安東研中間報告会

2013年5月1日

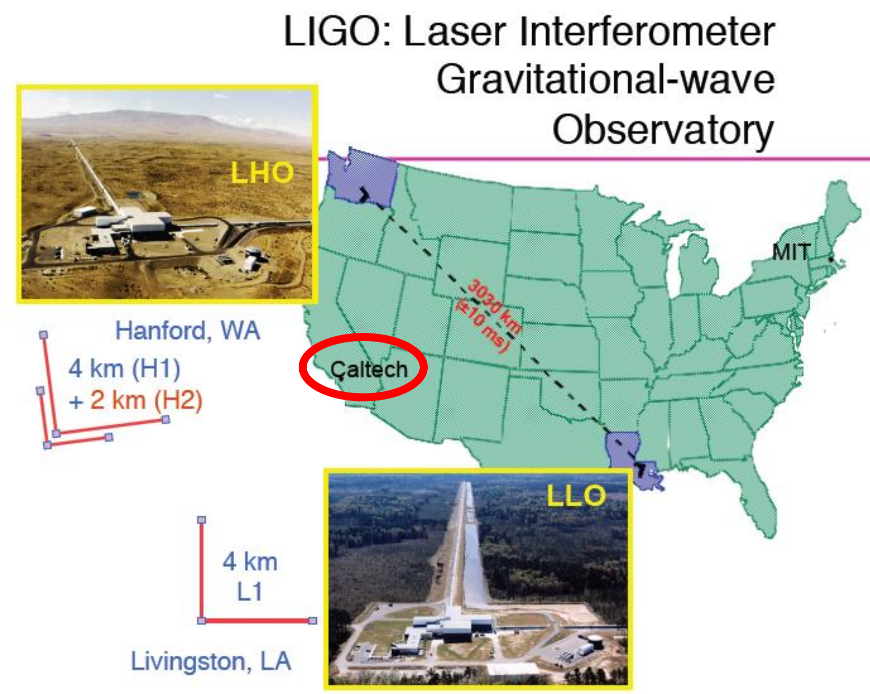
Caltech 40m 報告

道村唯太
東京大学大学院理学系研究科物理学専攻
安東研究室 博士課程2年

40mプロトタイプ干渉計とは

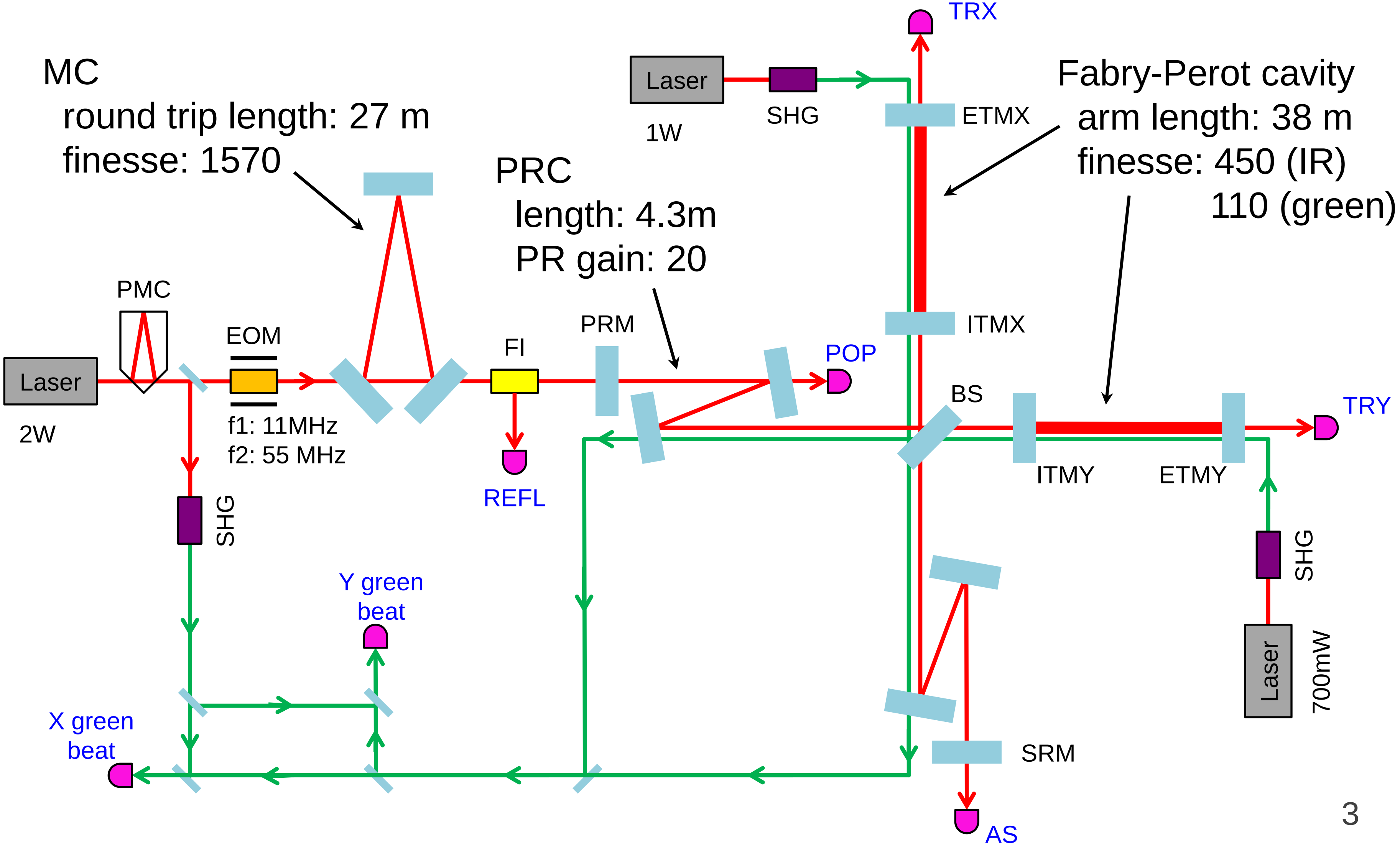
- Caltechキャンパス内にある
- aLIGO(やその先)を加速させるためのいろいろなテスト/開発/教育をするところ

http://www.ligo.caltech.edu/~ajw/LIGO_SURF09.pdf



40mの干渉計構成

- aLIGOやKAGRAとだいたい同じ



40mの現状

- 目標: green lockを用いたDRFPMIの長さ制御
- 2012年4月 和泉究氏が40mを去る
  片腕のgreen lockで博士論文
  K. Izumi+: JOSA A **29** (2012) 2092
- 2012年7月 両腕のgreen lock
  ビート周波数測定系の改善
- 2012年後半 新しい鏡の導入など
- 2013年2月 PRCの不安定問題を解決
- 現在 PRMI制御の改善(REFL55I&Q)
  end table upgrade など

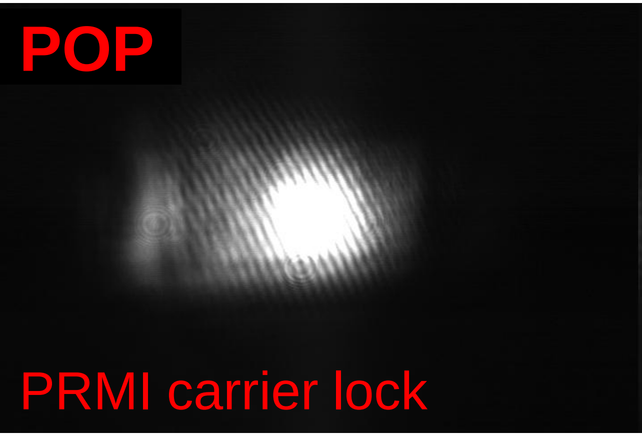
今回のお話
その2
(以前輪講
で話した)
+ phase
trackerの話

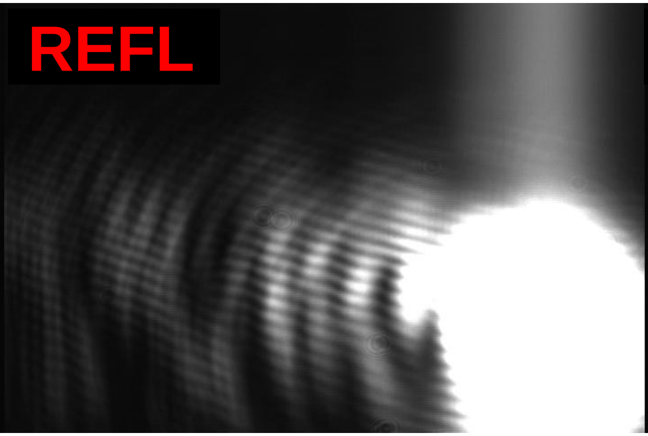
今回のお話 その1
(春の学会発表練習で話した)

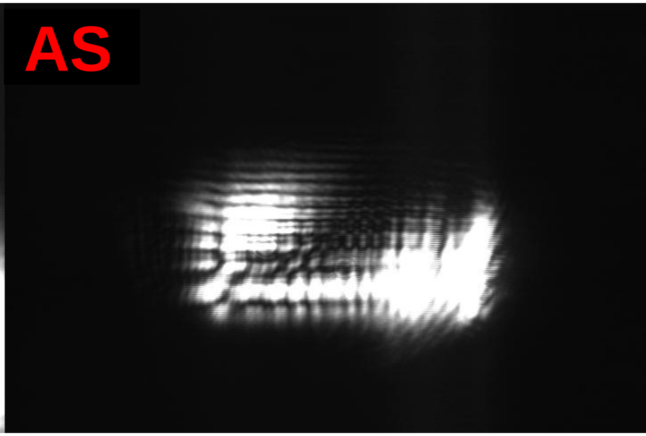
PRC
(2013年2月)

PRCにあった問題点

- PRC内のモードがおかしい





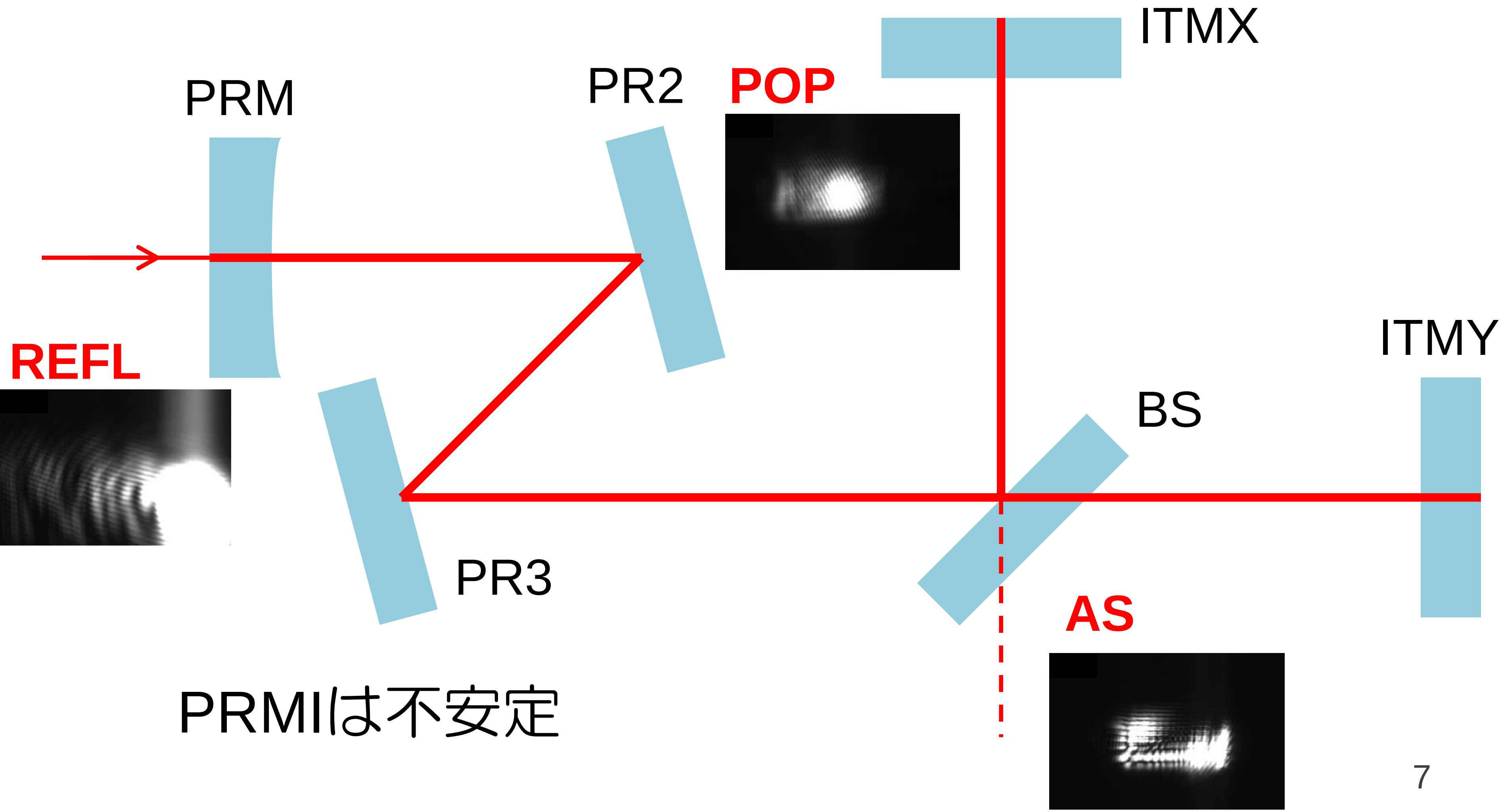


- リサイクリングゲインが ~5 しかいかない
  (PRMIでの設計値45)
- ビームの揺れが激しい
- 復調信号にグリッチがのり、ロックが持たない

- これで2年以上悩んでいた

PRCの調査

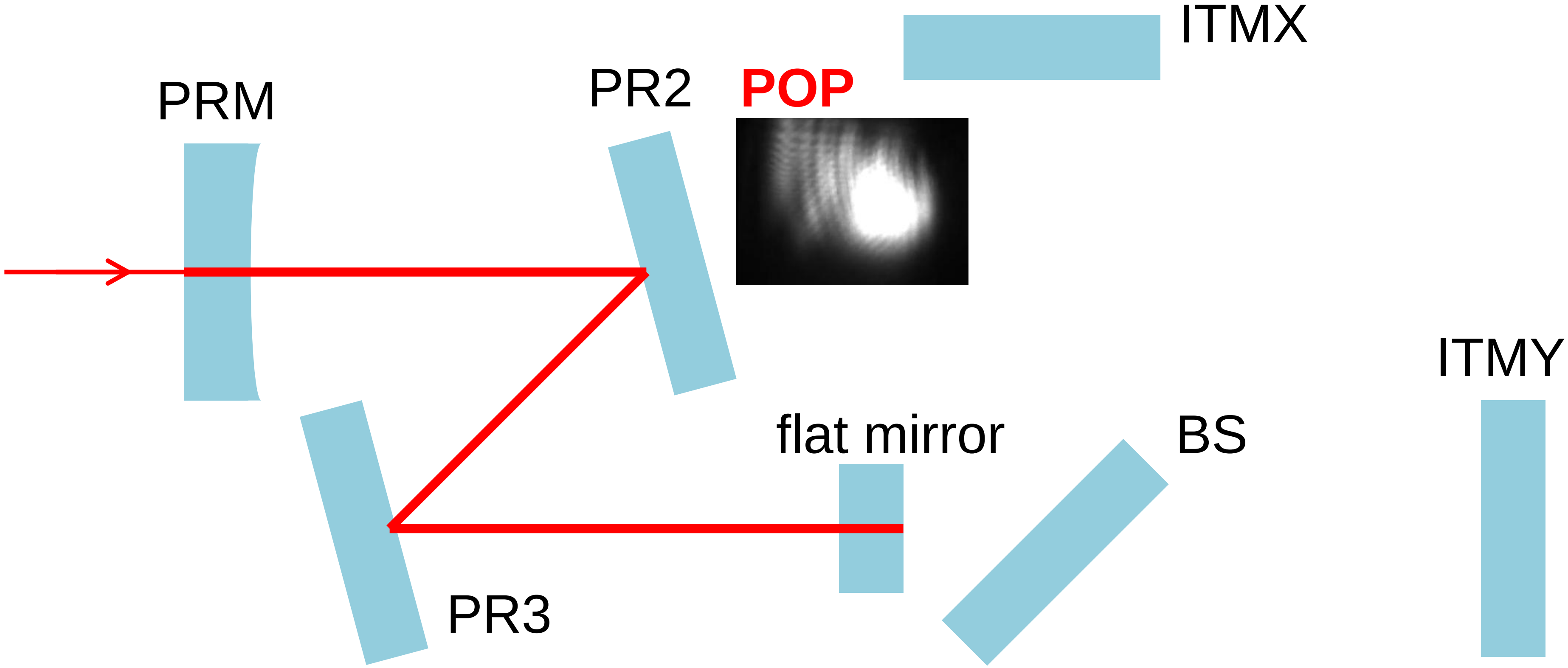
- 少しずつ鏡の枚数を減らし、原因を特定



PRMIは不安定

PRCの調査

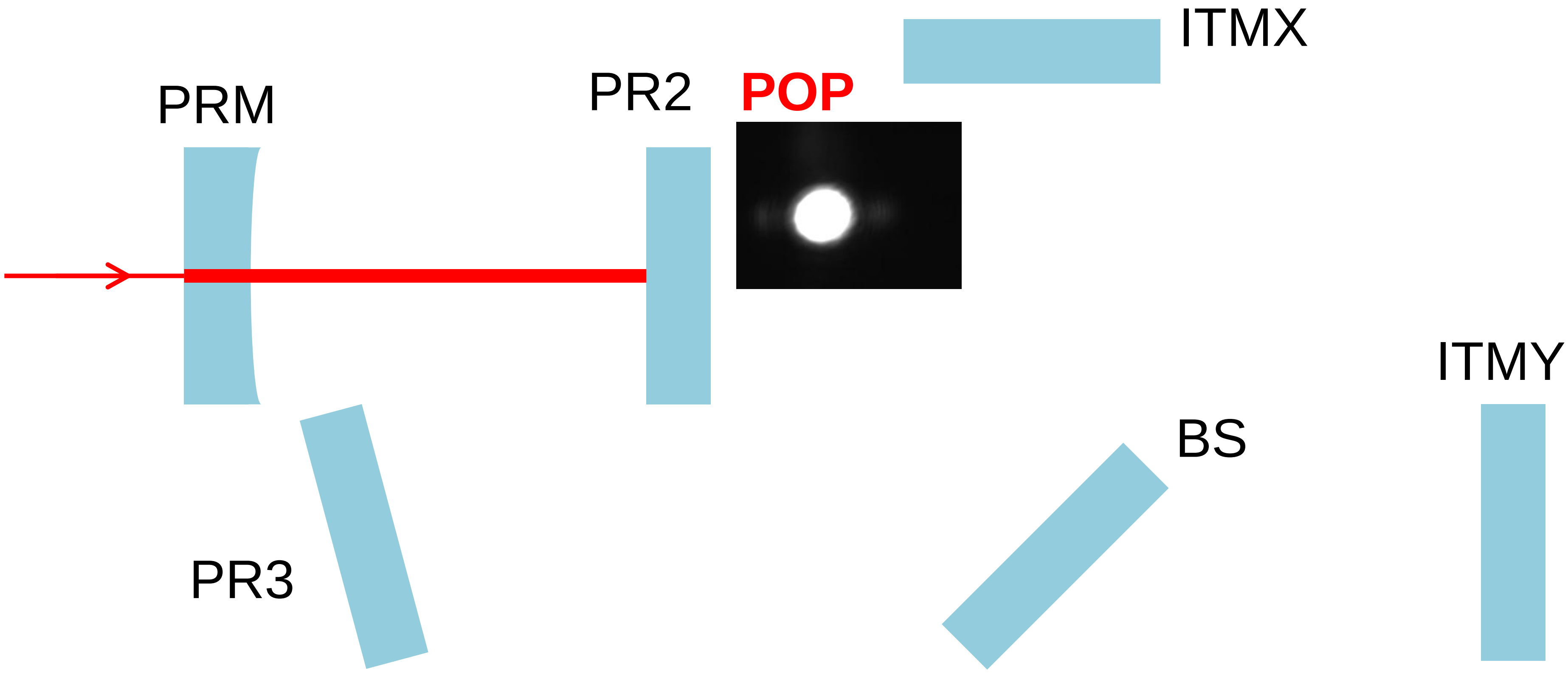
- 少しずつ鏡の枚数を減らし、原因を特定



PRM-PR2-PR3-flatも不安定

PRCの調査

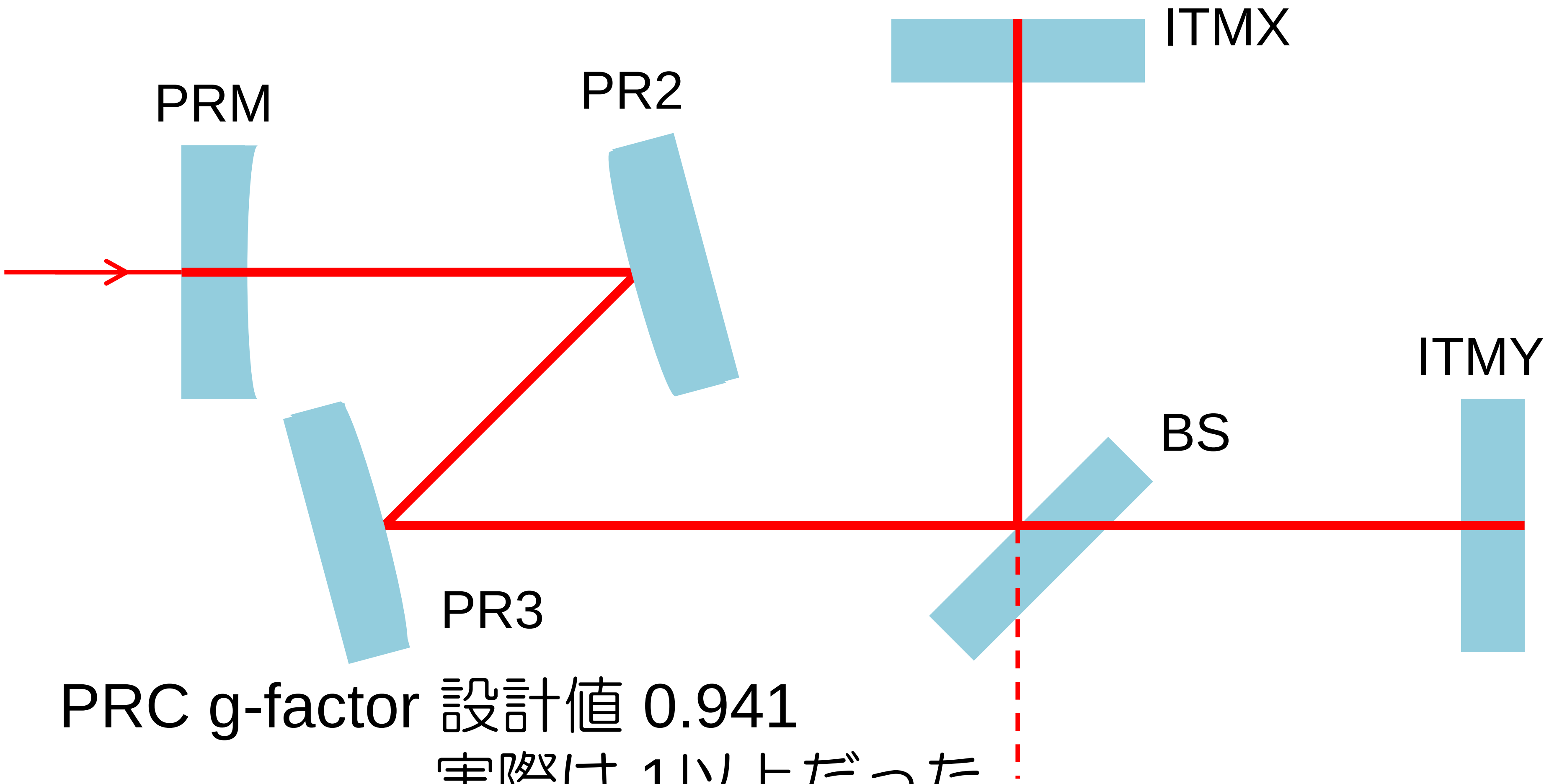
- 少しずつ鏡の枚数を減らし、原因を特定



PRM-PR2は安定

PR2/PR3の曲率が原因だった

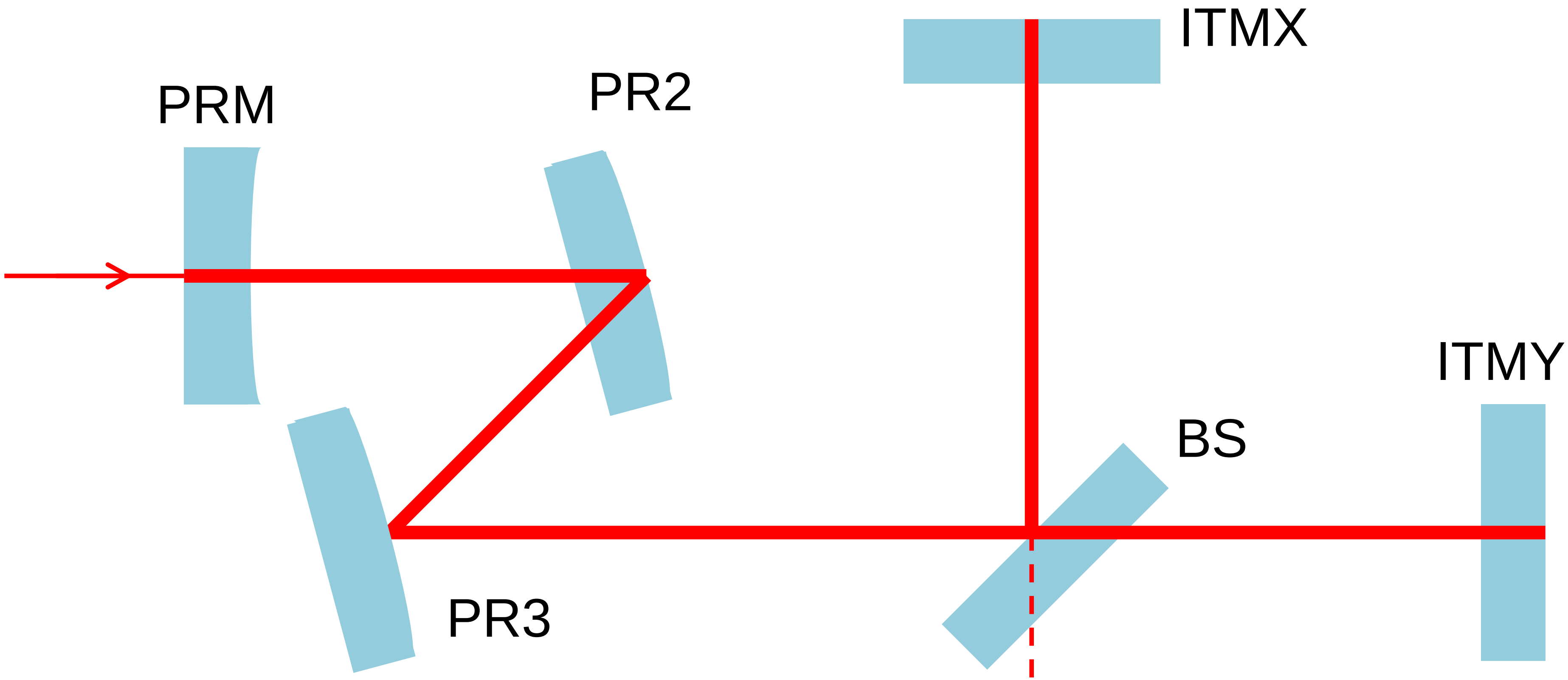
- 曲率測定の結果、PR2/PR3が凸だった
  RoC ~ -600 m (PRCL=4.34 m)



PRC g-factor 設計値 0.941
実際は 1以上だった

PR2の反転

- とりあえずPR2を反転させることで安定化に成功

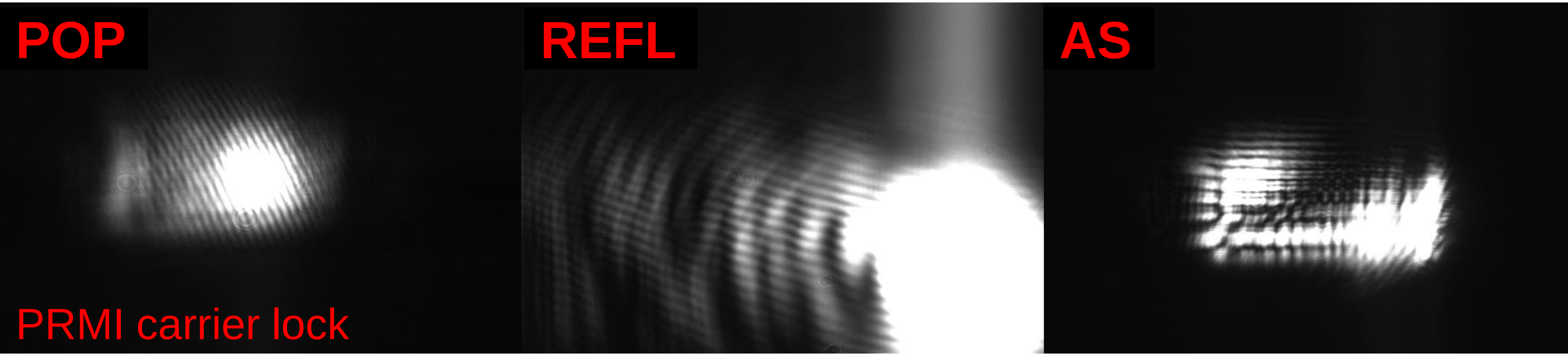


PRC g-factor 予想値 0.939 (s) / 0.966 (t)

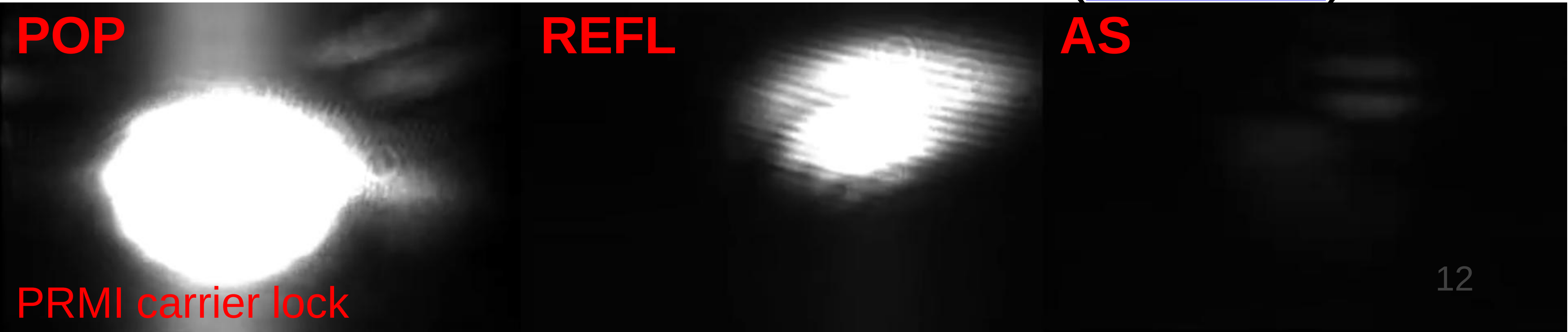
実測値 $0.97^{+0.01}_{-0.04}$ / $0.96^{+0.02}_{-0.05}$

PRC内モード

- PRC不安定時(PR2反転前、2012.07.28)
  リサイクリングゲイン ~5



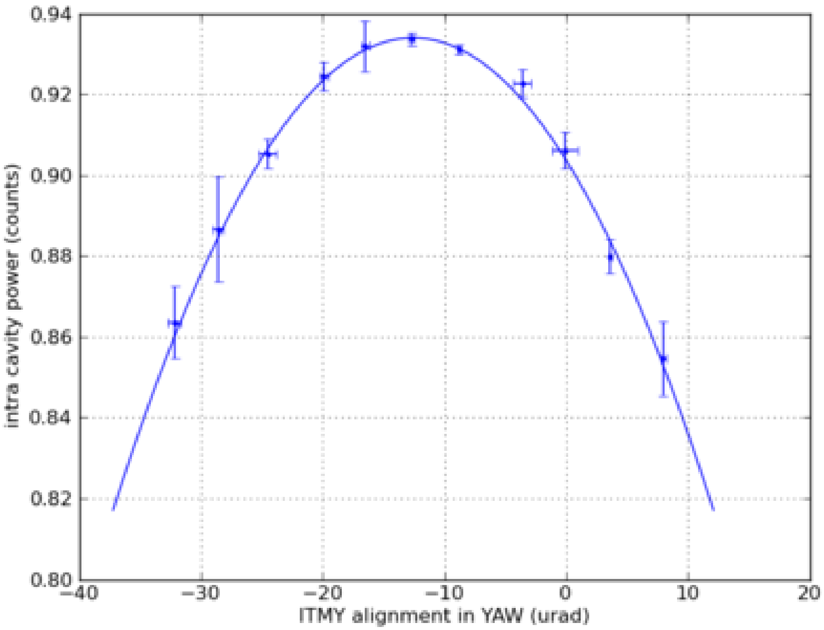
- PRC安定化後(PR2反転後、2013.02.28)
  リサイクリングゲイン ~25　(YouTube)

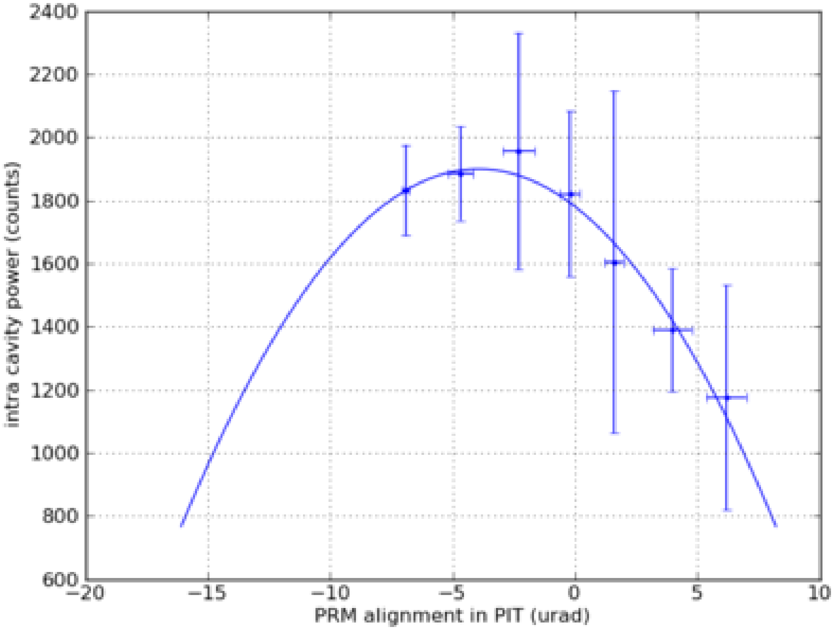


PRMIのg-factor測定

- PRMIのロック中に
  - 鏡を少しずつ傾けてPOPを測定

    今回やった方法
  - 鏡をditherしながら少しずつ傾けて POPの傾きを測定
  - 鏡をditherしてPOPを1次と2次で復調
- 鏡の傾きは光てこで較正

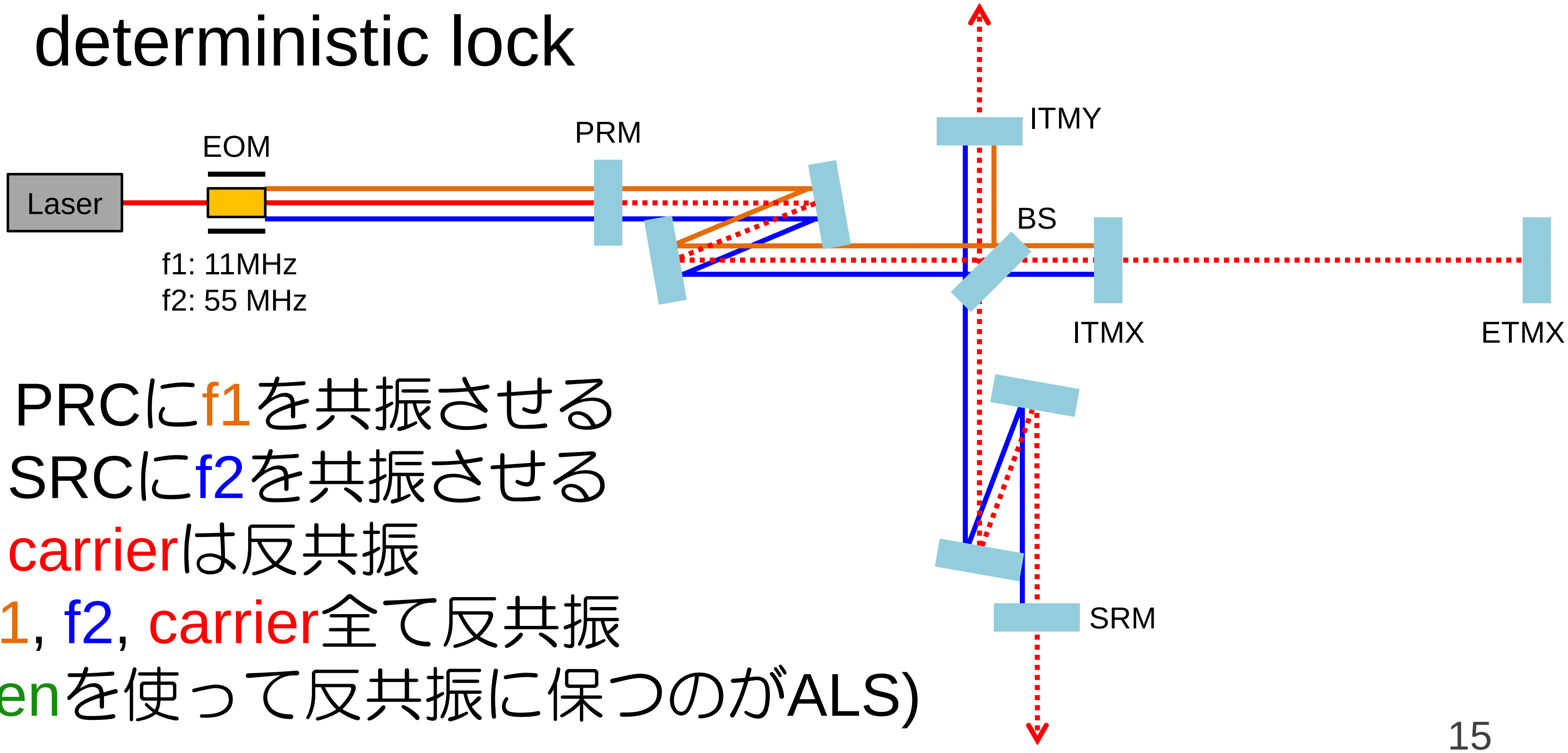




ALS
(2012年7月)

ALSの目的

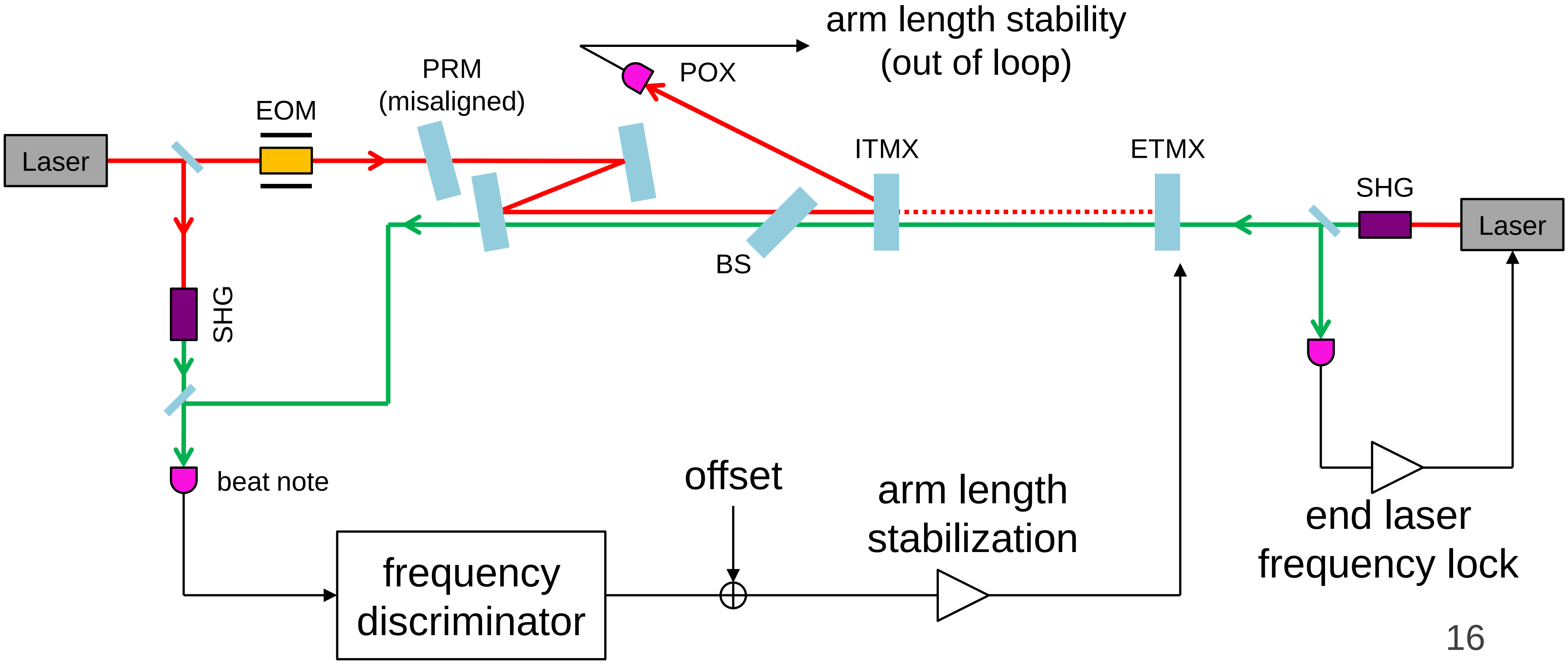
- 共振器長が揺れると、腕の(複素)反射率が変わる
  → DRMIのロックを保てない
- 共振器長を予め安定化させ、確実にDRMIのロックを保つ。その上で、腕を共振に持って行く
  deterministic lock



DRMI: PRCにf1を共振させる
SRCにf2を共振させる
carrierは反共振
両腕: f1, f2, carrier全て反共振
(greenを使って反共振に保つのがALS)

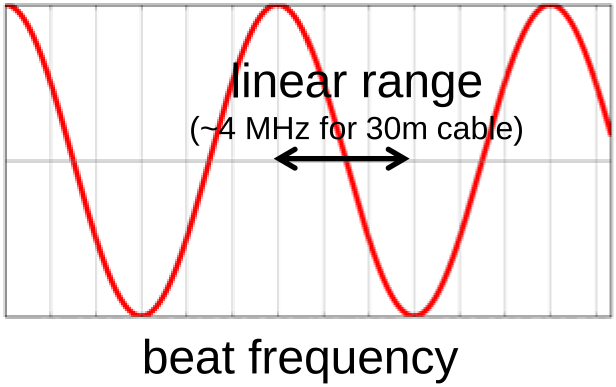
ALSのセットアップ

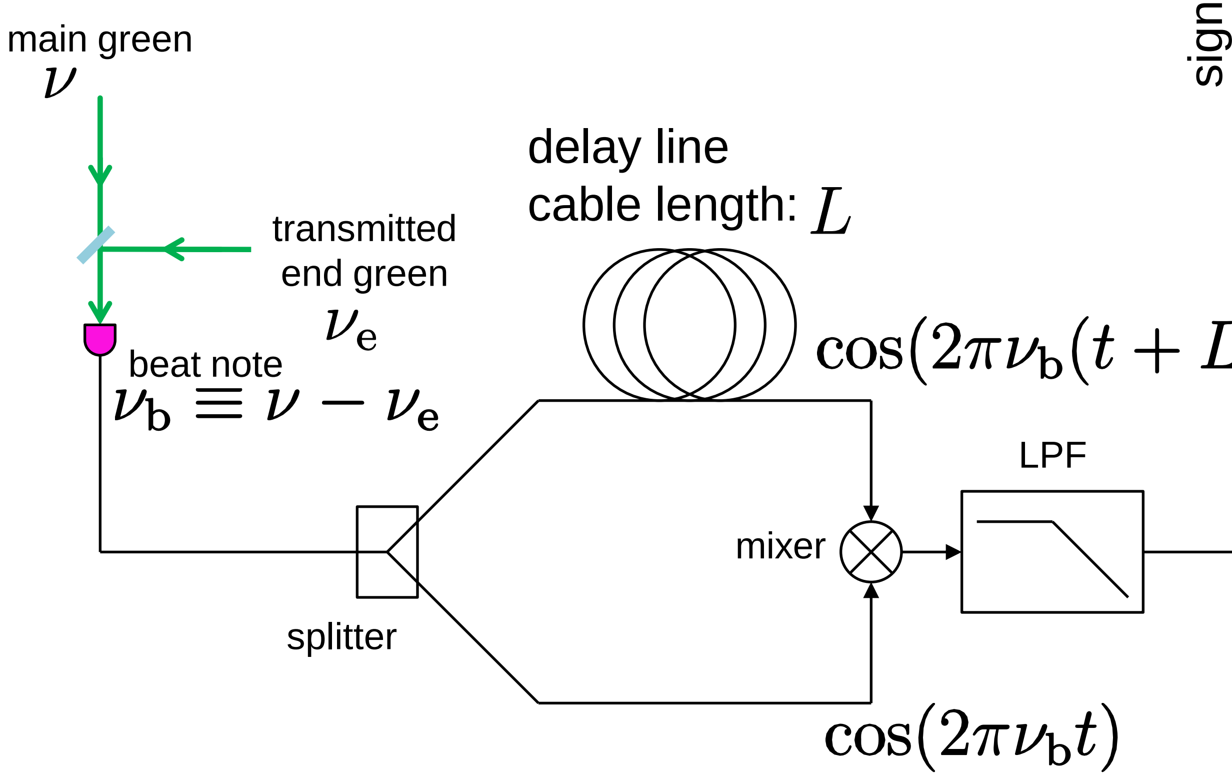
- ETM側から倍波(green)を入射し、end greenの周波数を共振器長に追従させる
- end greenとmainのgreenの周波数を比較し、共振器長を制御



Frequency Discriminator

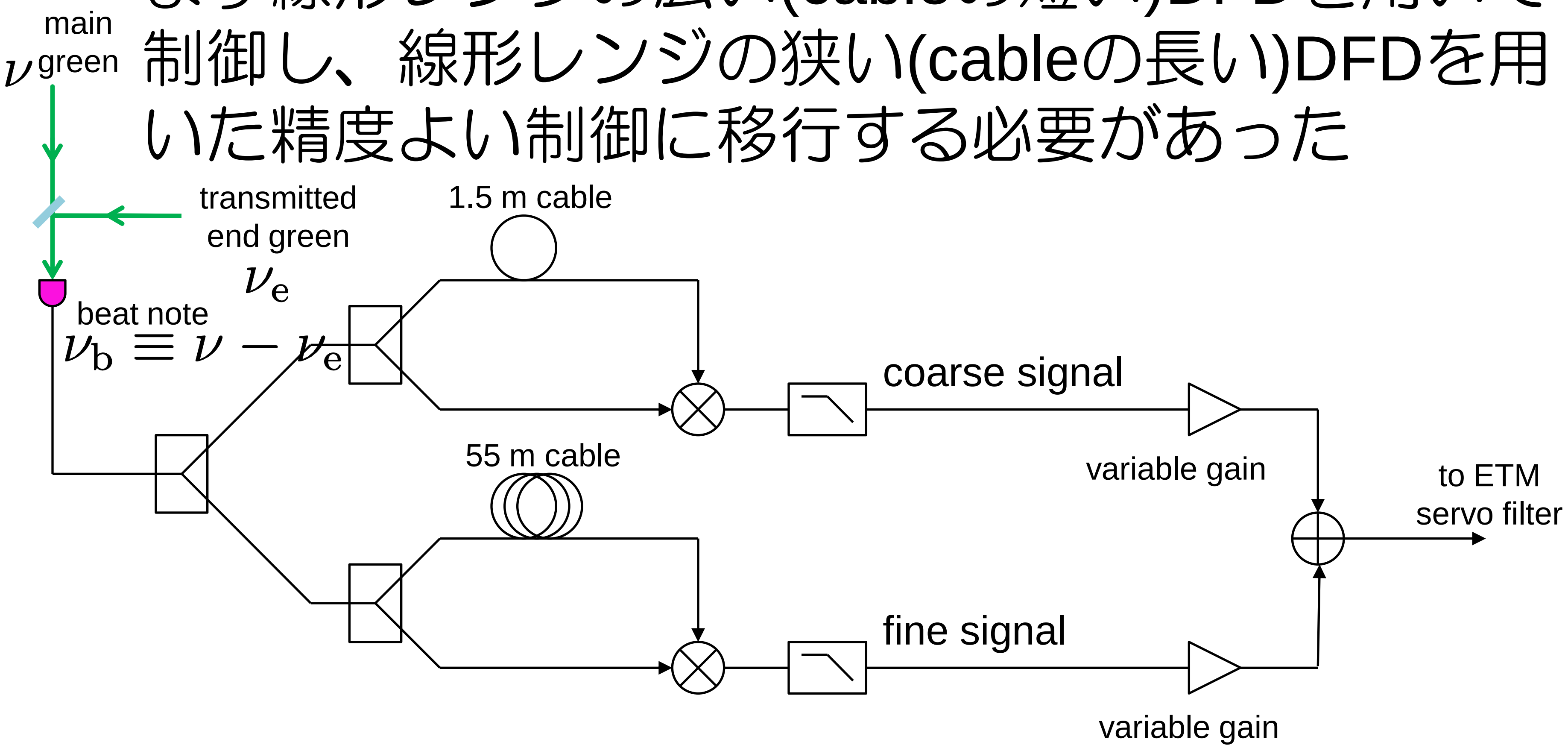
- delay lineを用いるDFD
- cableが長いほど、感度が良いが線形レンジが狭い





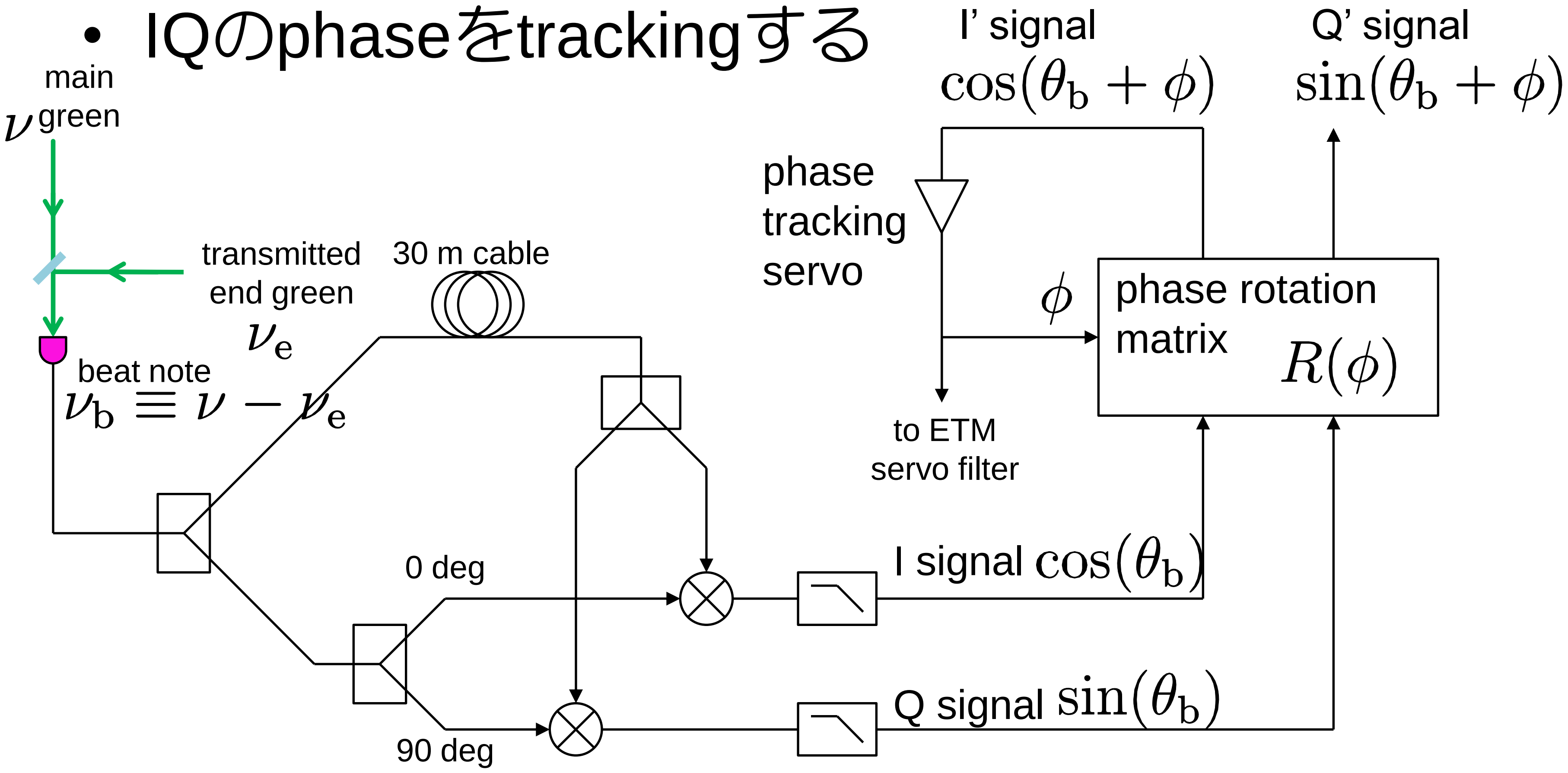
これまでのシステム

- 異なる長さのdelay cableからなるDFDを2つ用意
- まず線形レンジの広い(cableの短い)DFDを用いて制御し、線形レンジの狭い(cableの長い)DFDを用いた精度よい制御に移行する必要があった



新システム

- IQ phaseを用いる
- IQのphaseをtrackingする

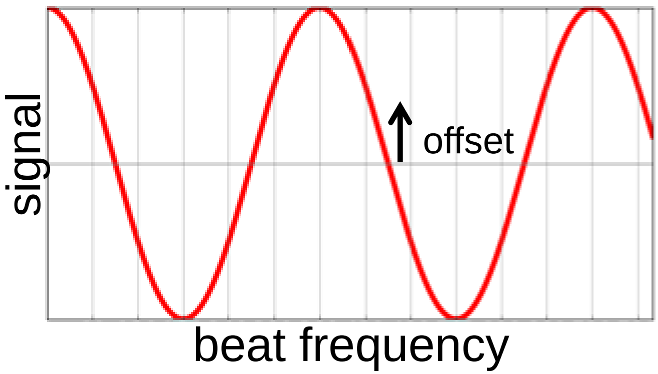


$$\theta_{\mathrm{b}} \equiv 2\pi\nu_{\mathrm{b}} L / c_{\mathrm{m}}$$

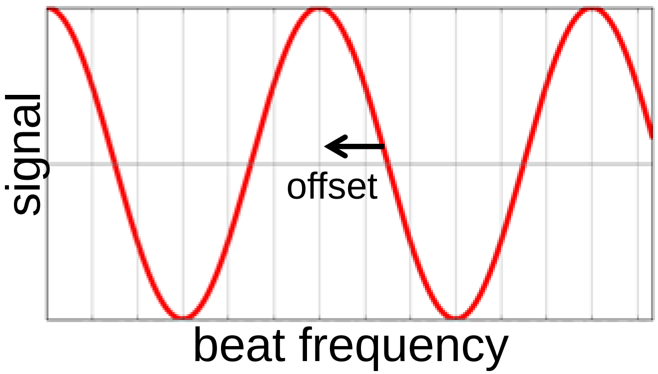
新システムの利点

- coarse/fineの切り替え不要
- phase tracking servoのループ内にオフセットを加えることで、任意の共振器長に持っていける
- 強度雑音に強い

これまで: 制御点をゼロ点からずらすことで、
共振器長を変化させていた



これから: phaseをずらすので、
制御点は常にゼロ点

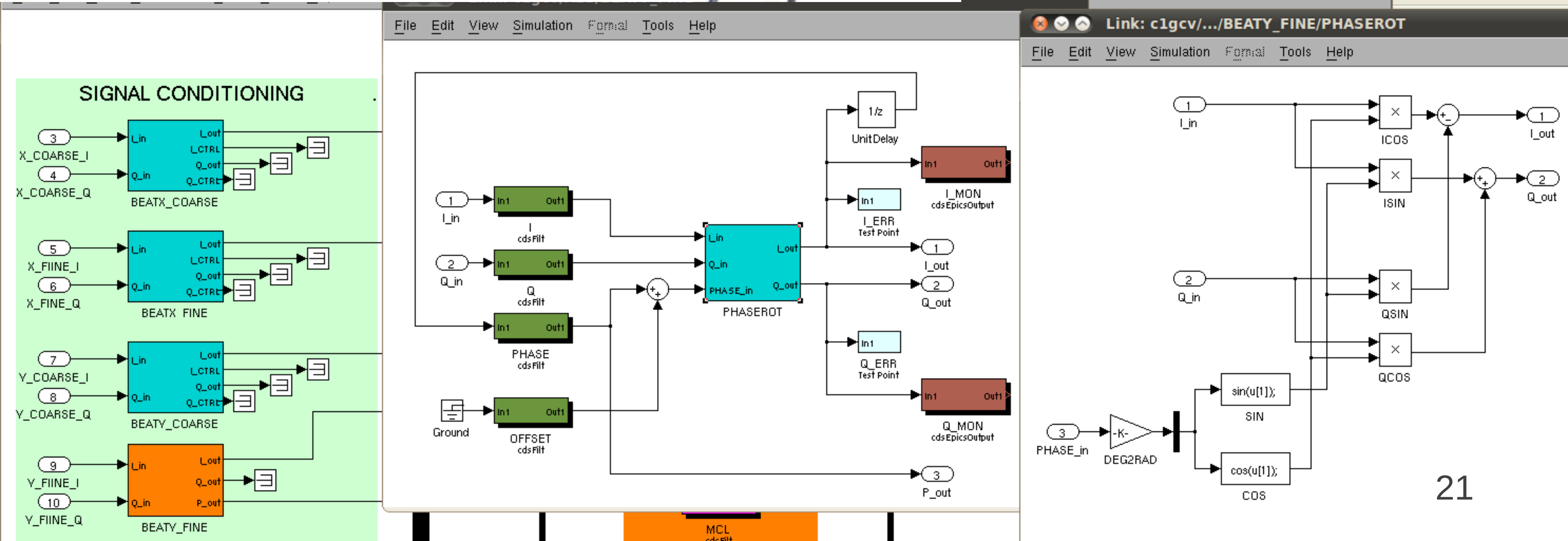


実装

(note that this is an older version of the beatbox)

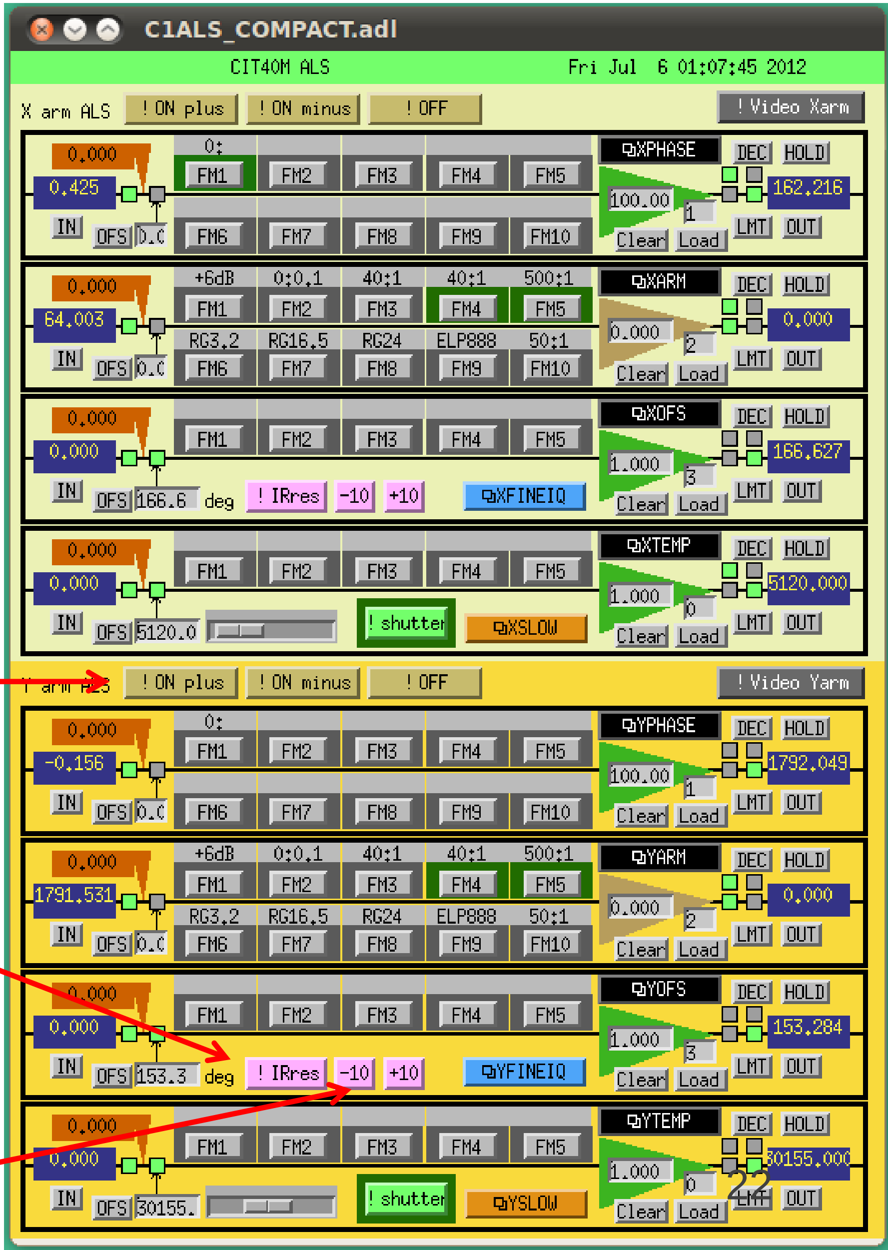
きれいな
RF回路系

IQがあればなんでも
できるデジタル系



洗練されたALS

- 共振器長をsweepして、IRの共振を自動的に探すスクリプト
- IRの共振から何 MHz detuneさせるか自在に操れる

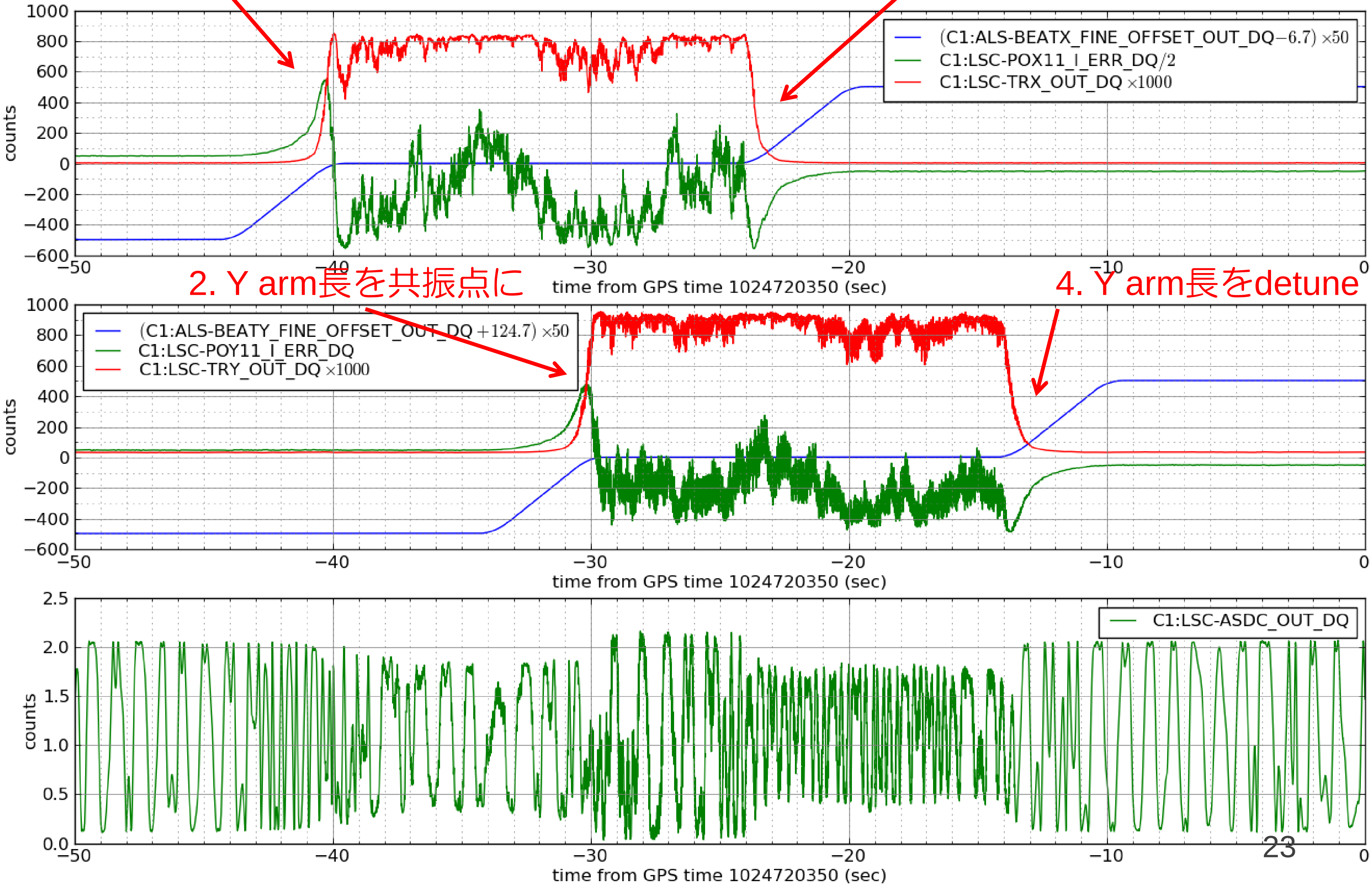


ALS on/offのボタン

IR共振を探すボタン

0.1 MHz detuneさせるボタン

ALSの威力



1. X arm長を共振点に

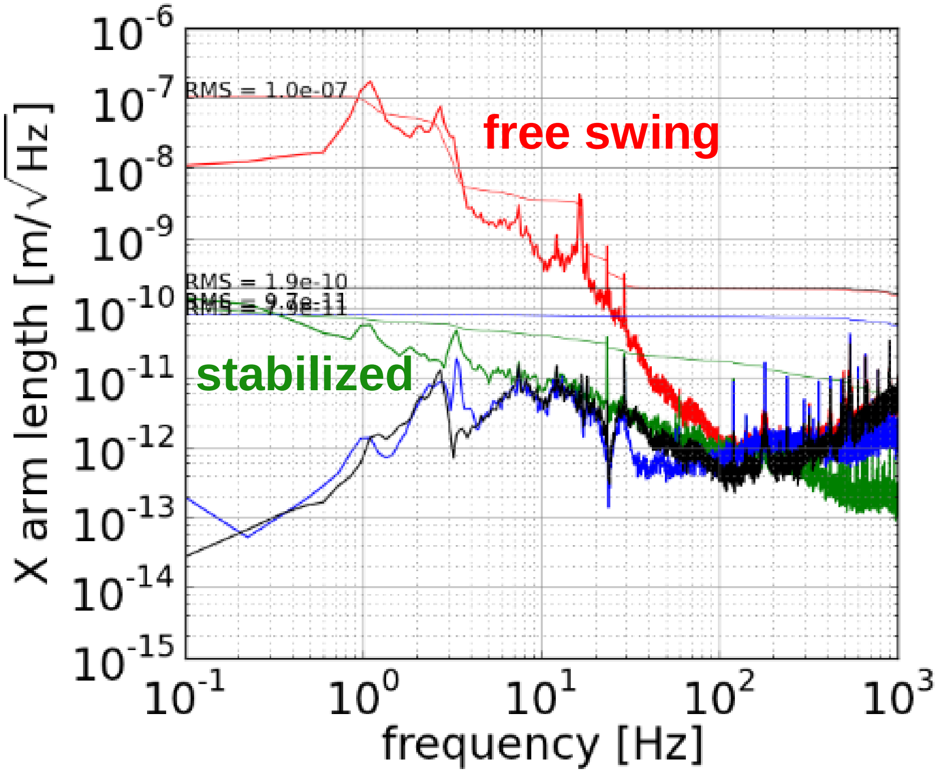
2. Y arm長を共振点に

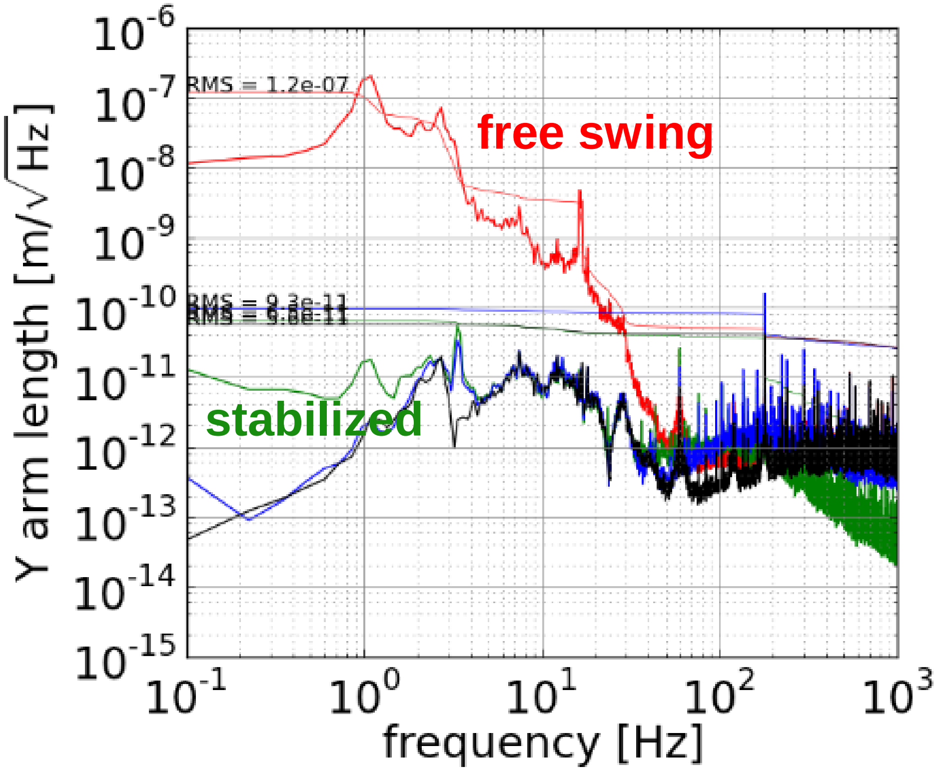
3. X arm長をdetune

4. Y arm長をdetune

ALS後の共振器長安定度

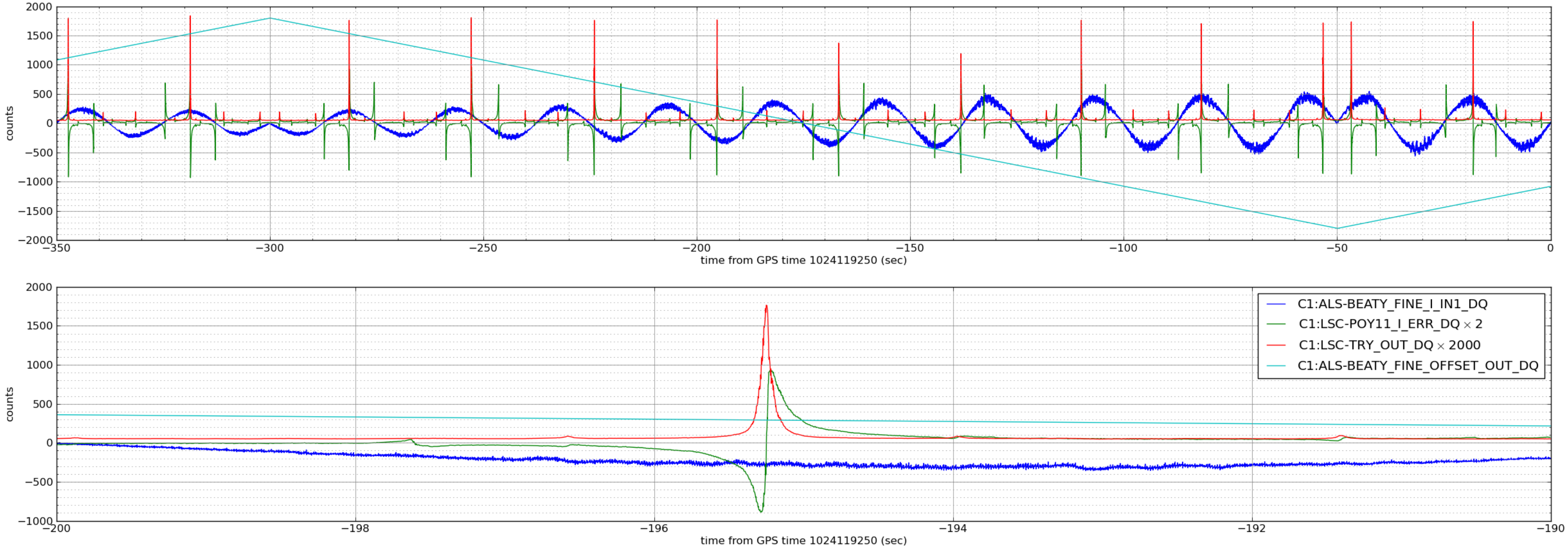
- RMSでX armは97 pm，Y armは 65 pm程度
  free swingでは0.1 um
- 和泉さんの到達RMS 24 pm(Y arm)より~3-5倍大
  ADC雑音？　end laserの周波数安定度？





きれいなMode Scanが可能に

- 8FSRにわたるscan



X arm

Mode matching	MMR = 91.2 +/- 0.3 % (~2% of 01/10 mode)
FSR	FSR = 3.97 +/- 0.03 MHz
finesse	F = 416 +/- 6
g-factor	g1*g2 = 0.3737 +/- 0.002
length	L = 37.6 +/- 0.3 m
ETM RoC	R2 = 60.0 +/- 0.5 m

Y arm

Mode matching	MMR = 86.7 +/- 0.3 % (~5% of 01/10 mode)
FSR	FSR = 3.96 +/- 0.02 MHz
finesse	F = 421 +/- 6
g-factor	g1*g2 = 0.3765 +/- 0.003
length	L = 37.9 +/- 0.2 m
ETM RoC	R2 = 60.7 +/- 0.3 m

Phase Tracker
(2013年2月)

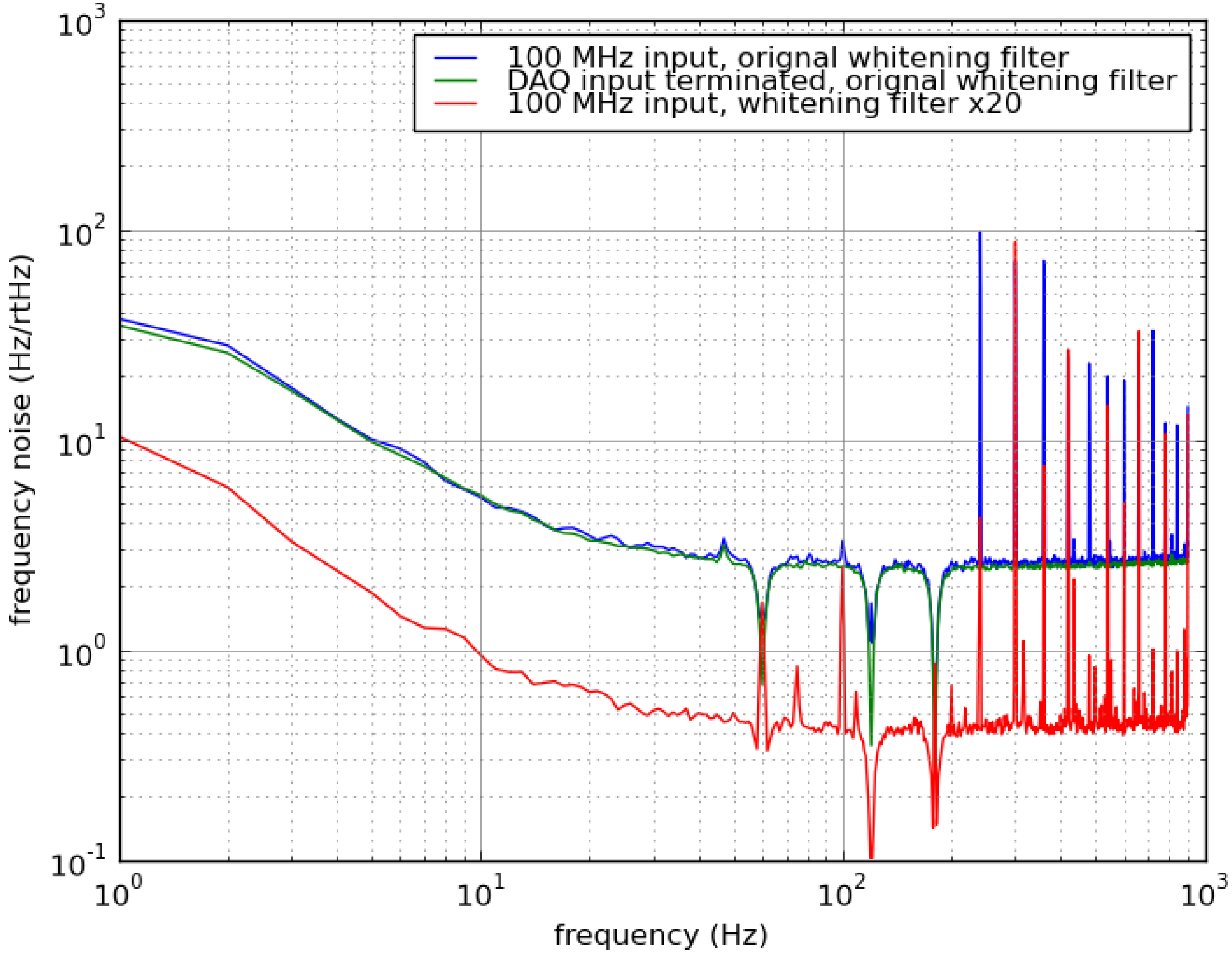
Phase tracker

- 新システムをphase trackerと名付けた
- 他のfrequency discriminatorと比較してどうなのか
  - 測定したもの
    - 雑音レベル
    - 線形レンジ
  - 測定していないもの
    - 応答性(バンド幅)
    - 強度雑音カップリング係数

- 参考
  S. Schilt+: Rev. Sci. Instrum 82 123116 (2011)

Phase tracker 雑音レベル

- < 0.4 Hz/rtHz @ 100 Hz
- ADC雑音なのでwhitening filter等の改善が必須



雑音レベル比較

- 現状では低雑音とはいえない

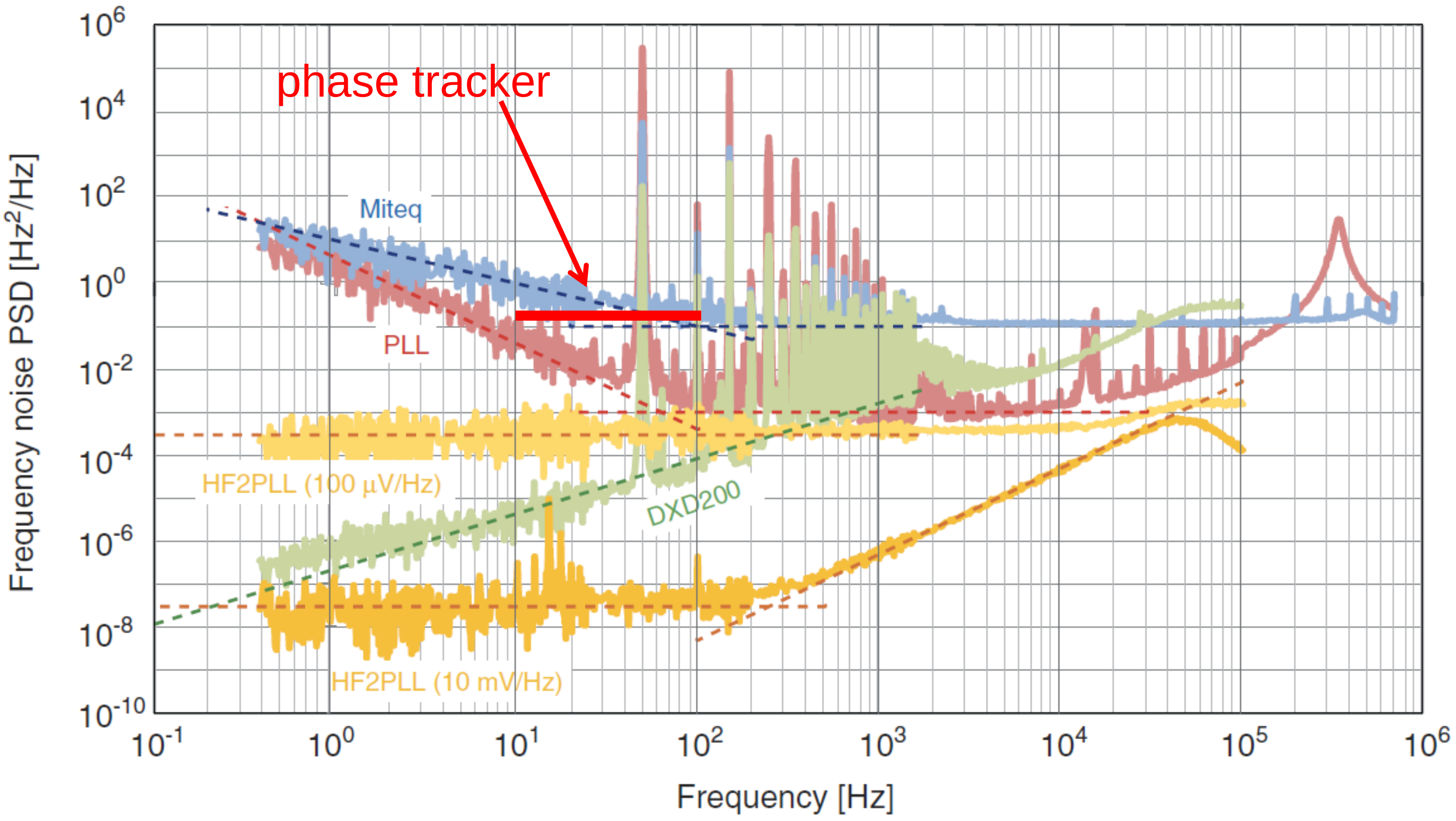
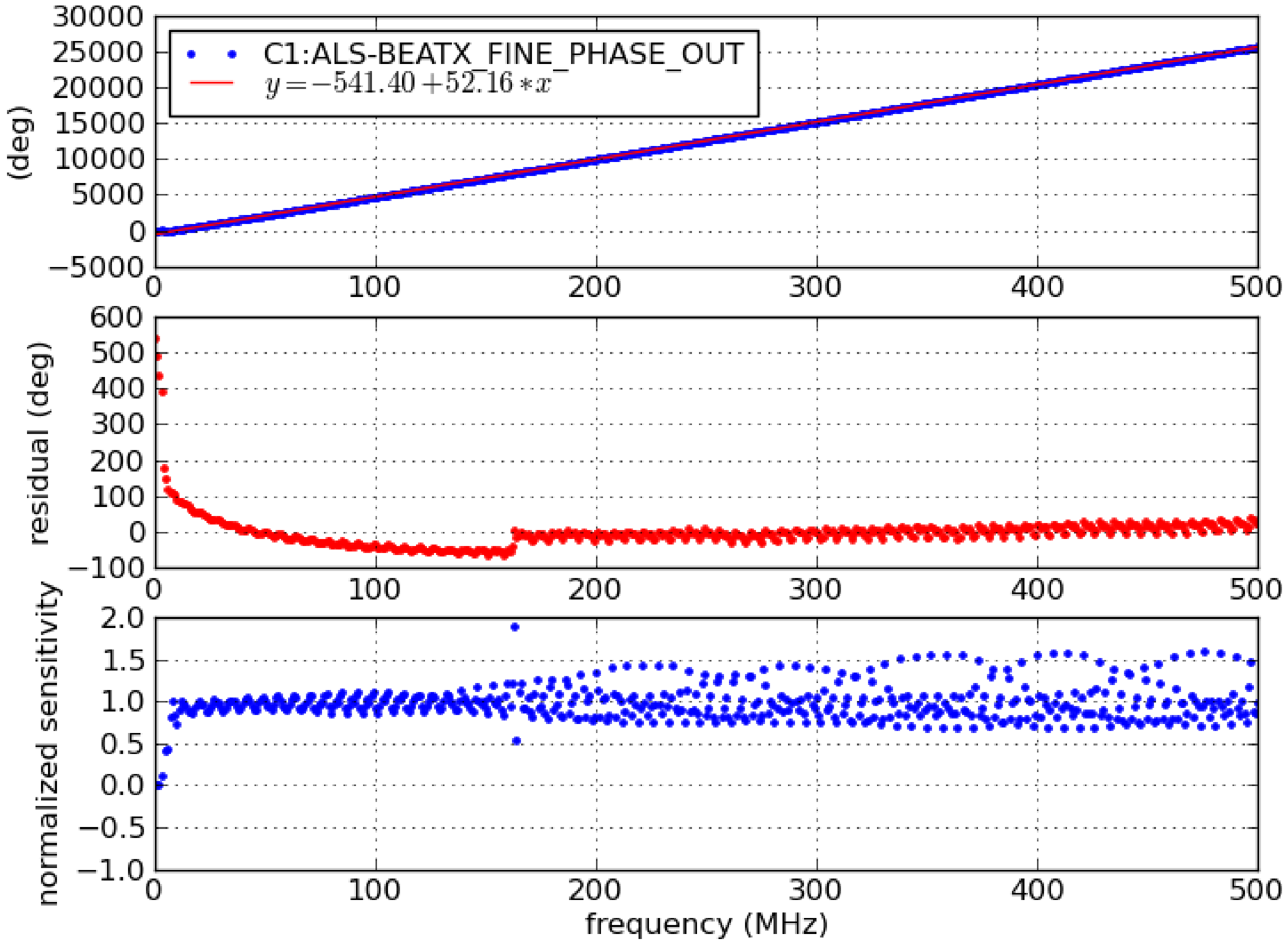


FIG. 5. (Color online) Noise floor of the different discriminators. The noise floor of the analog PLL depends on the PI gain and is presented here in an optimized configuration. The white frequency noise of the HF2PLL (at low frequency) results from white noise at the analog output and thus scales as $1/D_\nu{}^2$ for sensitivities up to $D_\nu = 10$ mV/Hz. It is displayed here for two cases, $D_\nu = 100$ μV/Hz and $D_\nu = 10$ mV/Hz. The dashed lines represent an approximation of the noise floor of each discriminator in terms of a power series of f ($f^{-2}, f^{-1}, f^{0}, f^{1}$, and f^2).

Phase tracker 線形レンジ

- 一応測定したが問題あり
- Hybrid splitter的に30 ~ 100 MHz程度



線形レンジ比較

- 線形レンジは広そう
- 他のは10 MHz程度

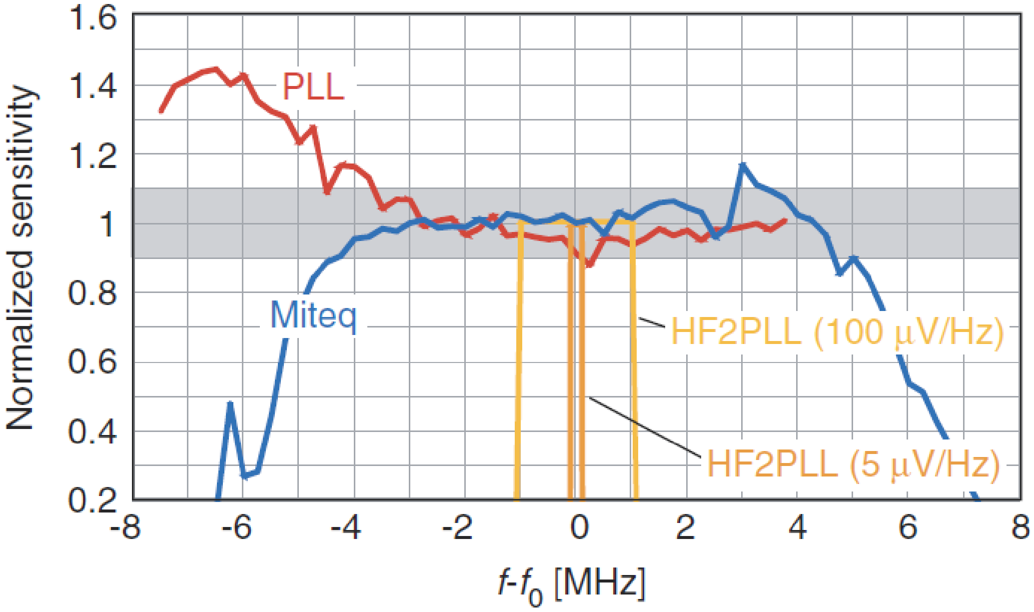


FIG. 4. (Color online) Normalized sensitivity of the frequency discriminators (measured for 1 kHz modulation frequency) as a function of the carrier frequency detuning. The gray area indicates the linear frequency range Δf_{lin} of each discriminator, defined as the frequency interval for which the discriminator response differs by less than ±10% (±0.9 dB) from its nominal sensitivity. The frequency range of the HF2PLL is inversely proportional to the software-selected sensitivity D_ν ($\Delta f_{\mathrm{lin}} = \pm 10\mathrm{V}/D_\nu$) and is shown here for two particular cases ($D_\nu = 100\ \mu\mathrm{V/Hz}$ and $D_\nu = 5\ \mu\mathrm{V/Hz}$) for illustration.

バンド幅

- ALSができたということは ~ 1um/sec の速度に追従できたということ
  → ~ 80 MHz/sec に相当
  → 1 kHz / ~1e-5 sec
- バンド幅 ~80 kHz以上程度のはず
  (S. Schilt+の定義で)

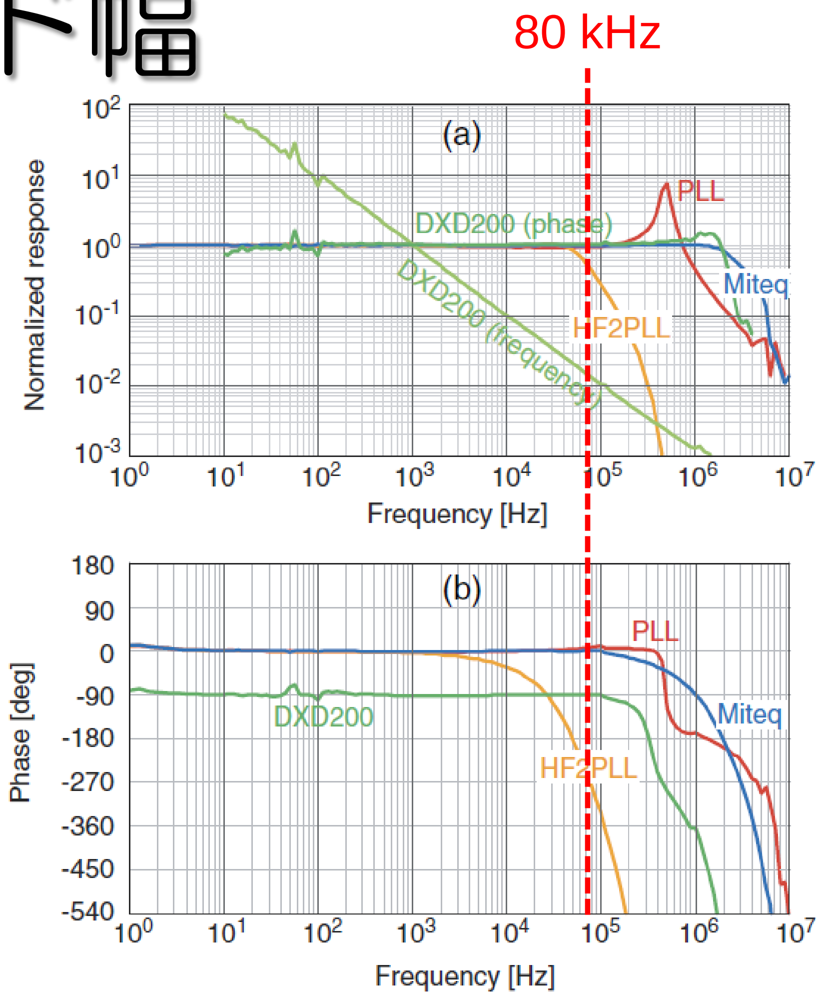


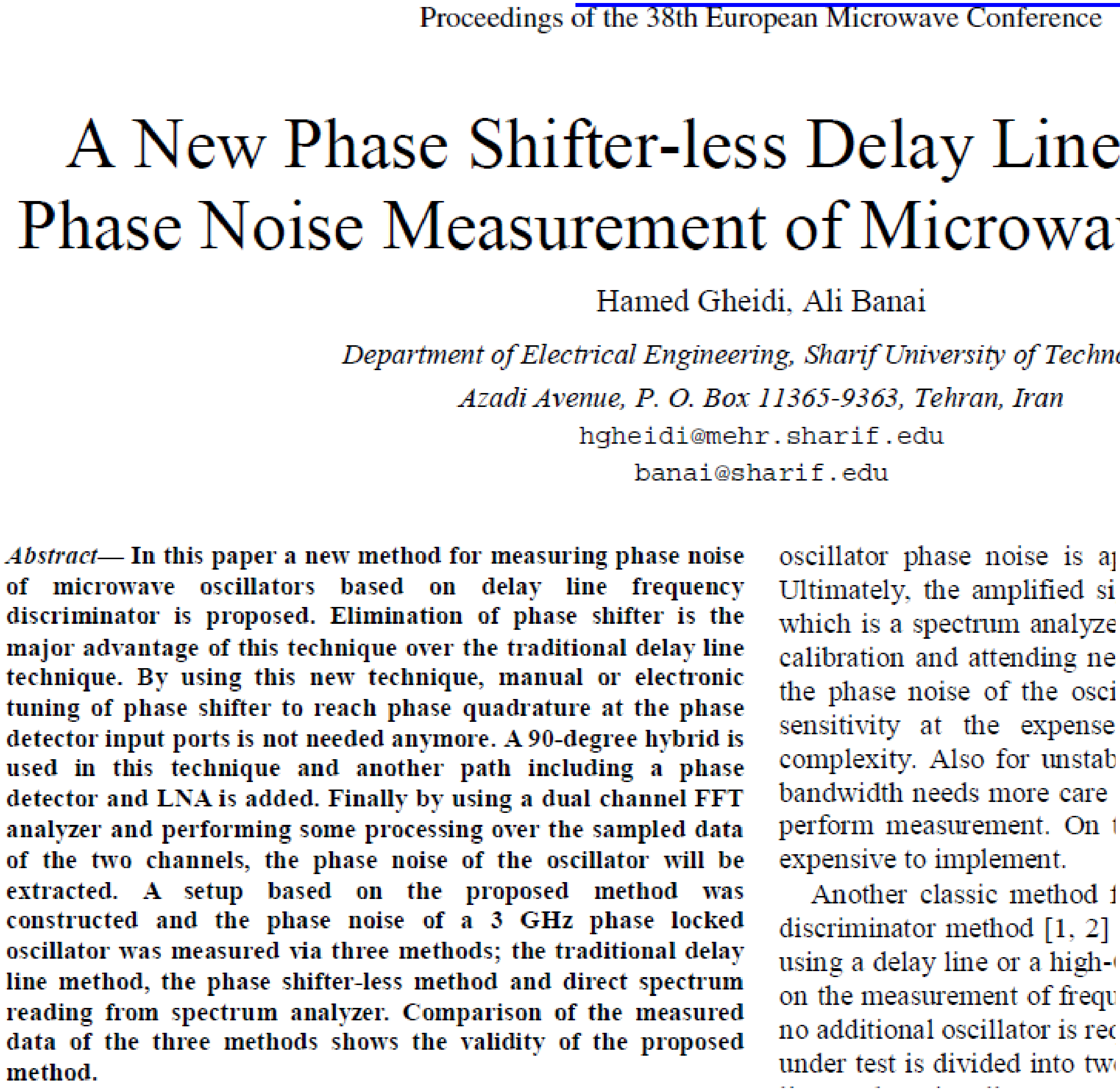
FIG. 3. (Color online) Amplitude (a) and phase (b) of the normalized transfer function of the different discriminators, measured by applying a frequency-modulated input carrier and performing lock-in detection of the discriminator demodulated signal. Each transfer function has been normalized by the discriminator sensitivity measured at 1 kHz modulation frequency ($D_\nu = 7 \times 10^{-7}$ [V/Hz] for PLL, $D_\nu = 1.25 \times 10^{-6}$ [V/Hz] for Miteq, $D_\nu = 10^{-3}$ [V/Hz] for HF2PLL, $D_\nu = 1.8 \times 10^{-5}$ [V/Hz] or $D_\varphi = 1.8 \times 10^{-2}$ [V/rad] for DXD200). The amplitude response of the digital phase detector DXD200 is represented both in terms of response to frequency and phase modulation.

優位性

- IQ demodulationは他にもあるが、IQを使って位相にfeedbackする例は見つかってない
- IQがあれば別に後で位相情報を取り出せる
  岡田さんのように
- phase trackerの利点はリアルタイムで位相情報を読み出せること
  つまり制御に使えるということ
- しかし、制御するのはなぜかというとセンサーの線形性を保つため
- phase trackerが必要となるのはALSのようなかなり限定的な用途？

IQ demodulationの例

- H. Gheidi+: 10.1109/EUMC.2008.4751454



Proceedings of the 38th European Microwave Conference

A New Phase Shifter-less Delay Line Method for Phase Noise Measurement of Microwave Oscillators

Hamed Gheidi, Ali Banai

Department of Electrical Engineering, Sharif University of Technology
Azadi Avenue, P. O. Box 11365-9363, Tehran, Iran
hgheidi@mehr.sharif.edu
banai@sharif.edu

***Abstract*— In this paper a new method for measuring phase noise of microwave oscillators based on delay line frequency discriminator is proposed. Elimination of phase shifter is the major advantage of this technique over the traditional delay line technique. By using this new technique, manual or electronic tuning of phase shifter to reach phase quadrature at the phase detector input ports is not needed anymore. A 90-degree hybrid is used in this technique and another path including a phase detector and LNA is added. Finally by using a dual channel FFT analyzer and performing some processing over the sampled data of the two channels, the phase noise of the oscillator will be extracted. A setup based on the proposed method was constructed and the phase noise of a 3 GHz phase locked oscillator was measured via three methods; the traditional delay line method, the phase shifter-less method and direct spectrum reading from spectrum analyzer. Comparison of the measured data of the three methods shows the validity of the proposed method.**

oscillator phase noise is a
Ultimately, the amplified si
which is a spectrum analyze
calibration and attending ne
the phase noise of the osci
sensitivity at the expense
complexity. Also for unstab
bandwidth needs more care
perform measurement. On t
expensive to implement.

Another classic method i
discriminator method [1, 2]
using a delay line or a high-
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no additional oscillator is re
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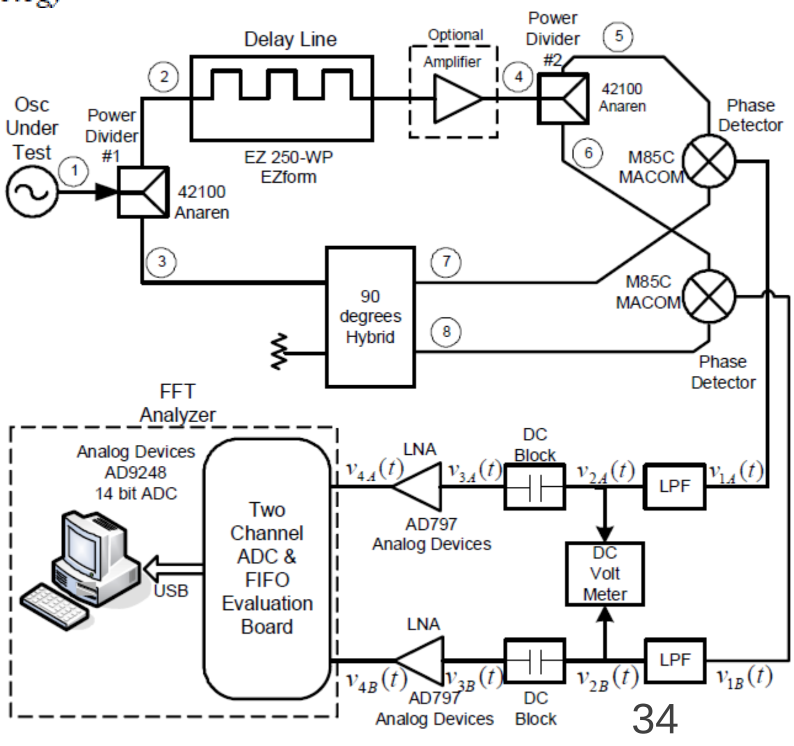
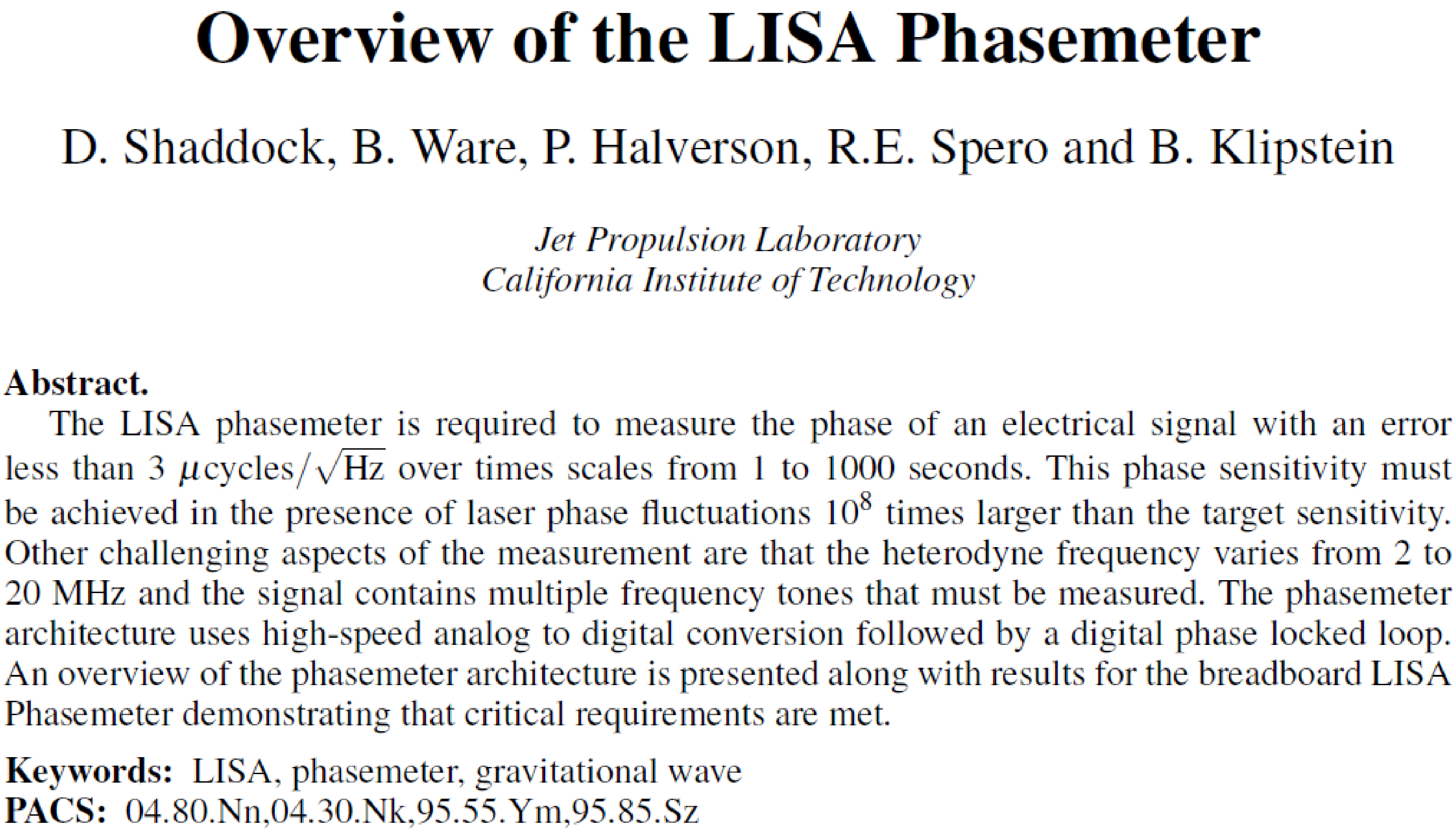


Fig. 2 Proposed phase noise measurement setup.

LISA phasemeter

- D. Shaddock+: AIP Conf. Proc. 873, 654 (2006)



Overview of the LISA Phasemeter

D. Shaddock, B. Ware, P. Halverson, R.E. Spero and B. Klipstein

Jet Propulsion Laboratory
California Institute of Technology

Abstract.
The LISA phasemeter is required to measure the phase of an electrical signal with an error less than 3 μcycles/$\sqrt{\text{Hz}}$ over times scales from 1 to 1000 seconds. This phase sensitivity must be achieved in the presence of laser phase fluctuations 10^8 times larger than the target sensitivity. Other challenging aspects of the measurement are that the heterodyne frequency varies from 2 to 20 MHz and the signal contains multiple frequency tones that must be measured. The phasemeter architecture uses high-speed analog to digital conversion followed by a digital phase locked loop. An overview of the phasemeter architecture is presented along with results for the breadboard LISA Phasemeter demonstrating that critical requirements are met.

Keywords: LISA, phasemeter, gravitational wave
PACS: 04.80.Nn,04.30.Nk,95.55.Ym,95.85.Sz

LISA phasemeter

- ヘテロダイン干渉計のビート出力の位相を検出
- LO周波数にfeedbackしており、phase trackerと似ている

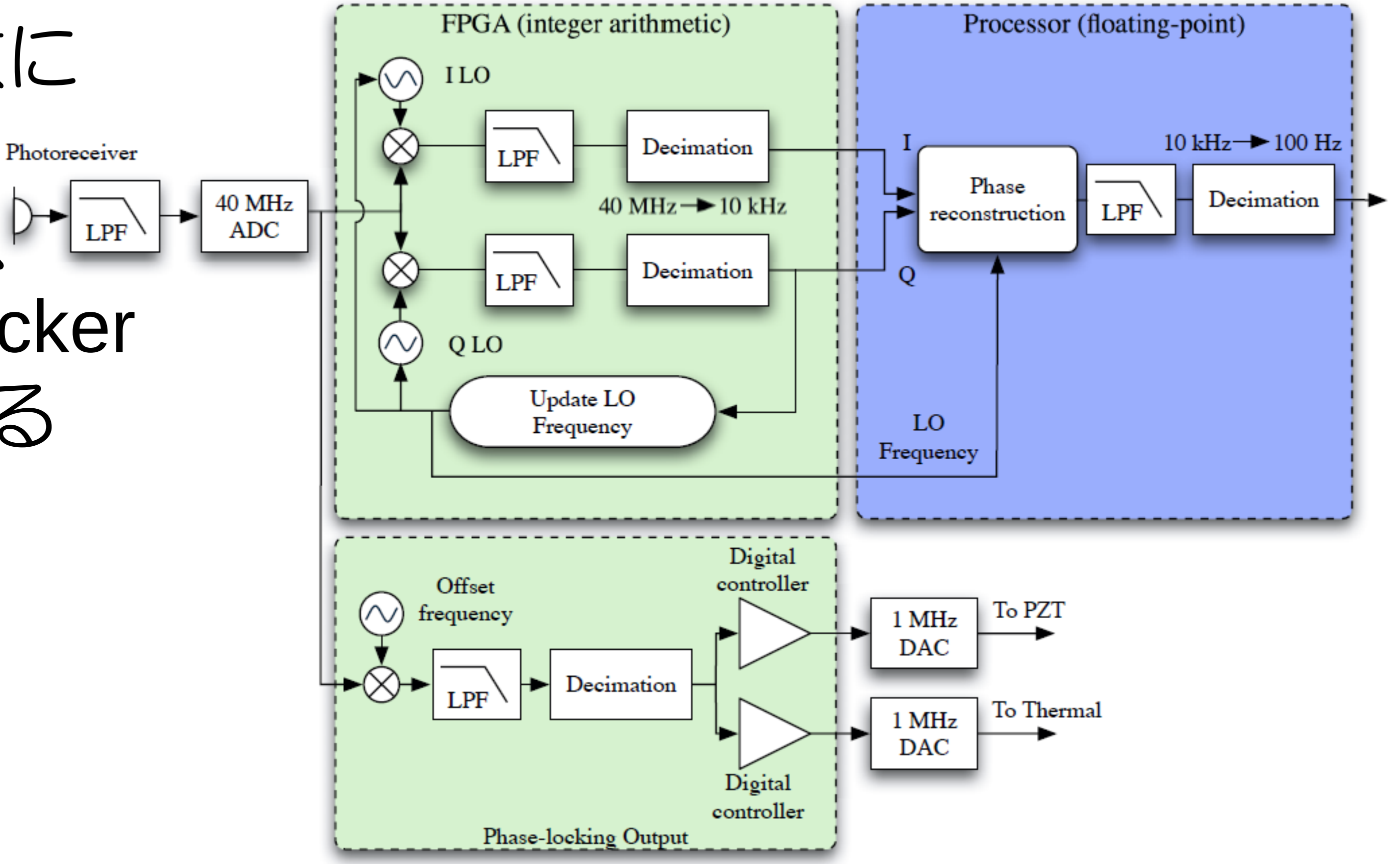
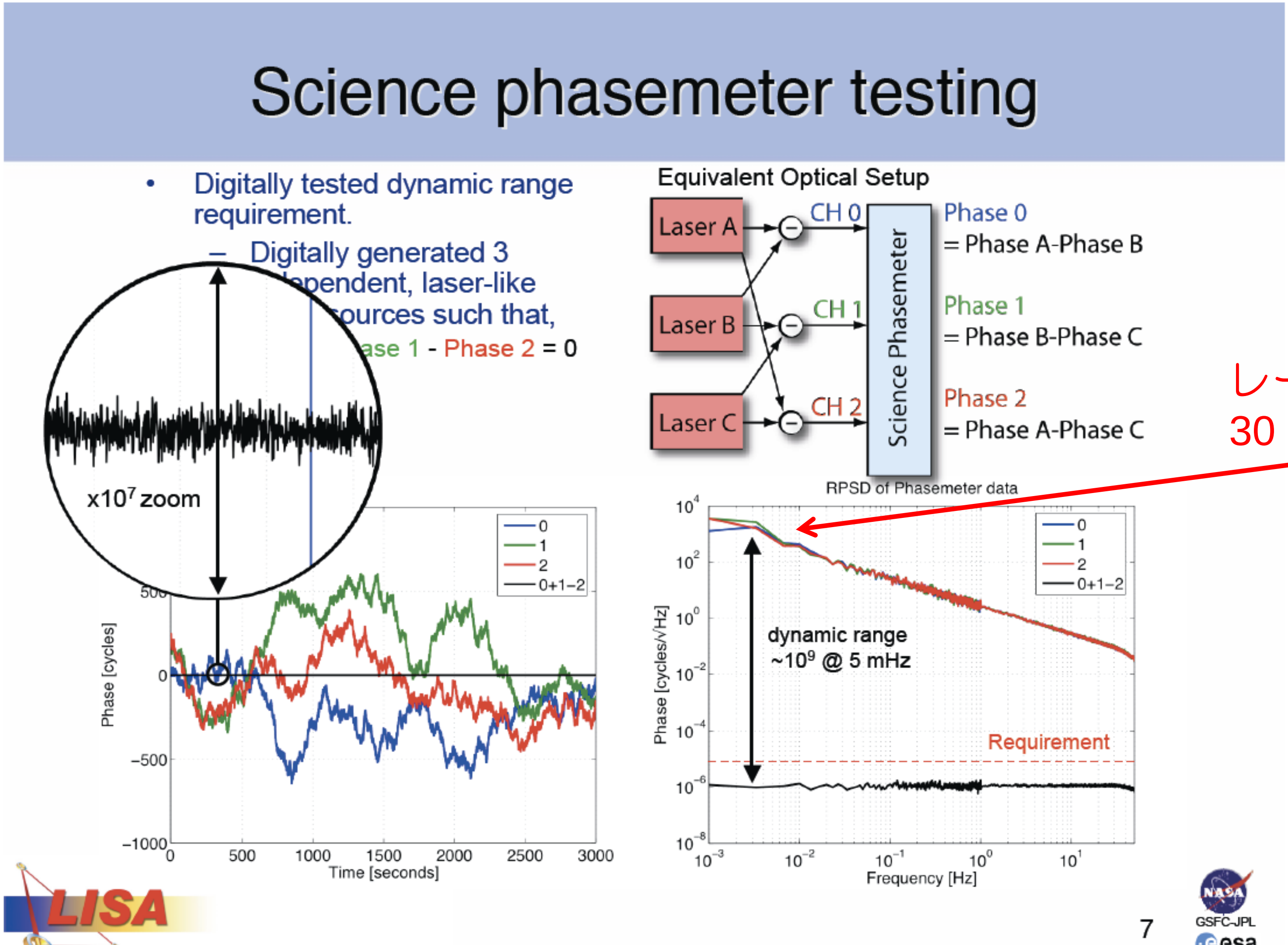


FIGURE 1. Phasemeter block diagram, showing the integer field programmable gate array (FPGA) and floating point processor which make up the science phasemeter, and the phase-locking output. The 40 MHz digitized signal is filtered and decimated to 10 kHz in the FPGA, then filtered and decimated again to 100 Hz for recording. The signal bandwidth for the science phasemeter is from 1 mHz to 1 Hz. LO: local oscillator. LPF: low pass filter. ADC: analog to digital converter.

LISA phasemeter

- 3e-8 Hz/rtHz??



Science phasemeter testing

- Digitally tested dynamic range requirement.
  - Digitally generated 3 …ependent, laser-like …ources such that, …ase 1 - Phase 2 = 0

レーザー周波数雑音
30 Hz/rtHz

http://www.ligo.caltech.edu/~rana/docs/PhaseMeter_Shaddock.pdf

まとめ

- 両腕ALSの実現とALSの改善
- PRC (& SRC)の不安定問題が解決
- フルロックがみえてきたか？

- 残された課題
  - ALSによるFPMIがなぜかできない
  - ALSからIRへの移行手順の検討
  - PRCのビーム軸の揺れは依然として大きい
  - sensing matrixの測定、復調位相などの調整