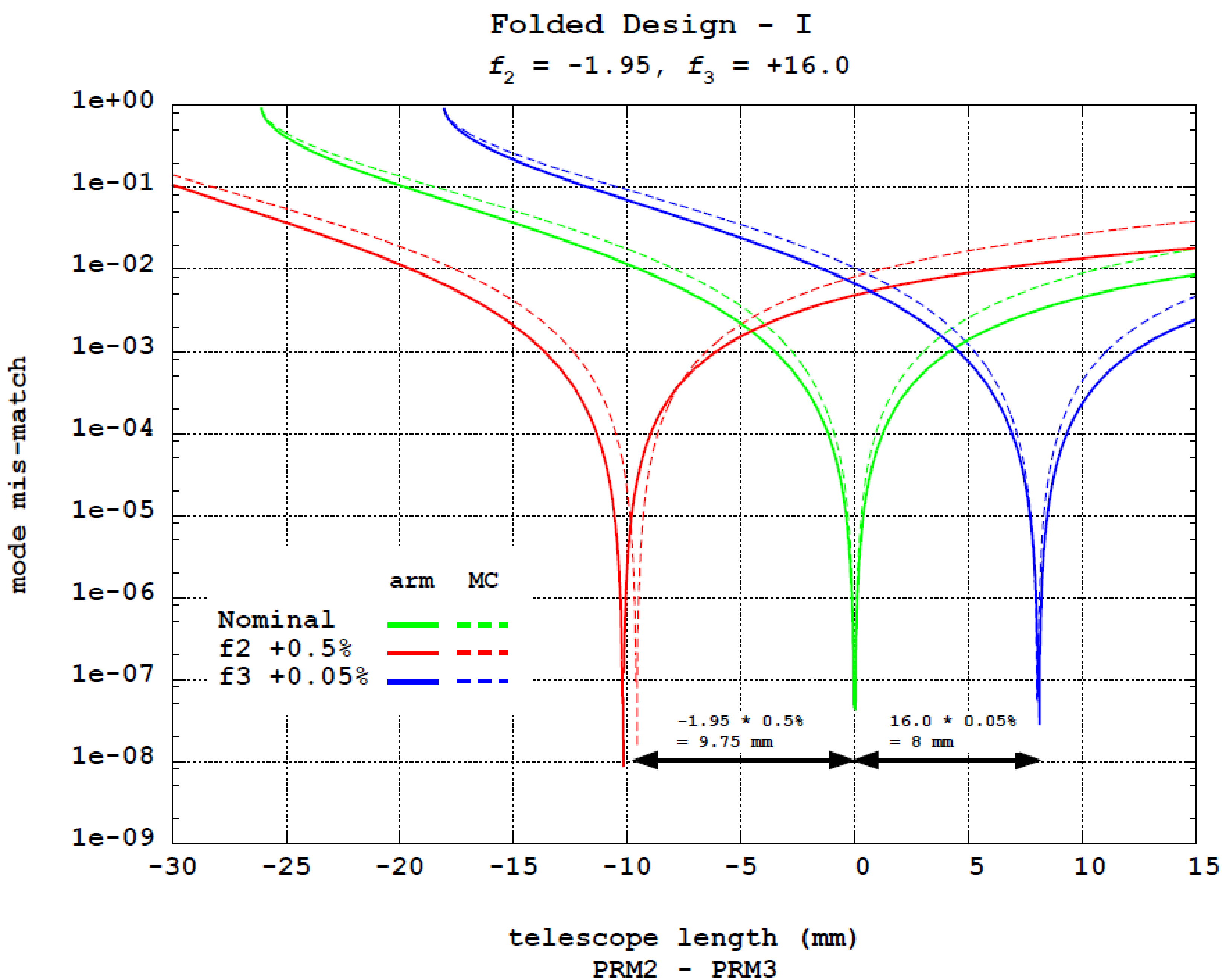
→ One-way Gouy Phase shift of 20 deg.

Folding configuration by D. Tatsumi



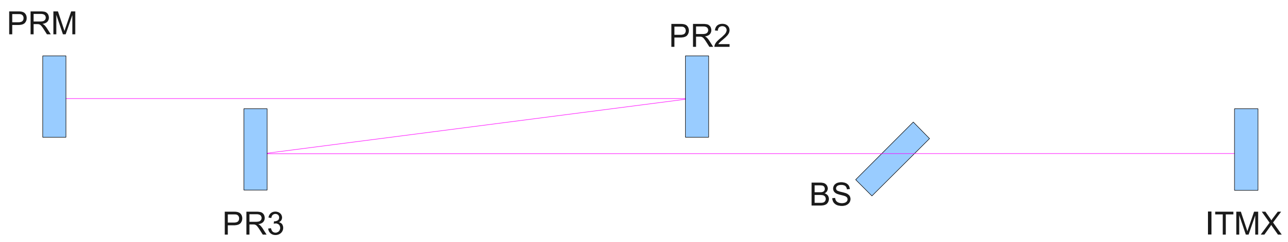
Effect of the ROC errors in the folding mirrors

We have to be able to adjust the folding mirror positions by +/-5cm or so.



Folding Mirrors and Alignment

How do we get the alignment information of the folding mirrors ?



Even if it is folded, there is only one cavity axis

↓

There are 2 DOF per rotation axis, translation and tilt.

WFS senses the translation and tilt with respect to the incident beam.

But there are 4 mirrors to be controlled

Any motion of the 4 mirrors can in principle be canceled by moving two mirrors ?

→ More investigations on the cavity geometry needed

Arm Cavity g-factor

sqrt(1/3) --> L=3000m, ROC=7098.08m (Conventional number)
-sqrt(1/3) --> L=3000m, ROC=1901.92m (Alternative)

Beam Size: 3.5cm for both cases
HOM degeneration: the same for both cases
Angular instability:

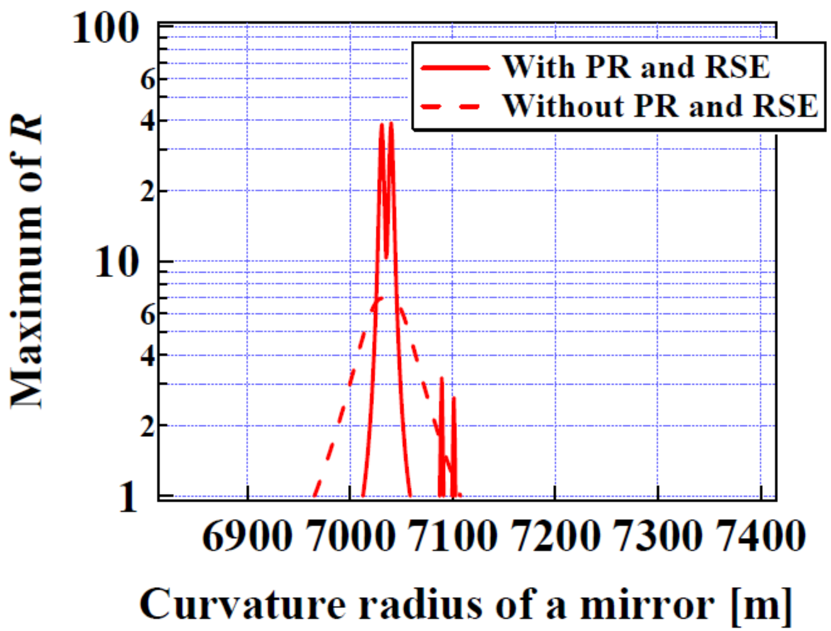
Two eigen-frequencies are 1.66Hz and 0.86Hz for a sapphire mirror
(Moment of inertia = 0.173 [kg*m^2])
For positive g, 1.66Hz becomes unstable while it is 0.86 for negative g.

Parametric Instability:

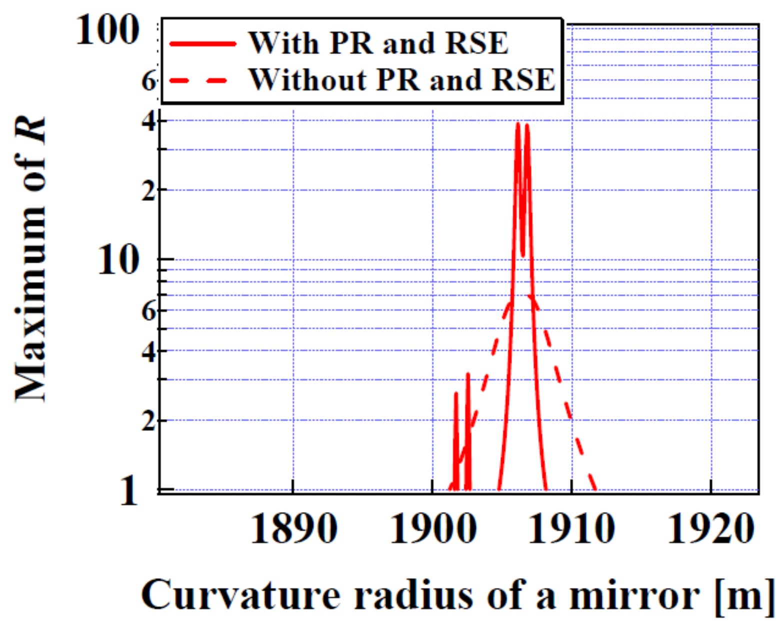
There are preferred regions in the g factor space from the view point of PI.
The regions are the same for positive and negative g.
However, dg/dR is different by a factor of 13 (negative g is larger).
Therefore, negative g is more sensitive to the ROC error (not limited to the PI actually).

PI calculation by K. Yamamoto

Positive g-factor



Negative g-factor



The error requirement on the mirror ROC is stricter for the negative g-factor.
by $(R_p / R_n)^2$

Mirror sag is proportional to 1/ROC.
So required machining precision may be independent on the ROC ?

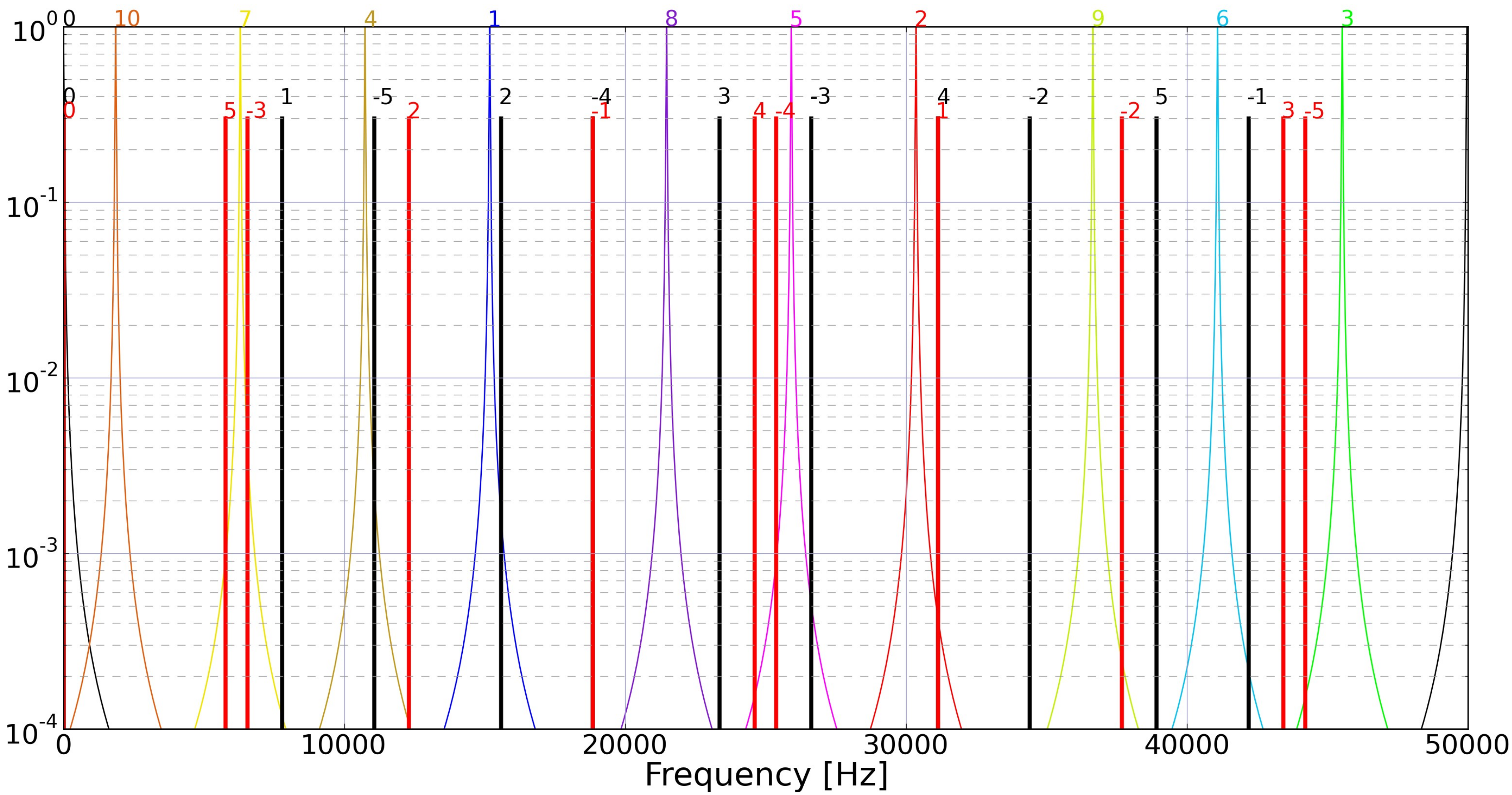
If so, we should employ the negative g-factor

RF Sideband Higher Order Mode in the Arm Cavity

Arm Cavity FSR = 50kHz

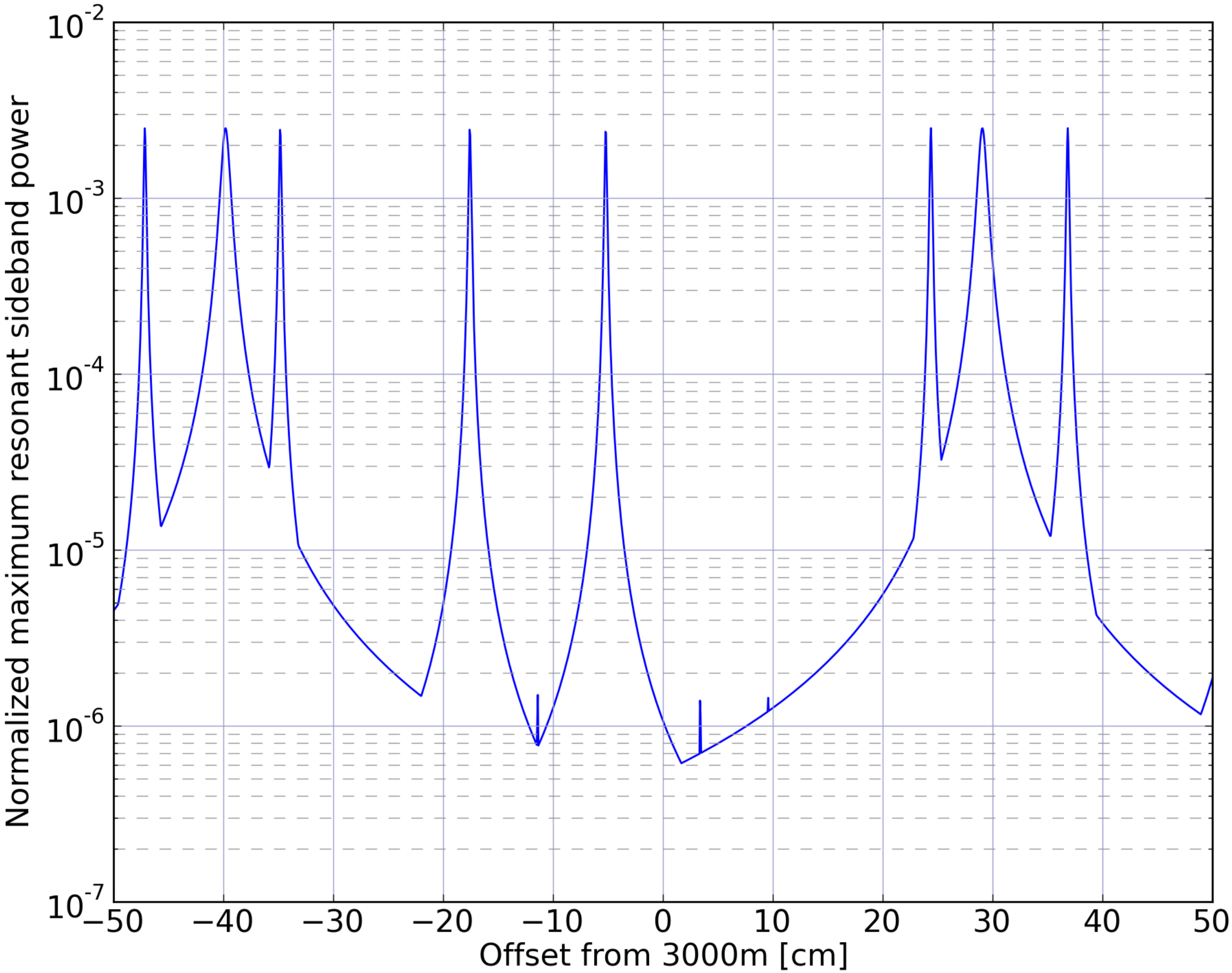
RF Sidebands >10MHz

Accidental resonances of HOM RF sideband may happen



Only a small arm length change can drastically change the RF sideband power in the arms.

Arm length tuning range of +/-10cm would be necessary

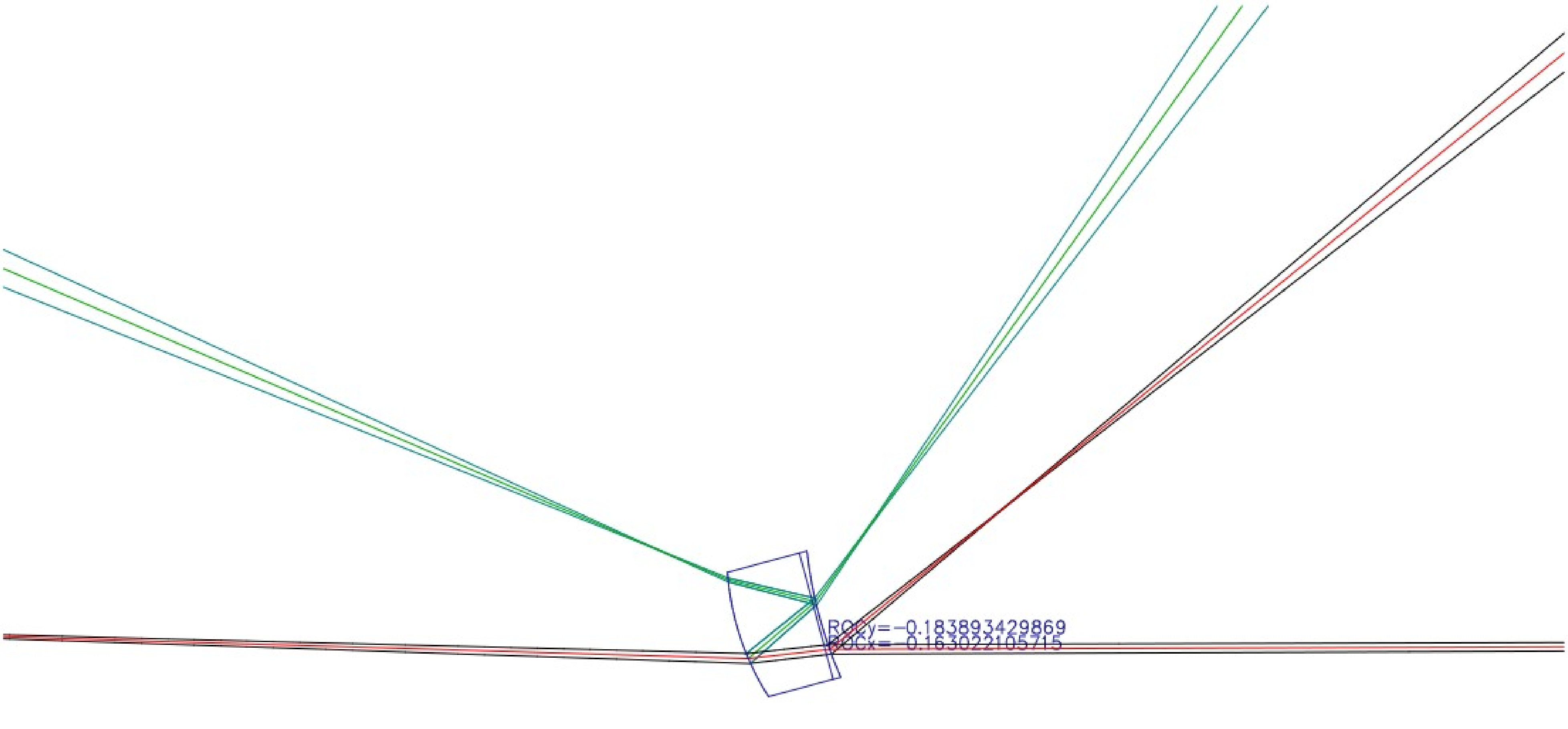


Optical Layout

Necessary to decide how to handle stray light and signal ports

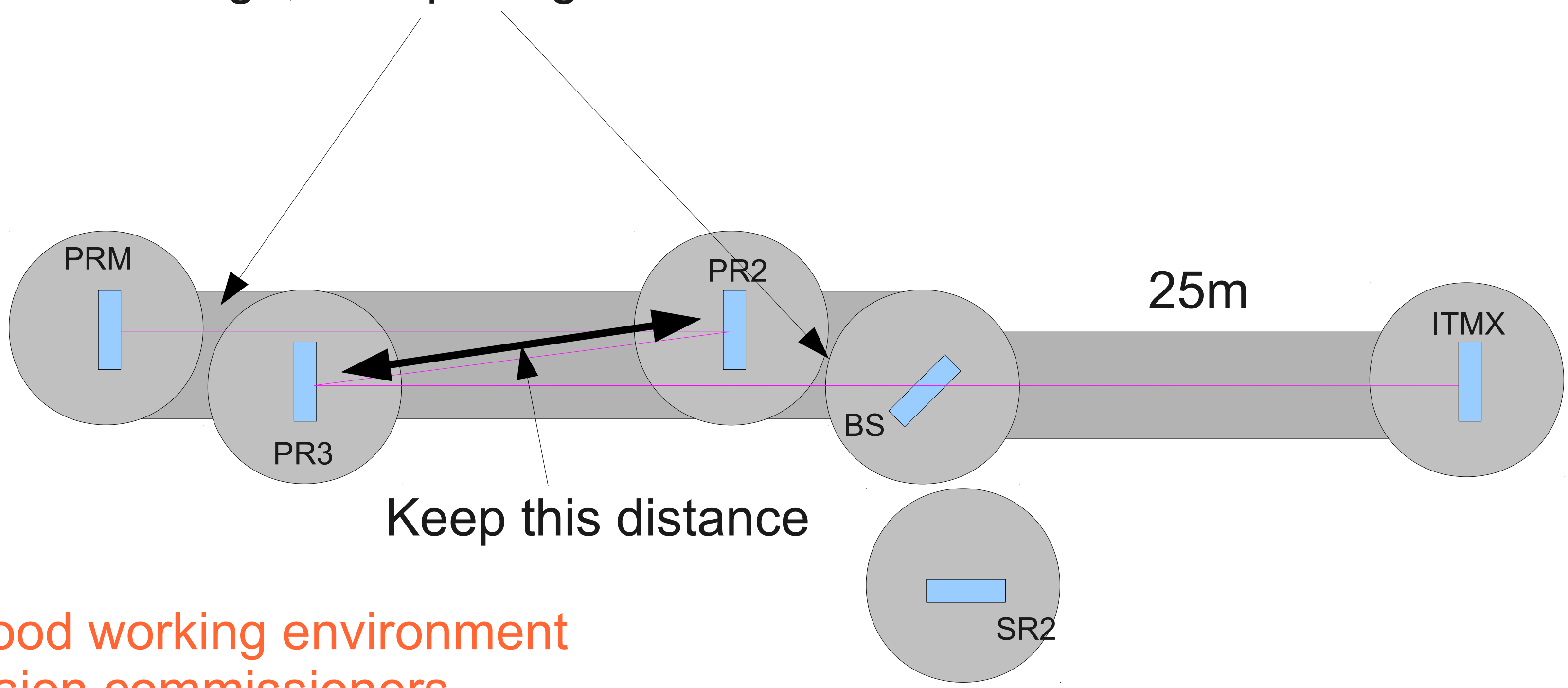
Tool

- A python module to automatically compute the propagation, reflection, deflection of Gaussian beams.
- Programmatic design of the IFO optical layout to satisfy various quantitative requirements at the same time



Vacuum Chamber Spacing

With the current design, the spacing between the chamber centers is 3m.



This is not a good working environment for the suspension commissioners.

- To reduce astigmatism, we want to keep the distance between PR2 and PR3.
- The total length of the RCs are fixed by the LSC scheme.
- Can we reduce the BS-ITM distance by 2m and give it to the BS-PR3 and PR2-PRM spacings ?

Interface between: ISC, Cryo, Vacuum and Suspension

Output Telescopes

At some output ports, beam size is large (3.5cm).
We have to reduce the size of the beams first --> Output Telescopes

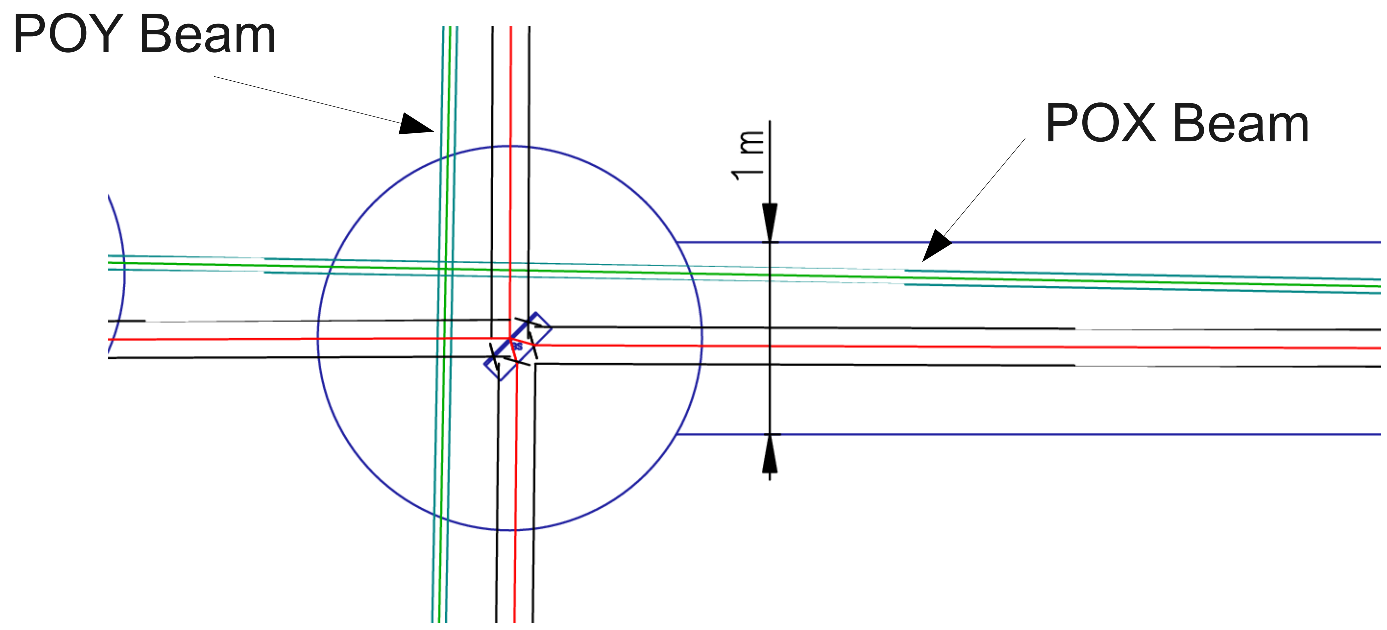
Port	Beam Size
REFL	5mm
POP	3.5cm or 5mm
Green	3.5cm or 5mm
POX, POY	3.5cm
AS (Before OMC)	5mm
TRX, TRY	3.5cm

In vacuum telescopes ?
Suspended ?
Reflective or transmissive ?

Interface with Input Output Optics Group

Radiation Baffles and PO Beams

Pick-off beams from the ITMs are separated from the main beam in the BS tank.

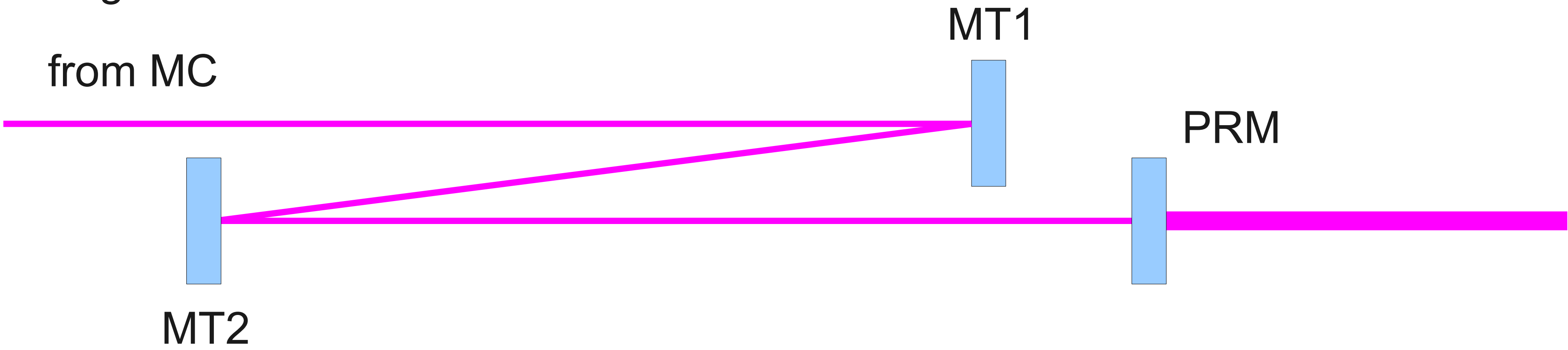


The current configuration will interfere with the radiation shield baffles.

Interface with Cryo-Group

Input Steering Mirrors

The current design uses the mode matching telescope as the input beam steering mirror.



We should check if the telescope can produce both beam translation and tilt with enough actuation range.

Output Mode Cleaner

- No design so far ?
- 4 mirror cavity ?
- How to lock it ?
- How to align it ?

Interface with Input Output Optics Group

Summary

- LSC scheme has been studied in detail
- There are at least several feasible candidates for LSC scheme.
- ASC scheme is the big missing stuff in LCGT
- I personally recommend negative g-factor
- Folding cavity design and the HOM resonance issue both require the suspensions be movable by +/- 10cm. (ETMs and folding mirrors)
- A rough plan for Green-Lock exists
- A draft optical layout exits
- Needs more discussions with other sub-systems

TO DO

LSC
- Check the Optickle results with Finesse

ASC
- Find a reasonable signal extraction scheme with Optickle
- Check noise coupling from ASC to LSC

Optical Layout
- Finalize the main optics layout
  - Need to decide on the vacuum chamber spacing
- Auxiliary beam handling
- Output telescope

Green Lock
- Detailed optical configuration
- Noise estimates

Issues, Risks, Worries

- MZ noise coupling
- PRM matching with arm may be poor --> increased REFL shot noise for DDM
- Is feed forward accuracy of 1% possible ? Adaptive Filtering ?
- Is it possible to align the folded cavity with WFS ?
- PRM thermal lensing