Length Sensing and Control of AdLIGO

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ISC session, LSC at LSU
2006.8.14

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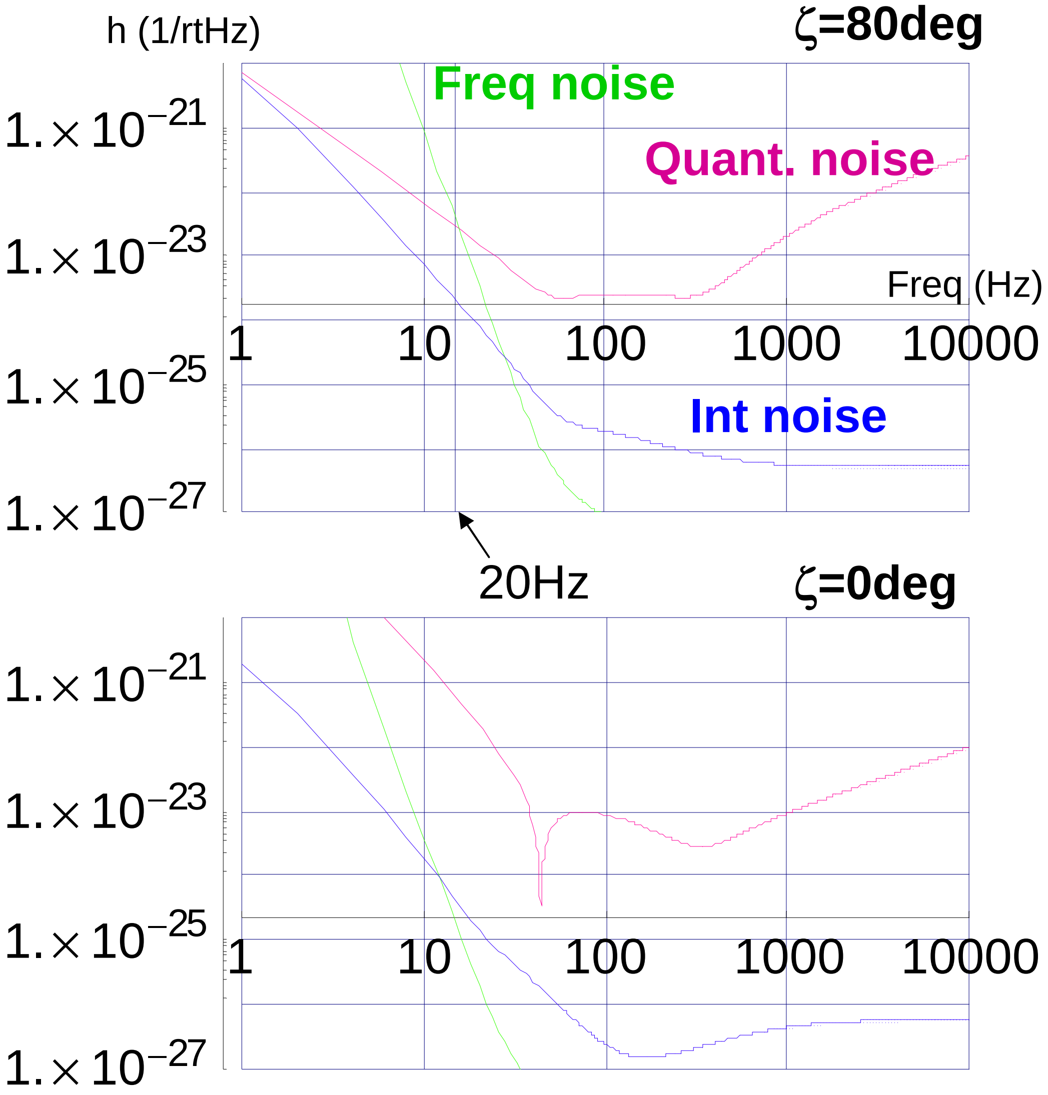
  - Constraints from MC, PRC, and Asymmetry
  - Simulation software

- Development of a calculation tool

- I'll show 4 candidates; let's pick one
  - Possibility of "flexible detuning"
  - Comparison

Brief Review of LSC

DC readout in RSE



Readout quadrature is determined by a ratio of contrast defect due to loss imbalance and offset light.
(~30ppm)

The better one for binaries (ζ~90deg) requires more offset light.

→ Laser noise becomes big.

Upper limit will be ~80deg.
Also PD can afford <100mW light.

We choose 78 deg.

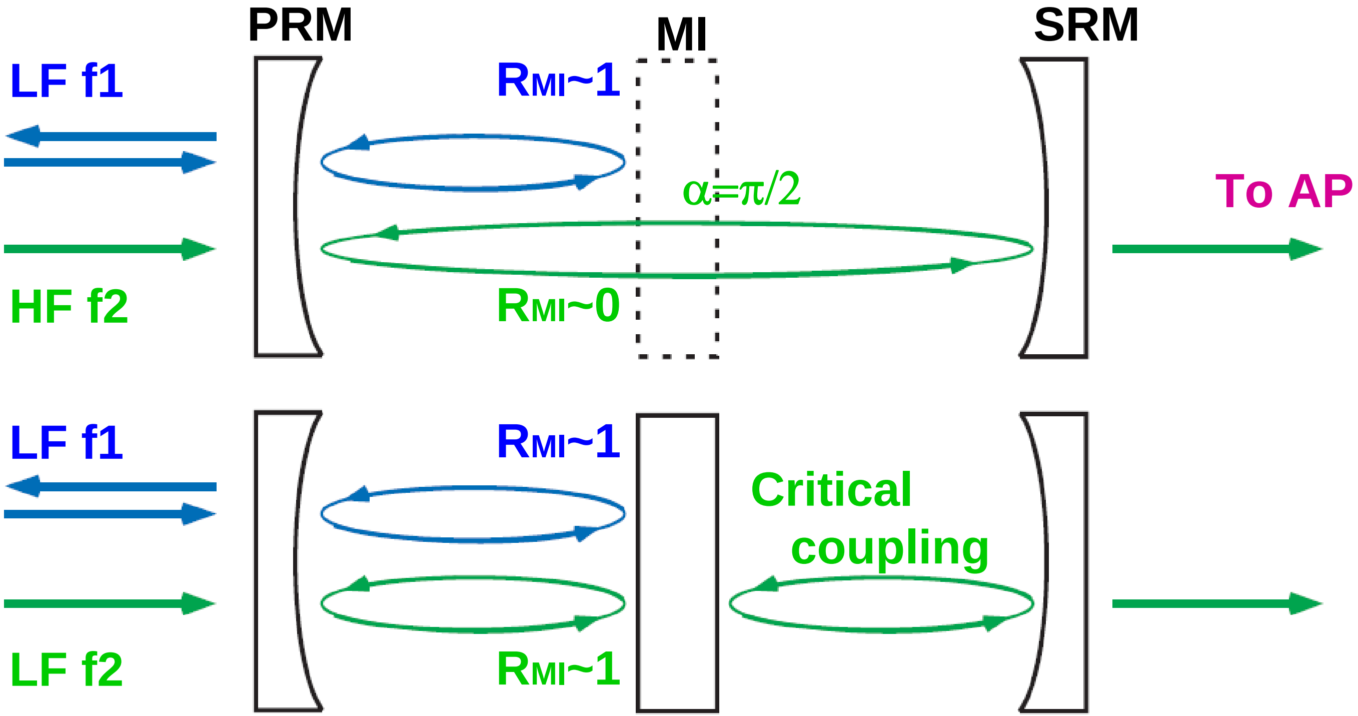
(~5.6e-12m offset)

Double demodulation with HF/LF control

L- : AP-DC readout, L+ : SP-RF readout

slp(l+), slm(l-), sls(ls) ⟶ Double demodulation

There are 2 ways of choosing 2 RF-SB frequencies.



9MHz-180MHz is HF, and 27-45MHz is LF control scheme.

Constraints from MC and Asymmetry

- AdLIGO uses same vacuum chambers as LIGO
- FSR of MC is fixed to ~9MHz
- Asymmetry can be extended but only up to 75cm

HF scheme

9-180MHz (Δl=40cm) requires too-high DDM freq.
Due to Δl<75cm, the lowest possible f2 is 108MHz.

LF scheme

Required asymmetry is ~4cm.
Use of common multiple of 9MHz helps to avoid harmonics problem.

Here we pick up 9-108MHz and 27-45MHz scheme.

Simulation software

Now we must calculate noise spectra to evaluate control schemes.

Which freq-domain software should we use?

- FINESSE : High utility, RF- and DC-readout is available
  Radiation-pressure is not included (no optical spring)
- MIT code : Radiation pressure and squeezing effects are included
  RF-control is not included
- Analytical work : Most things can be calculated by Mathematica
  It won't cover everything
- Optickle : RF-control and Radiation pressure effect are included
  Squeezing is not available yet

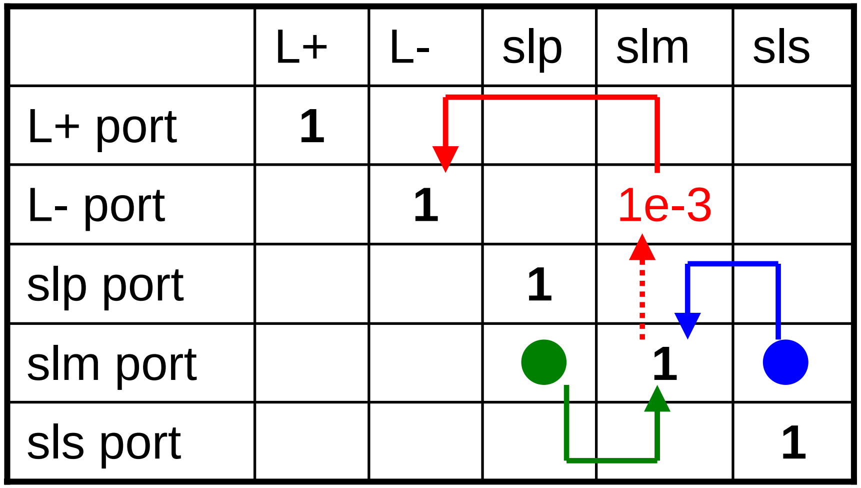
We use both FINESSE and my Mathematica code, and combine them on Matlab.

Calculation of control-loop noise

~ development of tool

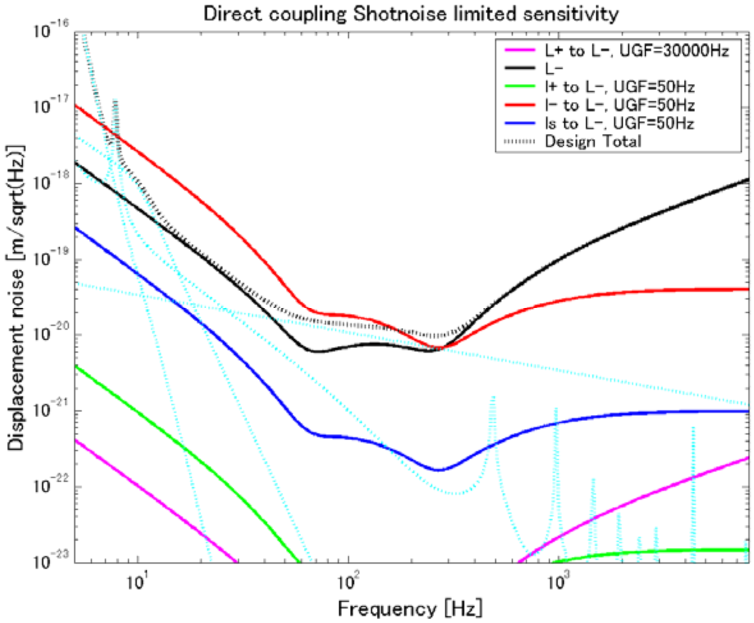
What we used to do

Length-sensing matrix (by FINESSE)



	L+	L-	slp	slm	sls
L+ port	**1**				
L- port		**1**		1e-3	
slp port			**1**		
slm port			●	**1**	●
sls port					**1**

L- noise is calculated by BENCH.

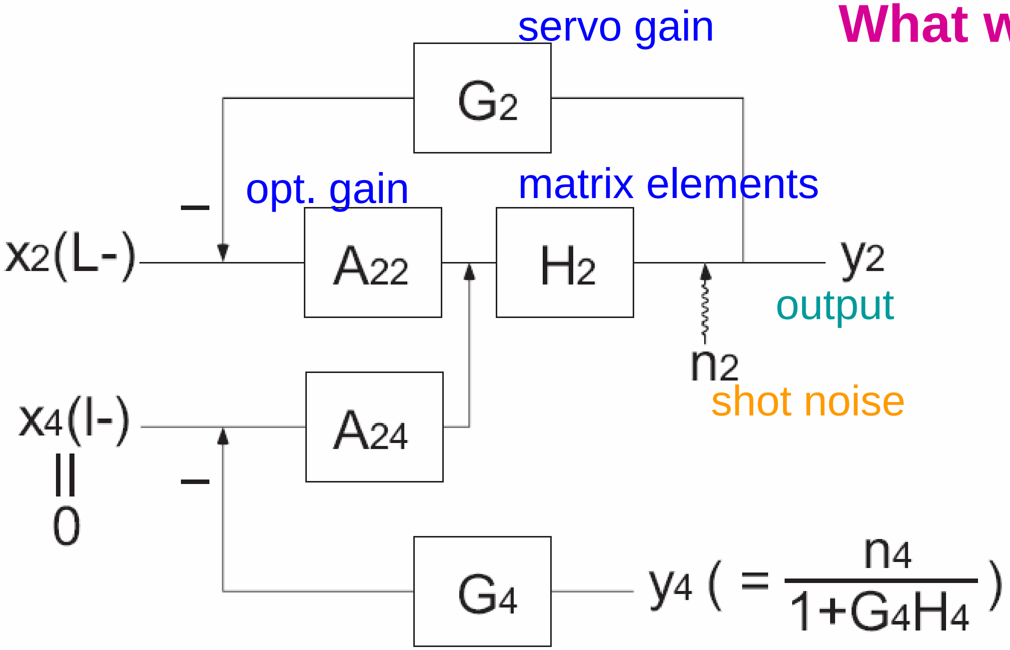


- 1st order and 2nd order contributions were considered
- Degeneracy of signals did not appear in sensitivity
- Flat frequency response was assumed
- Improvement by factor of ~30 by feed-forward was assumed

Degeneracy causes reduction of gain; should be included.

Block diagram expression

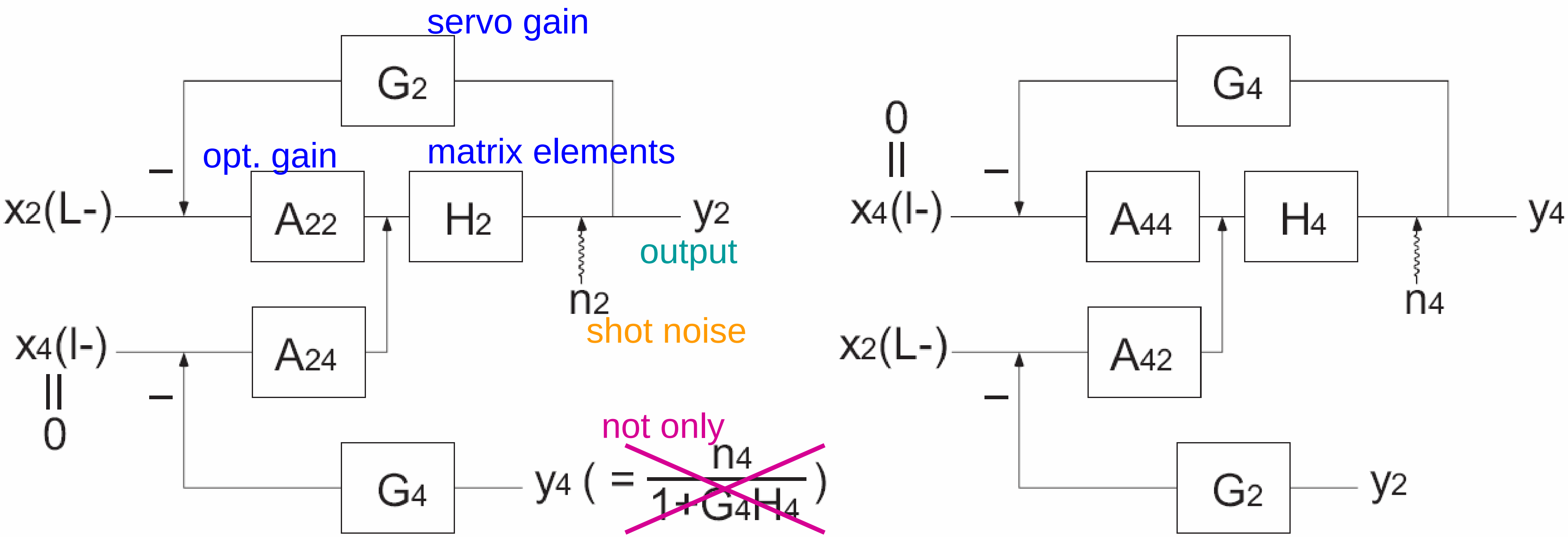
What we did can be described like this.



- Shot-noise-limited sensitivity (x4=0)
- n4 appears on y2 when GH>1
- Degeneracy does not appear

There must be a better way to express the system.

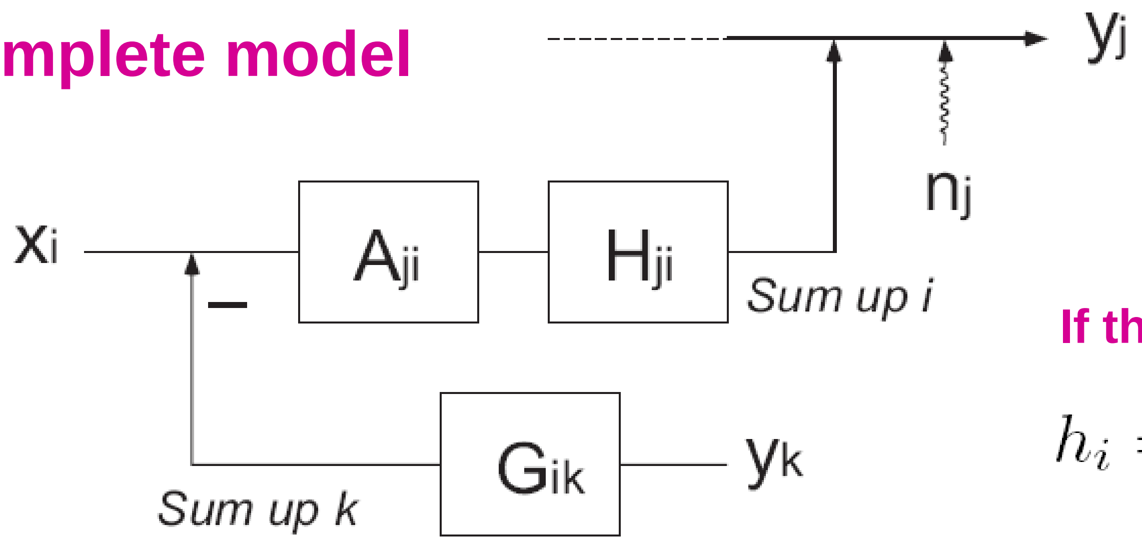
Block diagram expression



- **y4 is not only n4, even though x4 is zero**
- **Because y4 may include x2 (signal)**
- **The mixture of x2 will cause the gain reduction**

Block diagram expression

Complete model



If the gains are high,

$$h_i = \sum_j (A^{-1})_{ij} n_j / H_j$$

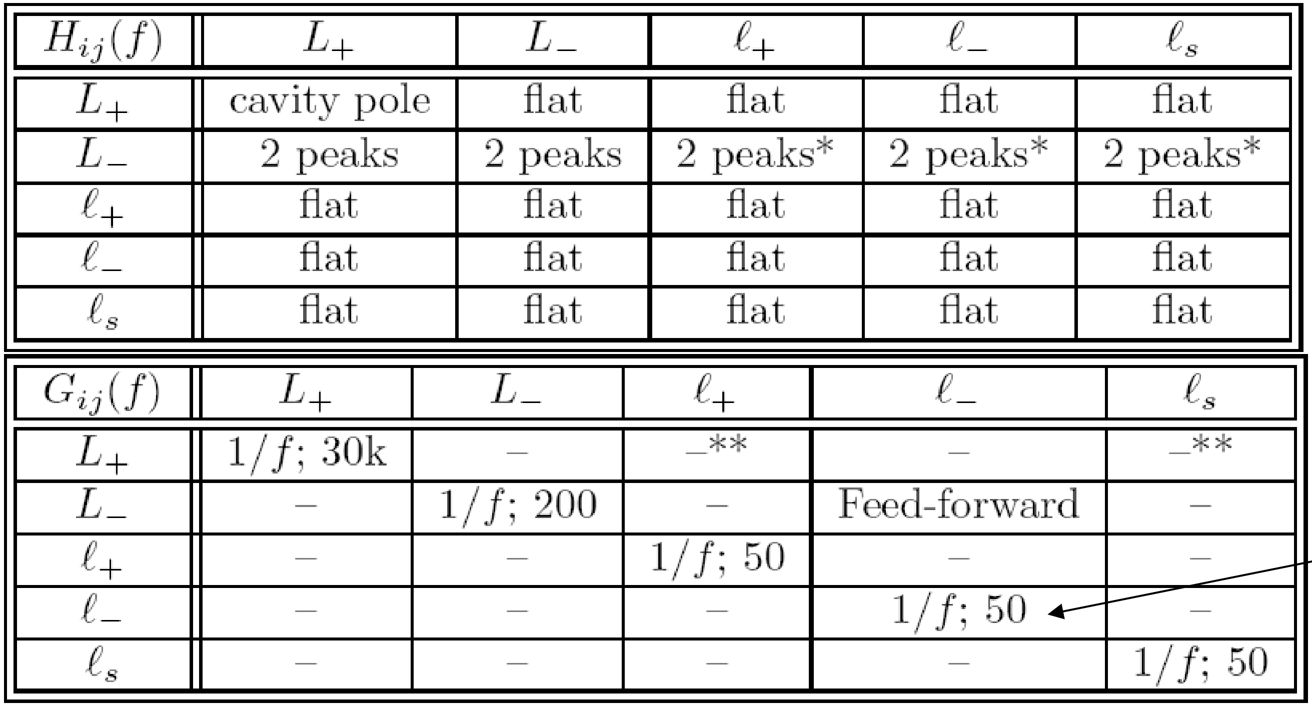
Noise is big if det[A]~0, which means degeneracy.

Now we combine tools.

A_{ij} (sensing matrix at DC) : FINESSE
H_{ij} (transfer function) : Mathematica
x_j and n_j (signal and noise) : Mathematica
G_{ij} (servo gain) : Matlab

frequency dependent

Frequency dependence



$H_{ij}(f)$	L_+	L_-	ℓ_+	ℓ_-	ℓ_s
L_+	cavity pole	flat	flat	flat	flat
L_-	2 peaks	2 peaks	2 peaks*	2 peaks*	2 peaks*
ℓ_+	flat	flat	flat	flat	flat
ℓ_-	flat	flat	flat	flat	flat
ℓ_s	flat	flat	flat	flat	flat

$G_{ij}(f)$	L_+	L_-	ℓ_+	ℓ_-	ℓ_s
L_+	$1/f$; 30k	–	–**	–	–**
L_-	–	$1/f$; 200	–	Feed-forward	–
ℓ_+	–	–	$1/f$; 50	–	–
ℓ_-	–	–	–	$1/f$; 50	–
ℓ_s	–	–	–	–	$1/f$; 50

Unity-gain frequency

- Only limited numbers of elements are calculated
  - ~ We need Optickle to complete all the elements
- TF from slm to L- shows 2 peaks like L- response
  - ~ It would be same for slp or sls to L-
- Feed-forward can be included
- Coupling from L+ to slp and sls via laser freq is not included

Downselection of control scheme

~ Let’s see the first two candidates

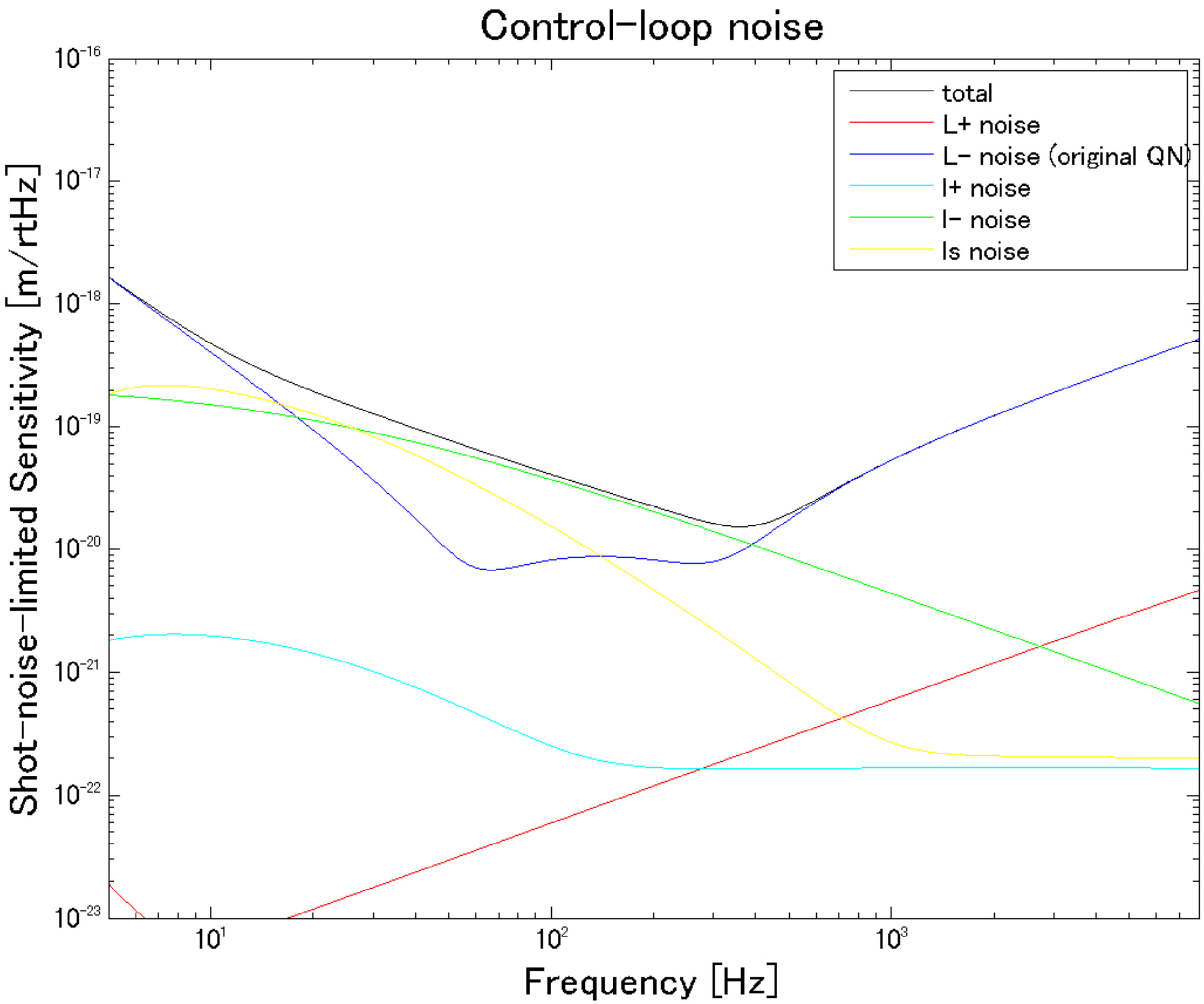
9-108MHz scheme

A_{ij}

j i	L+	L-	Slp	Slm	Sls	H	det/sh
SP f1	1	2.6e-3	1.1e-3	3.3e-6	2.1e-7	8.5e20	--
AP DDM	3.7e-4	1	1.1e-6	1.3e-3	1.7e-6	8.5e19	0
SP DDM	-9.1e-3	-6.2e-5	1	-0.042	0.341	1.3e17	213%
AP DDM	4.4e-3	7.2e-3	-0.310	1	-0.438	-9.2e15	69%
PO DDM	-8.6e-3	1.3e-5	0.542	-0.110	1	9.4e14	<1%

- A[24] is determined by finesse of arm cavities.
- A[43] and A[45] is big due to large asymmetry for f1 (75cm, 9MHz).
- SP detector noise could be reduced by a use of SSB for f2.
- AP detector noise is large also due to big asymmetry for f1.

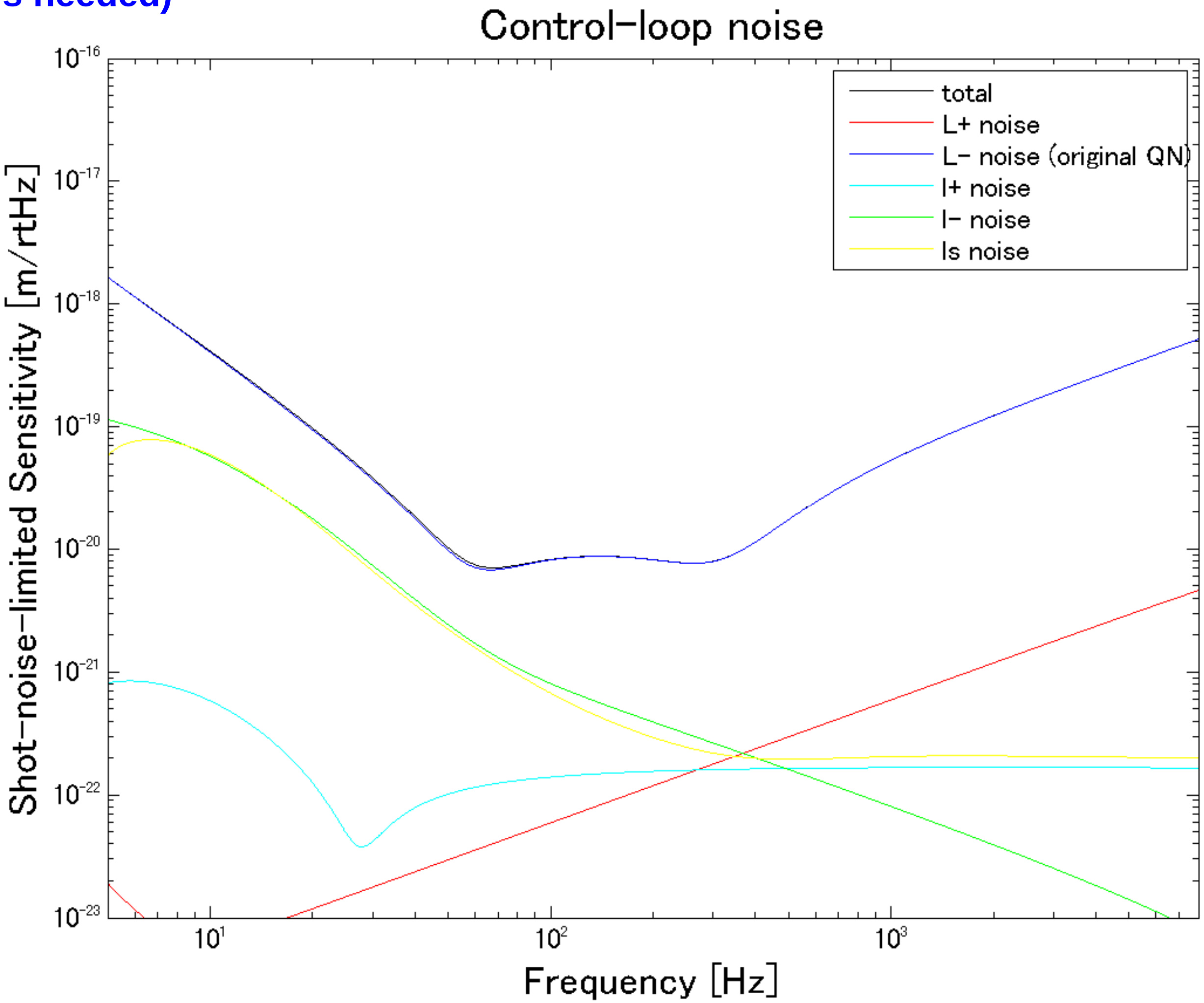
9-108MHz scheme



Sensitivity is limited by l- noise and ls noise.
Let’s try feed-forward.

With Feed-forward
(1% accuracy is needed)

9-108MHz scheme



UGF=20Hz
FF:1-pole LPF

Now we have a good sensitivity curve.
But we need 1% accuracy for feed-forward gain.

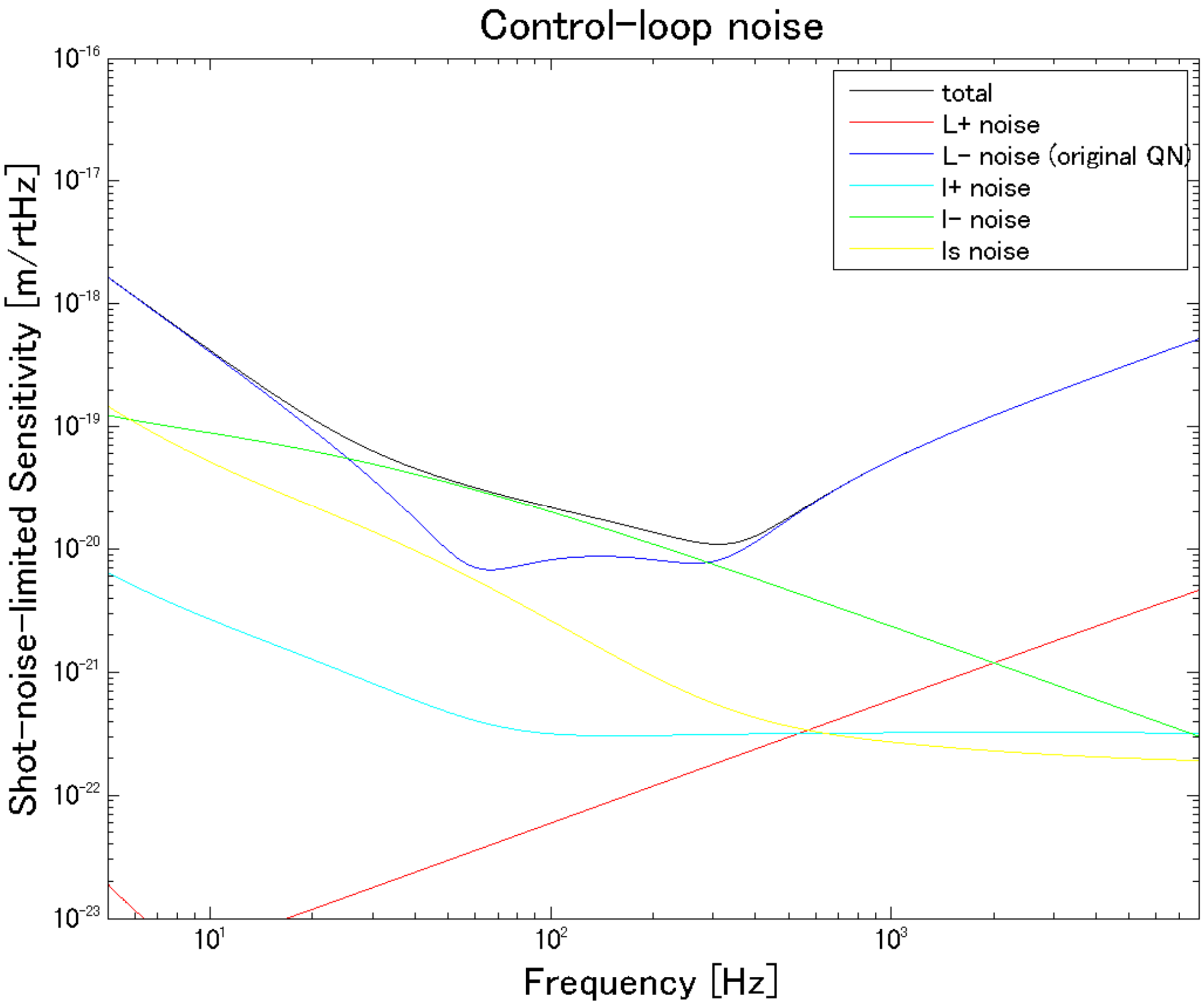
27-45MHz scheme

A_{ij}

j i	L+	L-	Slp	Slm	Sls	H	det/sh
SP f1	1	2.5e-3	1.1e-3	2.1e-6	9.4e-7	9.0e20	--
AP DDM	3.7e-4	1	1.1e-6	1.3e-3	1.7e-6	8.5e19	0
SP DDM	7.8e-4	1.3e-3	1	0.784	0.880	-5.9e16	165%
AP DDM	6.8e-5	1.4e-3	0.083	1	0.094	-1.0e16	3%
PO DDM	1.6e-3	2.7e-3	0.318	1.589	1	-1.0e15	1%

- Optical gains (H) are similar to those of 9-108MHz scheme.
- A[43] and A[45] is small due to small asymmetry for f1 (4cm, 27MHz).
- SP detector noise could be reduced by a use of SSB for f2.
- AP detector noise is small also due to small asymmetry for f1.

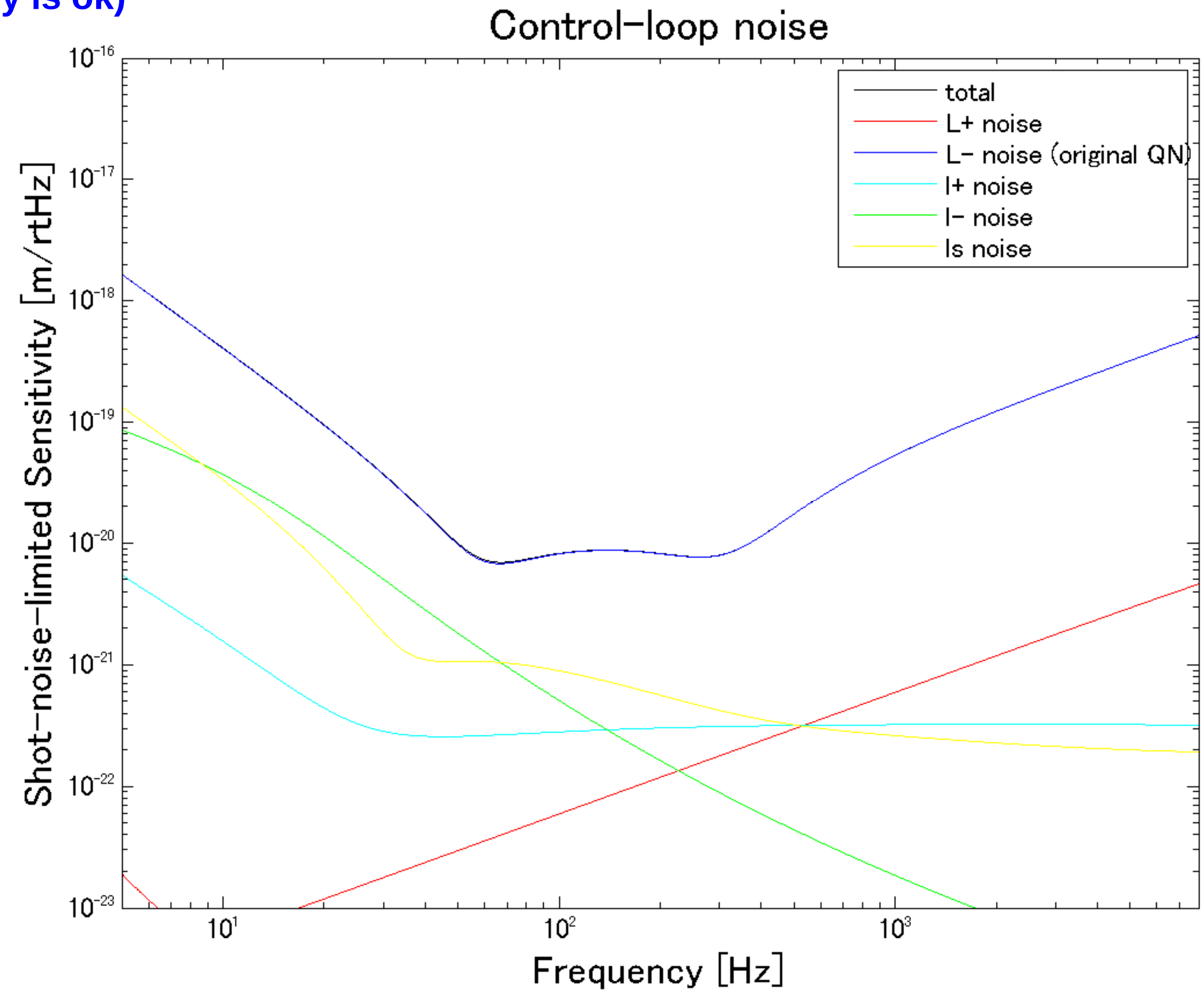
27-45MHz scheme



Sensitivity is limited by l- noise.
Let’s try feed-forward.

With Feed-forward
(10% accuracy is ok)

27-45MHz scheme

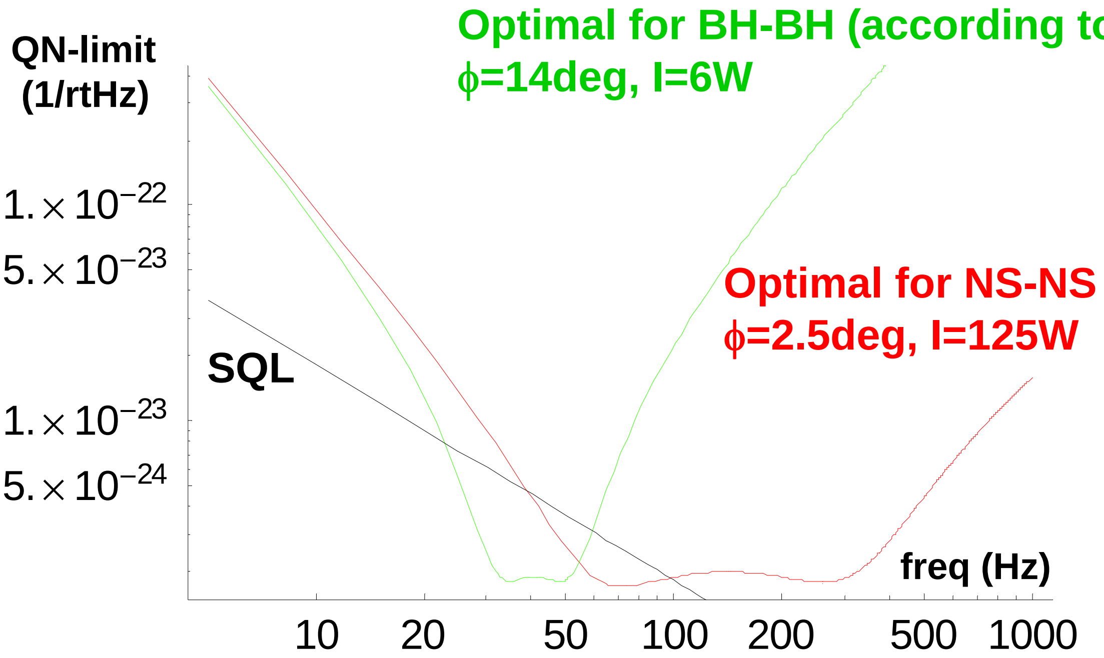


UGF=20Hz
FF:1-pole LPF

27-45MHz scheme looks better than 9-108MHz scheme.
Are there any other conditions that we should meet?

Flexible detuning

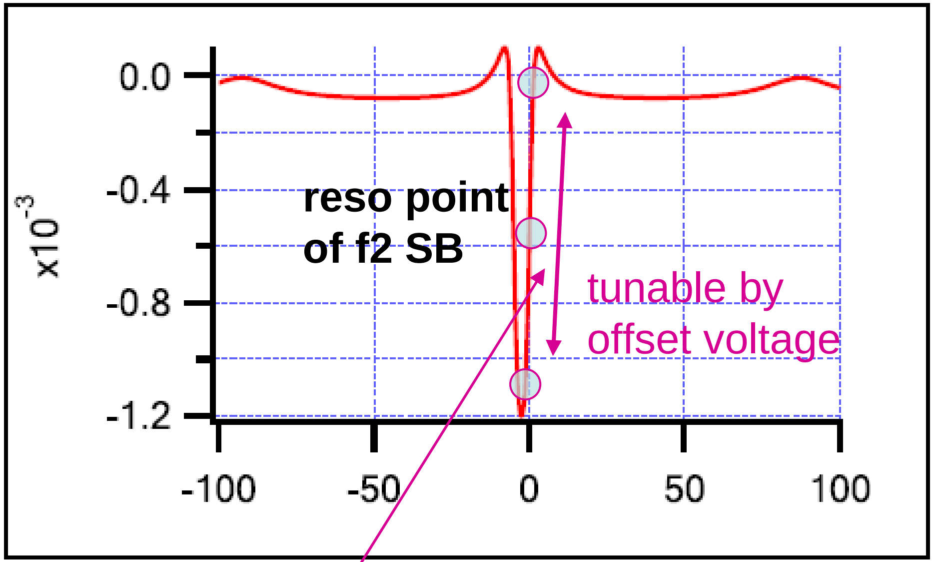
- Detune phase is determined by f2-SB freq that resonates in SRC.
- So, it is fixed, so far to the optimal one for NS-NS binaries.
- But we may want to change it to the optimal for BH-BH.
- Or we may use lower power at the beginning; optimal phase changes.



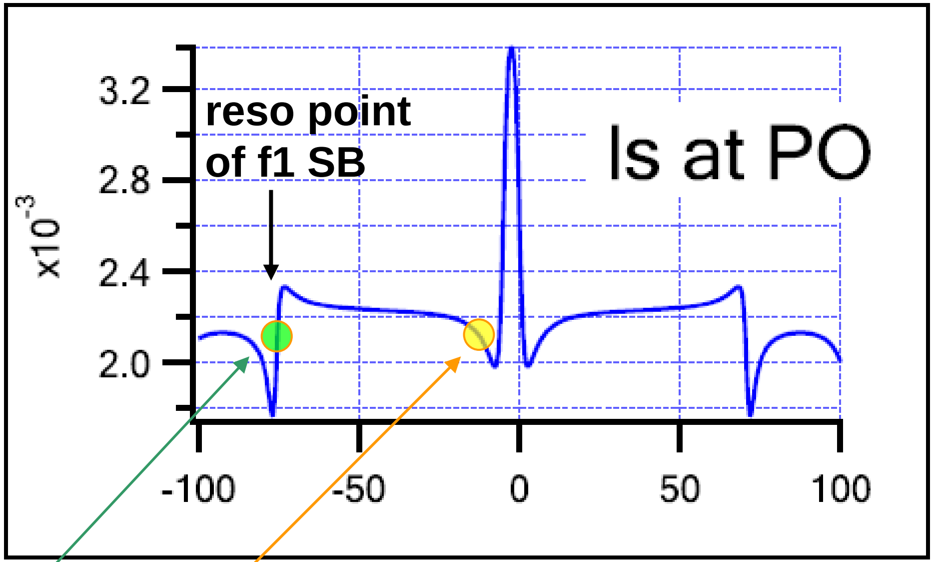
Can we shift detuning by
- adding offset to ls signal,
or
- changing SB freq within MC bandwidth?

Dynamic range of clean ls signal

Error signal of ls (HF scheme)



(LF scheme)



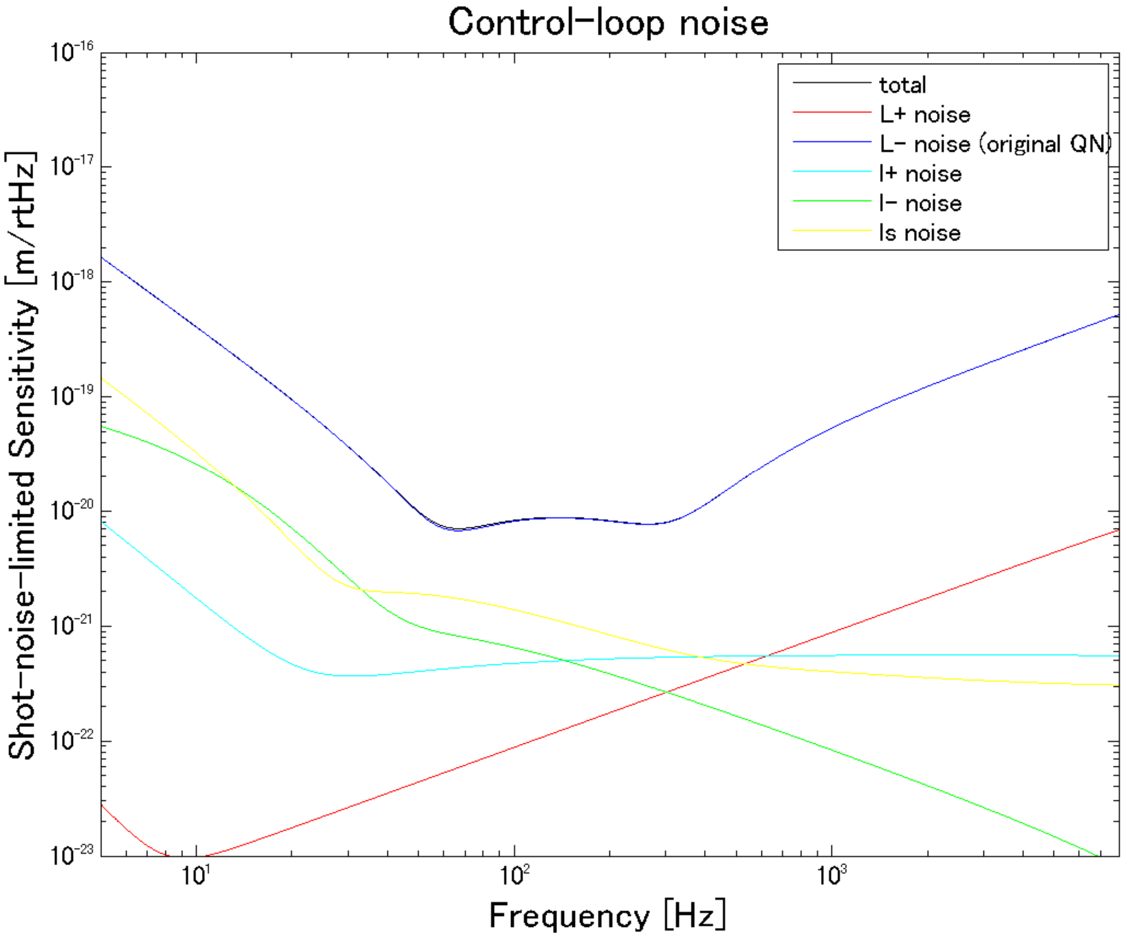
- Tunable range is ~+/-2 deg, regardless of HF or LF.
- Maybe we can lock to somewhere like here (non-resonant point).
- We have another operation point where f1 SB resonates in the SRC.

(HF scheme doesn’t have this feature due to a large asymmetry.)

Let’s see loop-noise spectrum for each situation.

Slight detune-phase-shift by offset

27-45MHz with Feed-forward



ϕ=2.5deg

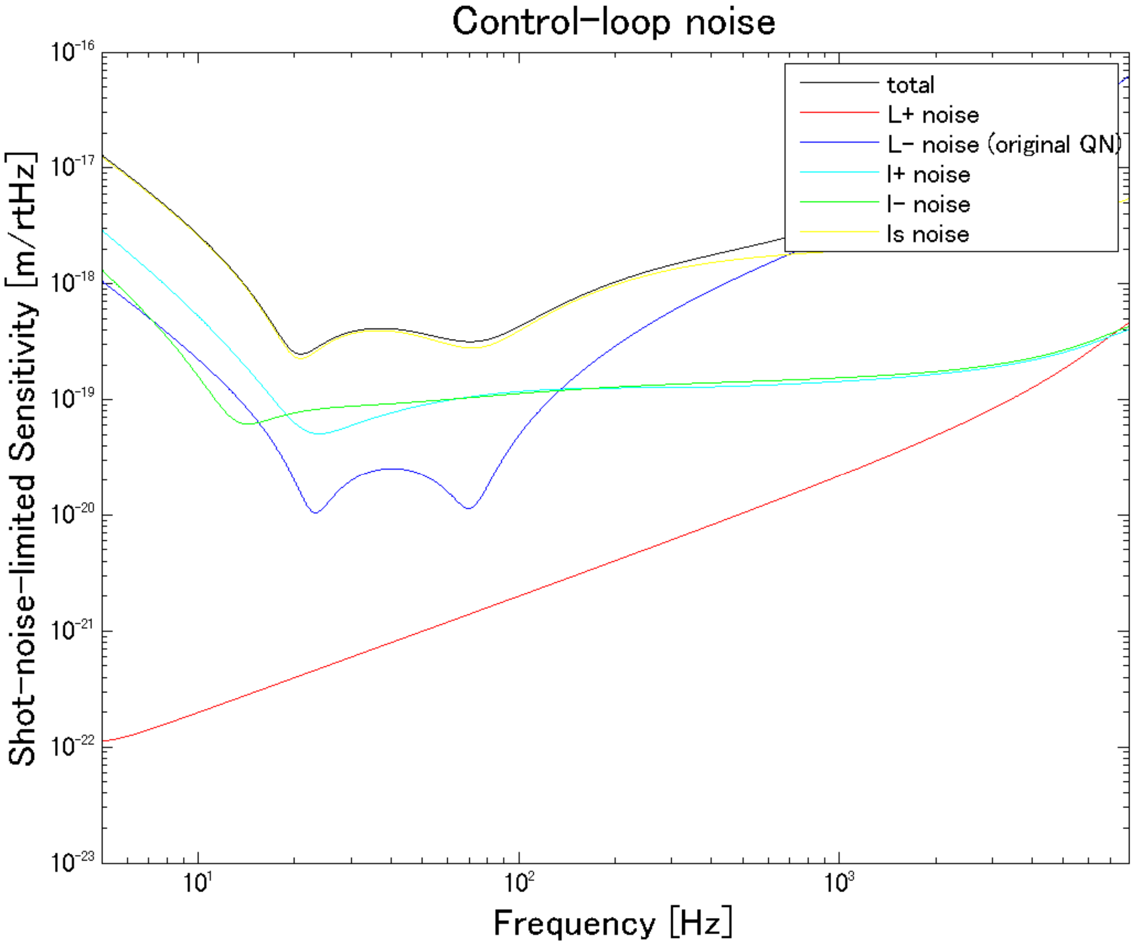
ϕ=3.5deg

Freq-dependence
Of ϕ=2.5 is used.

Almost no change. Very good.

Operation at non-resonant point

w/o feed-forward



Very bad.

Operation with f1 being resonant

Relation between detune phase and RFSB frequency:

$$\frac{c}{2L_s} = \pi \times \frac{f_1}{n_1\pi - \phi_1} = \pi \times \frac{f_2}{n_2\pi - \phi_2}$$

n=integer

Difficulty comes from the fact that f1 and f2 should be multiple of 9MHz.

If we set ϕ2 to be 2.5 deg,

w/ telescope ↓

27-45MHz >> ϕ1=35deg (Ls= 7m or 57m)

9-45MHz >> ϕ1=37deg (Ls=13m or 53m)

9-63MHz >> ϕ1=26deg (Ls=14m or 52m)

27-63MHz >> ϕ1=25deg (Ls=12m or 62m)

What if f1 is higher than f2?

Can we choose f1/f2 for 2.5deg and 14deg?

If we set ϕ2 to be 2.5 deg,

45-27MHz >> ϕ1= 4.1deg (Ls=17m or 50m)

45-9MHz >> ϕ1=12.5deg (Ls=16m or 50m)

63-9MHz >> ϕ1=17.5deg (Ls=16m or 50m)

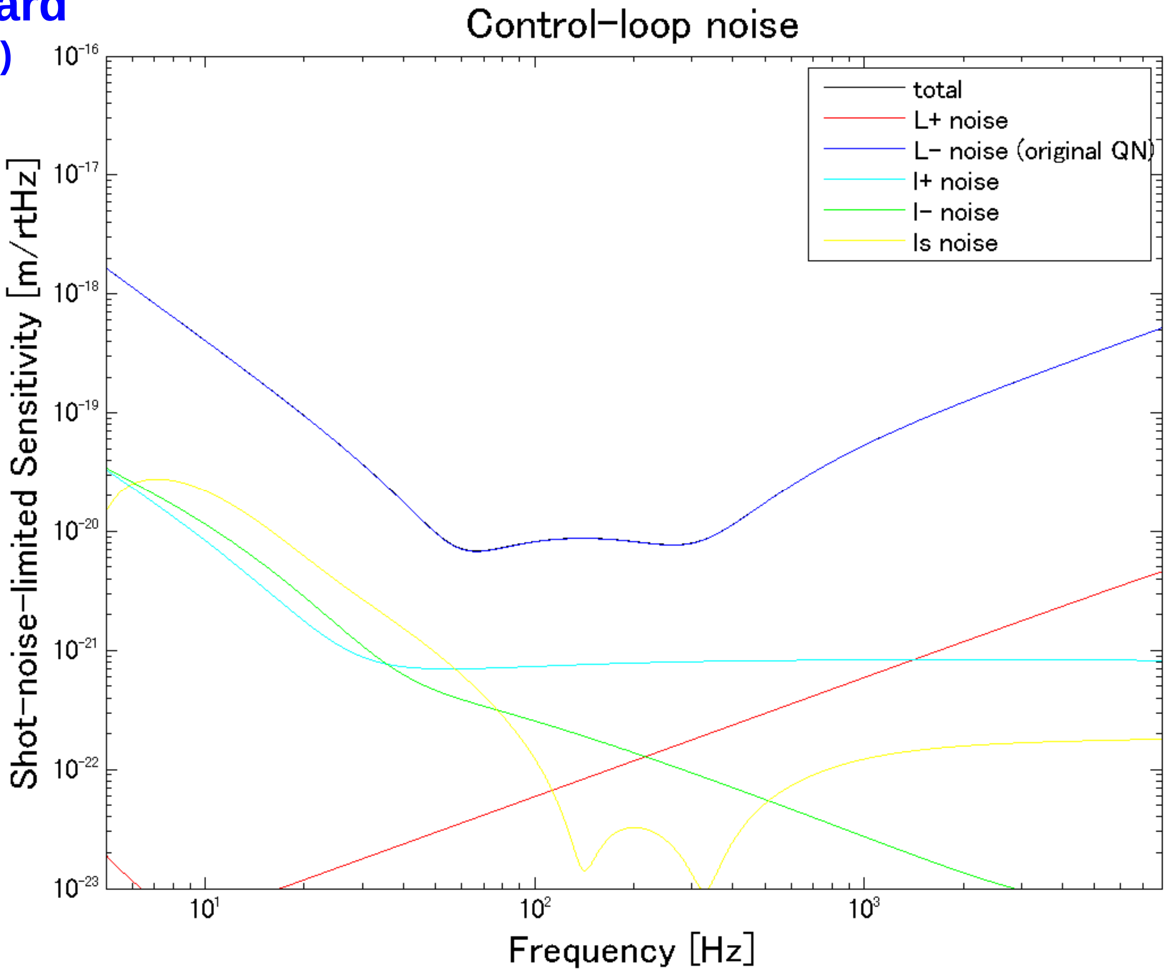
63-27MHz >> ϕ1= 5.8deg (Ls=17m or 50m)

This one looks good.

- Asymmetry is set not to be optimized to one of them but middle
- For BHBH, as input power is low, we can increase m (set to 0.8)
- Attenuators can be removed but other optics are all fixed

45-9MHz scheme for NS-NS

With Feed-forward
(15% accuracy is ok)

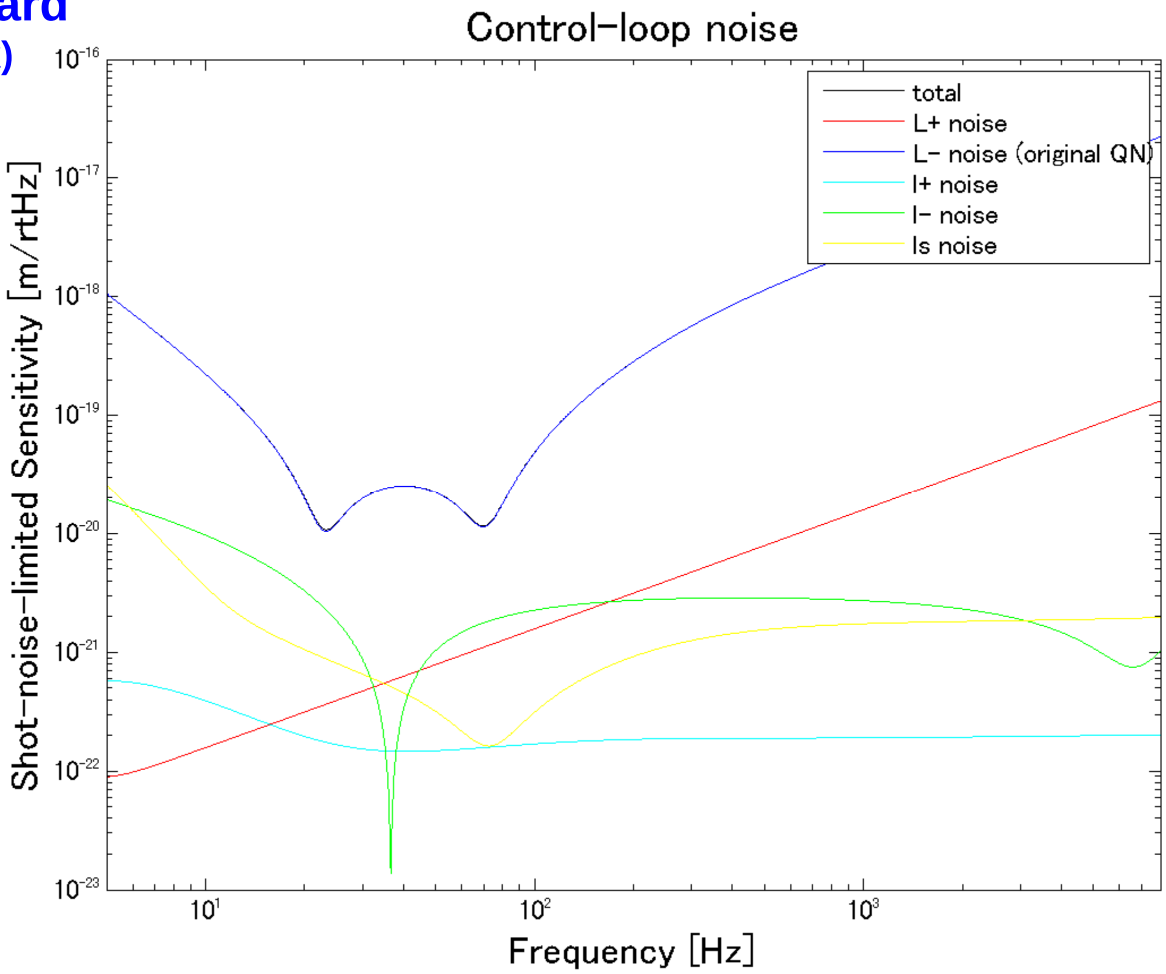


Very good.

45-9MHz scheme for BH-BH

With Feed-forward

(15% accuracy is ok)



Very good.

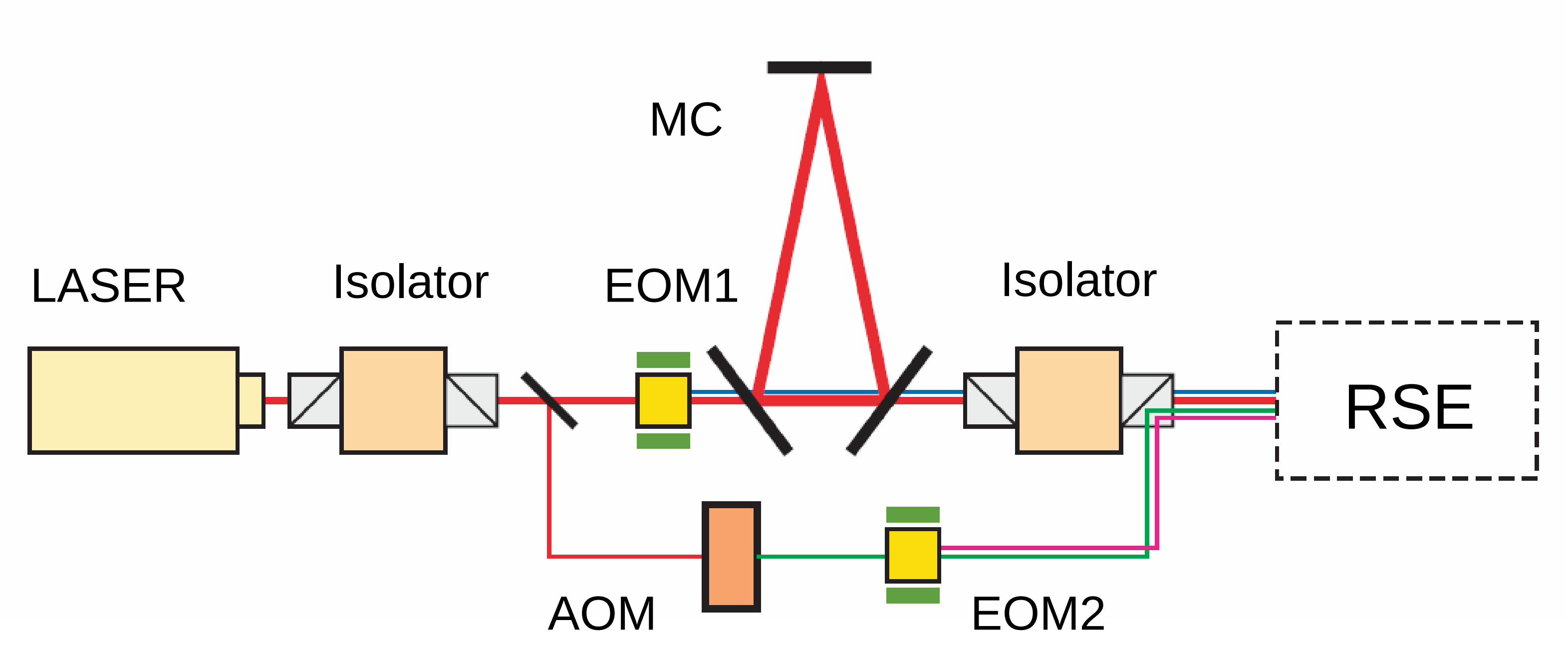
Actually,…

It'd be better if we can continuously change detuning.

Is it possible?

We need new scheme.

Control scheme with the other polarization



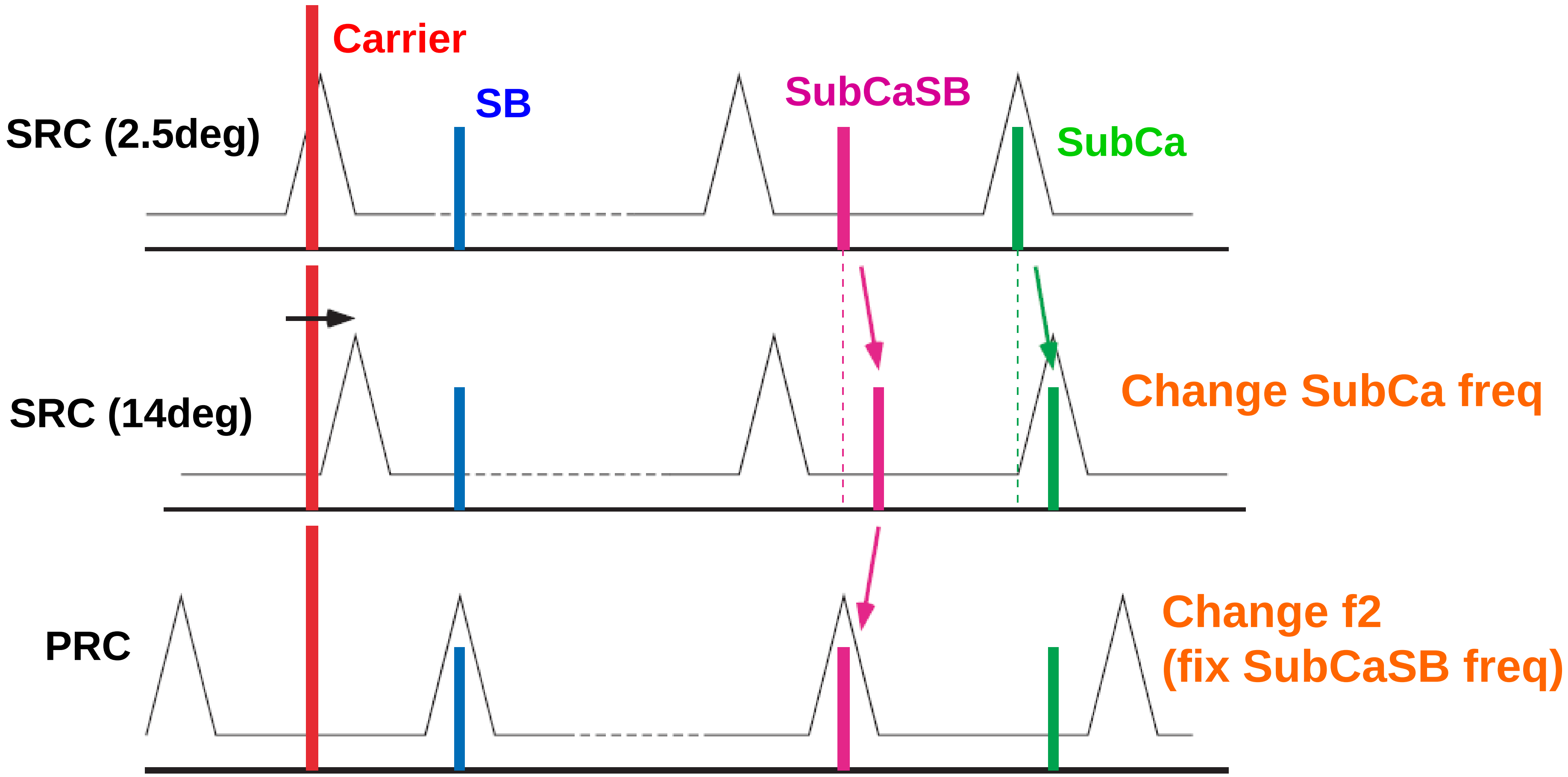
- Flexible detuning may be possible with light that doesn't transmit MC
- We'll have Faraday after MC ⟶ Let's inject light from Faraday

$$\left.\begin{array}{l}\textbf{Carrier}\\ \textbf{SB}\end{array}\right\} \longrightarrow L+$$

$$\left.\begin{array}{l}\textbf{Sub-Carrier}\\ \textbf{Sub-Ca SB}\end{array}\right\} \longrightarrow l+,\ l-,\ ls$$

Single demodulation!
No Mach-Zehnder!

Flexible detuning



SubCa should resonate in PR-SRC to probe Is signal.

SubCaSB should resonate in PRC to probe I- signal.

Sideband frequencies

Carrier SB (PM)

It should better resonate in the PRC

It shouldn’t resonate in the SRC

m=0.1

→ 9MHz or 27MHz

SubCa SB (SSB)

m=1.15

It should resonate in the PRC to probe l-

Asymmetry factor should be as low as possible

Modulation frequency should be as low as possible

→ 216MHz (~ SubCa-108MHz)

SubCa

1W

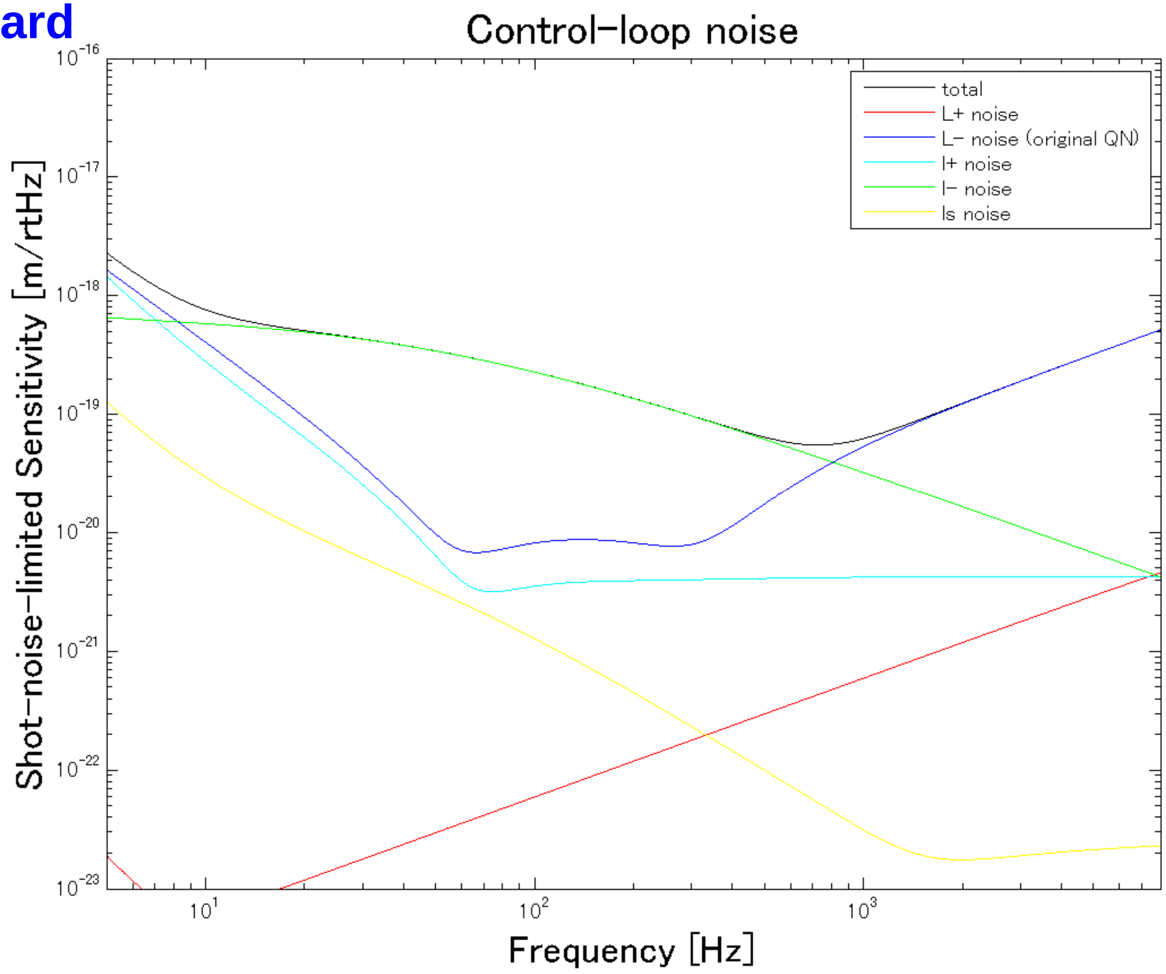
It should transmit Michelson part (HF scheme)

→ ~324.3MHz

Let’s see the sensitivity curve.

Dual-polarization control scheme for NS-NS

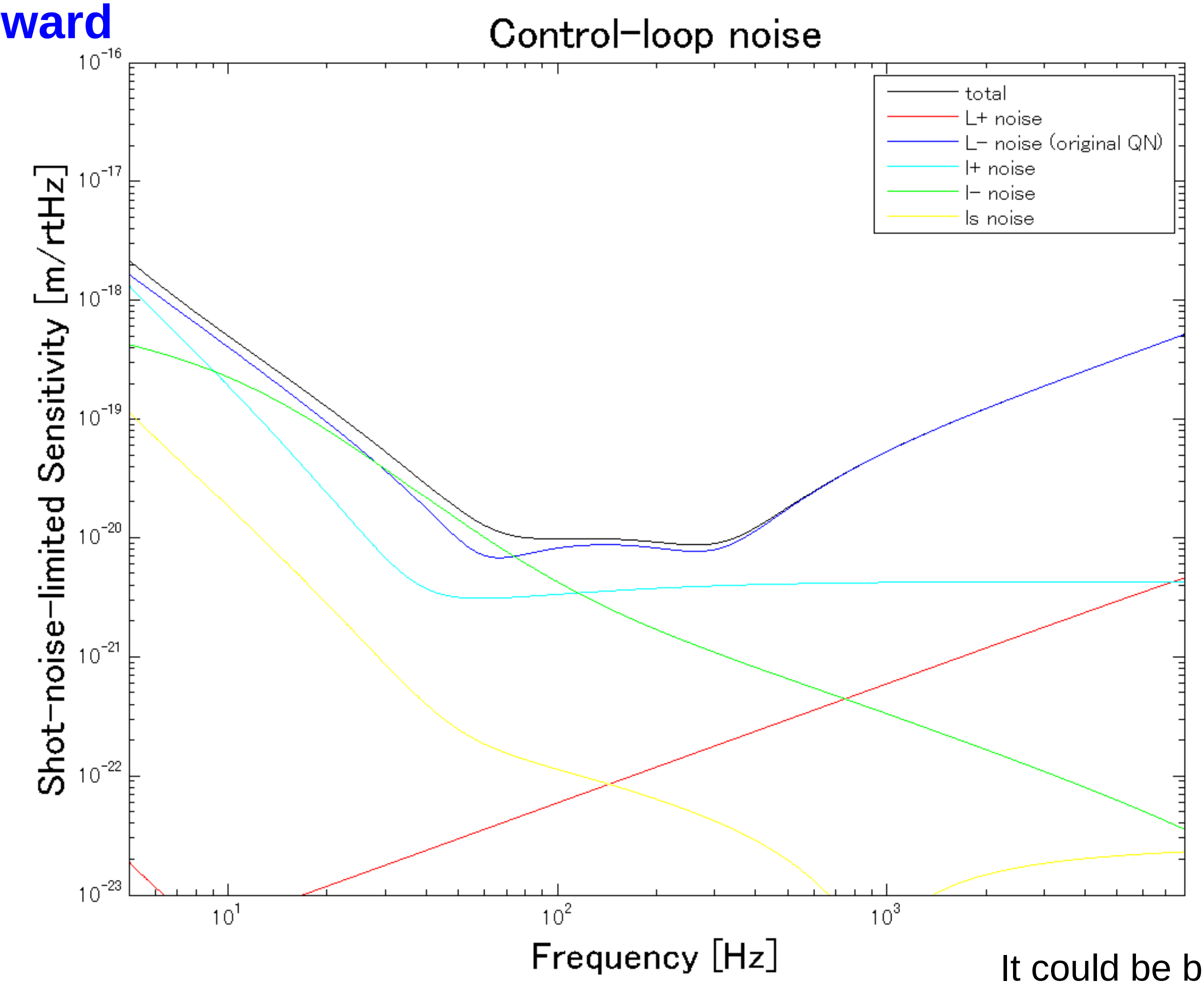
w/o feed-forward



Quite bad.

Dual-polarization control scheme for NS-NS

with feed-forward



It could be better with f1=9MHz.

Not good but close.

Let’s make comparison

Now we have 4 candidates

1. f1=27MHz, f2=45MHz, asymmetry=4cm (LF scheme)
2. f1=9MHz, f2=108MHz, asymmetry=75cm (HF scheme)
3. f1=45MHz, f2=9MHz, asymmetry=6.7cm (LF scheme)
4. f1=27MHz, SubCa=324MHz, f2=108MHz, asymmetry=75cm

Let’s make comparison

	27-45LF	9-108HF	45-9LF	dual-pol.
SB frequency	Low	High	Low	High
Loop noise	Good	Good	Good	Bad
Flexibility	1 for NS, the other is useless	Only for NS	1 for NS, the other for BH	It should be good
Misc.	--	Tested at the 40m	Harmonics ?	Many unknowns

- LF schemes look good
- Decision would depend on how we want flexibility
- How can we test LF scheme at the 40m?

Summary

- We developed a tool to calculate control-loop noise
- Now we can compare control schemes
- We look at Low-freq scheme and it works well
- Flexible detuning is attractive while quite hard to realize
- Using the other polarization is one possibility
- We’ll be soon ready to pick one for AdLIGO, hopefully

- We’re waiting for Optickle to be ready (esp. for vacuum!)
- Some parts in our calculation still needs modification
- How to test at the 40m is a thing to be considered