Towards BHD

D3 Masaya Ono

Ando Lab Seminar 2025.12.05

Abstract

- What needs to be done for achieving the DARM readout with Balanced Homodyne Detection
- First, share what is happening in the 40m experiment
- Second, introduce plans to acquire the lock by BHD
- Let us discuss the things to make them more concrete. What is overlooked? What is too abstracted?

Contents

- Recent achievements
  - Lock acquisition of the PRFPMI
  - Low noise operation by 1f control of the PRCL & MICH

- What needs to be done
  - Wavefront sensor
  - Output mode cleaner
    - Install OMCs
    - Mode cleaner length control for small RMS
    - Alignment control to the OMCs
  - Balanced Homodyne Detection
    - Lock the local oscillator phase
    - Hand off the DARM control to the homodyne readout
  - Fix SRM (PRFPMI ==> DRFPMI)
    - Lock the signal recycling cavity on the (tuned) resonant sideband extraction

- What I can discuss in this work
  - Lock acquisition of BHD for GW detection
  - DARM sensitivity (RF, DC, BHD)
  - Contrast defect
  - Shot noise when SRM is detuned

Contents

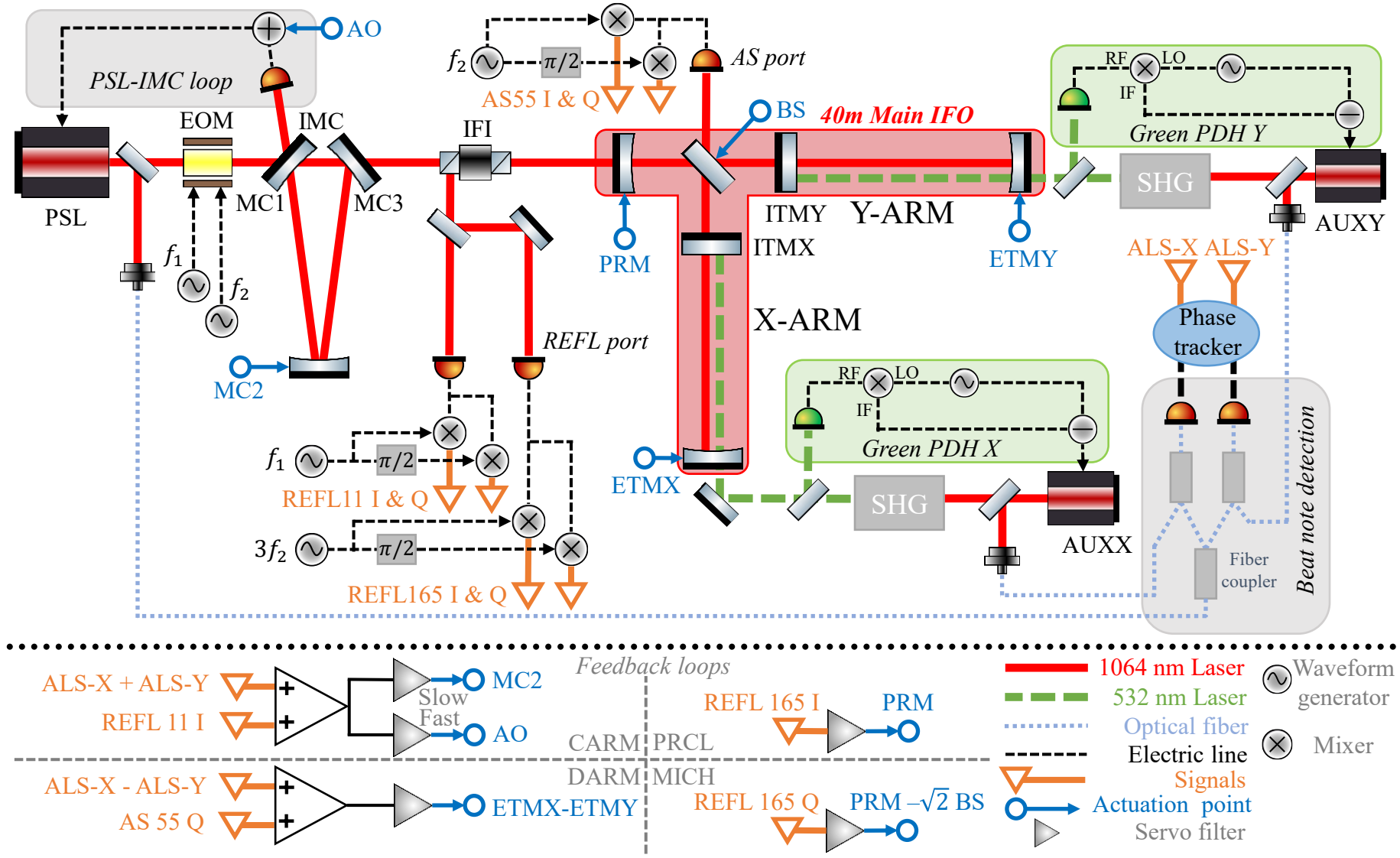
- Recent achievements
  - Lock acquisition of the PRFPMI
  - Low noise operation by 1f control of the PRCL & MICH

- What needs to be done
  - Wavefront sensor
  - Output mode cleaner
    - Install OMCs
    - Mode cleaner length control for small RMS
    - Alignment control to the OMCs
  - Balanced Homodyne Detection
    - Lock the local oscillator phase
    - Hand off the DARM control to the homodyne readout
  - Fix SRM (PRFPMI ==> DRFPMI)
    - Lock the signal recycling cavity on the (tuned) resonant sideband extraction

- What I can discuss in this work
  - Lock acquisition of BHD for GW detection
  - DARM sensitivity (RF, DC, BHD)
  - Contrast defect
  - Shot noise when SRM is detuned

Experimental setup for PRFPMI lock acquisition in the 40m

- Green for ALS is put in from the back of the ETMs
- ALS lock is achieved by actuating the IMC length and the frequency of the laser
- After achieving ALS lock, ~50 pm offset is applied to CARM (The arm cavity line width is about 590 pm)
- PRMI is controlled by $3f_2$
- Reducing the offset to 0, CARM & DARM controls are handed off to RF



Result of PRFPMI lock acquisition

a: Arm length is stabilized by ALS

b: CARM offset is applied

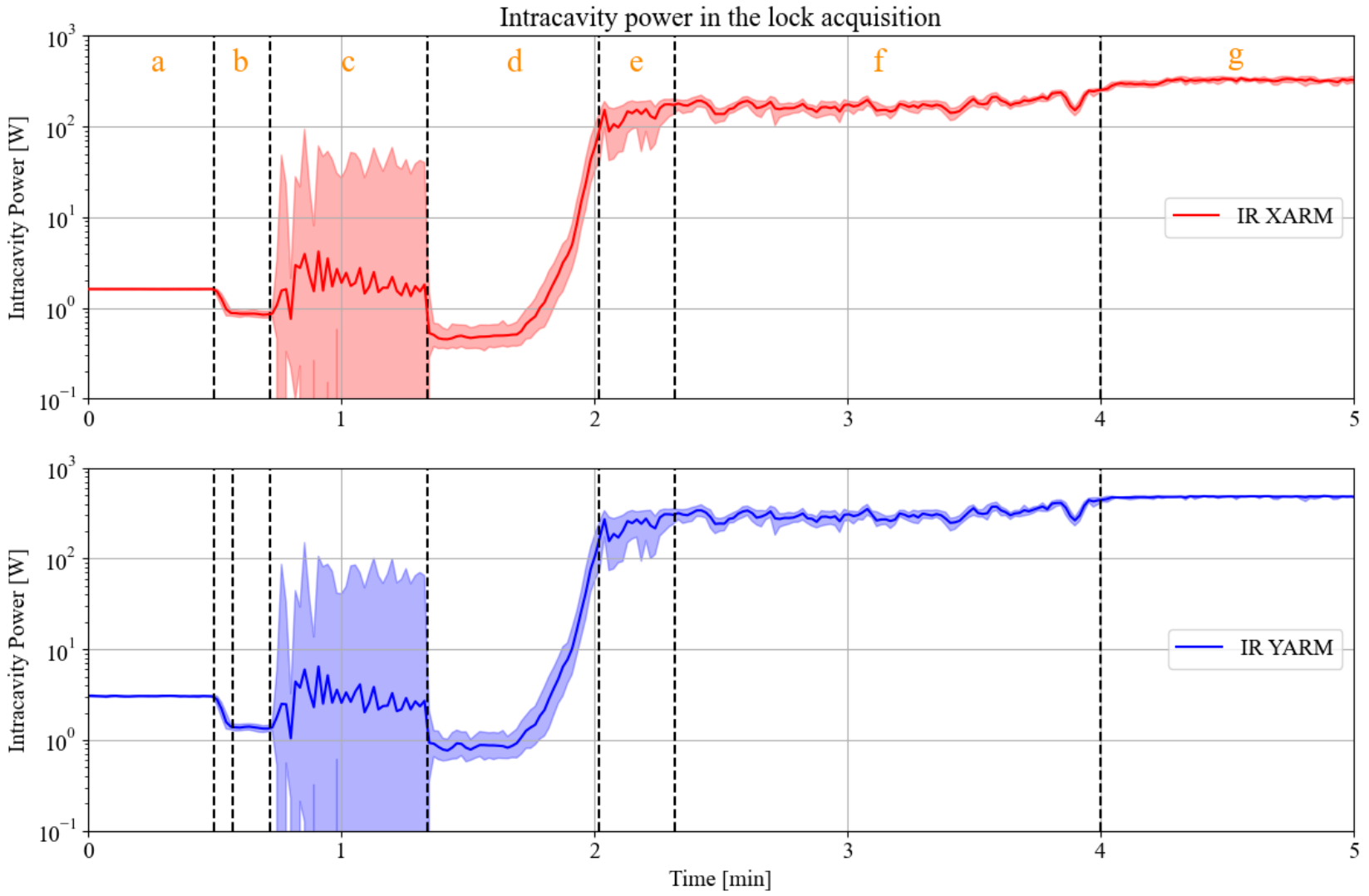
c: PRM is aligned

d: PRMI is locked and offset is reduced

e: Handing off the CARM control from ALS to RF (REFL $1f_1$)

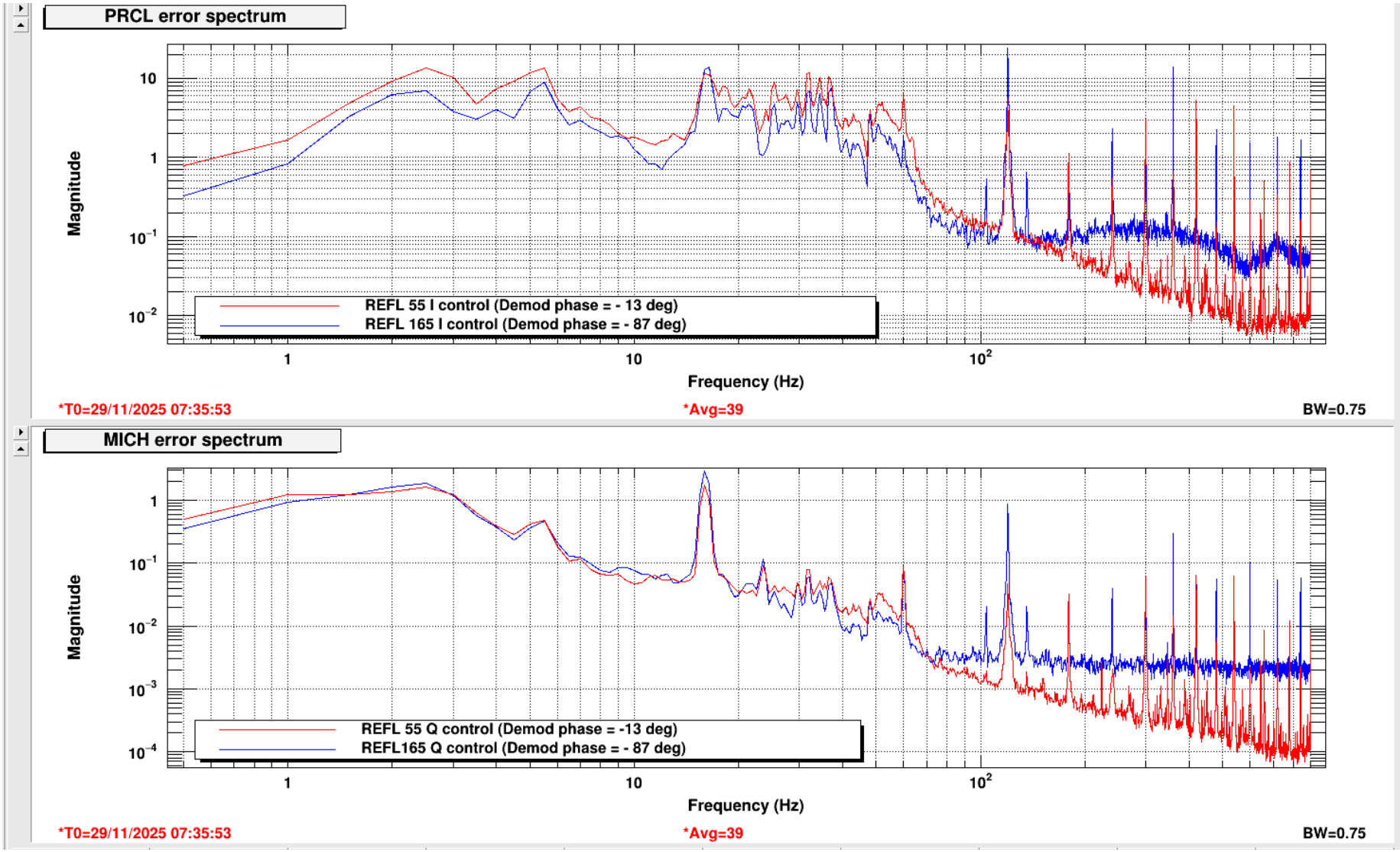
f: RF CARM control is acquired

g: Handing off the DARM control from ALS to RF (AS $1f_2$)



PRCL and MICH handover from 3f to 1f

- 1f has better SNR than 3f
- Successfully handed over the PRCL and MICH control from $3f_2$ to $1f_2$
- Lower noise was obtained by 1f at high frequencies (> 100 Hz)
- But not good in the low frequencies. This is because the demodulation phase is not fine-tuned yet.
- Will do Lock-in



Contents

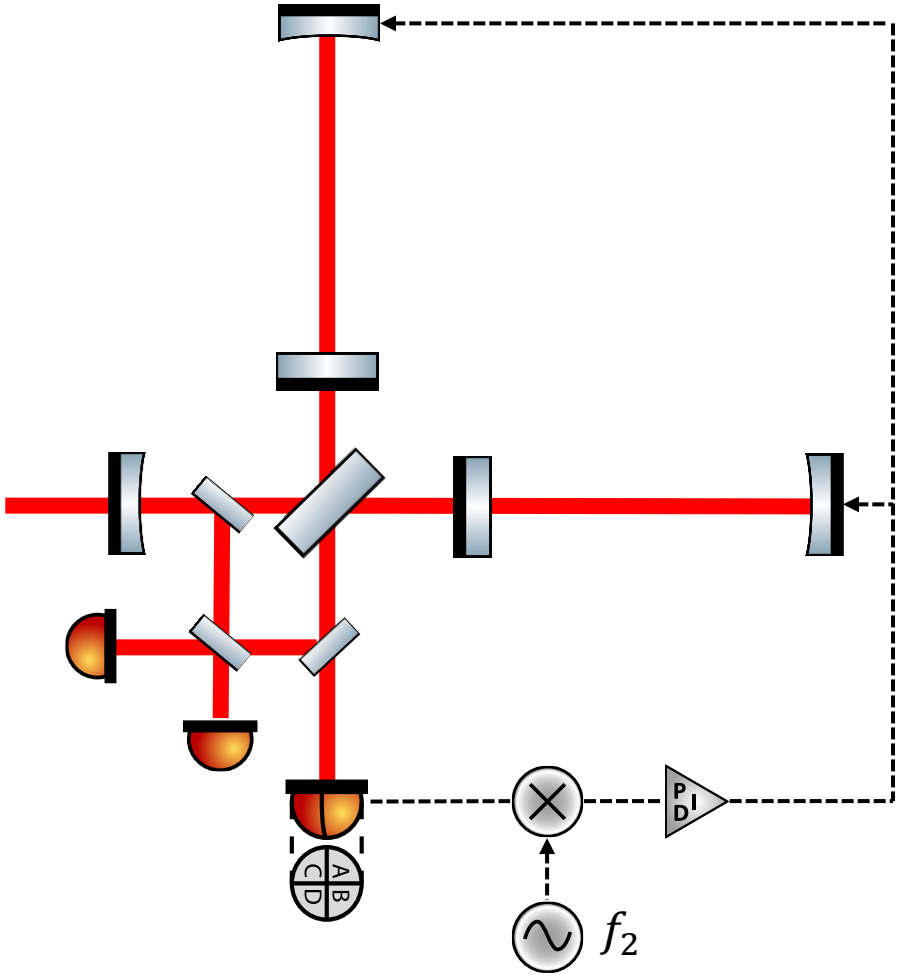
- Recent achievements
  - Lock acquisition of the PRFPMI
  - Low noise operation by 1f control of the PRCL & MICH

- What needs to be done
  - Wavefront sensor
  - Output mode cleaner
    - Install OMCs
    - Mode cleaner length control for small RMS
    - Alignment control to the OMCs
  - Balanced Homodyne Detection
    - Lock the local oscillator phase
    - Hand off the DARM control to the homodyne readout
  - Fix SRM (PRFPMI ==> DRFPMI)
    - Lock the signal recycling cavity on the (tuned) resonant sideband extraction

- What I can discuss in this work
  - Lock acquisition of BHD for GW detection
  - DARM sensitivity (RF, DC, BHD)
  - Contrast defect
  - Shot noise when SRM is detuned

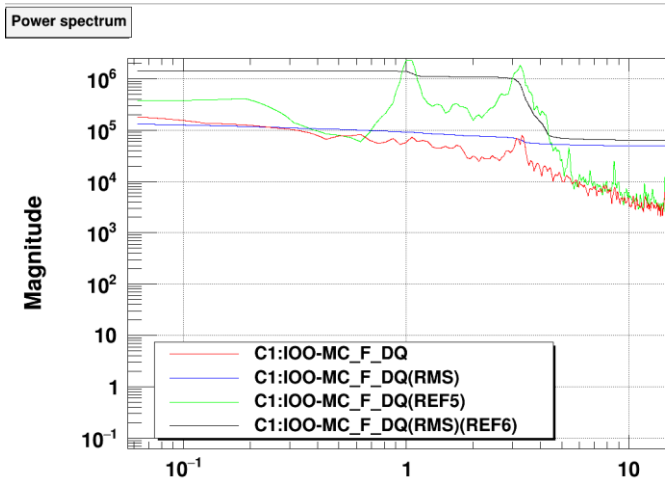
Wavefront sensor

- Wavefront sensor is necessary to get a stable alignment
- If the alignment is not stable and not good,
  - the optimal demodulation phase may drift
  - optical gains drift
- f_2 is used
- We have only one QPD on the AS port now, and trying to close a loop for **the differential ETM motion**
- We update this to the full DoFs preparing for three more QPDs if necessary
- How do you get WFS signals for PRC, SRC, MI?
  - Beat note between sidebands to avoid large response from ARM?
  - KAGRA uses
    - $f_2 - f_1$ for MI
    - ADS for PRC

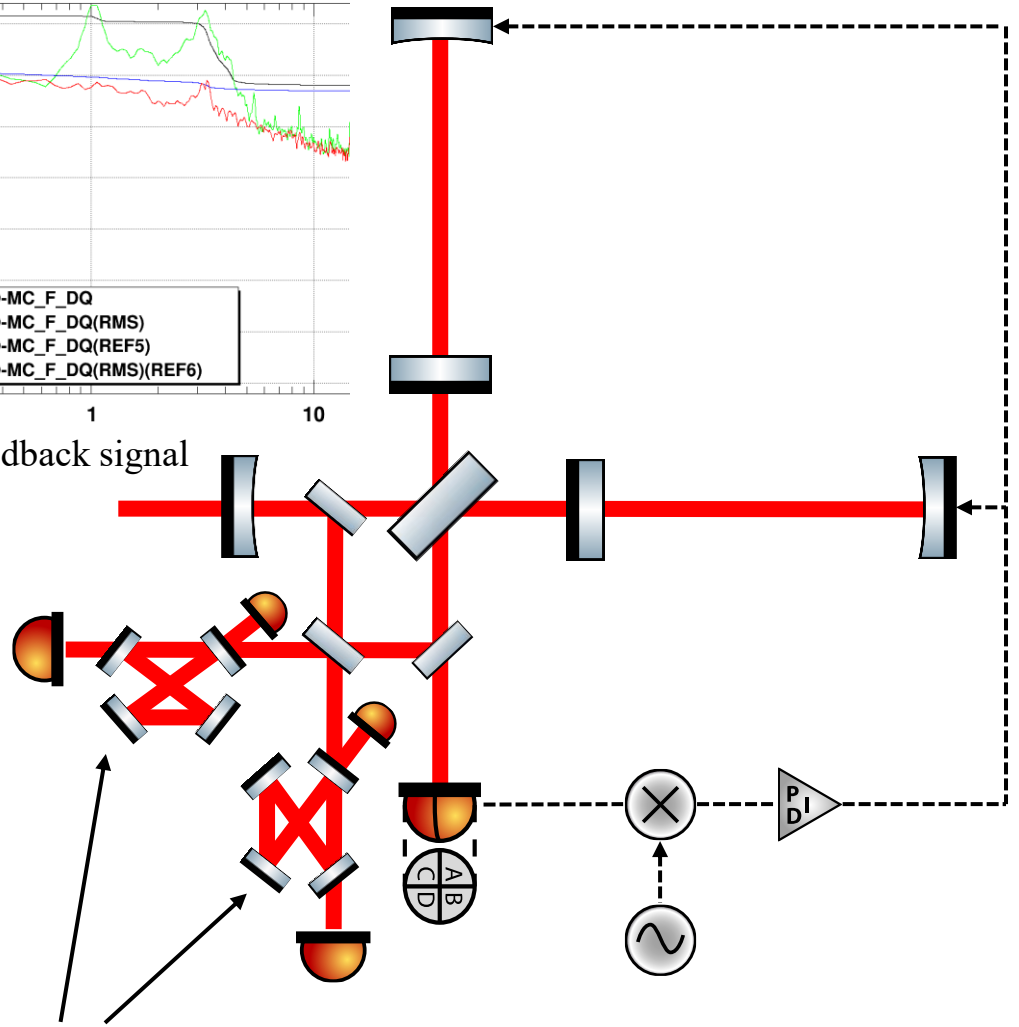


Output Mode Cleaner

- Two OMCs are necessary to get a good contrast
- Signal light from the AS port contains HOMs due to the mode-mismatch between the arm cavities whereas LO beam is picked off from the power recycling cavity, so should be close to the ideal fundamental mode
- OMC lock scheme is not designed yet
  - Which sideband should be used? Dither lock?
- For locking the OMCs, RMS of the frequency noise needs to be small. So, **IMC length servo may be required**
- **Alignment control to the OMC is also needed, but it is not designed how to yet.**
  - LO → OMC, Signal → OMC
  - Put QPDs on the reflection of the OMCs?



PSL-IMC loop feedback signal

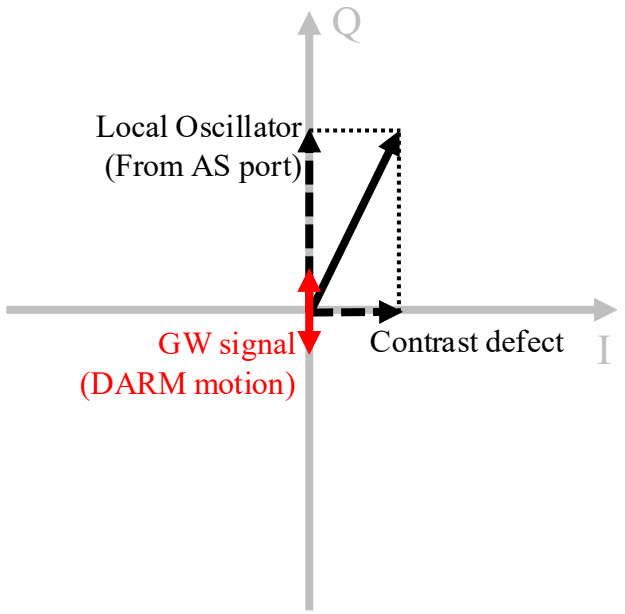


- Why do we need the two here?
  - Can we put them before the BS?
  - Do we need the OMC in the LO path in that case?
  - Non-zero carrier light is needed to lock

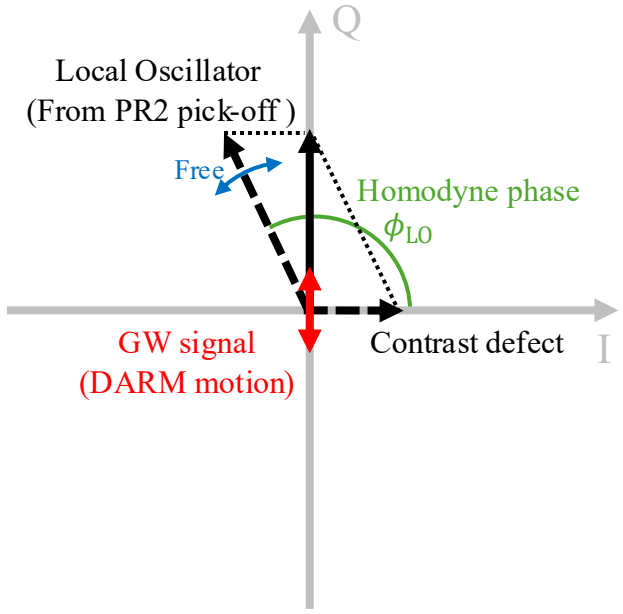
Balanced Homodyne Detection

- To do the balanced homodyne DARM readout, we need two loops
  - LO phase to the phase of the signal beam
  - Hand off the DARM to BHD

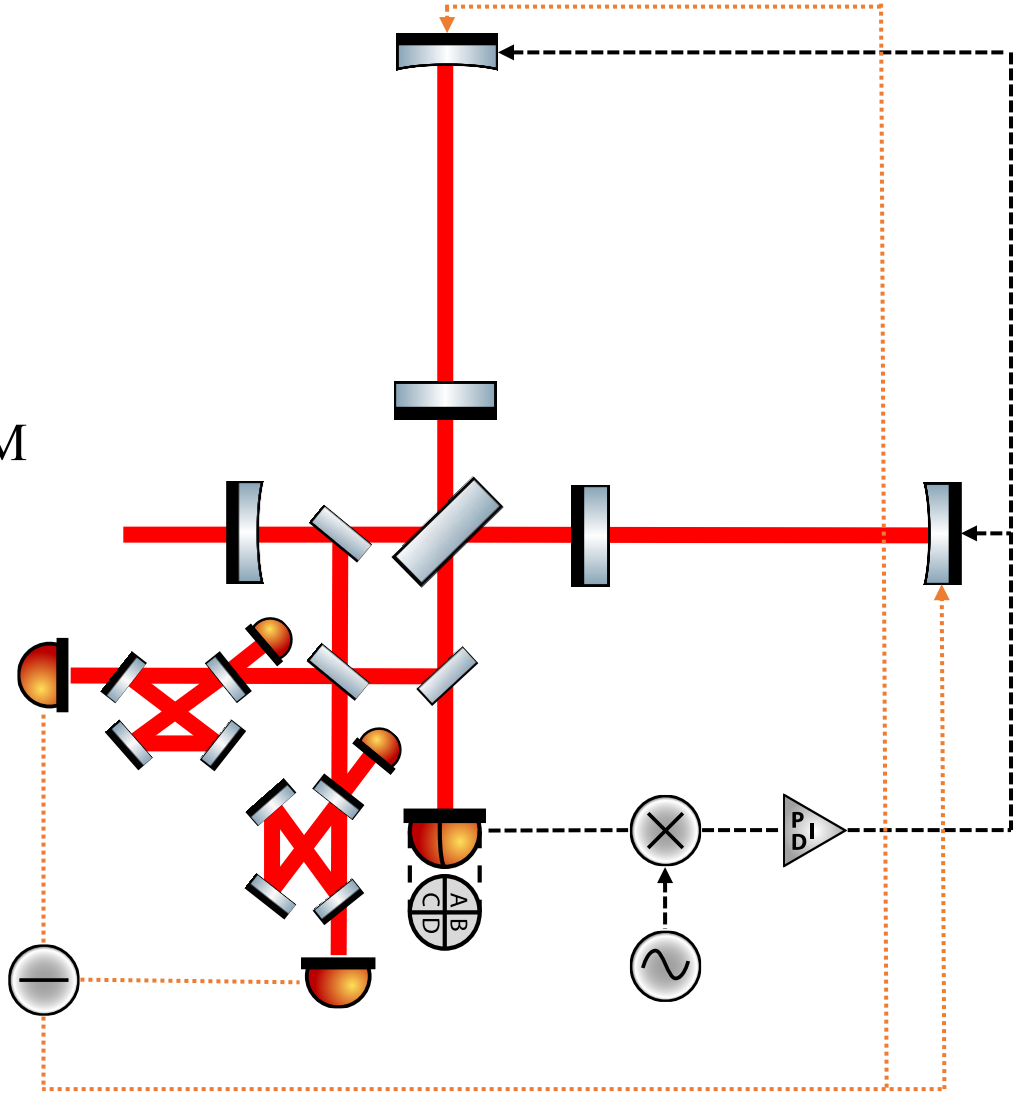
- LO phase is chosen so that it maximizes the response to the DARM



DC readout

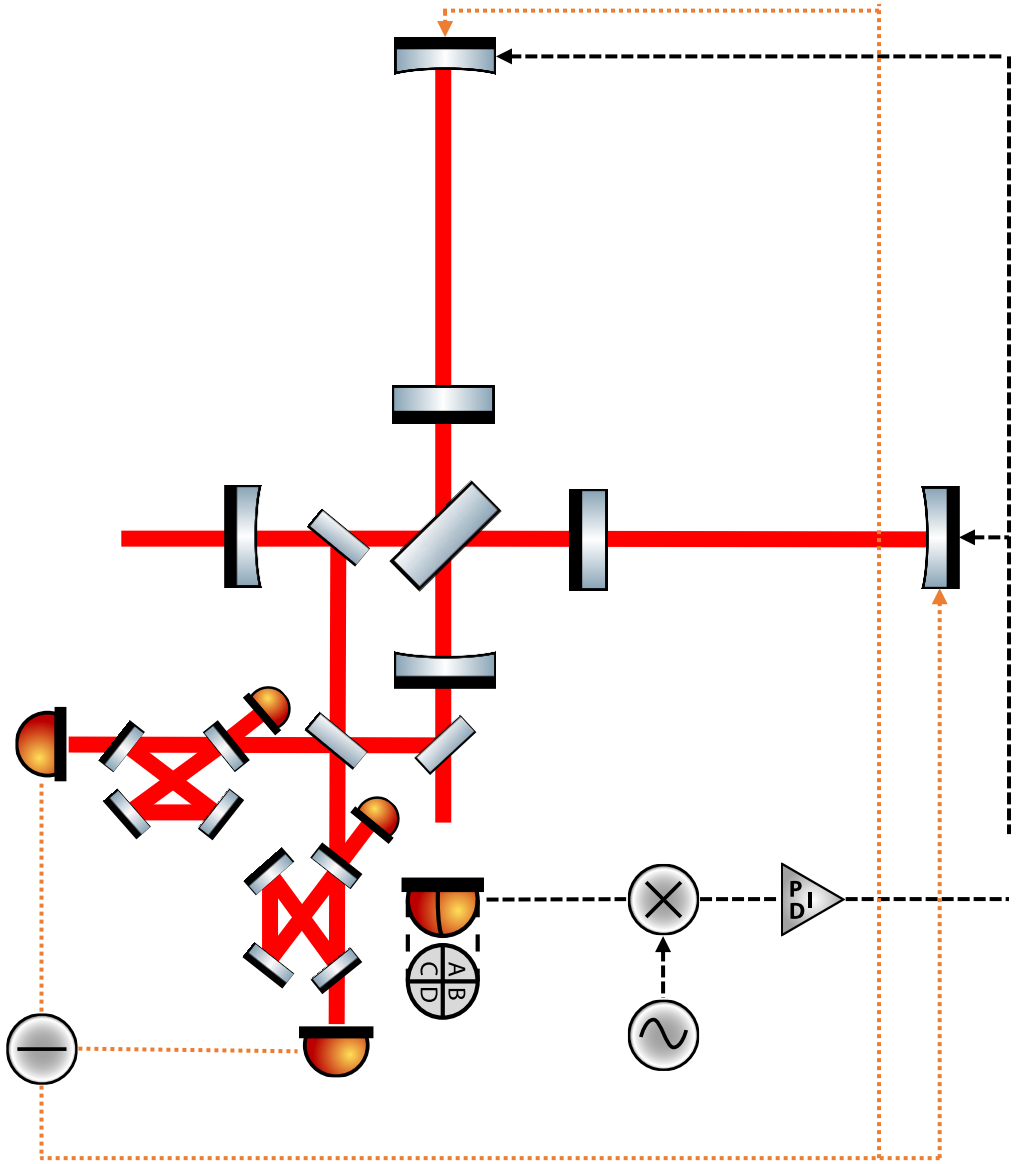


BH readout



Locking the signal recycling cavity

- The SRM (one OSEM) is broken and always misaligned now.
- After we achieve the BHD with PRFPMI, we will fix it and put it back to the aligned state for BHD of DRFPMI
- How do I get the signals? My plan is
  - DARM : AS f_2 Q
  - CARM : REFL f_1 I
  - MICH : **REFL f_1 Q**
  - PRCL : REFL f_2 I
  - **SRCL : REFL f_2 Q**
- Is the SR or RSE important for I and Q?
- f_2 is resonant to the SRC but f_1 is not



Contents

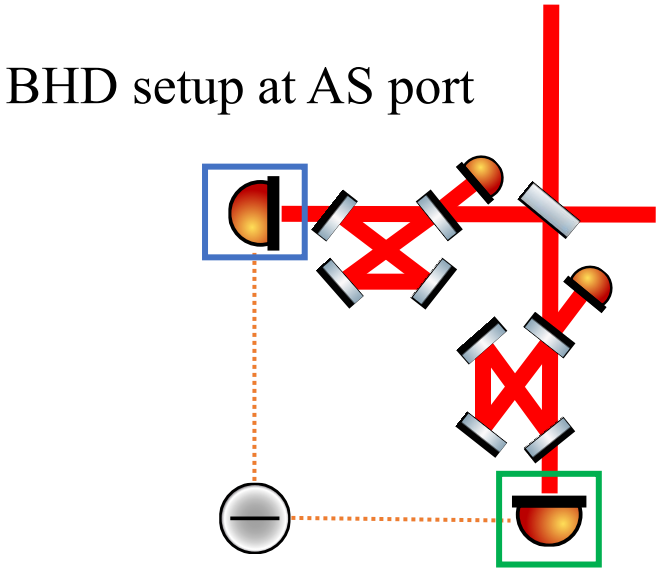
- Recent achievements
  - Lock acquisition of the PRFPMI
  - Low noise operation by 1f control of the PRCL & MICH

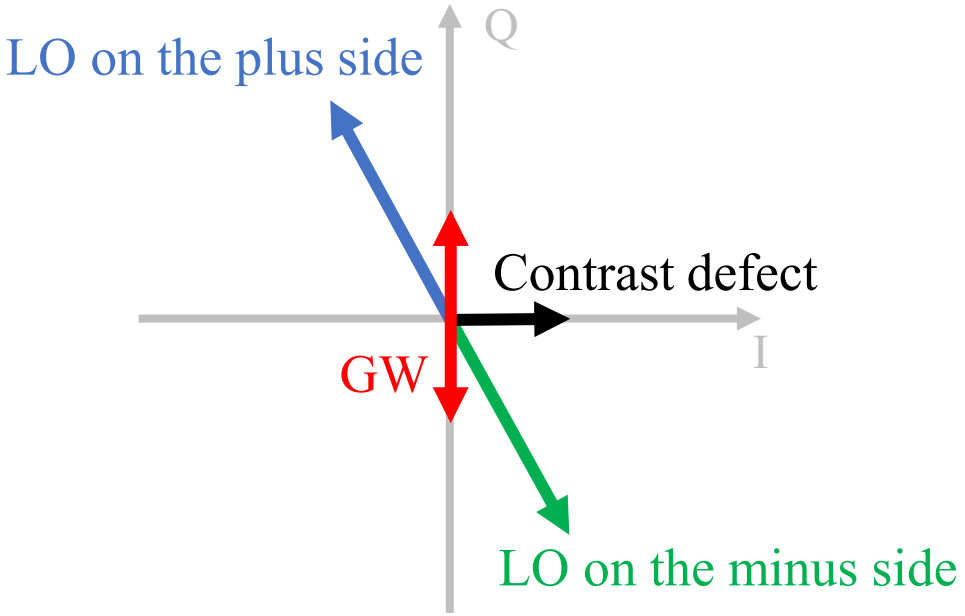
- What needs to be done
  - Wavefront sensor
  - Output mode cleaner
    - Install OMCs
    - Mode cleaner length control for small RMS
    - Alignment control to the OMCs
  - Balanced Homodyne Detection
    - Lock the local oscillator phase
    - Hand off the DARM control to the homodyne readout
  - Fix SRM (PRFPMI ==> DRFPMI)
    - Lock the signal recycling cavity on the (tuned) resonant sideband extraction

- What I can discuss in this work
  - Lock acquisition of BHD for GW detection
  - DARM sensitivity (RF, DC, BHD)
  - Contrast defect
  - Shot noise when SRM is detuned

Contrast defect

- Contrast defect is expected to be much larger than the present because the higher power is input to the main IFO in the next generation beyond O5
- However, we cannot handle the high power because PD has a damage threshold
- Can we set the LO phase so that the contrast defect is cancelled out simultaneously?
- In my mind, when the LO phase set so that the plus side is optimized, the minus side has more DC power than when the LO phase set to the same as the DC readout. Is that ok?



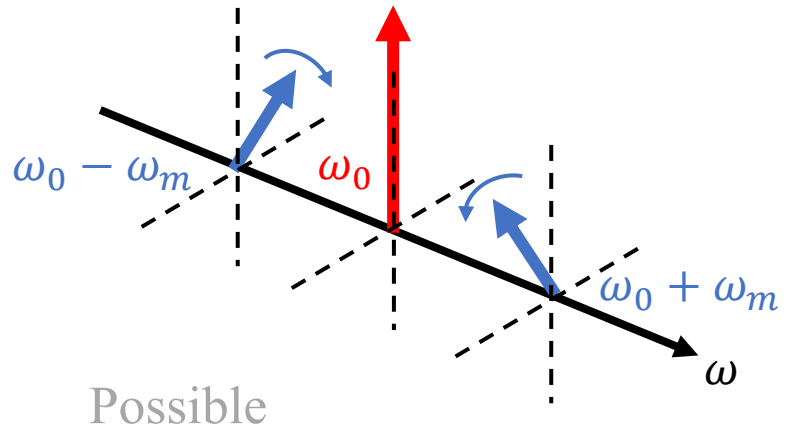


BHD lock acquisition

- Our first option to use for LO lock is $f_2 - f_1$ because the beat frequency between the carrier and the sideband has DARM, which is larger than the relative phase motion between the LO and the signal

- But we have f_2 RFPD as well to be able to compare to the differential frequency

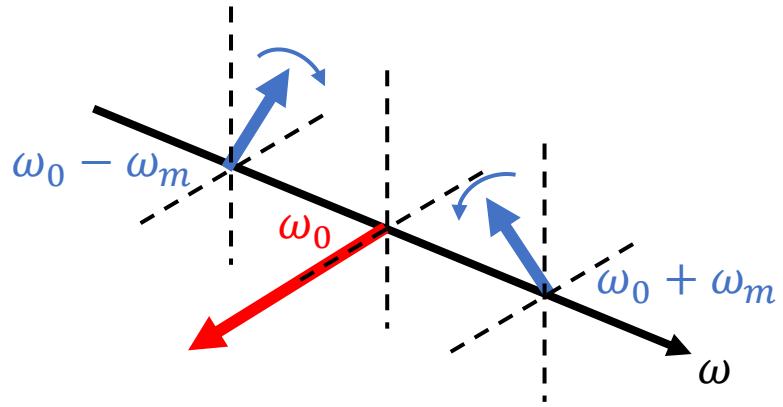
- It is said that we can freely choose the readout angle by setting LO phase properly. Is that true?
  - Can we get the error signal for LO phase is when there are sidebands on both plus and minus side?



Possible

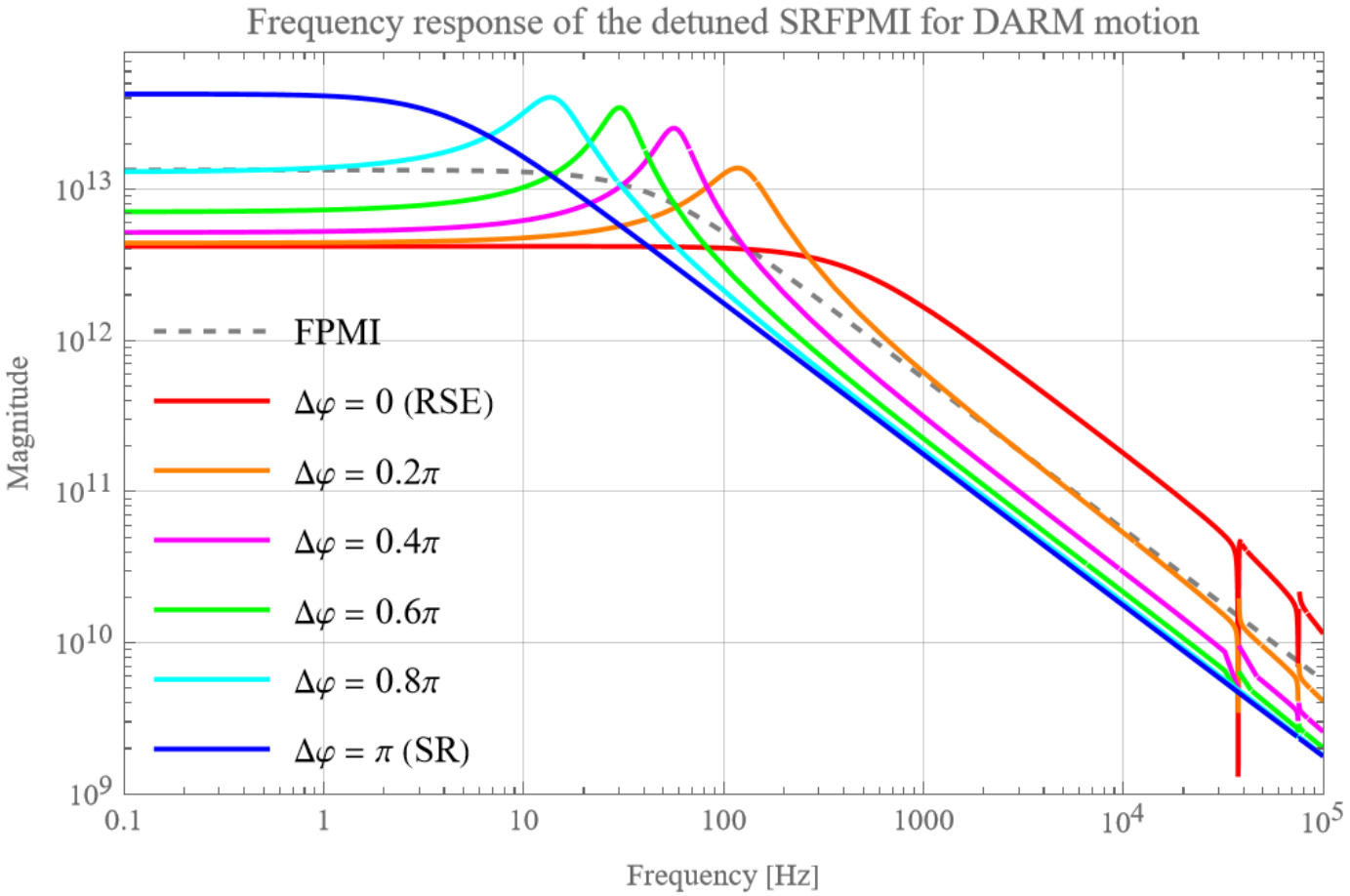
Carrier from the PRC pick off (LO)
Sideband from signal path (AS)

Impossible ?



Conflict of SRC and Detuning

- In the present GW detection, the detuning of the DARM is needed for LO beam, but it generates noise couplings from signal recycling cavity
- BHD can stop detuning of the DARM. Instead, the carrier as the local oscillator is picked off from the PRC.
- In that case, can we detune the signal recycling cavity and make some dips in the DARM sensitivity without bad quantum noise-couplings that are observed in the LIGO DRFPMI?



Summary

- To Do List in 6 months
  - Wavefront sensor
  - OMC install
  - Lock BHD
  - Fix SRM
  - Lock SRM

- To be discussed in thesis
  - How to get the full RF lock in the 40m
  - How to get BH DARM readout
  - Comparison of DARM sensitivity between RF, DC, BHD
  - How the contrast defect limits the sensitivity in the 40m, and how it scales up when converting it to future LIGO
  - Noise couplings under various SRC configuration, RSE, SR, and detuned states

End