External Review of
Main Interferometer Subsystem

2012/4/19

Yoichi Aso

Overview: Definition and scope of the subsystem

MIF includes: Arm cavities, Recycling cavities, Michelson part

Assigned tasks

- Parameter selection of the MIF
  - Length, ROC, etc
  - Optical layout
- Design of the control scheme
  - LSC, ASC
- Lock acquisition scheme
- Commissioning

For some reason, detector characterization is a part of MIF
Maybe the Instrument Control will be too

Interface with other subsystems

- Mirror
  - Reflectivity, ROC, Loss, other specs.
- Suspension
  - Isolation requirements
  - Actuator design
  - Installation procedure
- Suspension+AOS
  - Local sensors
- Laser
  - Power
- IOO
  - Intensity Noise
  - Frequency Stabilization Path
  - Input/Output mode matching
  - Detection ports
  - OMC
  - Green lock
- AOS
  - Scattered light
- Digital System
  - Servo model
- Analog electronics
  - PD, QPD, I-Q demodulator, servo filters, etc
- Vacuum
  - Layout

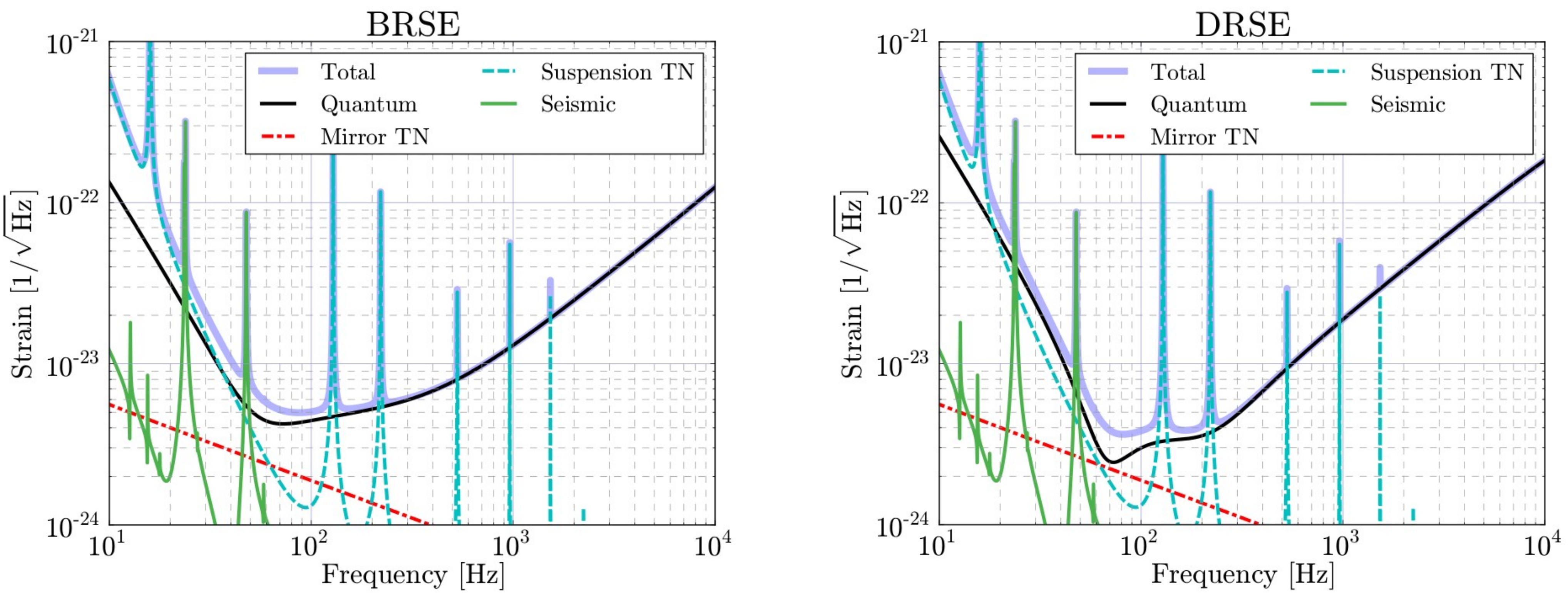
Design Status

IFO params	semi-final	LSC principle	final
ASC principle	preliminary	Servo modeling	TBD
Green Lock Design	preliminary	Optical Layout	final
Frequency Servo	preliminary	Commissioning Plan	TBD
OMC	early stage	Analog Circuits	TBD

ƄKAGRA

Requirements

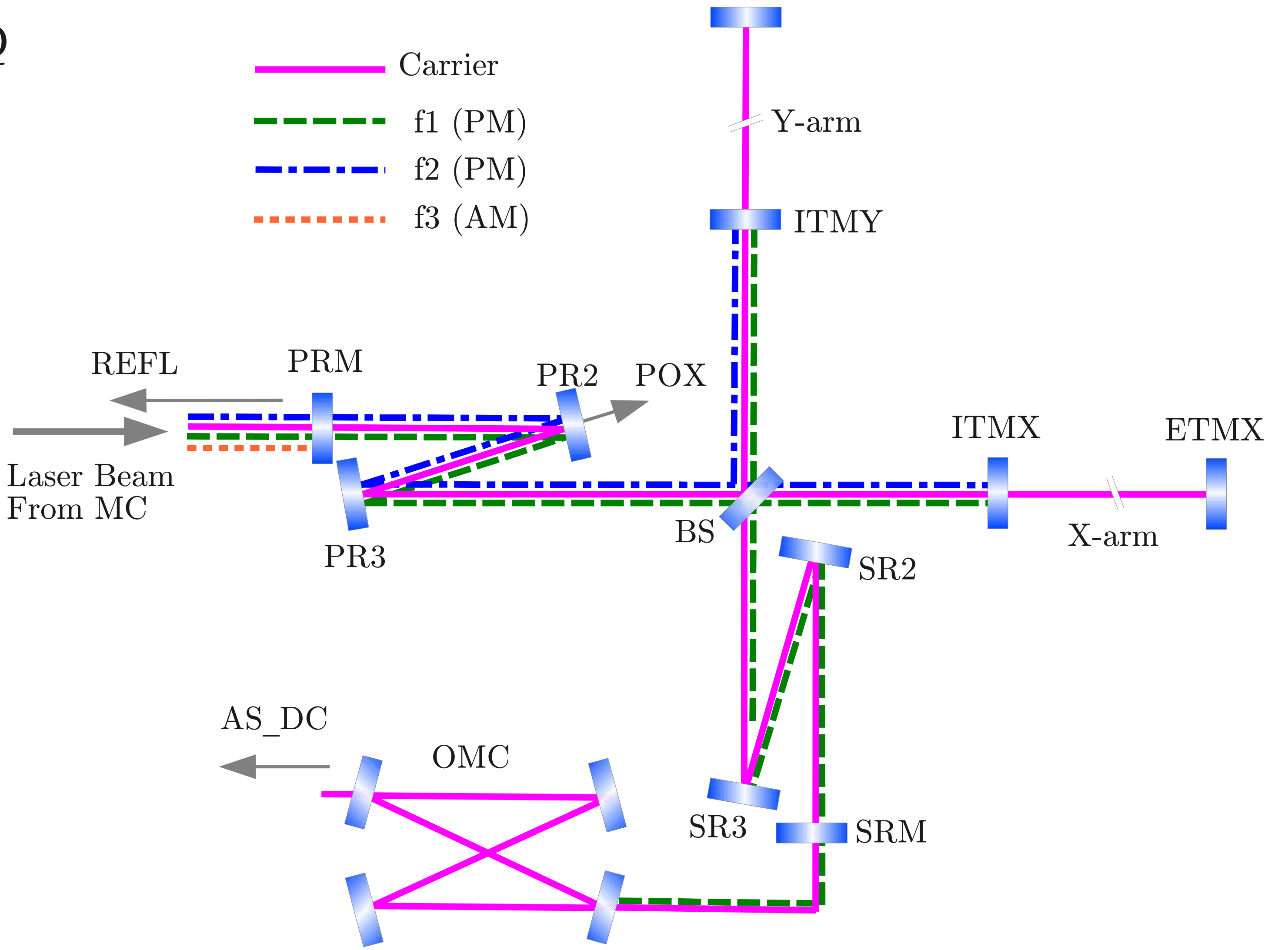
Operate the interferometer with the following noise level
Duty factor > 80% (Interferometer lock > 99%)



bKAGRA Interferometer

Signal Ports

DARM: AS_DC
CARM: REFL_1I
MICH: REFL_1Q
PRCL: POP_2I
SRCL: POP_1I



Almost Final Design

Interferometer Parameter

Arm Finesse	1550	Arm Length	3km	PRG	10
SRM Reflectivity	85%	Input Laser Power	51W	PRC Length	66.6m
SRC Detuning	3.5°	SRC Length	66.6m	MICH Asym.	3.33m
g1	-0.786	g2	-0.602	g1・g2	0.473
R1	1.68km	R2	1.87km		

For details:
http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/LCGT/subgroup/ifo/MIF/OptParam

MIF Design Document: JGW-T1200913

g-factor selection

Beam Size

ITM: 3.5cm, ETM:4.0cm

- 4.0cm is the maximum spot size for 22cm mirror.
- 3.5cm beam at the central part is easier to handle.
- Since ITMs have less coating layers, the thermal noise is not compromised by 3.5cm beam size on ITMs.

Decided: $g_1 \cdot g_2 = 0.473$

<u>Candidates</u>

- g1=0.786, g2=0.602 (R1=14km, R2=7.5km)
- g1=-0.786, g2=-0.602 (R1=1.68km, R2=1.87km)

Arm Cavity HOM Resonances

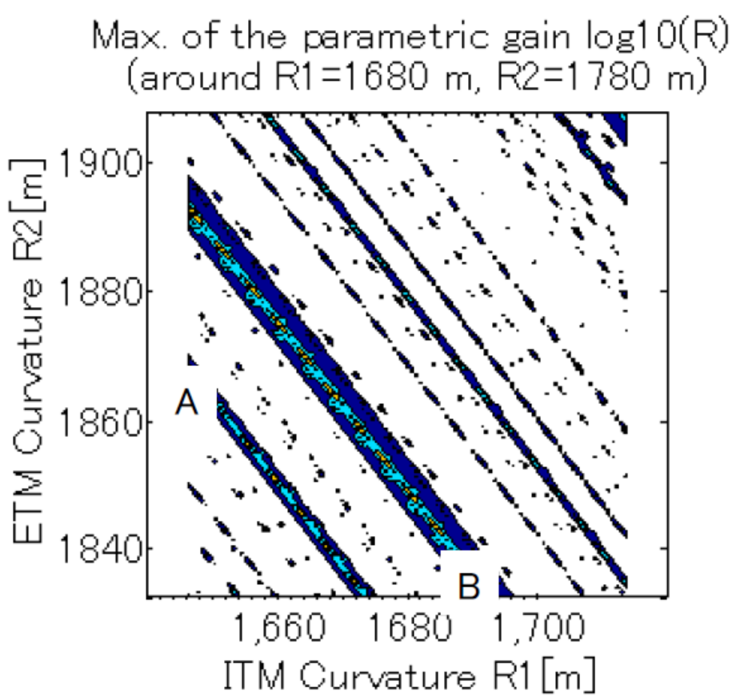
No significant difference between Positive and Negative

See JGW-G1200789

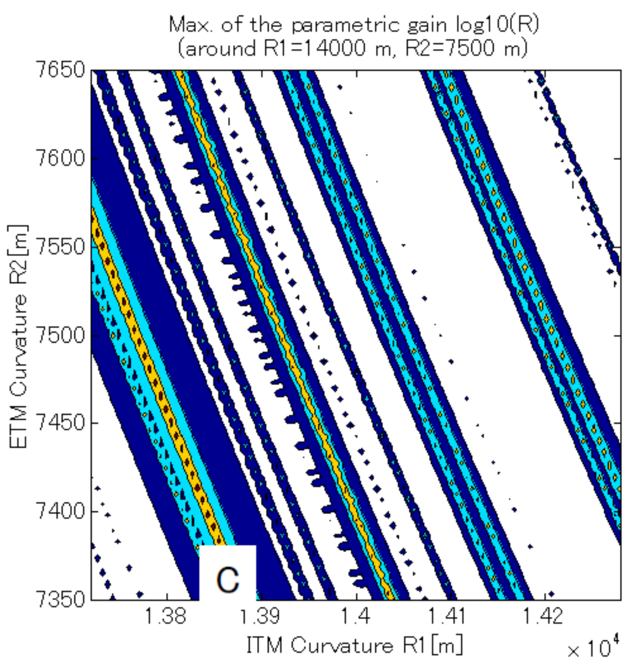
Parametric Instability

Colored area = Unstable mode exists

Negative g



Positive g



by K. Shibata

See JGW-T1200787

Sidles-Sigg Instability (ASC)

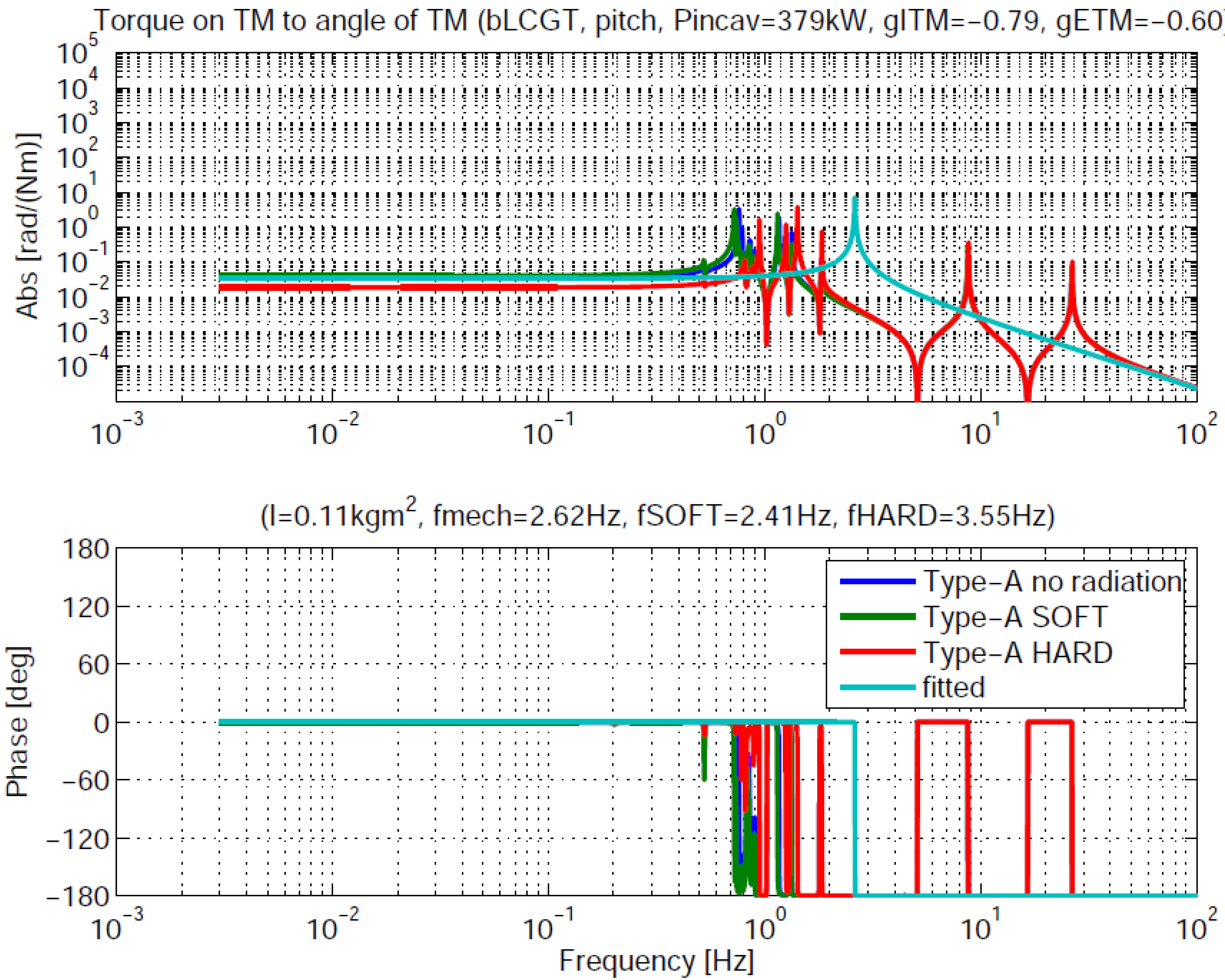
- WFS UFG for Pitch has to be lower than 1Hz
- For arm power > 330kW, Pitch instability frequency > 1Hz for positive g-factor
- Negative g-factor never makes Pitch unstable
- Current arm power (compromised to deal with high sapphire absorption) = 250kW --> even positive g-factor is OK
- Original (desirable) arm power = 376kW
  --> positive g-factor is not an option

Conclusion

Negative g-factor is better

Positive g-factor limits us to operate only with low power

TM Pitch Transfer Function



Gouy Phase Change in PRC/SRC

Factors to Consider

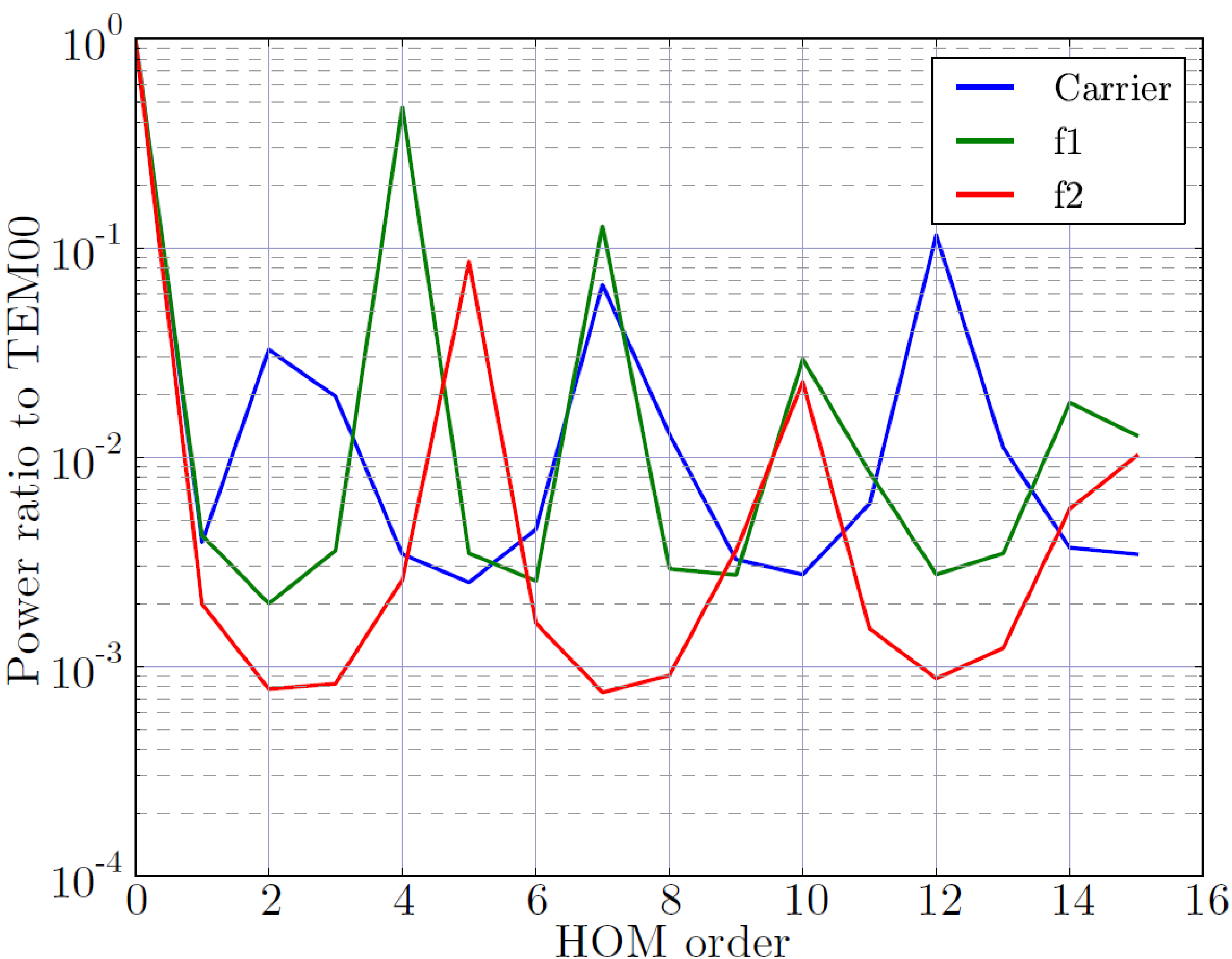
- Higher Order Mode Resonances in RCs
- WFS Signal

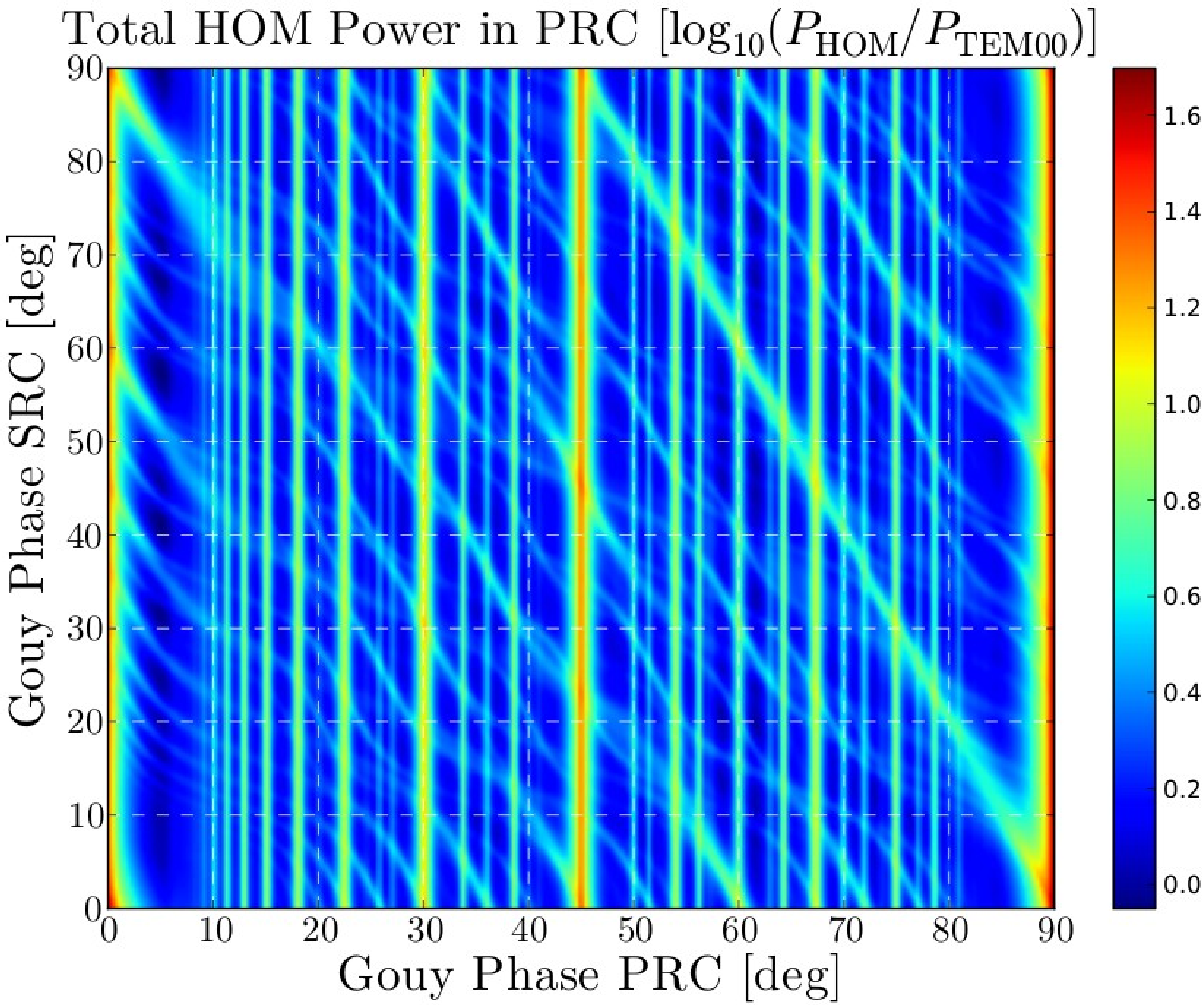
Stable Recycling Cavity → Suppression of TEM10/01
→ Small Arm WFS Signal

Smaller Gouy phase is better for WFS ? → Not So Simple

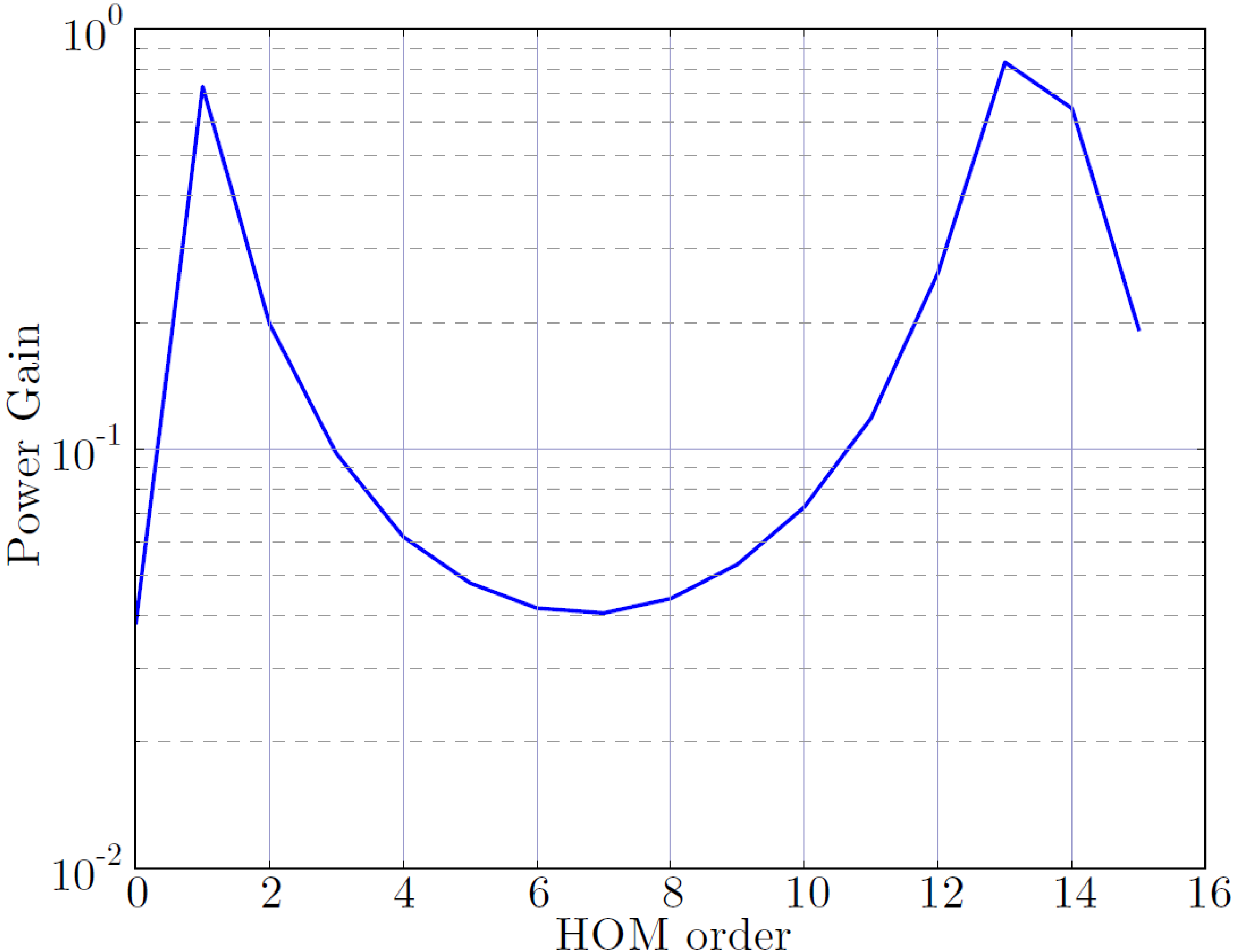
- For PRC Gouy phase $\sim 90^\circ$ is better for TEM10/01 transmission
- WFS signal separation for auxiliary mirrors has to be checked
- Large Gouy phase change requires small beam spot on PRM

HOM Power in PRC

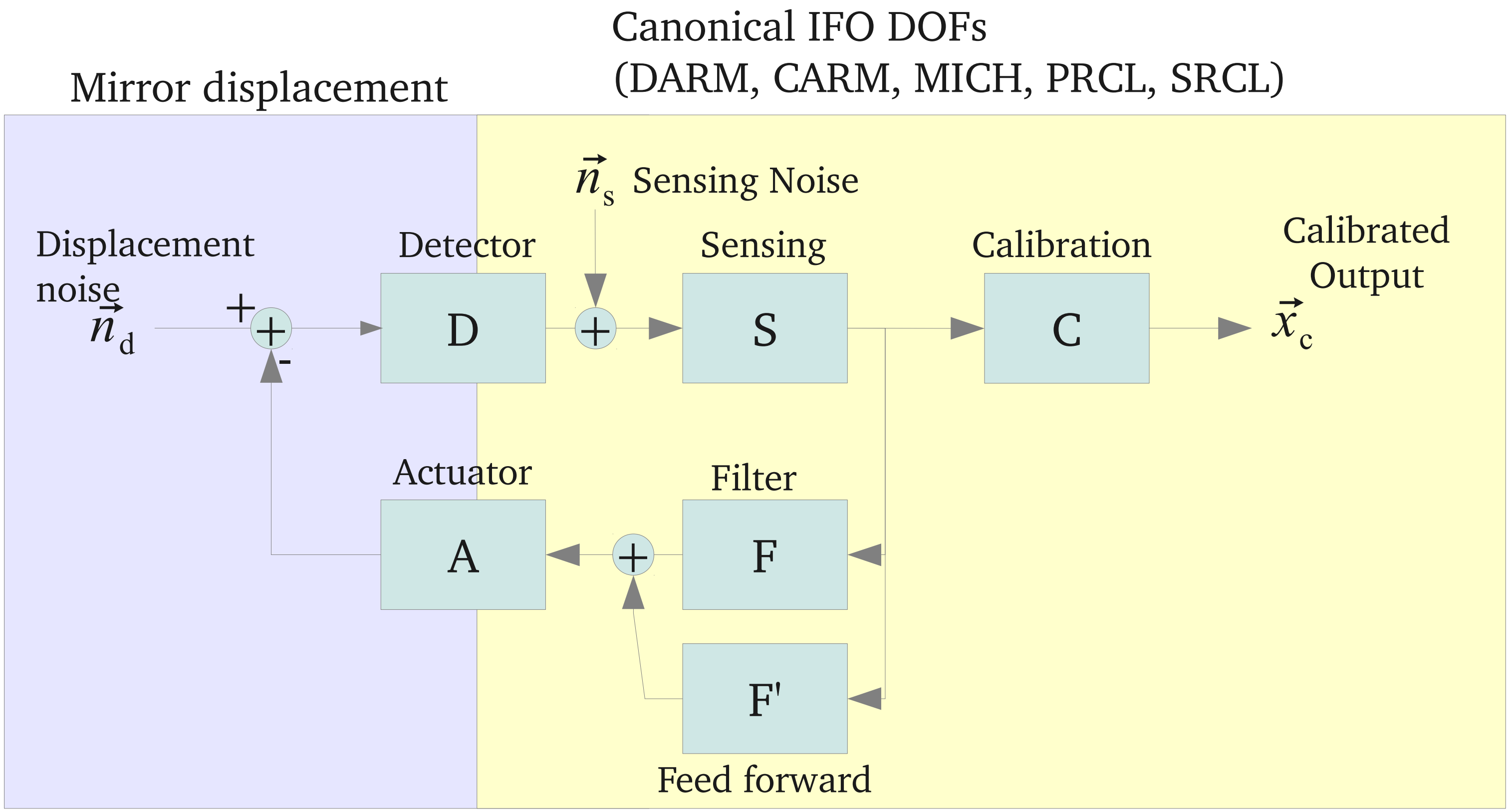



Total HOM Power in PRC [$\log_{10}(P_{\mathrm{HOM}}/P_{\mathrm{TEM00}})$]
Gouy Phase SRC [deg]
Gouy Phase PRC [deg]
0
10
20
30
40
50
60
70
80
90
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

SRC Carrier HOM Power Gain



Length Sensing and Control



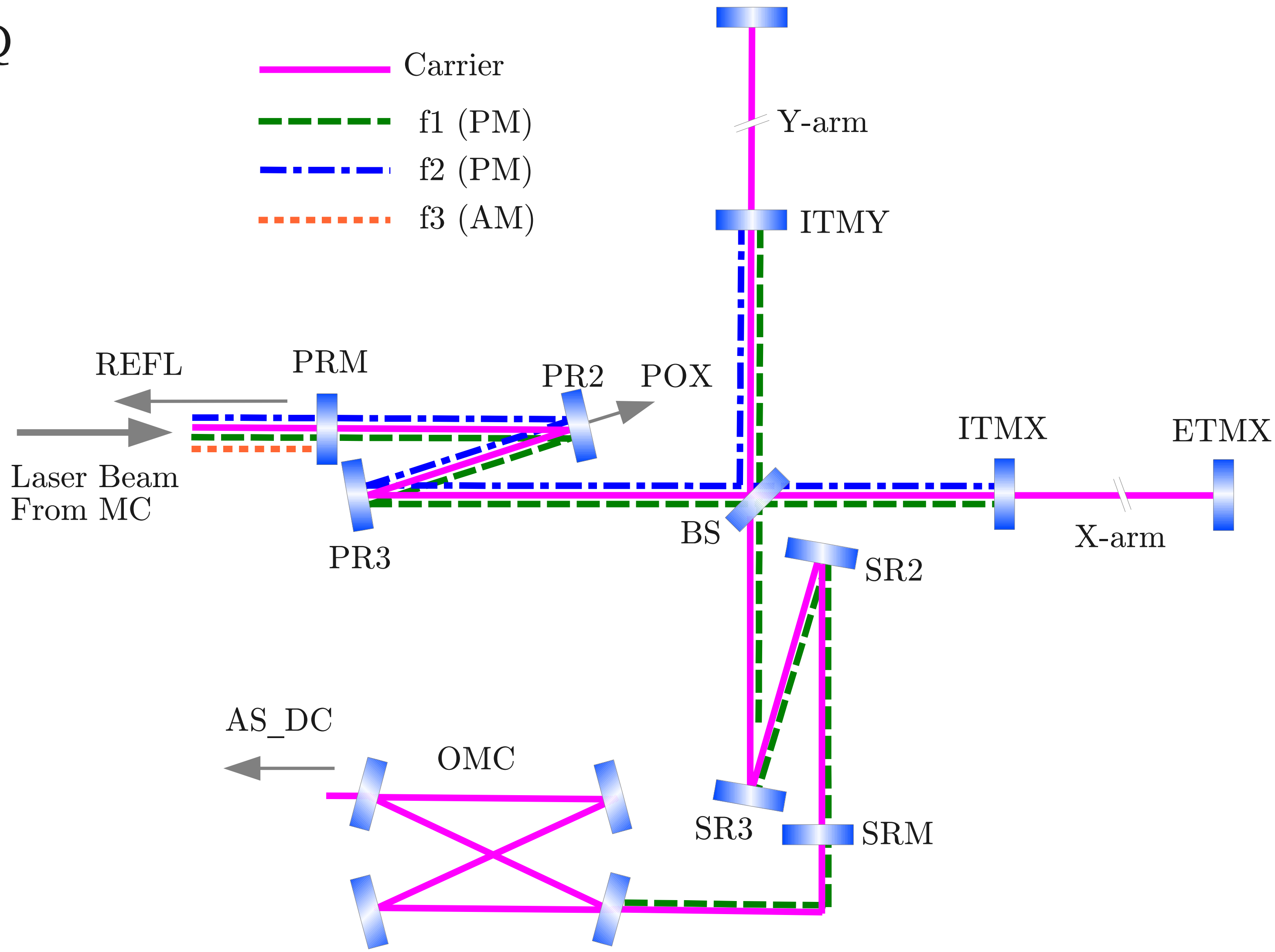
$$\vec{x}_c = (I+G)^{-1} \cdot S \cdot \vec{n}_s + (I+G)^{-1} \cdot SD \cdot \vec{n}_d$$

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

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)

bKAGRA Interferometer

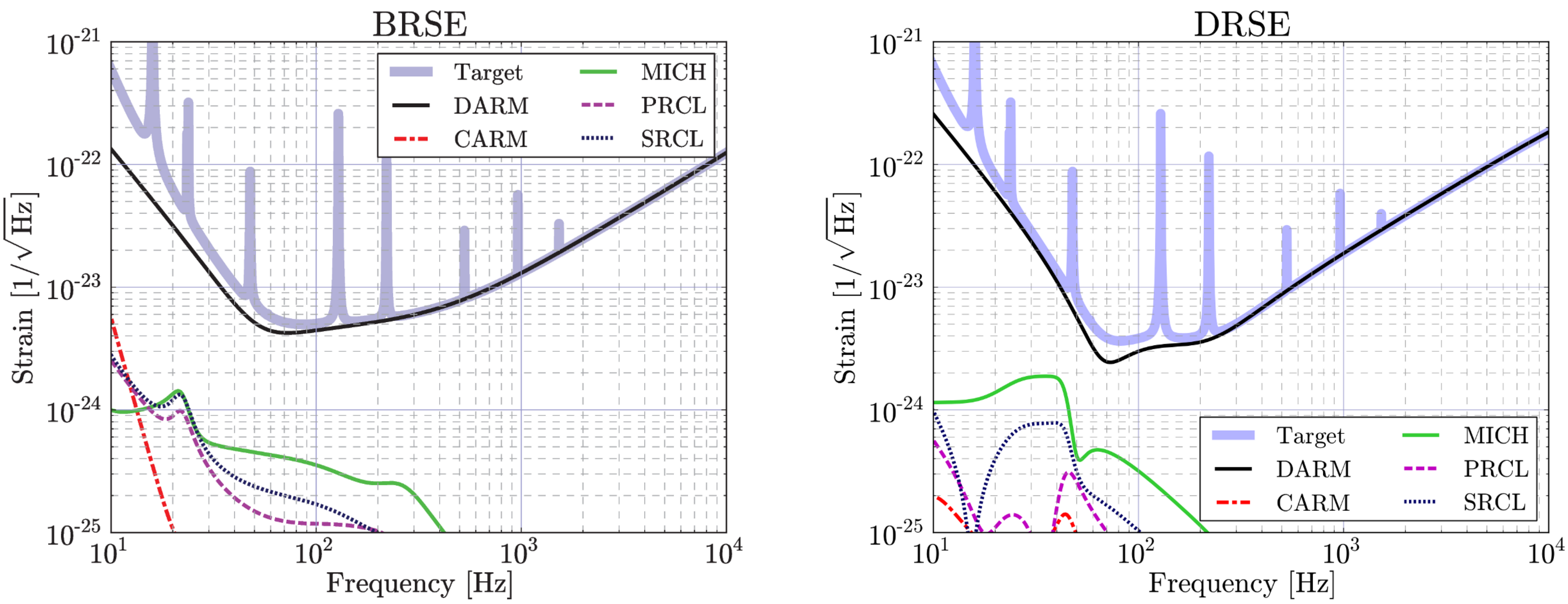
Signal Ports
DARM: AS_DC
CARM: REFL_1I
MICH: REFL_1Q
PRCL: POP_2I
SRCL: POP_1I



LSC Loop Noise Couplings

UGF DARM: 200Hz, CARM: 10kHz, Others: 50Hz

Feed Forward Gain: 100



ASC

WFS＋OpLev

by Y. Michimura

WFS Sensing Matrix [W/mrad/sqrt(2/pi)]

(Gouy phases at POP A:80.8, POP B:42.2 REFL A:80.6, REFL B:-0.9, AS A:89.0, AS B:-1.0, TR A:-67.8 deg)

だいたい
対角化できてる

	CS	CH	DS	DH	BS	PR3	PR2	PRM	SR3	SR2	SRM
TRX_ADC	-12.89	-2.36	-12.89	-2.36	0.00	-0.01	-0.00	-0.00	0.00	0.00	0.00
REFL_A1I	-29.45	-156.82	-0.00	-0.01	0.13	0.85	0.45	3.96	-0.04	-0.00	-0.00
TRY_ADC	-12.89	-2.36	12.89	2.36	-0.01	-0.01	-0.00	-0.00	-0.00	-0.00	-0.00
AS_A1Q	0.00	0.00	0.28	1.49	0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00
AS_B1Q	0.00	0.00	-0.02	-0.00	-0.01	0.00	0.00	0.00	0.00	0.00	-0.00
POP_A2I	-6.83	2.65	0.02	-0.01	3.95	11.31	1.47	1.30	-0.00	-0.00	-0.00
POP_ADC	-0.09	0.08	-0.00	0.00	0.07	0.16	-2.72	-2.35	0.00	0.00	0.00
REFL_B1I	2.08	0.30	0.00	-0.00	-0.94	-2.84	-0.37	12.12	-0.29	-0.04	-0.03
POP_B1I	0.07	0.01	0.00	-0.00	0.02	-0.03	-0.00	-0.01	-0.07	-0.01	-0.01
AS_ADC	1.07	-0.93	0.29	-0.10	0.13	-1.01	-0.13	0.87	-0.91	-0.12	0.80 $\times 10^{-3}$

← 制御自由度

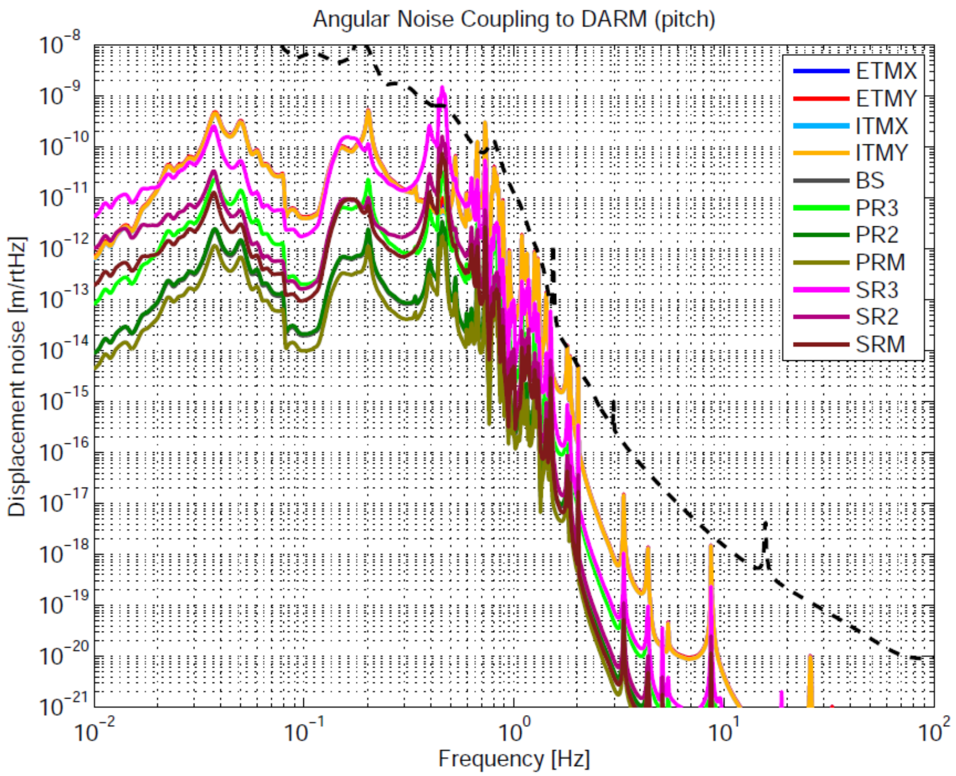
数字の色は信号の強さ

↑ 選択した信号取得ポート

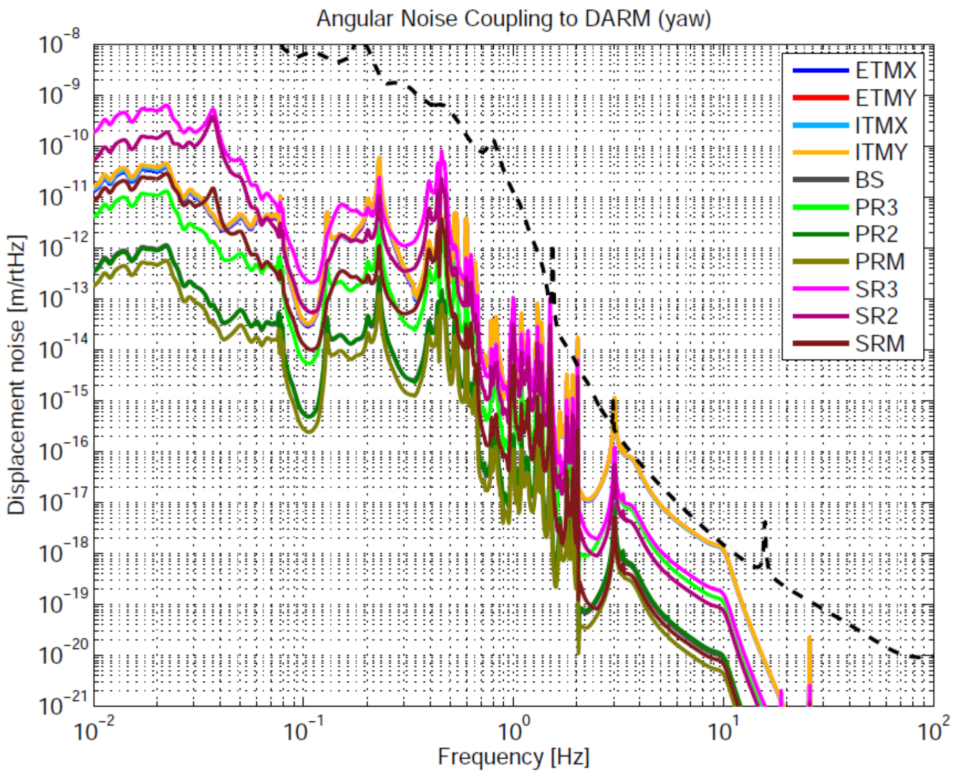
信号が出にくいためSR2はWFSでは制御しない

Total Angular Noise Couplings to DARM

Pitch



Yaw

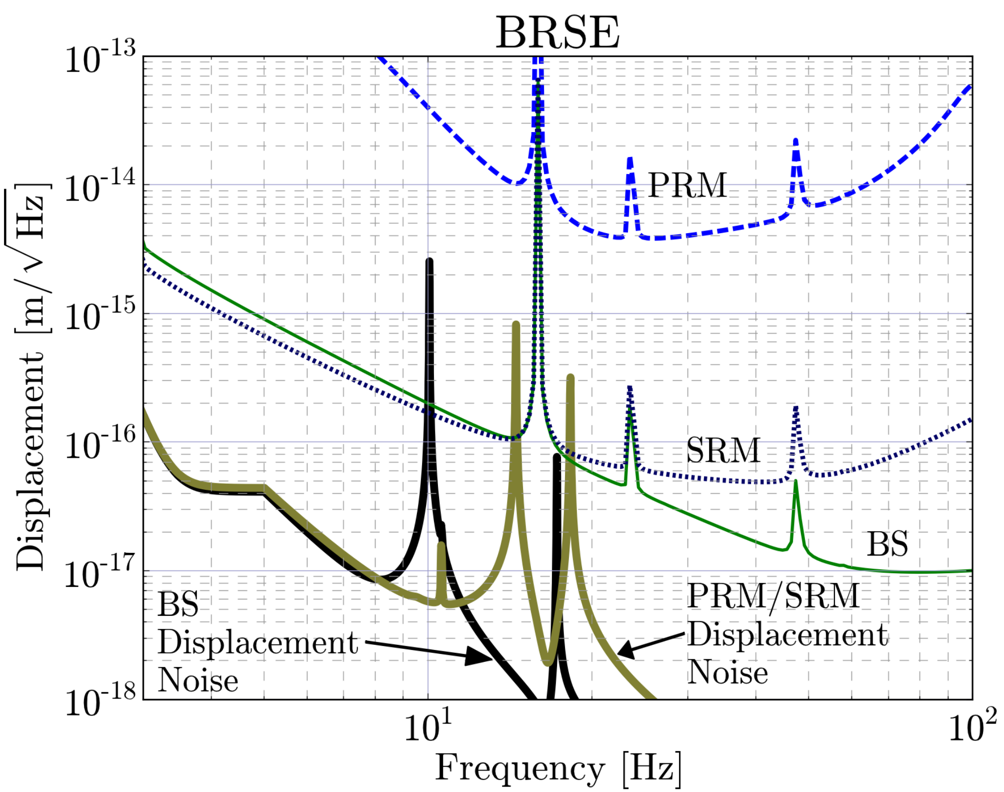


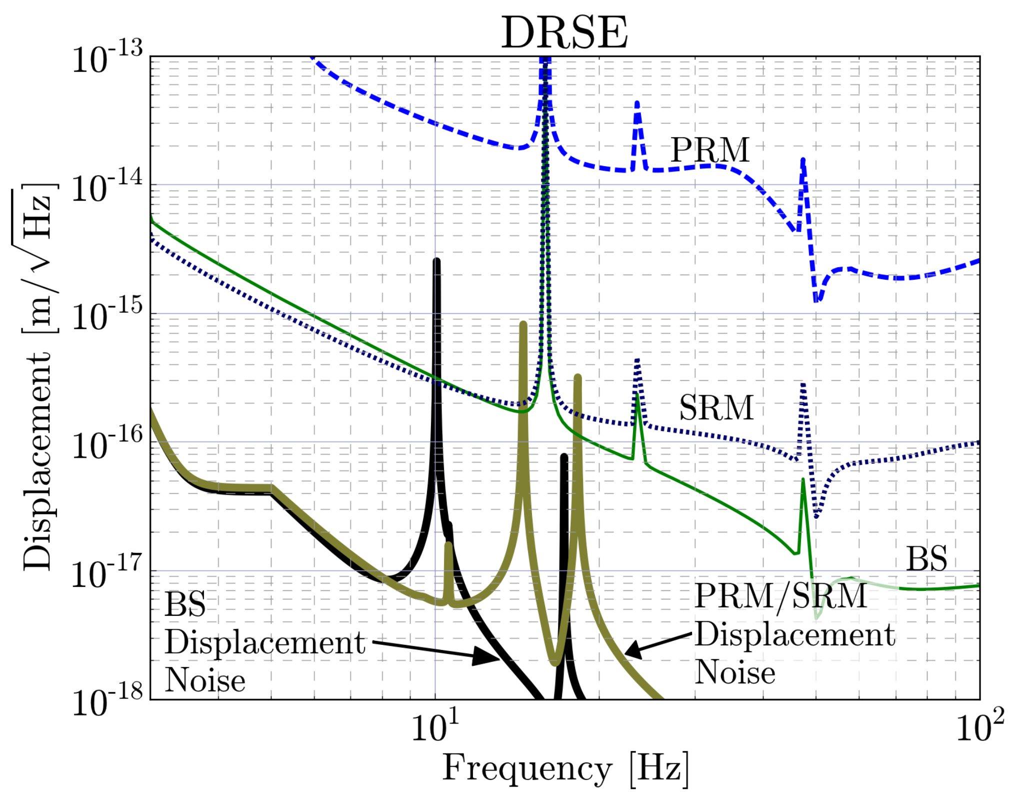
Practical Noise Requirements

- Auxiliary Mirror Displacement Noise
- Laser Frequency Noise / Intensity Noise
- RF Oscillator Phase Noise / Amplitude Noise
- Scattered Light Noise Couplings

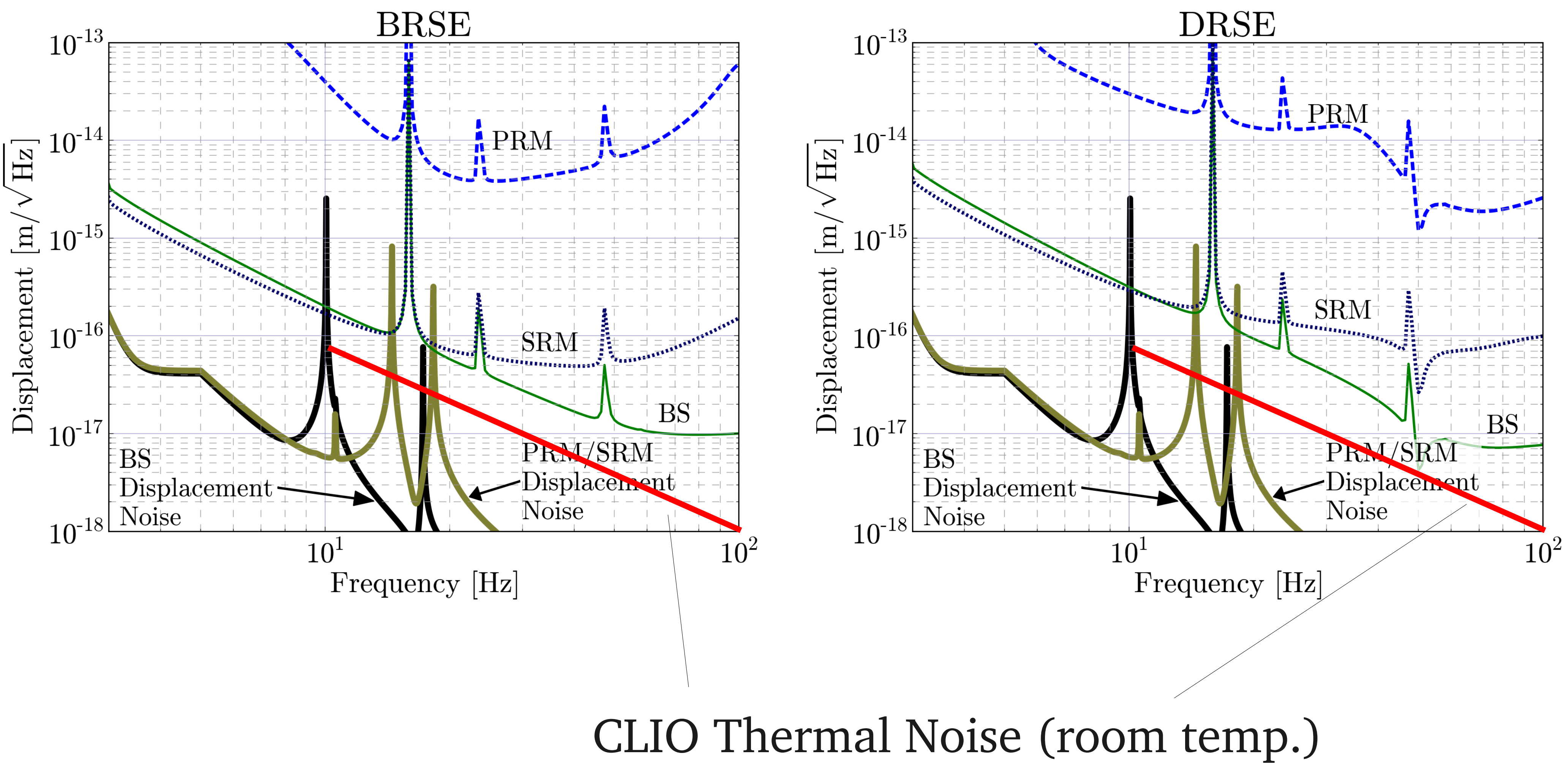
All the requirements include a safety factor of 10

Displacement Noise Requirements to Auxiliary Mirrors

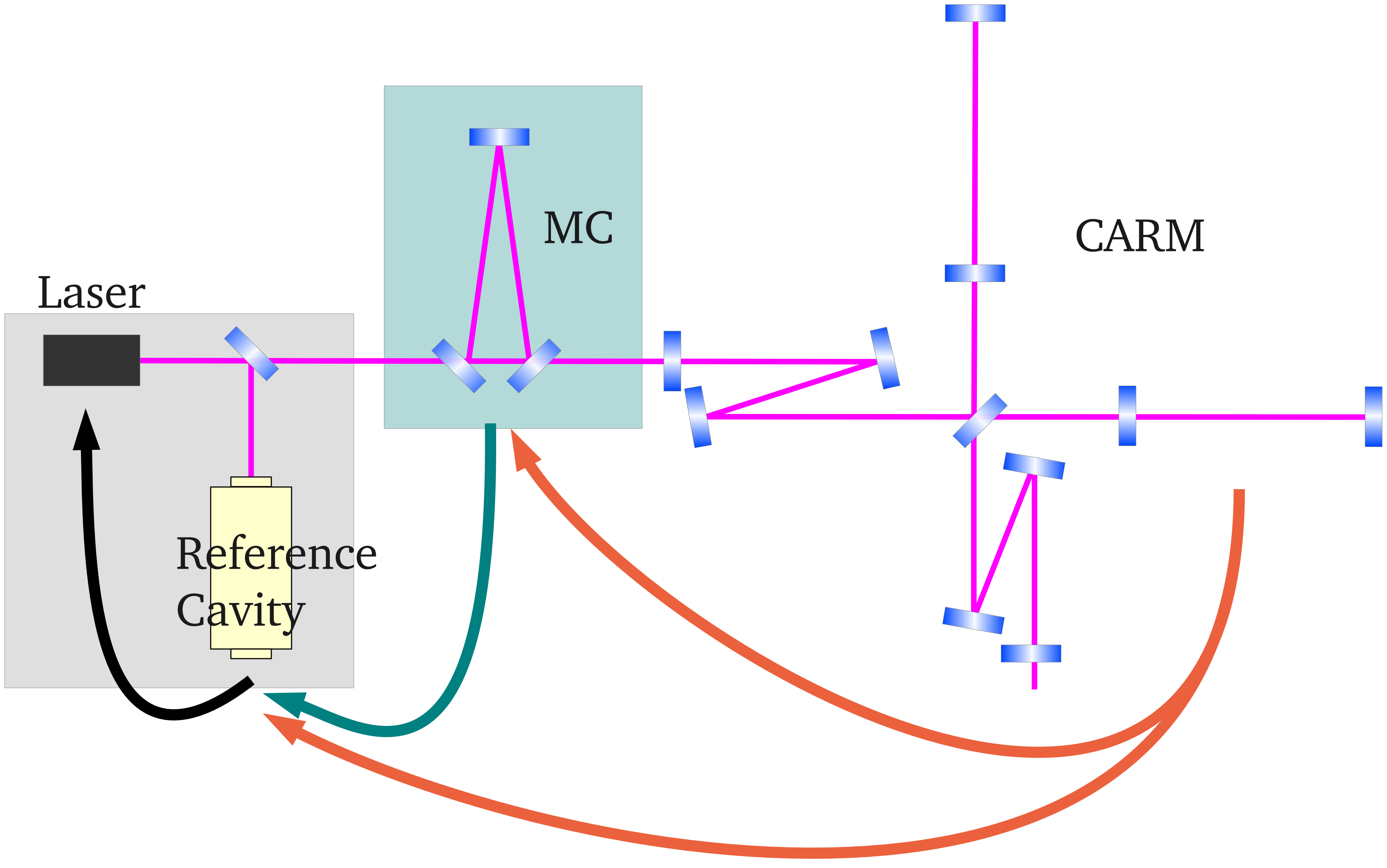




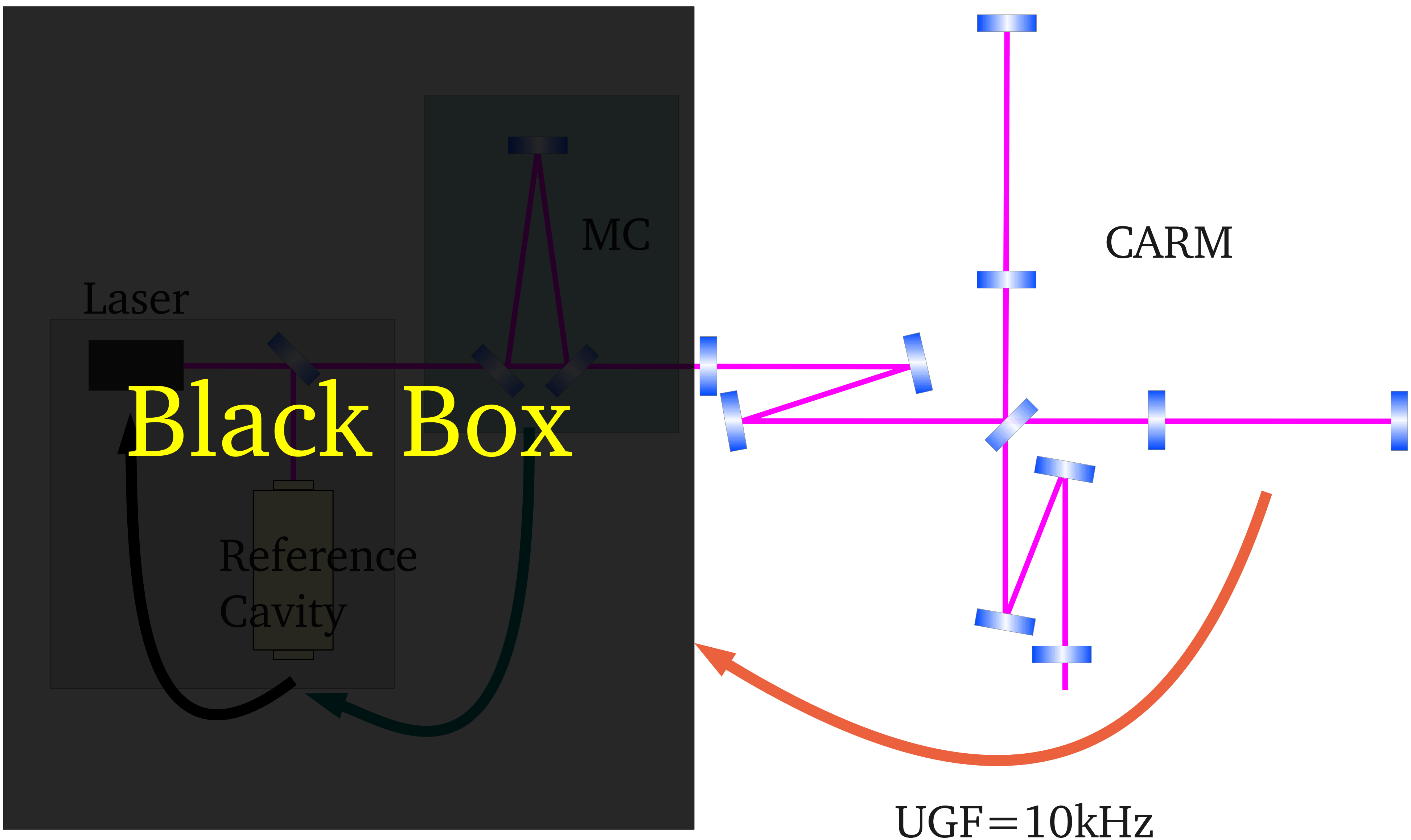
Displacement Noise Requirements to Auxiliary Mirrors



Frequency Stabilization Servo

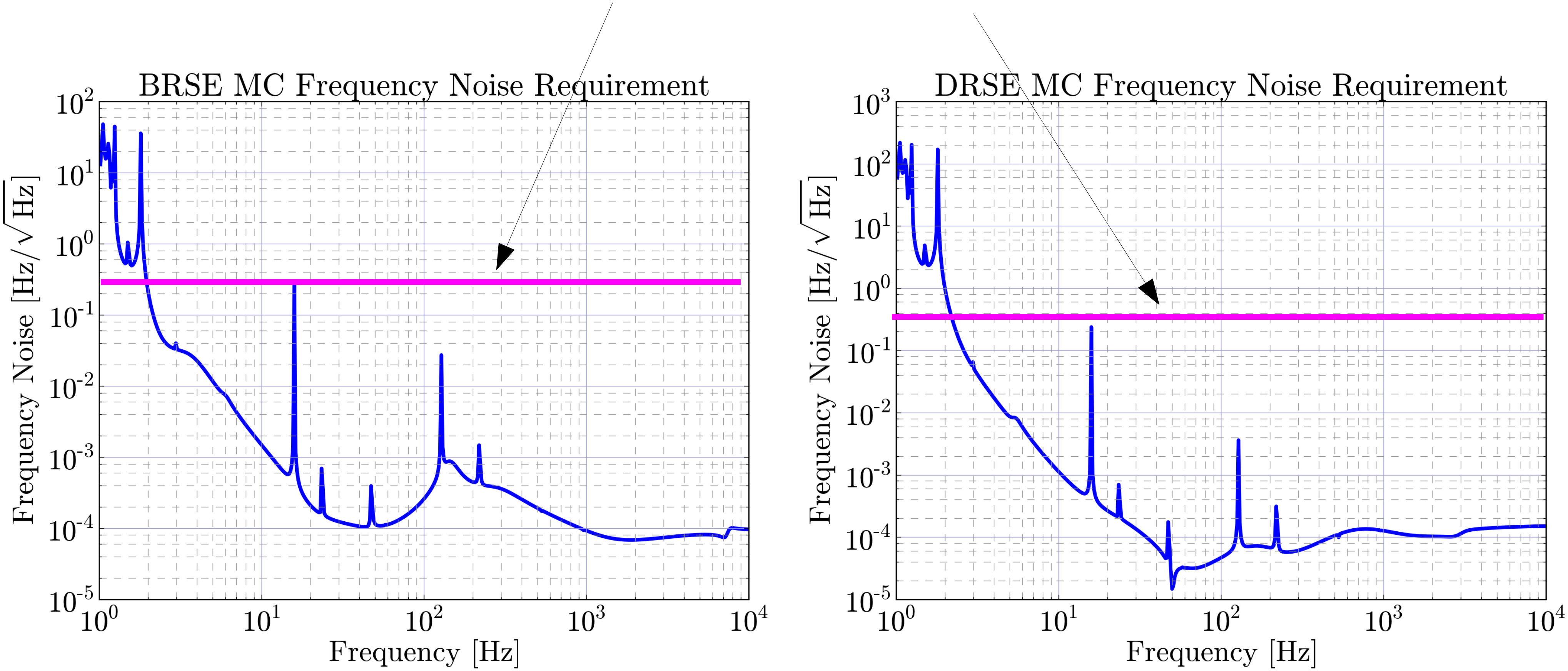


Frequency Stabilization Servo

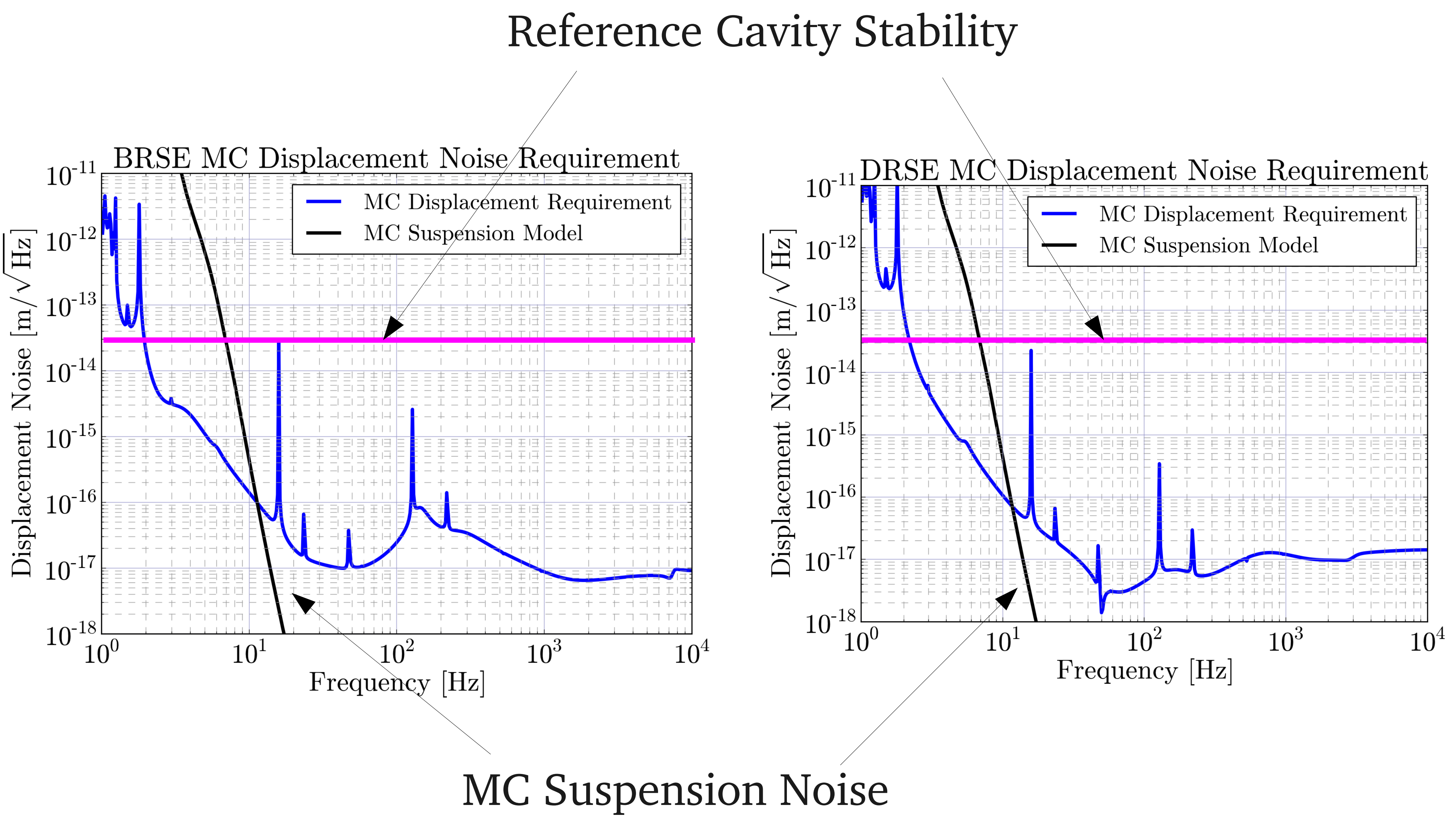


Laser Frequency Noise Requirements

Reference Cavity Stability

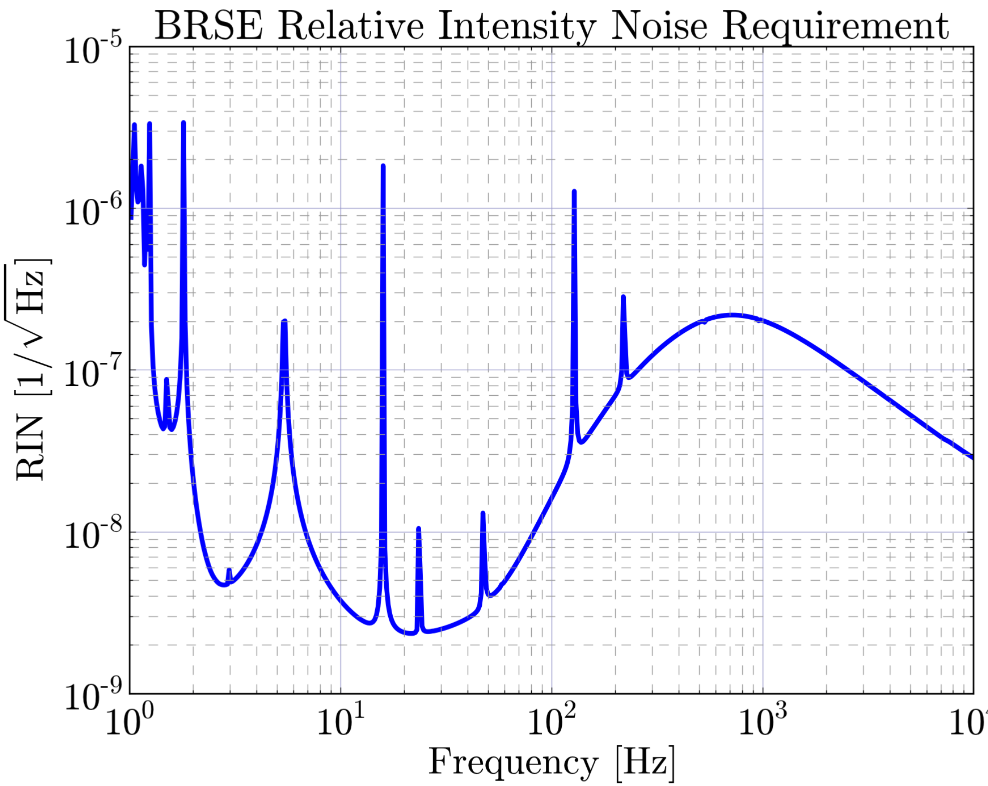


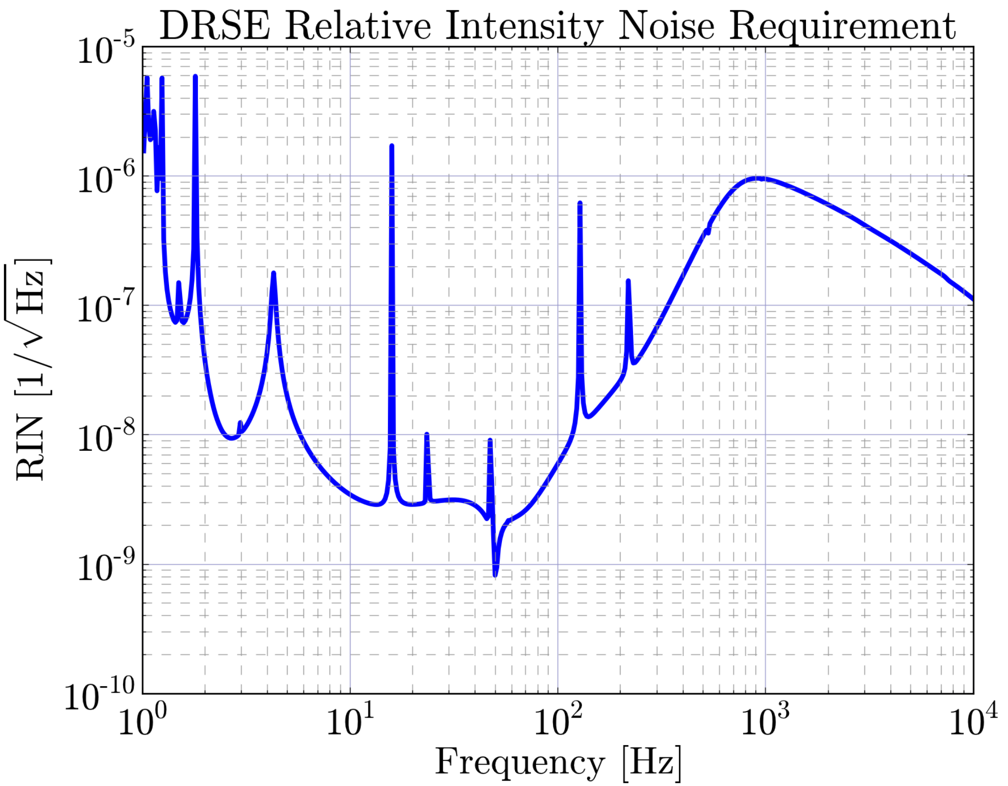
In terms of the MC displacement noise



Laser Intensity Noise Requirements

Relative Intensity Noise (RIN)

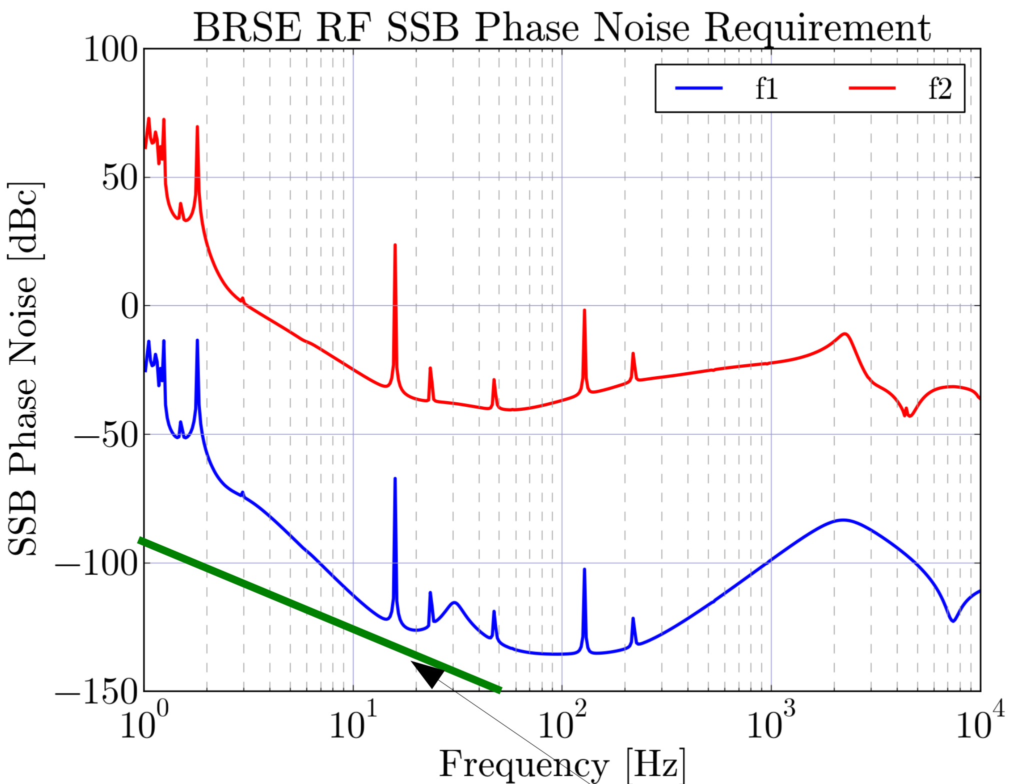


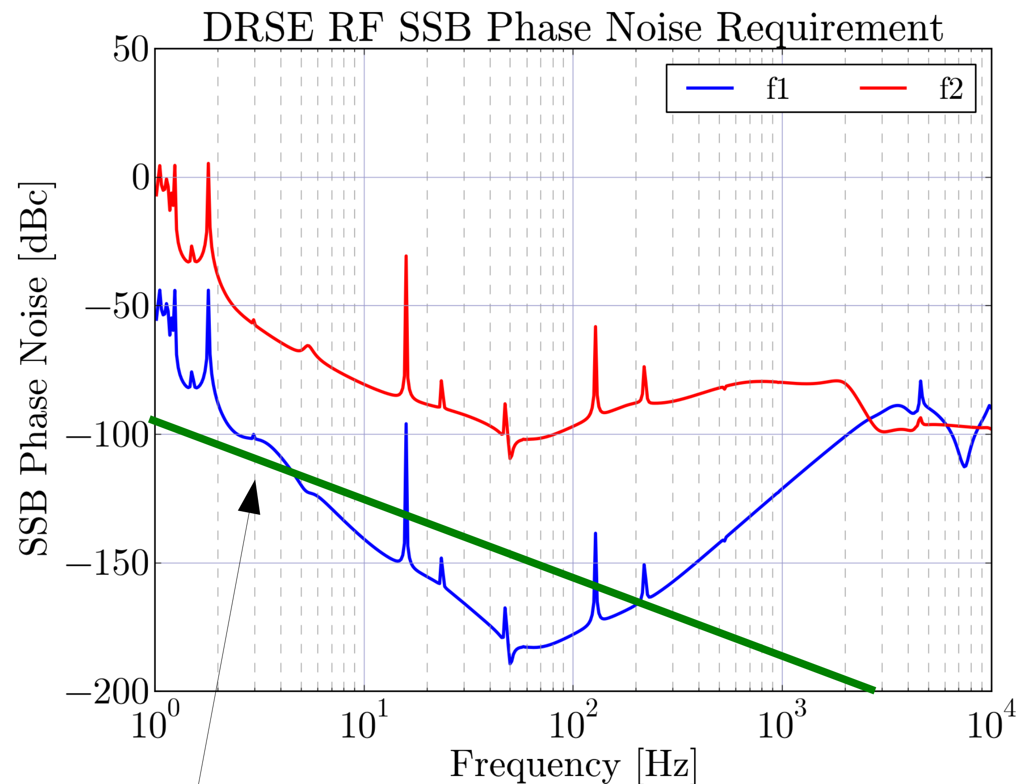


RIN = 10^{-9} is tough to achieve

RF Oscillator Phase Noise Requirements

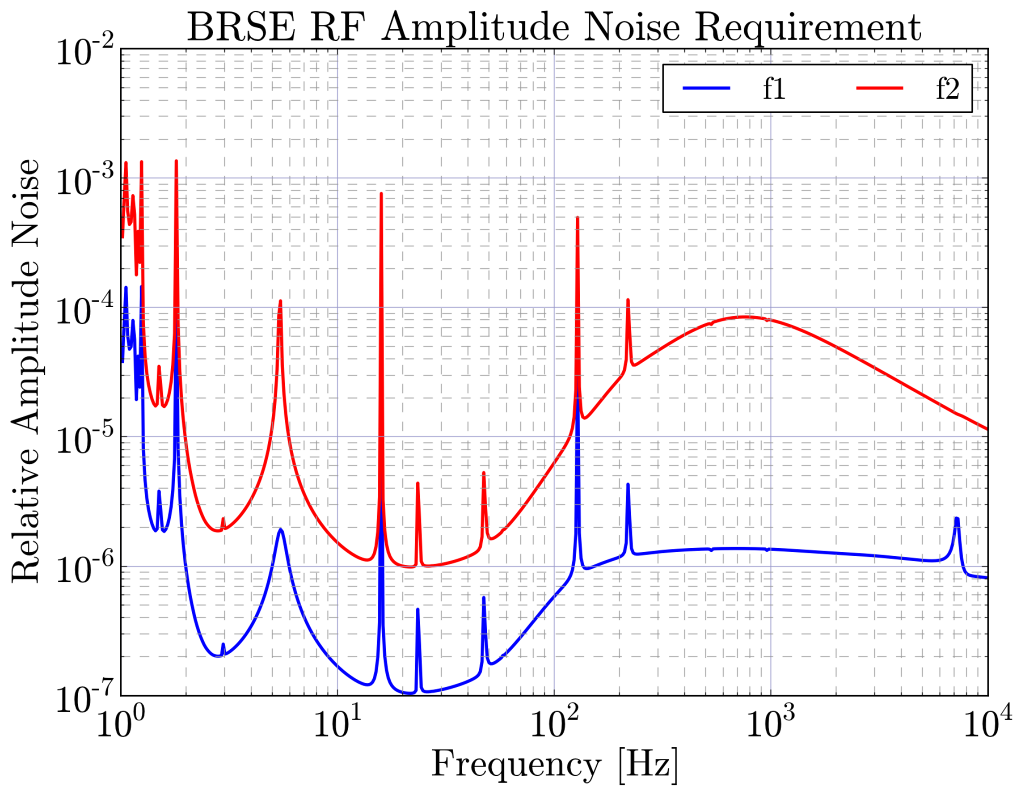
Single Sideband (SSB) Phase Noise = (Phase Noise SB Power)/(Carrier Power)

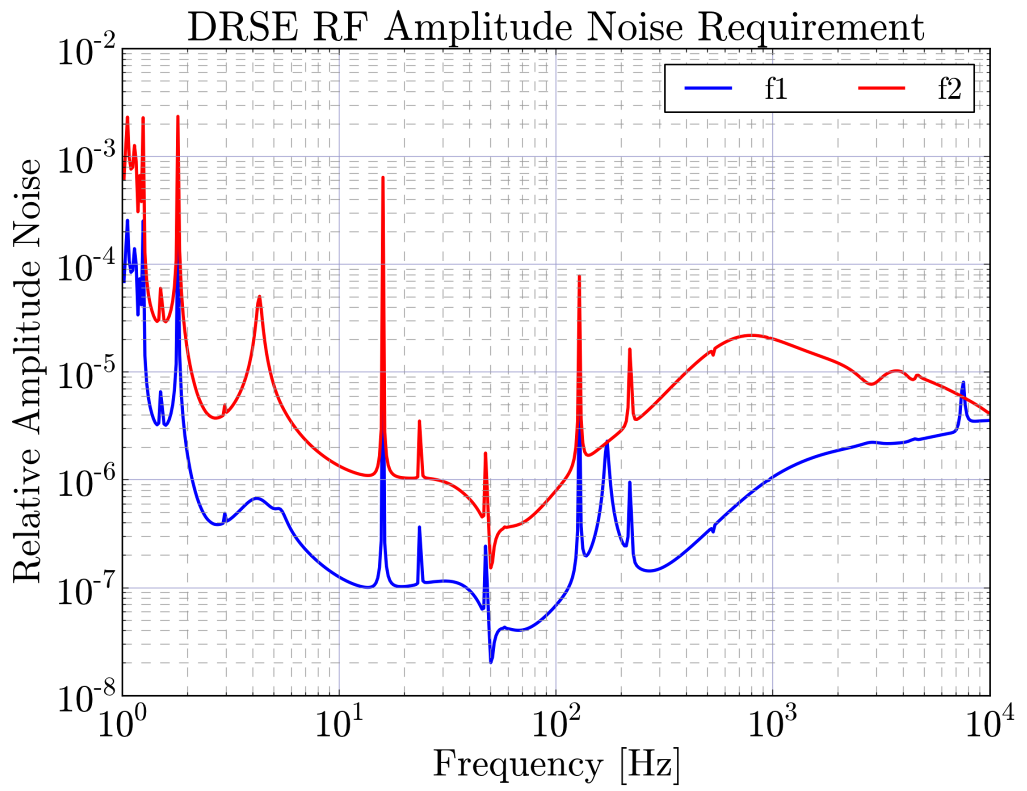




Wenzel OCXO

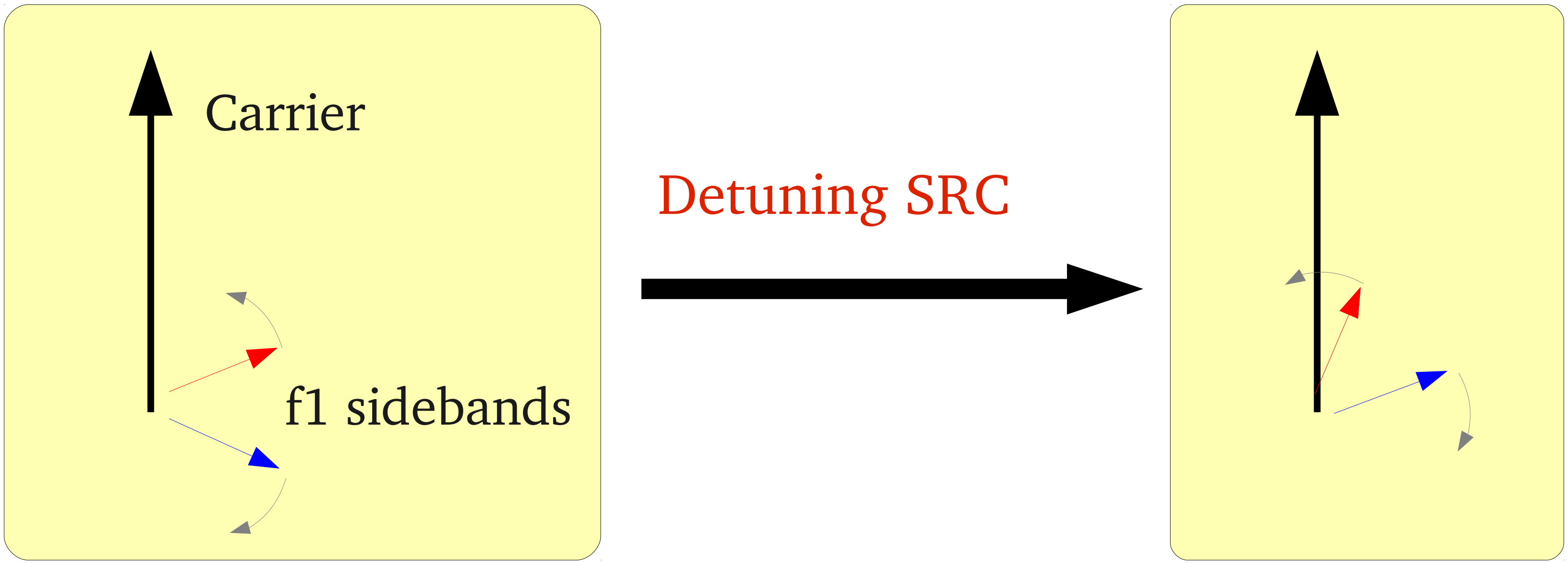
RF Oscillator Amplitude Noise Requirements





RF Amplitude 1V - Noise 100nV

Why are noise requirements for DRSE more stringent ?

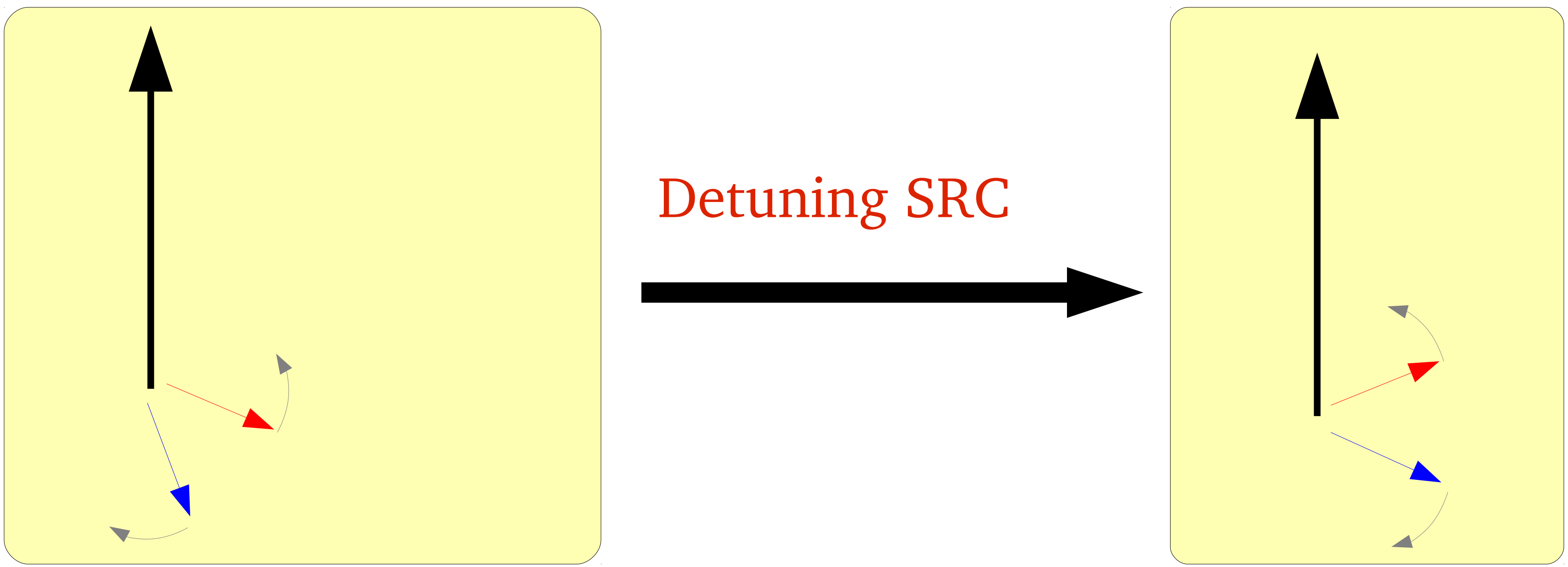


Pure Phase Modulation

Mixed Amplitude/Phase Modulation

→ Offset in the error signals

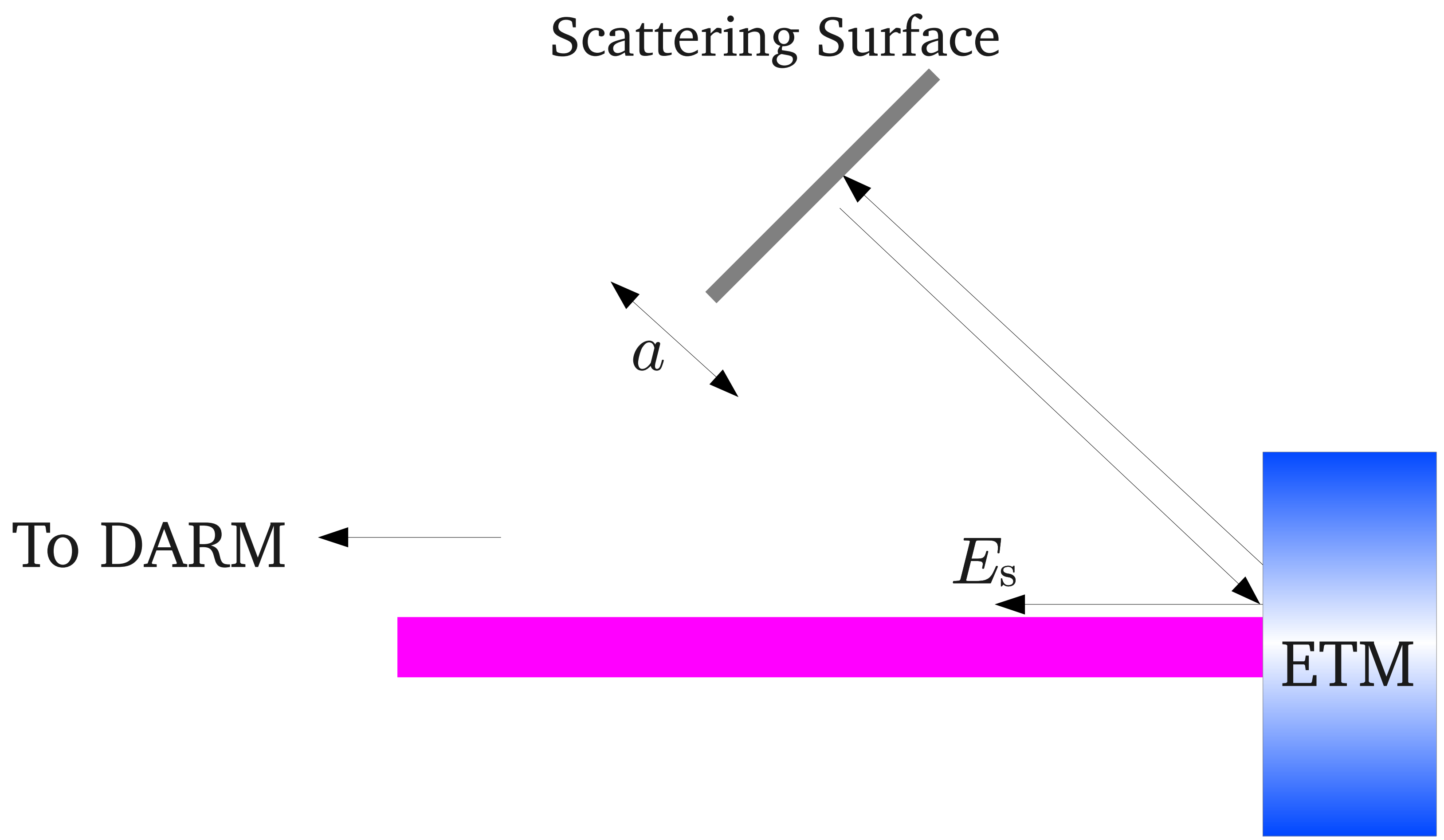
Solution ?



Prepare f1 as a mixture of AM/PM

Pure Phase Modulation

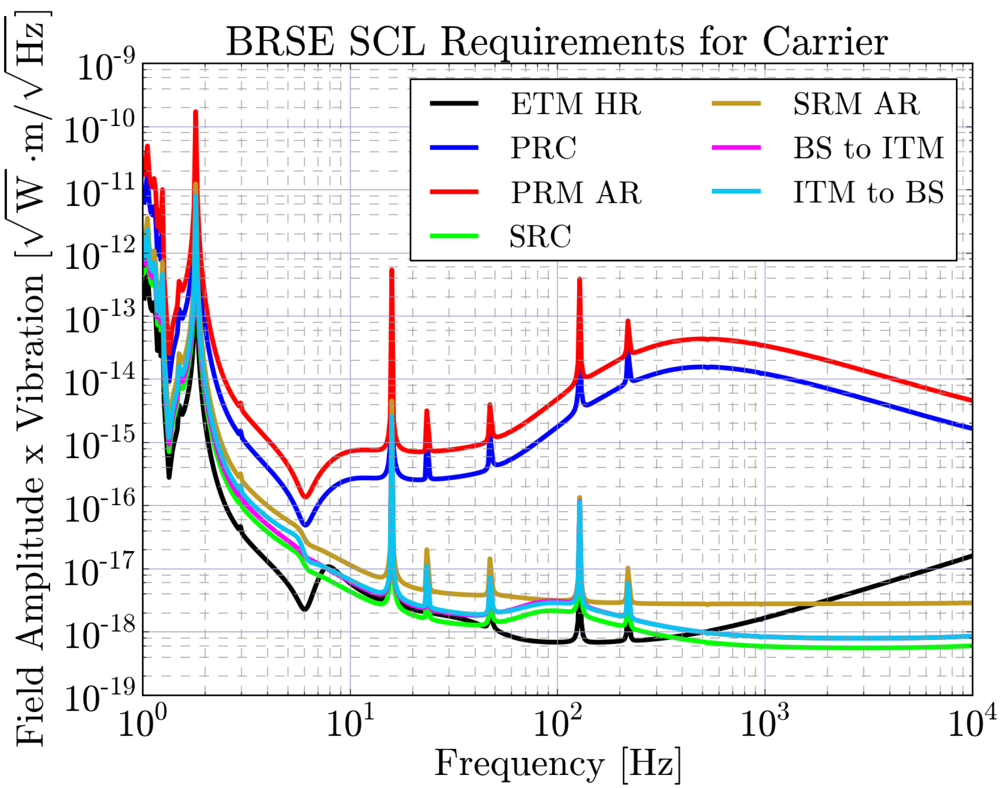
Scattered Light Modeling

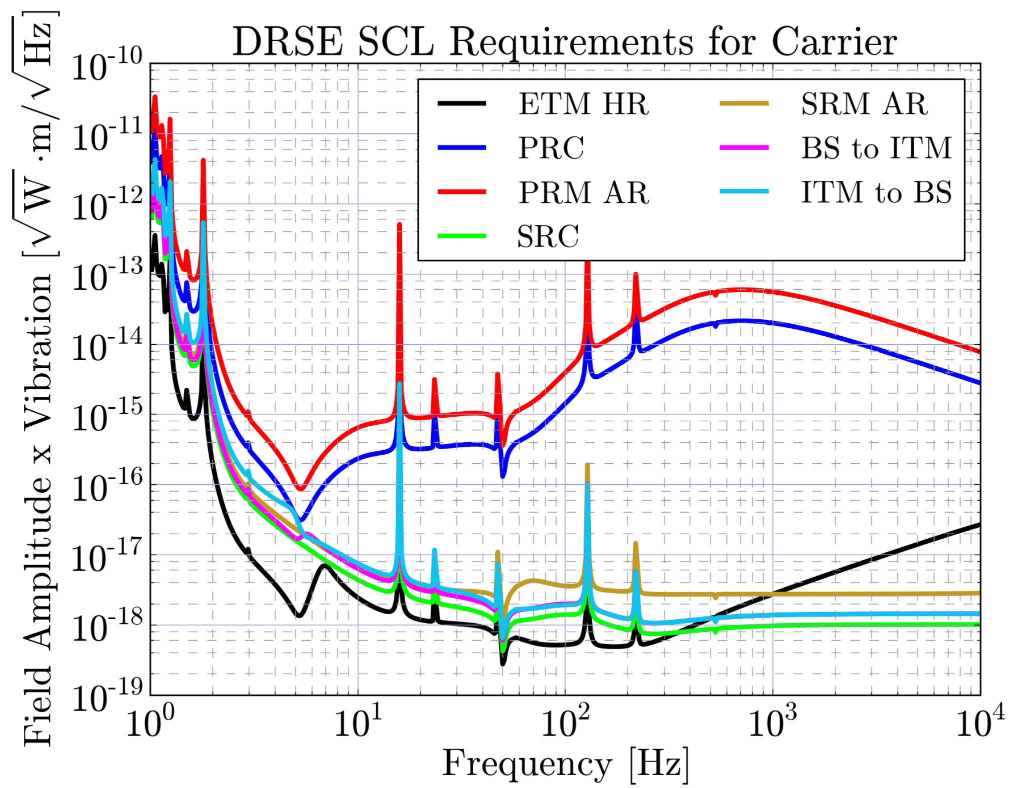


Scattered Light Noise $\propto E_{\mathrm{s}} \cdot a[\sqrt{\mathrm{W}} \cdot \mathrm{m}/\sqrt{\mathrm{Hz}}$

Requirements for Scattered Light Noise

$$E_s \cdot a \quad [\sqrt{W} \cdot m/\sqrt{Hz}]$$





Actual Scattered Light Noise: Calculation by Mike Smith

→ Proper arrangement of baffles will reduce the scattered light noise below the requirements

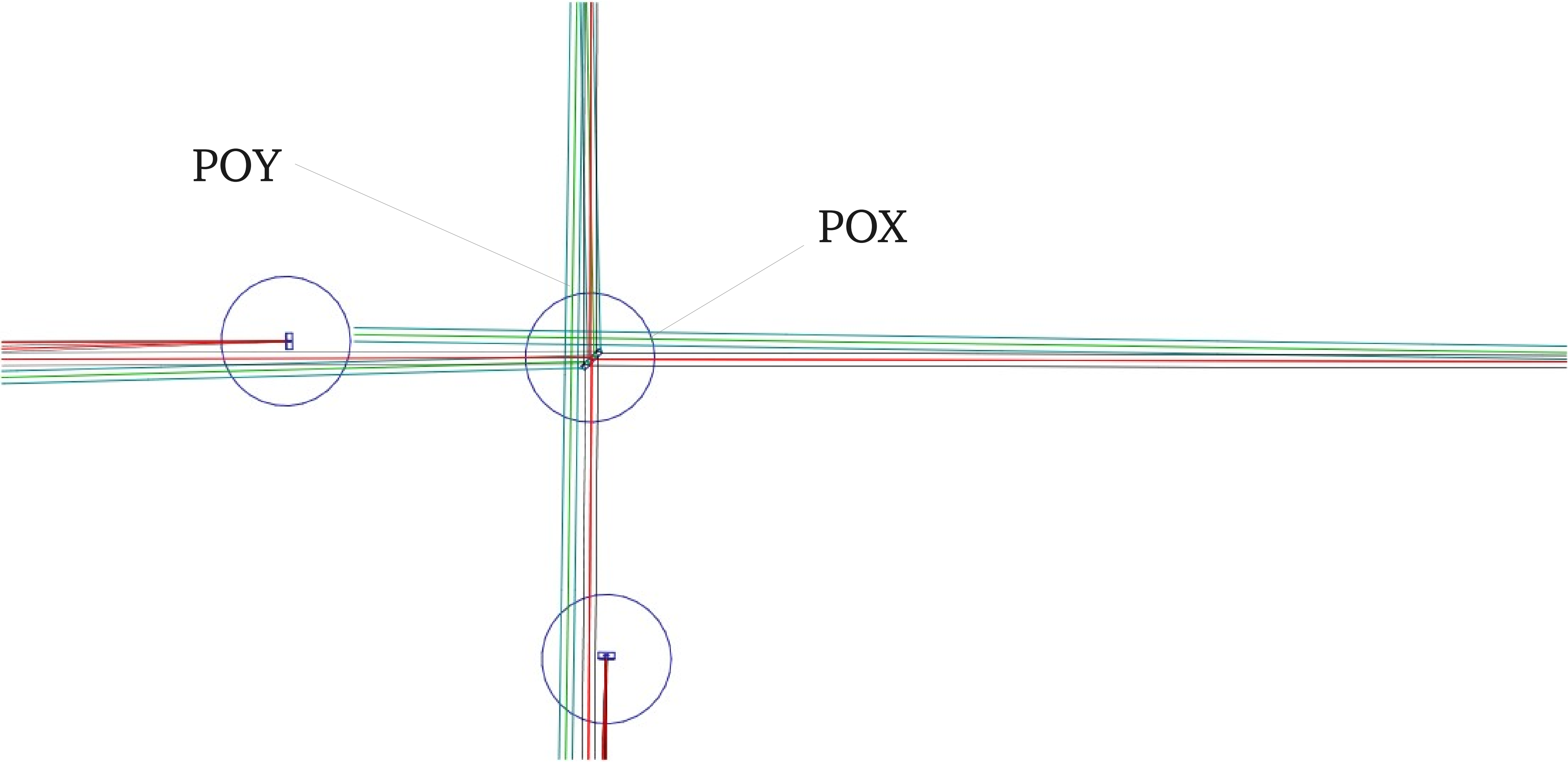
Optical Layout Issues

- Smaller Wedge Angles
- New POX/POY Extraction Ports
- RC Mirror ROC Error Tolerance
- Wedge Angle Error Tolerance

New Layout Philosophy

A Big Help from Mike Smith !

Before



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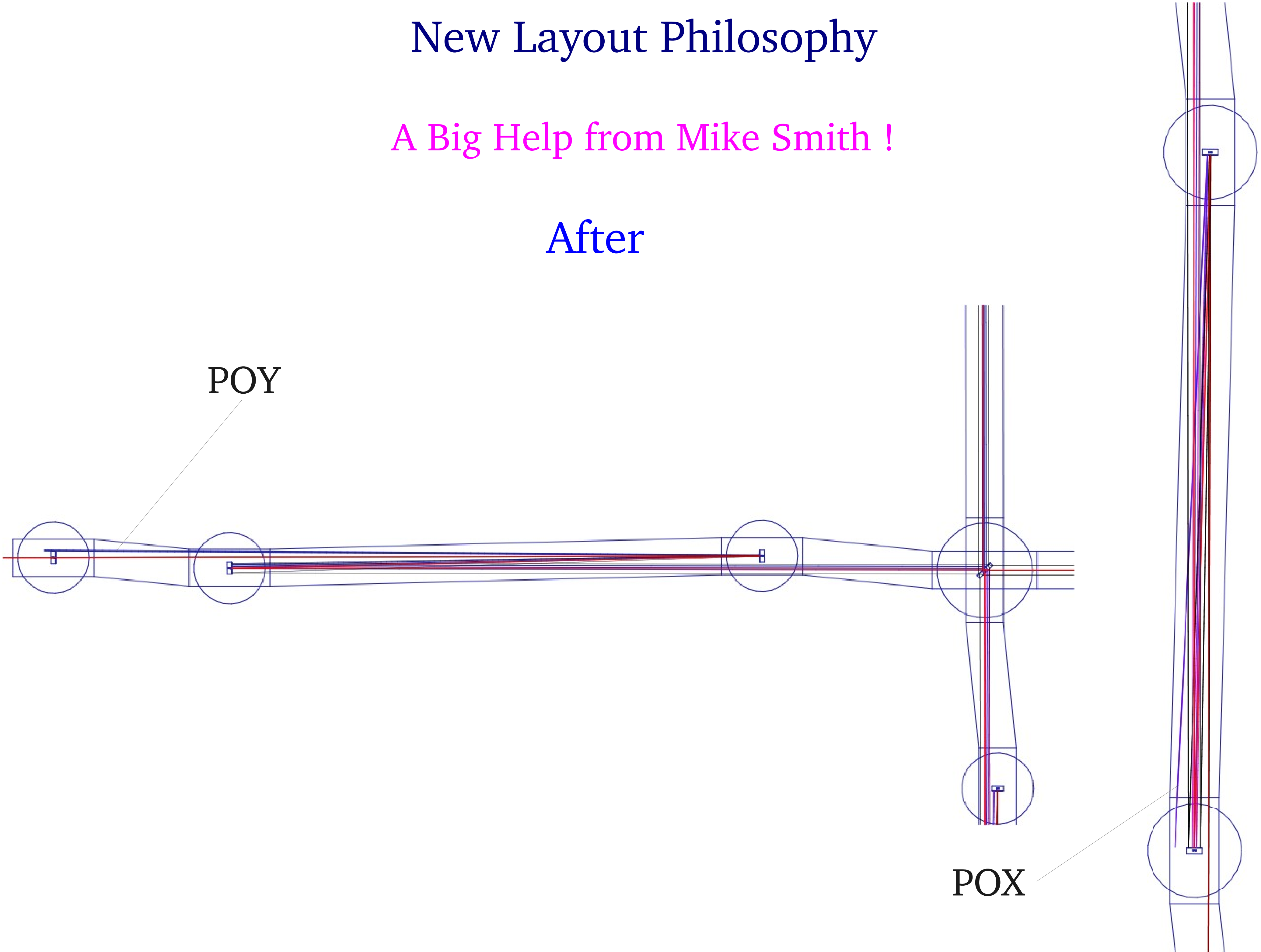
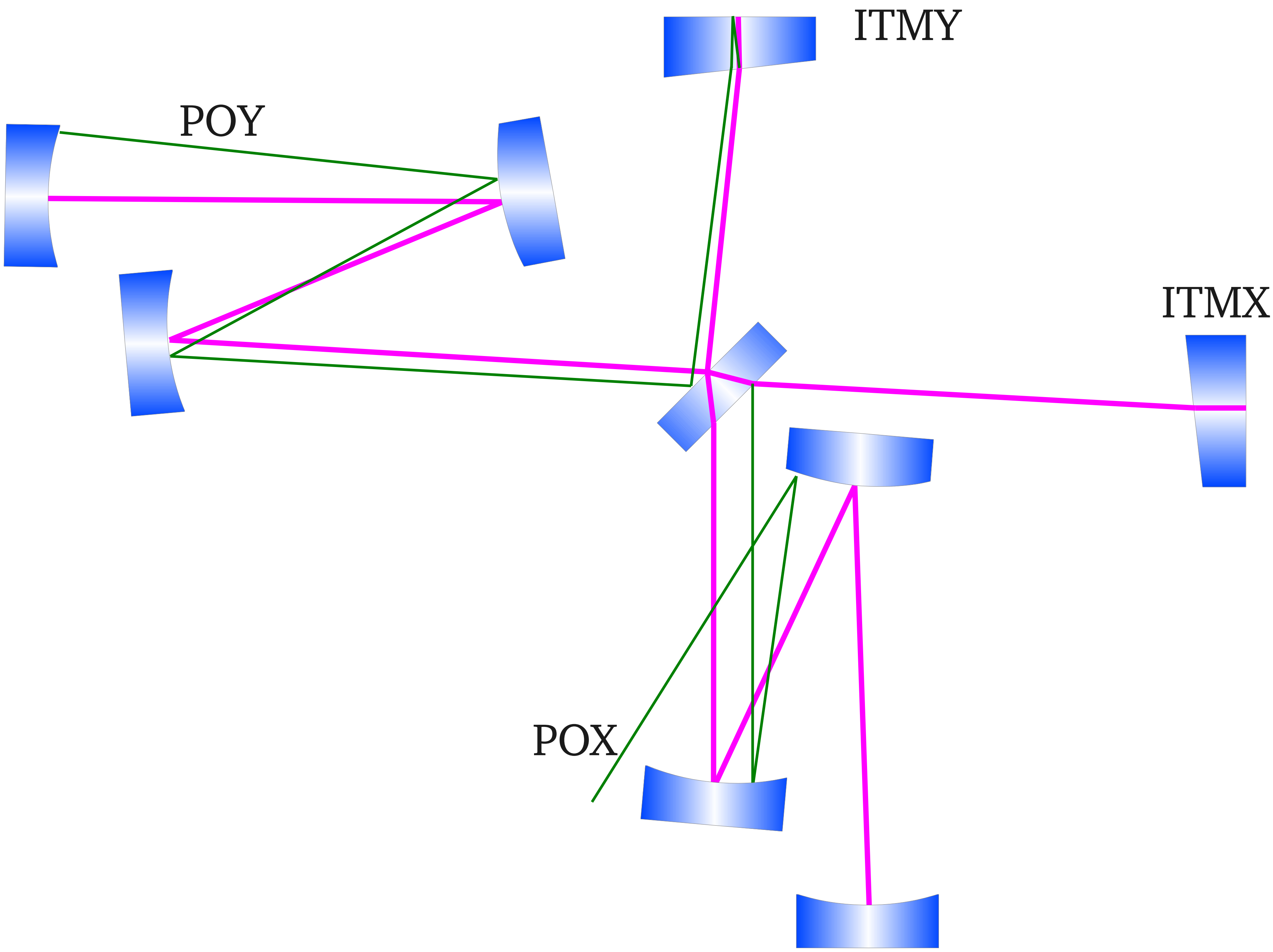
After





ITMY
POY
ITMX
POX

However, we cannot use Mike's layout as is.

New functionalities added to GTrace

- Non-sequential trace mode
  - Automatically trace all stray beams
  - Termination criteria: power, number of AR reflections
- Better rendering of beam width

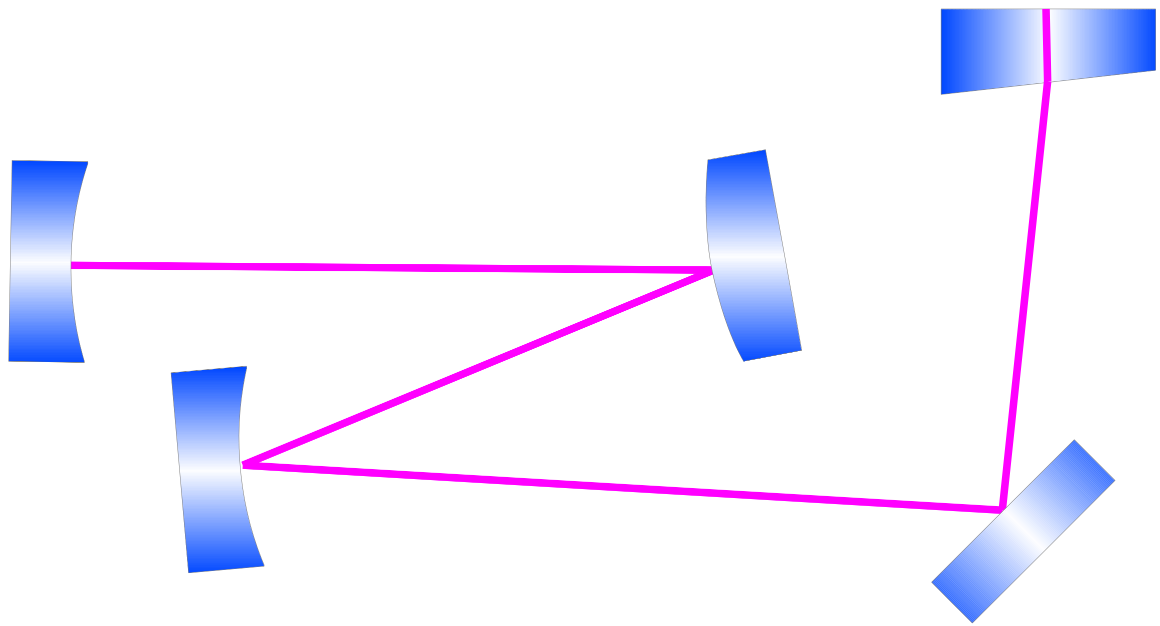
Wedge Angle Error Tolerance

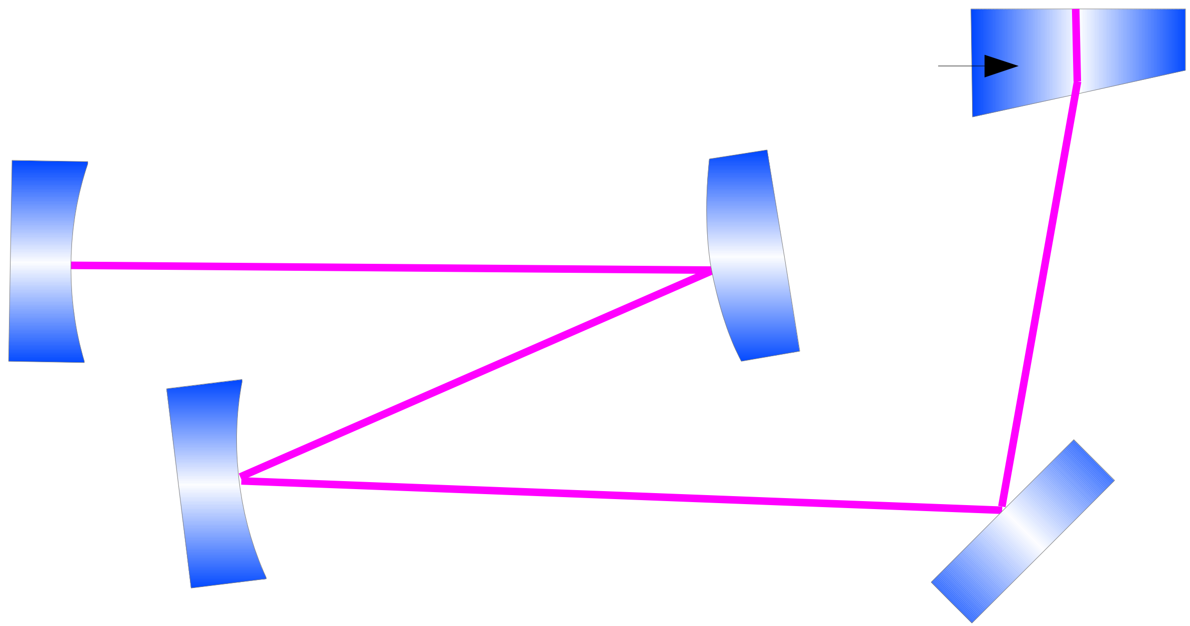
ITM Wedge Angle = 0.013(+0.003/-0.005) deg
BS Wedge Angle = 0.07(+0.005/-0.01) deg

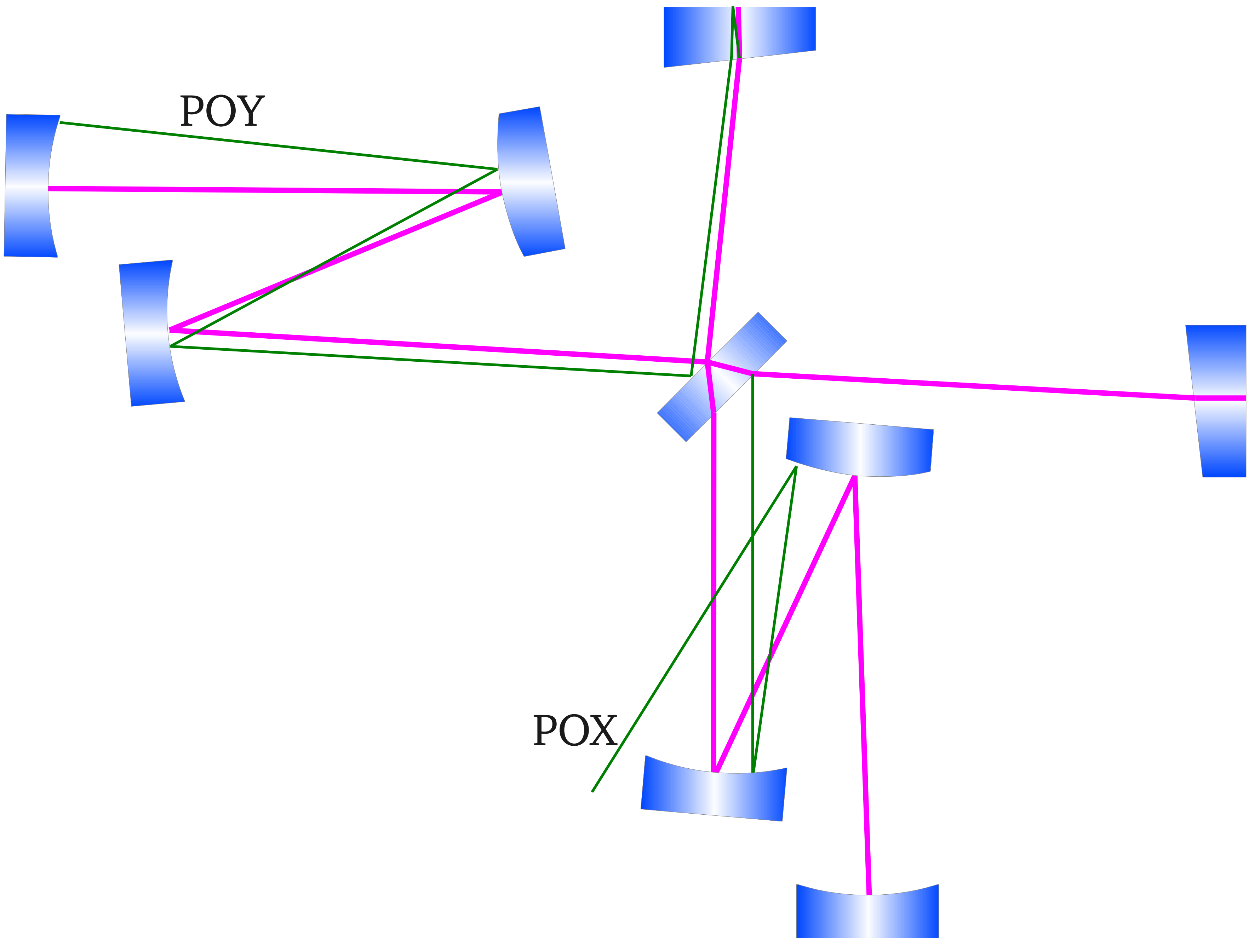
Wedge Angle Error → Optimal incident angle to BS from PRC changes
→ Positions of PR3/SR3 and ITMs change < a few mm

POX/POY beam separation from the main beam changes

Scan all possible combinations of error polarities in BS, ITMX and ITMY
→ Worst case scenario



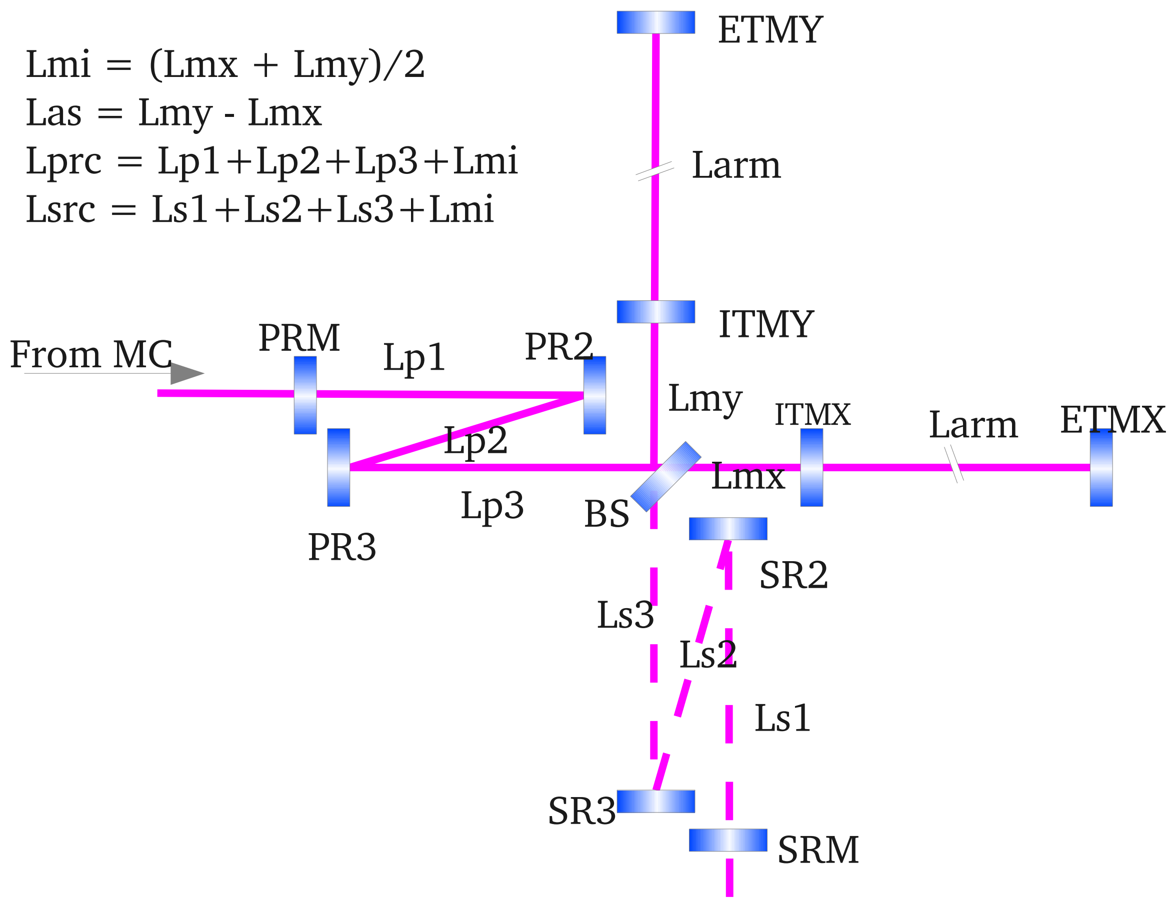



POY
POX

ROC Error Tolerance

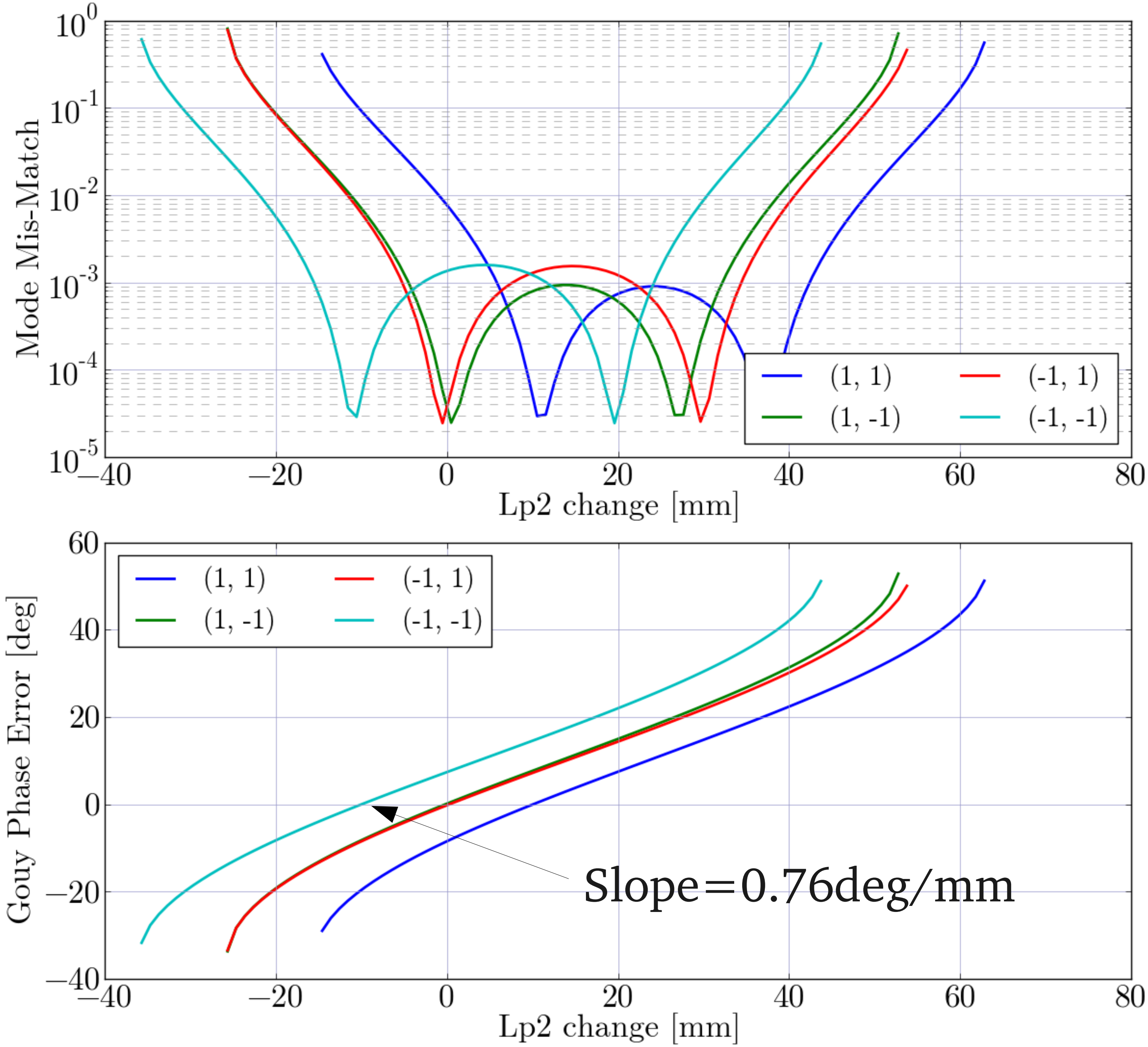
ROC Error of PR2/PR3 → Mode Mismatch , Gouy Phase Error

ROC error can be corrected by changing Lp2

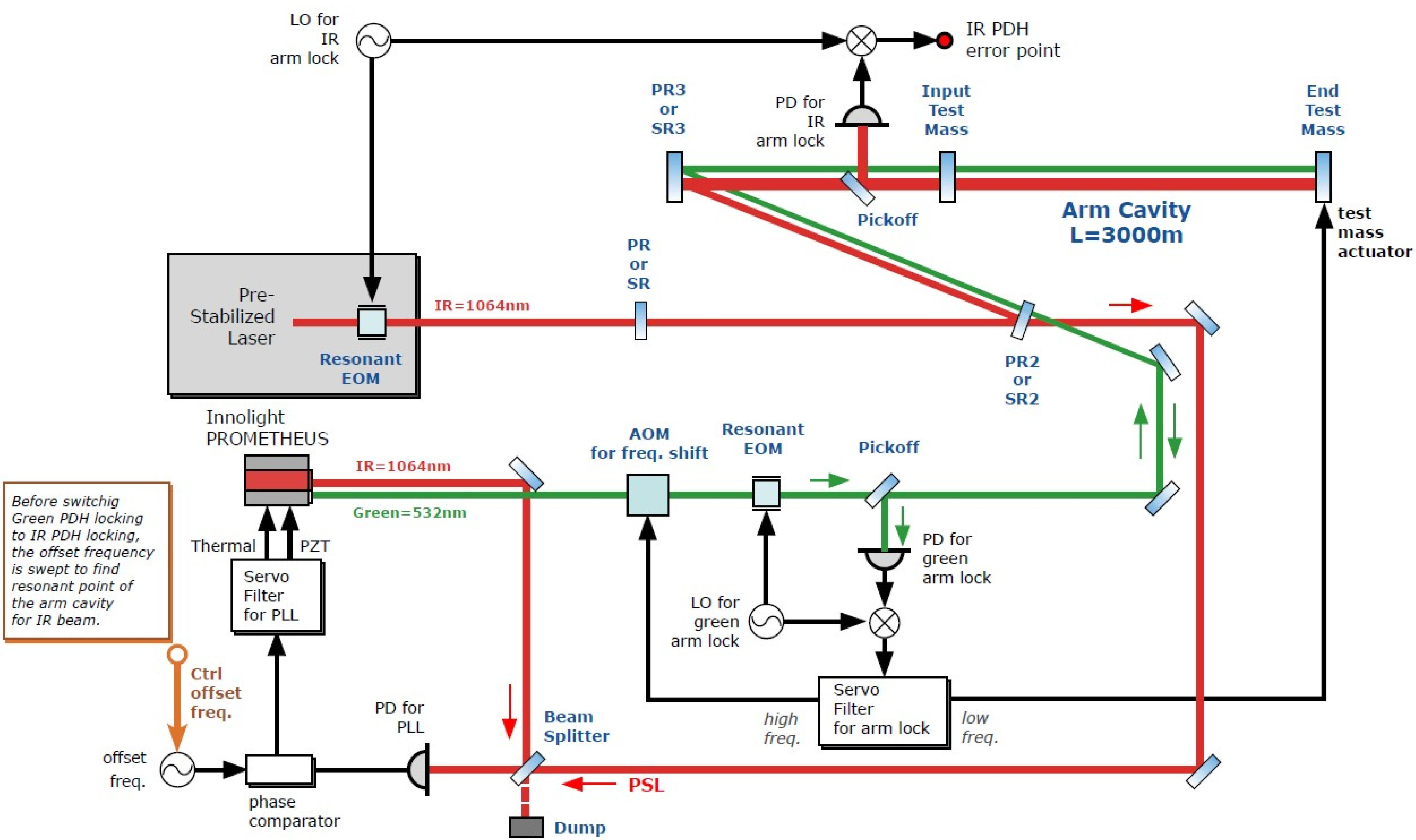


ROC error correction by Lp2

ROC Error = 1cm



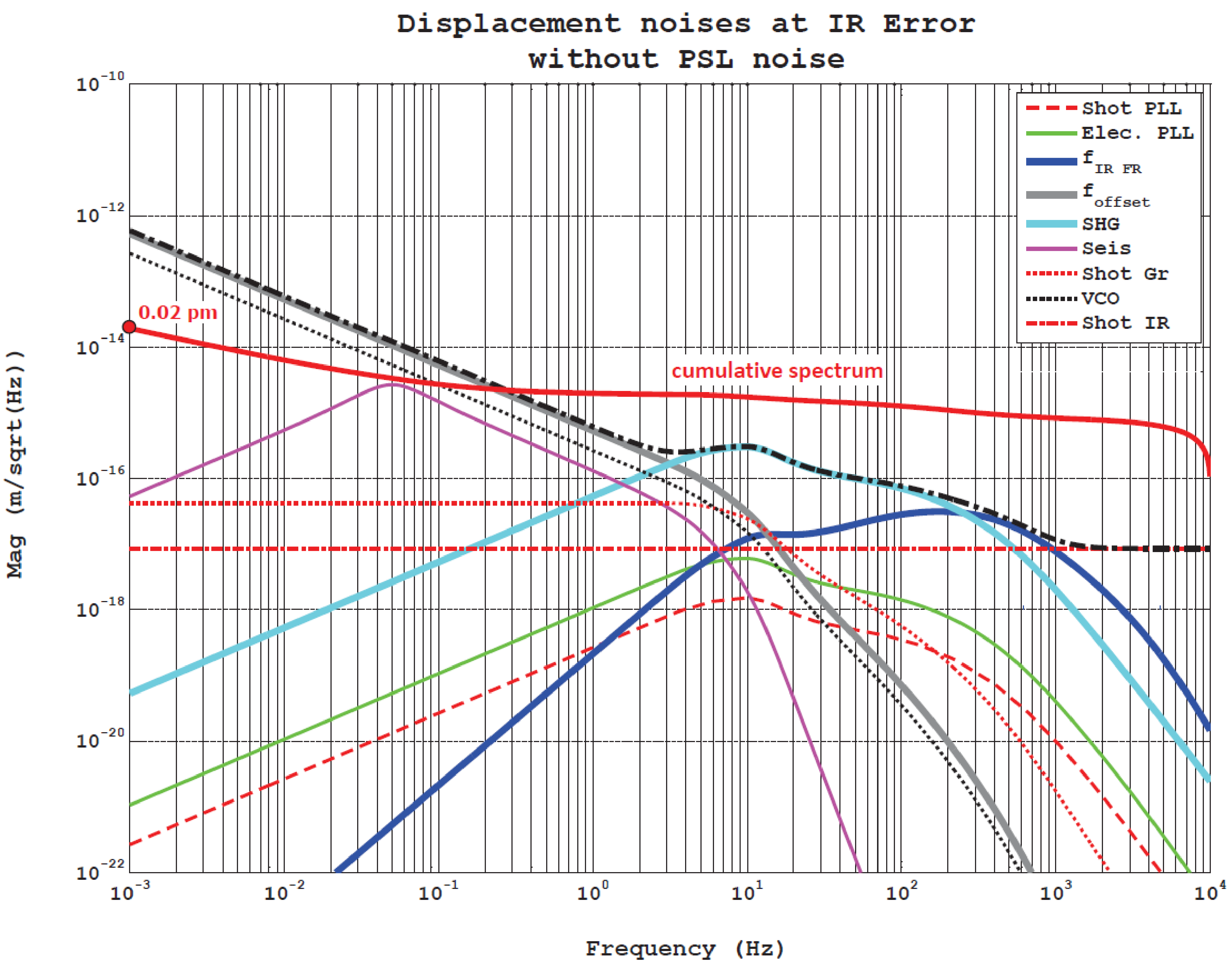
Green Lock Setup



D. Tatsumi & K. Arai

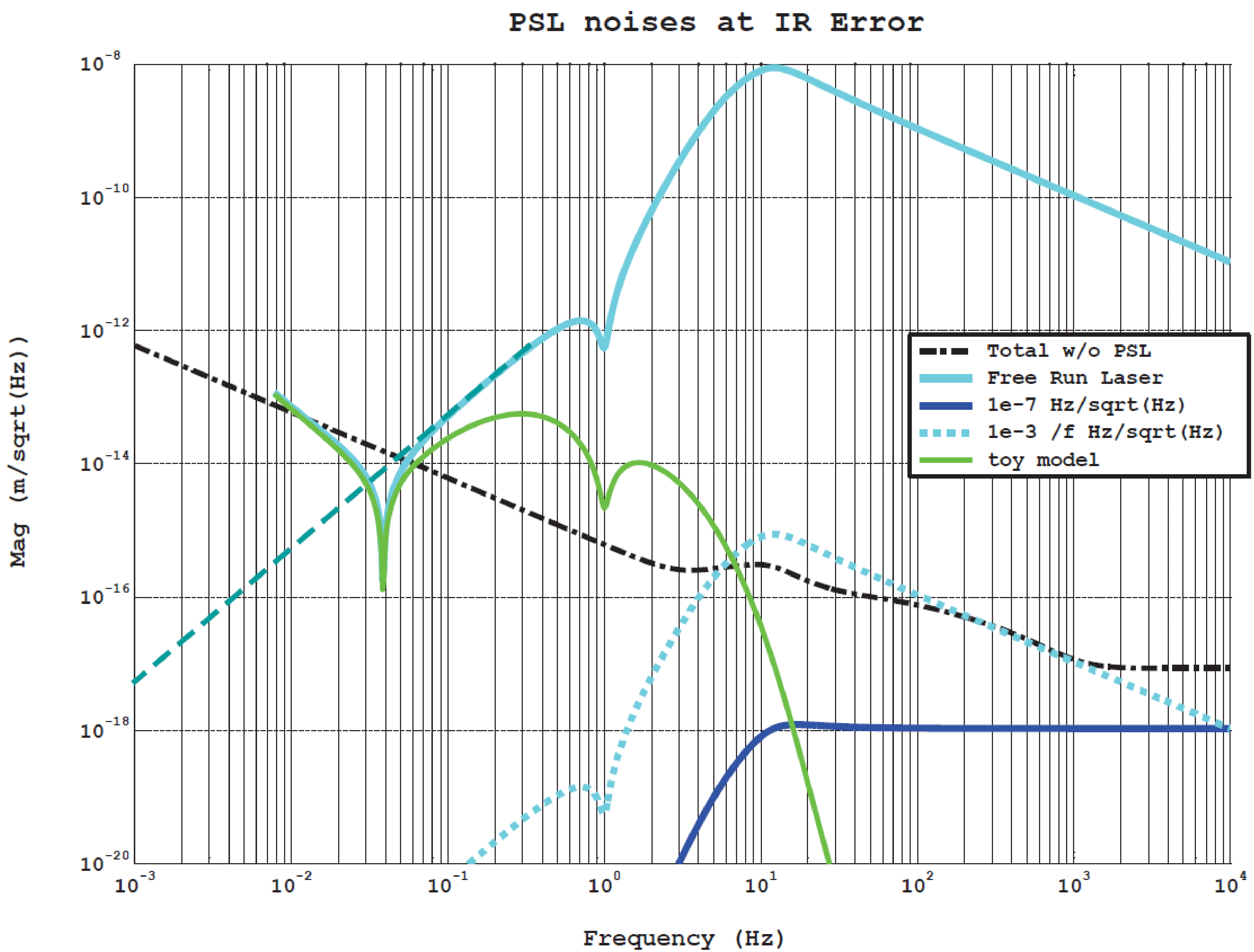
Arm Cavity Stability after Green Lock

Requirement: 0.3pm RMS

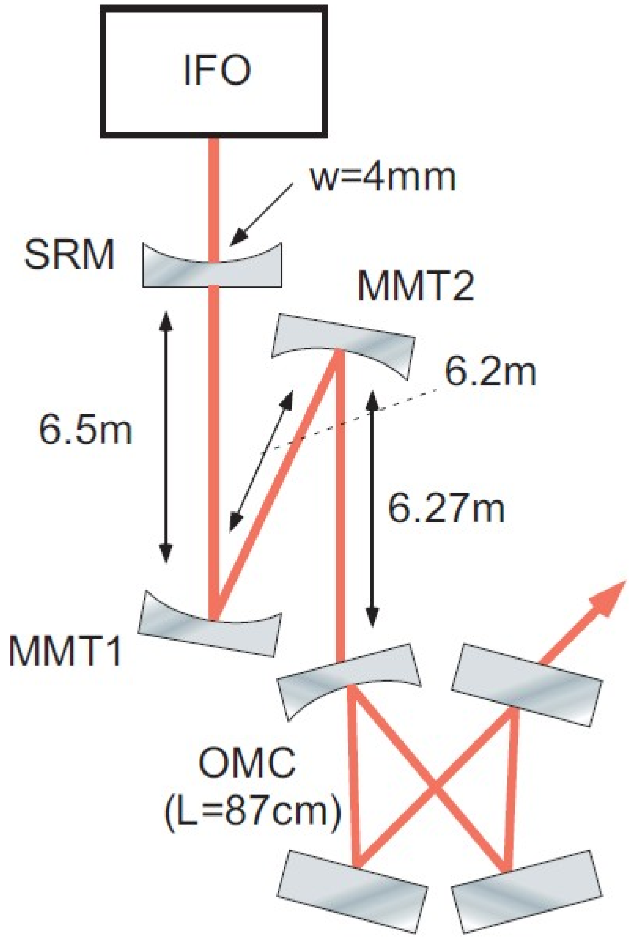


Arm Cavity Stability after Green Lock

Requirement: 0.3pm RMS



OMC

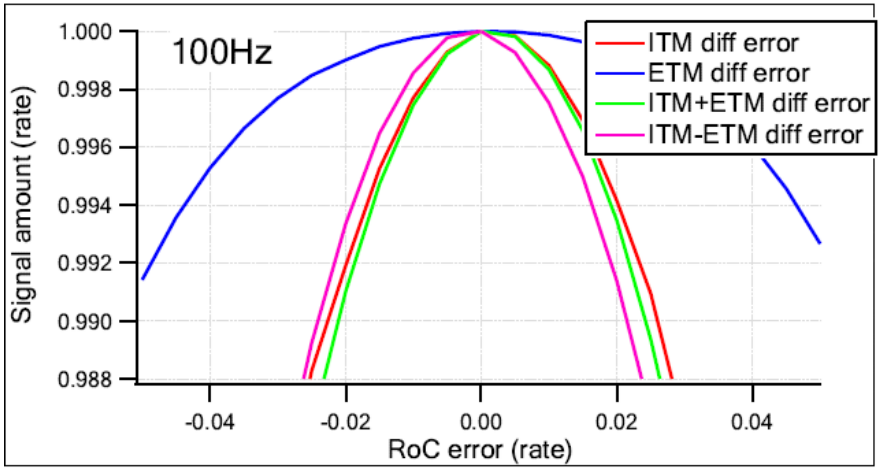


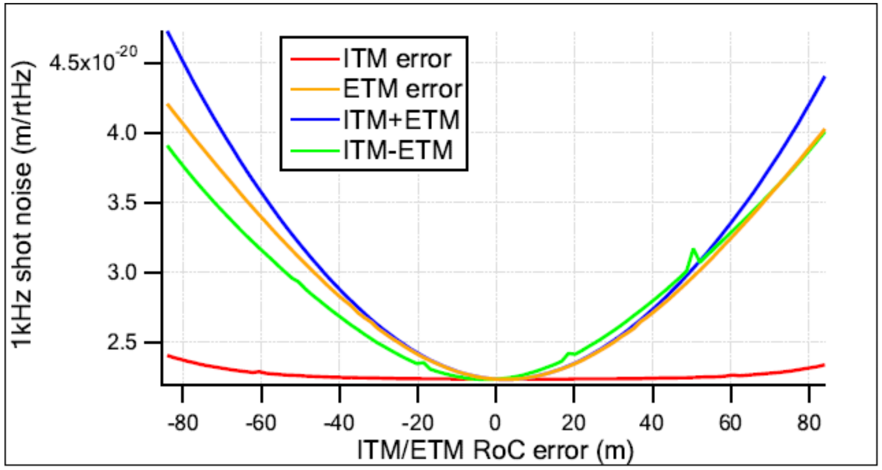
Conceptual Design by K. Somiya

	TEM00	TEM20	TEM02	TEM40	TEM04	TEM22
RF	$4\mu W$	4nW	4nW	$< 1nW$	$< 1nW$	$< 1nW$
	TEM00	TEM20	TEM02	TEM40	TEM04	TEM22
DC	$980\mu W$	100nW	100nW	$< 1nW$	$< 1nW$	$< 1nW$

Transmission Power after OMC

Signal Loss/Shot Noise Increase
by TM ROC Errors





Prototype Test

- ISC simulation using virtual interferometer on RTS
- Green injection table will be tested beforehand (Kashiwa ? NAOJ ?)
- OMC
- AM/PM mixed modulation

Quality Assurance

Commissioning is QA for MIF

Risk Management

Risk factors

- Arm cavity loss is too large: PRC under-coupled
  => Prepare a spare PRM with lower reflectivity
- Arm cavity reflectivities are so matched that the homodyne phase cannot be set to around 45°
  => Forget about BAE
- SRC detuning makes the practical noise couplings bigger
  => AM/PM mixture for f1 ?
- Commissioning takes too long (very likely to happen)
  => Work even harder folks !
- Lack of man power
  => Get money to hire people

iKAGRA

iKAGRA Design

Target Specs

- Stably operate Fabry-Perot Michelson Interferometer
- No sensitivity requirement

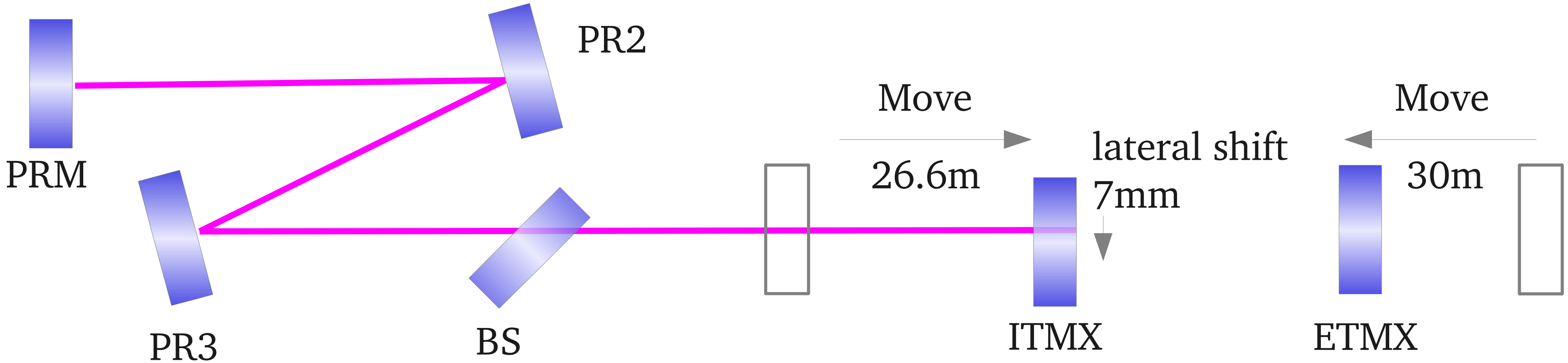
Final(?) Design

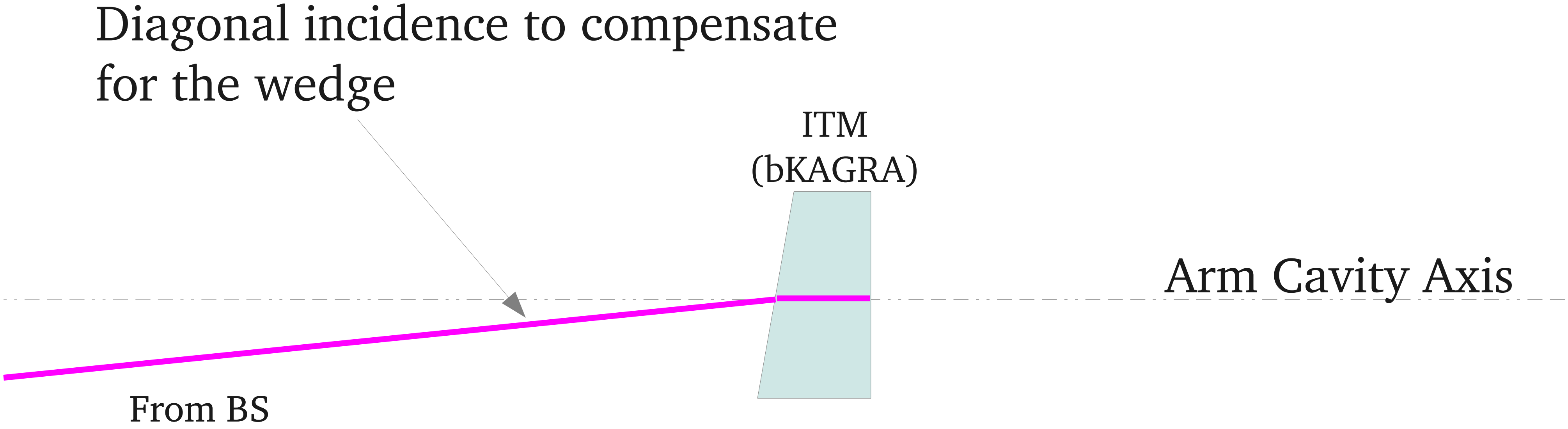
Based on bKAGRA design

- Use Silica TMs
- ROCs are the same as bKAGRA
- Locations of TMs are shifted by 26.6m/30m from bKAGRA
  - ITMs laterally shifted by 7cm
  - Arm GV is shifted accordingly
- No folding part optimization
- PRM will not be installed (PR2, PR3 will be)
- Tweak the Input MMT to get a reasonable mode matching
- SRC is isolated vacuum wise.
- Pick-off the AS beam before the GV
- Green lock may be tested with X-arm

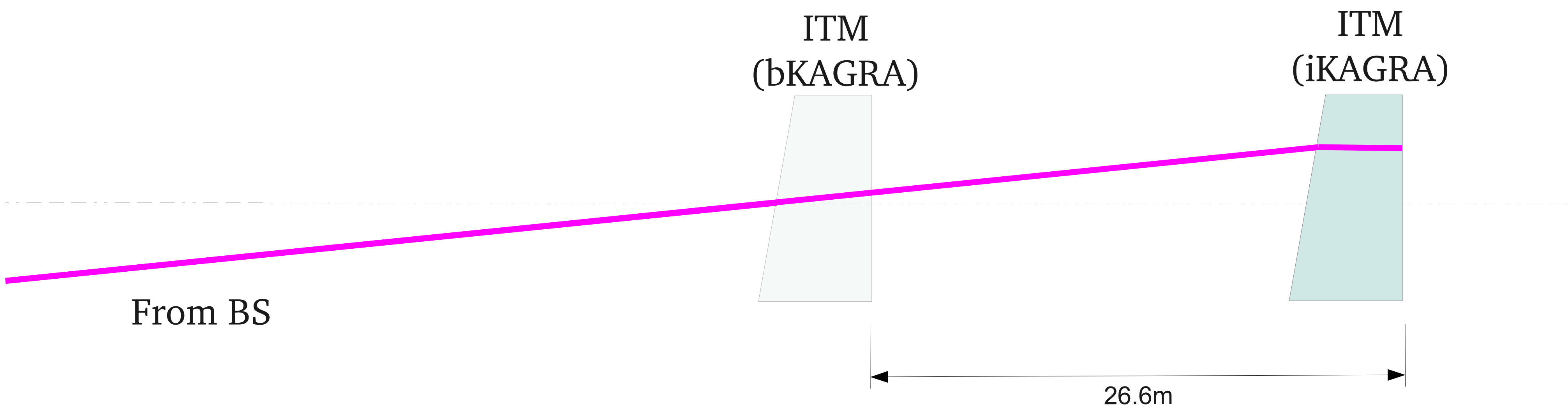
(Virtual) Layout Change in iKAGRA

Location of ITMs: Shifted by 26.6m from the bKAGRA position
Location of ETMs: Shifted by 30m from the bKAGRA position
ITM lateral shift: 7mm



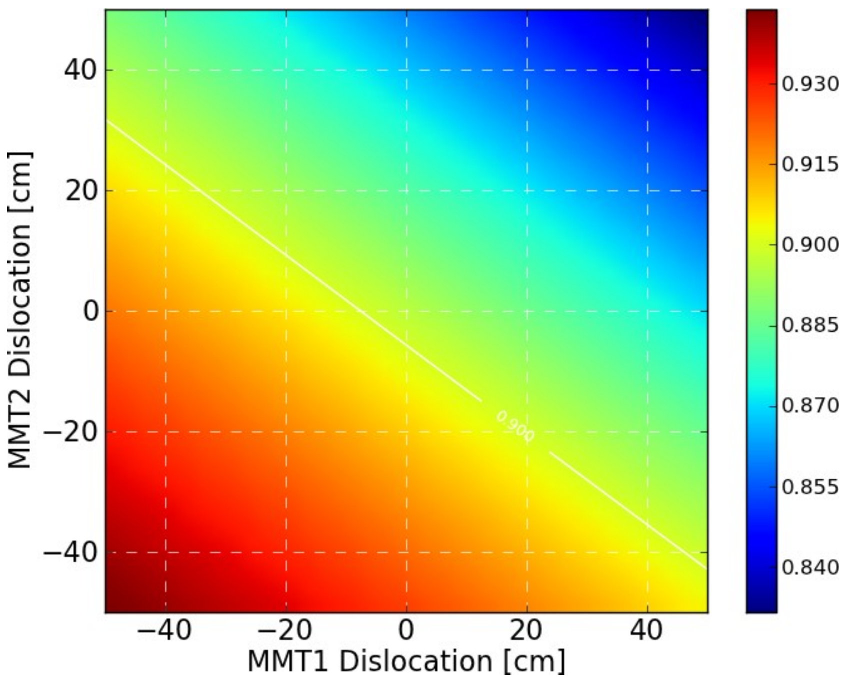

Diagonal incidence to compensate
for the wedge
ITM
(bKAGRA)
Arm Cavity Axis
From BS

Just moving the ITM 26.6m ahead will mis-center the beam

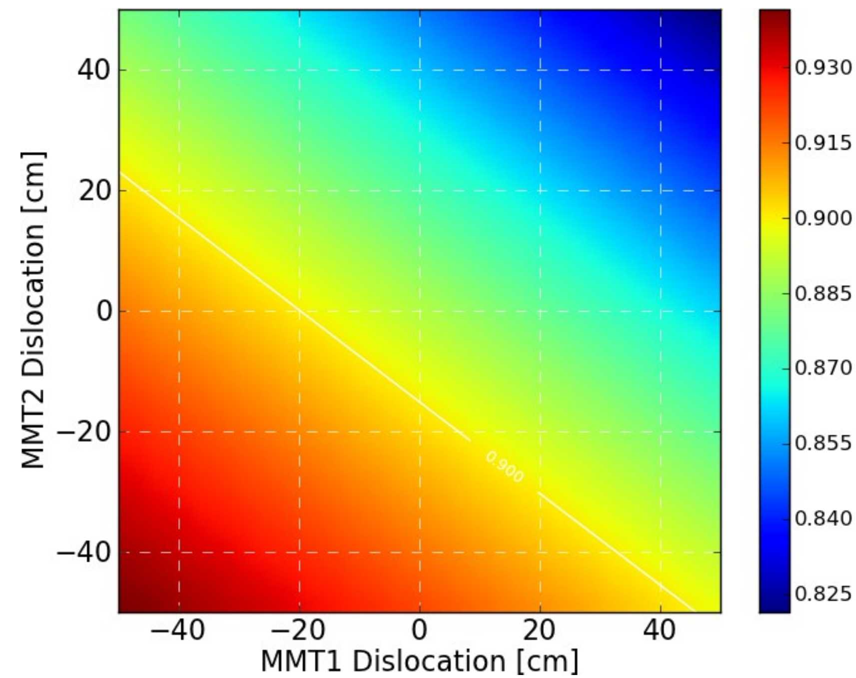


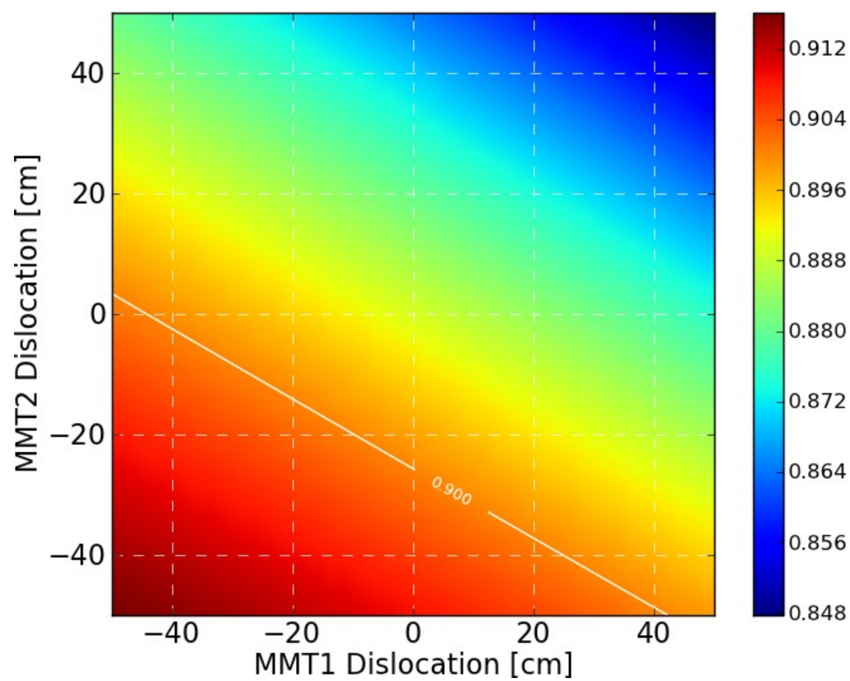
Mode Matching

With PRM



Without PRM





DRMI

JGW-G1200763-v1

iLIGO Test Masses for iKAGRA ?

Making new silica TMs costs a lot of money (~$1M)

Can we use the iLIGO TMs as is for iKAGRA ?

→ No ! the wedge angle is too much different

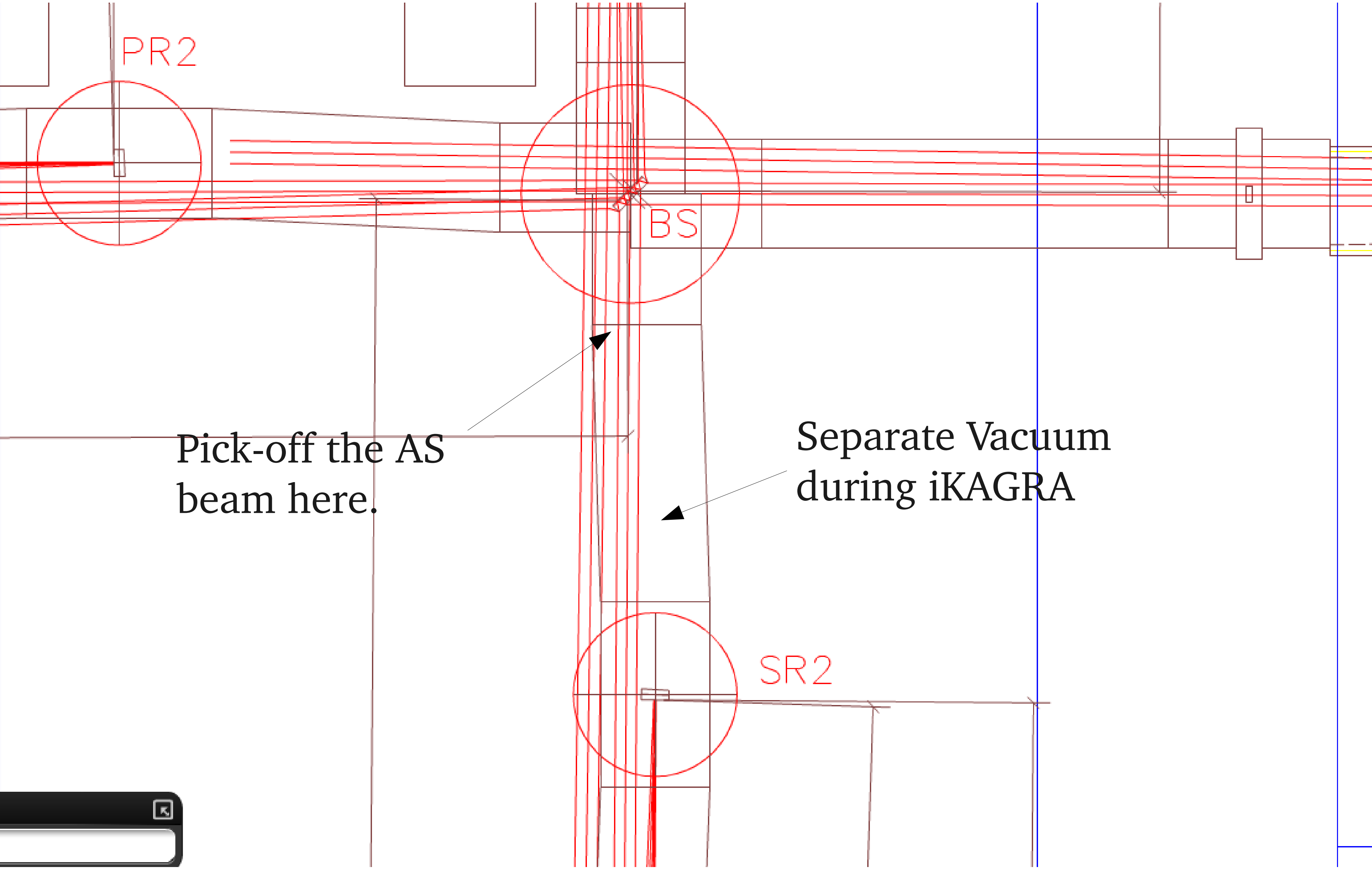
However

Is this possible ? → Re-polish and re-coat the AR surface

Even so, we have to at least make a new IMMT

Does this save money ?
Seems like cost more time.

Vacuum Isolation of SRC



Quality assurance

- Each component will be tested by corresponding subsystem (e.g. mirrors, laser, etc)
- The quality of MIF is the noise level of the interferometer
  - It is guaranteed that the quality will not meet the requirement at first
  - Thorough and careful planning for the commission is the best quality assurance

Risk Management

Risk factors

- StackB is too noisy
  => Strong damping, strong actuators at the expense of noise
- Laser frequency noise is too large
  => Spend more time on the frequency stabilization servo
- Mirror quality is poor
  => ....
- Commissioning takes too long (very likely to happen)
  => Work harder folks !

Schedule

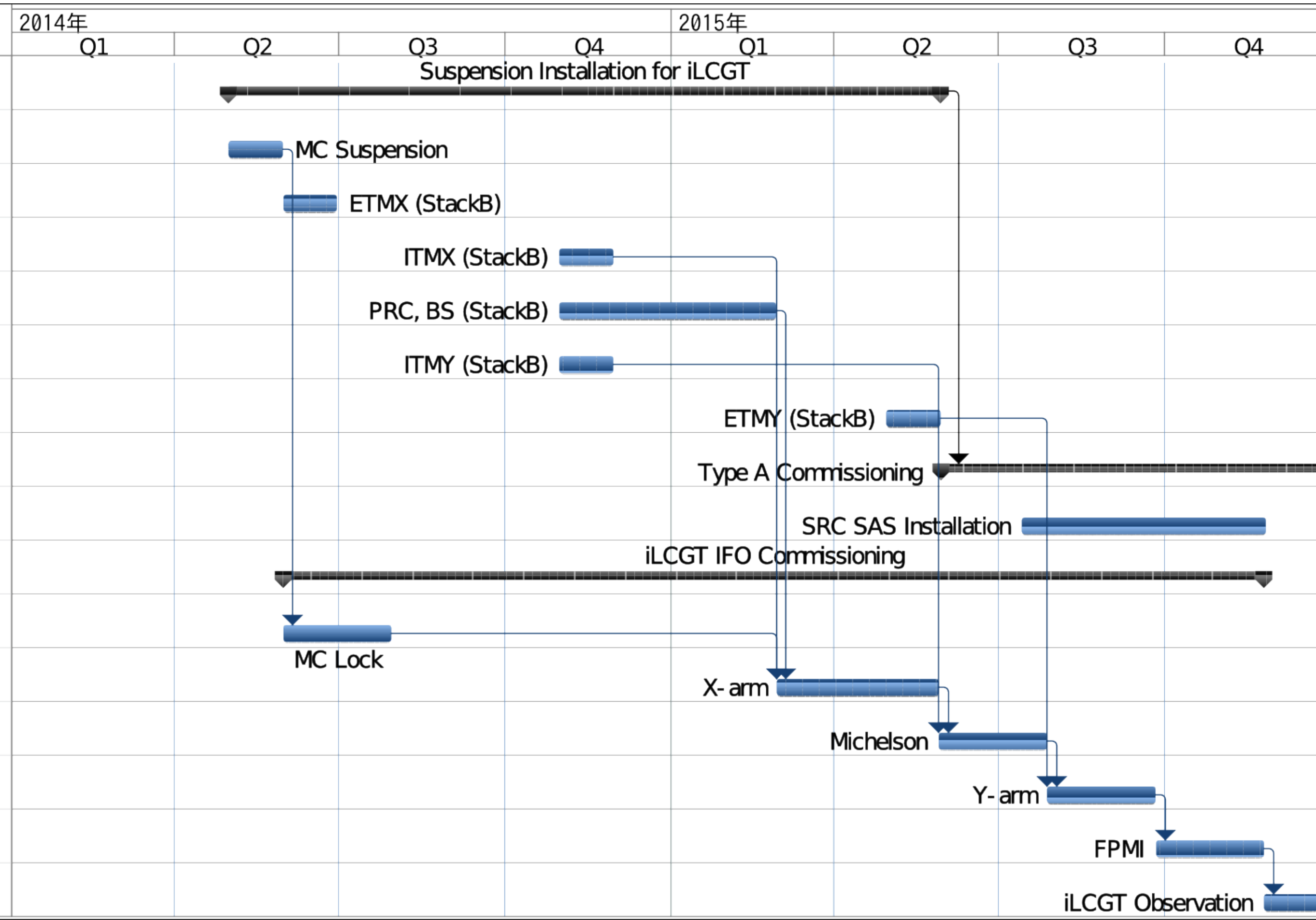
Task list during tunnel excavation (to be finished by March 2014)

- LSC/ASC Servo model including hierarchical actuation
- Frequency servo topology
- Servo model noise analysis
- Servo model implementation on RTS
- Green lock detailed design
- Green injection system assembly
- Commissioning planning
- Suspension positioning method
- Optical bench layout (with IOO)
- Analog electronics, design, manufacture, test

Installation & Commissioning Scenario

iKAGRA

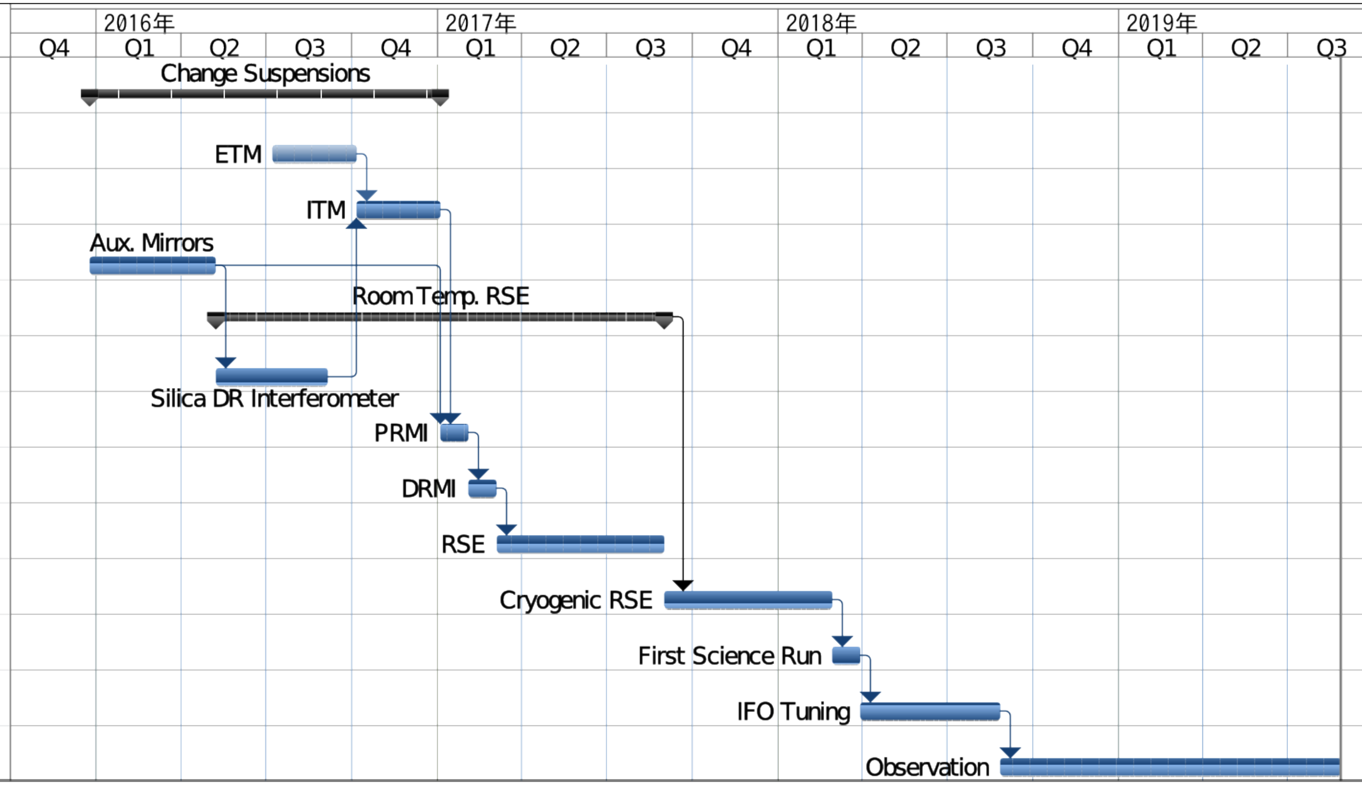
ID	タスク名	期間
40	**Suspension Installation for iLCGT**	394日
41	MC Suspension	1月
42	ETMX (StackB)	1月
43	ITMX (StackB)	1月
44	PRC, BS (StackB)	4月
45	ITMY (StackB)	1月
46	ETMY (StackB)	1月
47	**Type A Commissioning**	435日
55	SRC SAS Installation	4.5月
56	**iLCGT IFO Commissioning**	543日
57	MC Lock	2月
58	X-arm	3月
59	Michelson	2月
60	Y-arm	2月
61	FPMI	2月
62	iLCGT Observation	1月



Schedule & Installation Scenario

bKAGRA

ID	タスク名	期間
64	**Change Suspensions**	**376日**
65	ETM	3月
66	ITM	3月
67	Aux. Mirrors	4.5月
68	**Room Temp. RSE**	**481日**
69	Silica DR Interferometer	4月
70	PRMI	1月
71	DRMI	1月
72	RSE	6月
73	Cryogenic RSE	6月
74	First Science Run	1月
75	IFO Tuning	5月
76	Observation	365日



Human Resources

What we are hoping for ...

- 2012 - 2013 (Tunnel excavation period)
  - Fully engaged post-doc: 2
  - Grad. students: 4
  - Electric engineer: 2

- 2014 - 2018 (Commissioning period)
  - Fully engaged post-doc: 5
  - Grad. students: 10
  - Electric engineer: 2

What we have now ...

- Me, Kentaro, some students, working part time on KAGRA MIF
- Most staff scientists are chiefs of other subsystems
- Many people pledged to spend ~ 5% of their time
  → Sorry, they don't count

Instrument Control

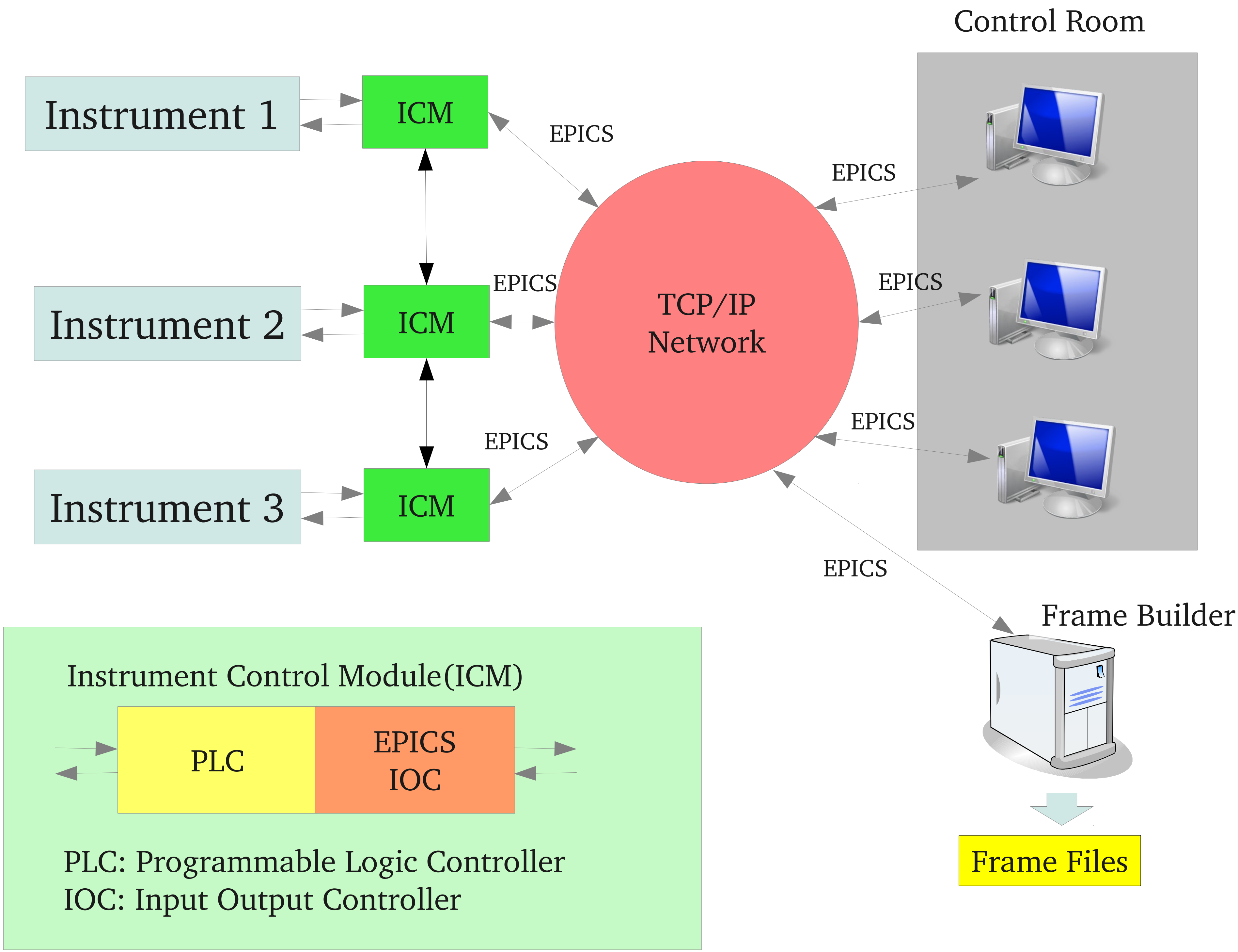
What we want to do

- Remote monitoring of instruments deployed across the site
  - Vacuum equipments, Cryocoolers, Lasers, etc ...
- Remote control of instruments
- Automatic and quick response to accidents (Interlock)
  - Closing gate valves in case of vacuum break
  - Shutting down lasers to prevent harm to human

Scope

- All the instruments not controlled by the RTS
  - Vacuum system
  - Cryogenic system
  - Laser
  - Environmental monitors (?)

Implementation Plan



Current Status

We don't have man power !

→ Outsource to companies

Talking with two companies, big and small

→ Costs money

We don't have money !

We need to get quotes from the companies
They need rough number of channels