Loss Dependence on Beam Position in the Arm Cavities of aLIGO
~SURF program を終えて~

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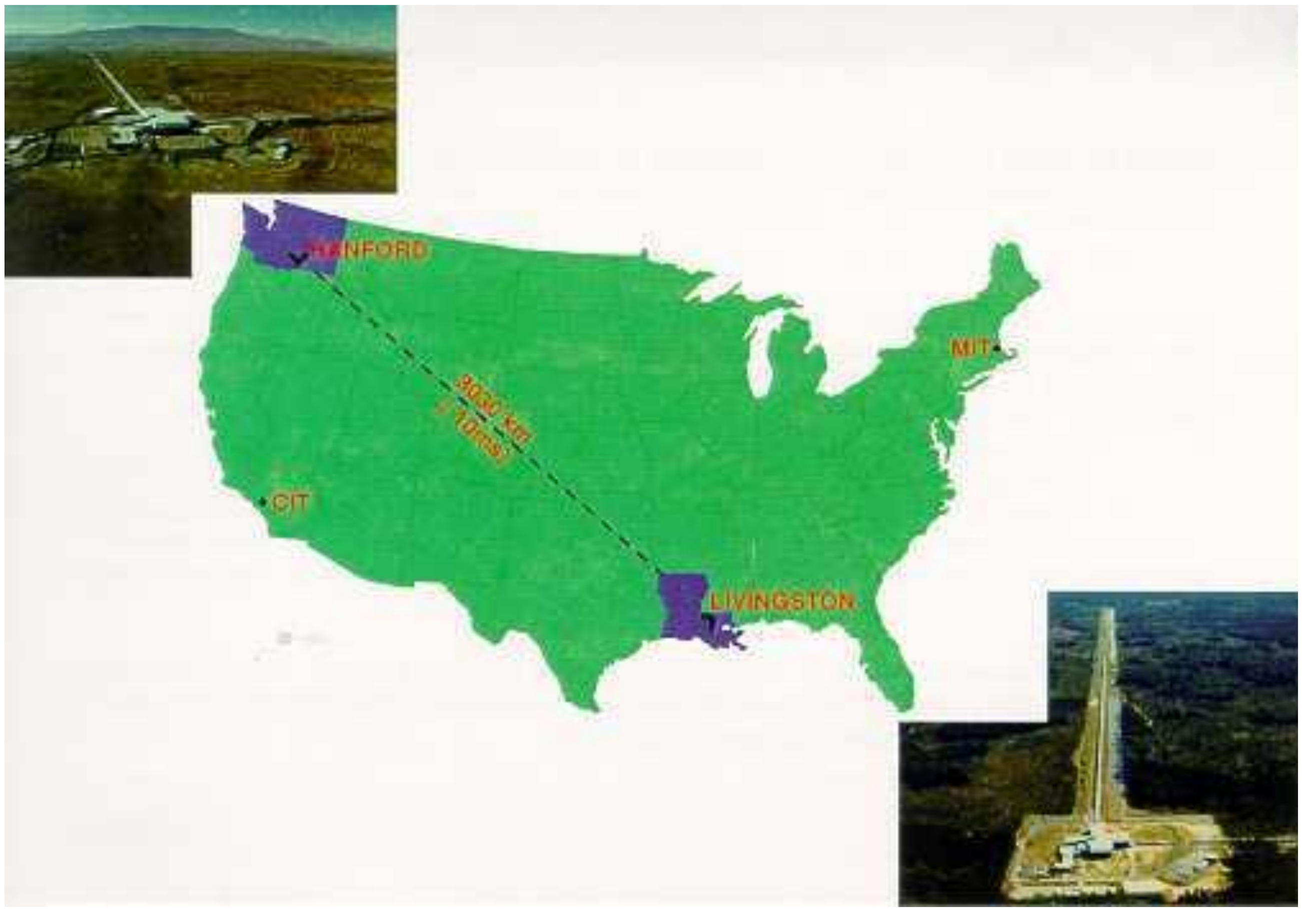
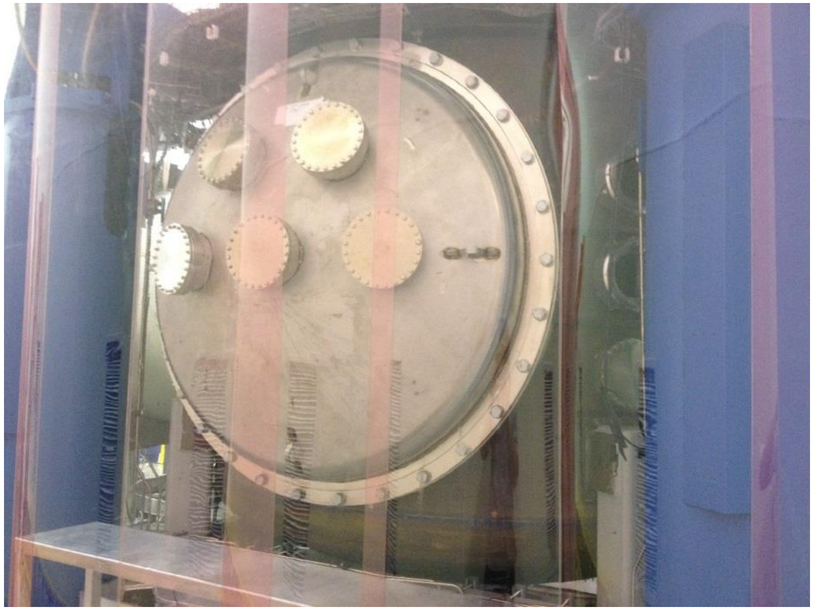
Table of contents

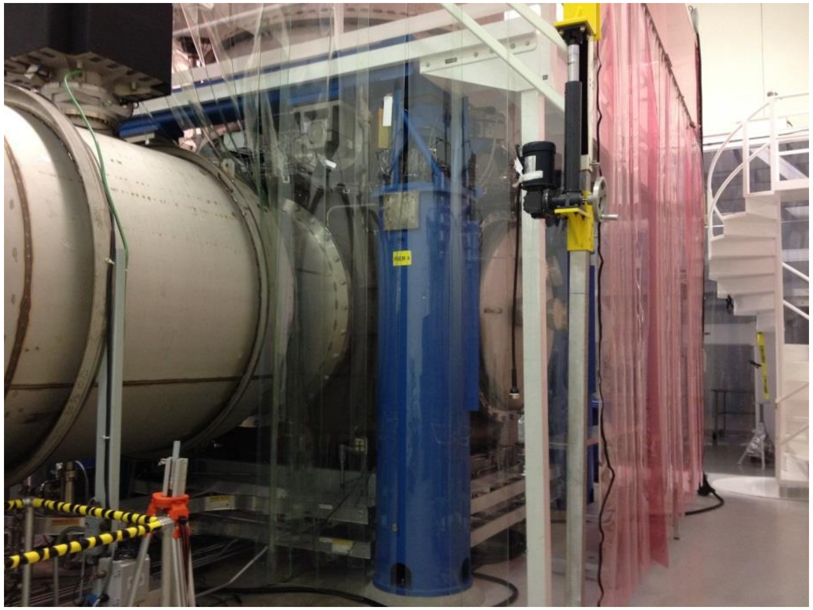
LIGO observatory at Livingston



Control room

LVEA room

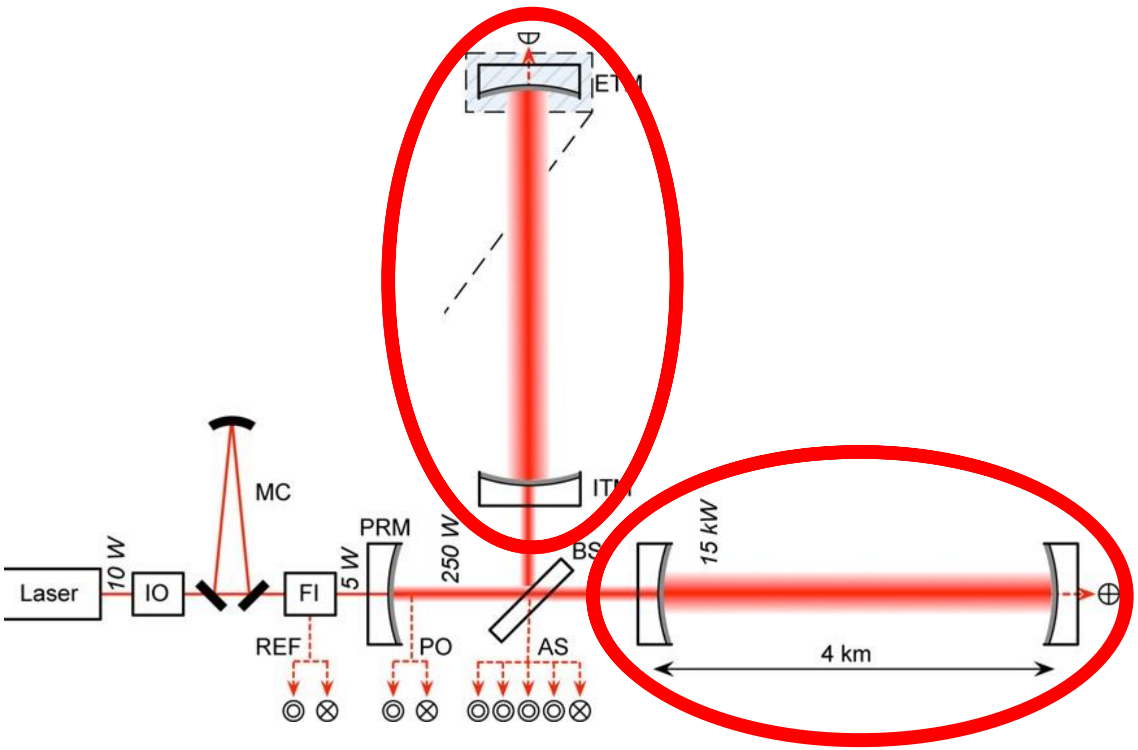




What did I do?

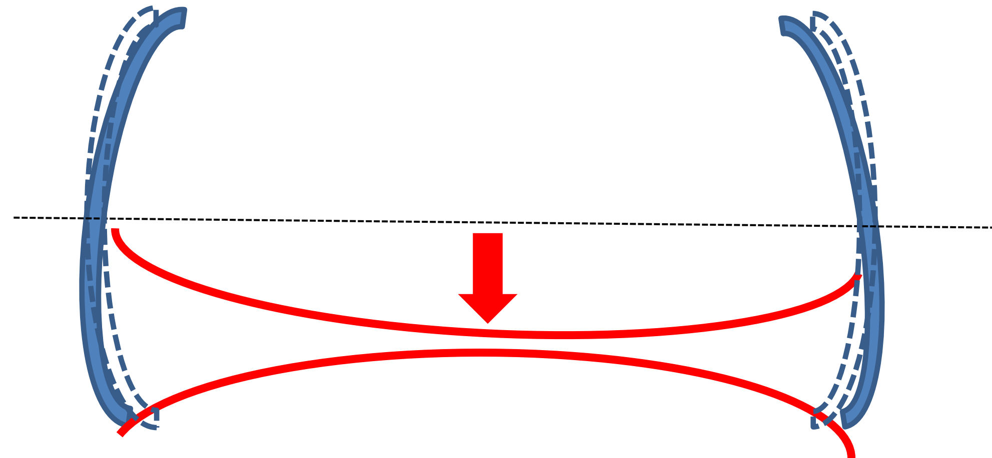
Optical loss in the 4km arm cavities

High cavity power → ○ High sensitivity!!

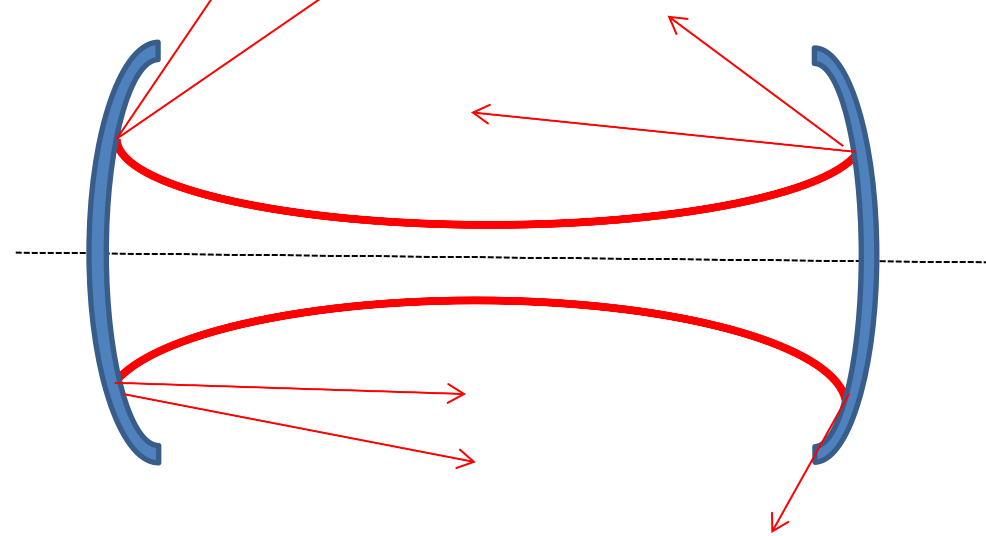


Where do the loss come from?

1 Geometrical loss

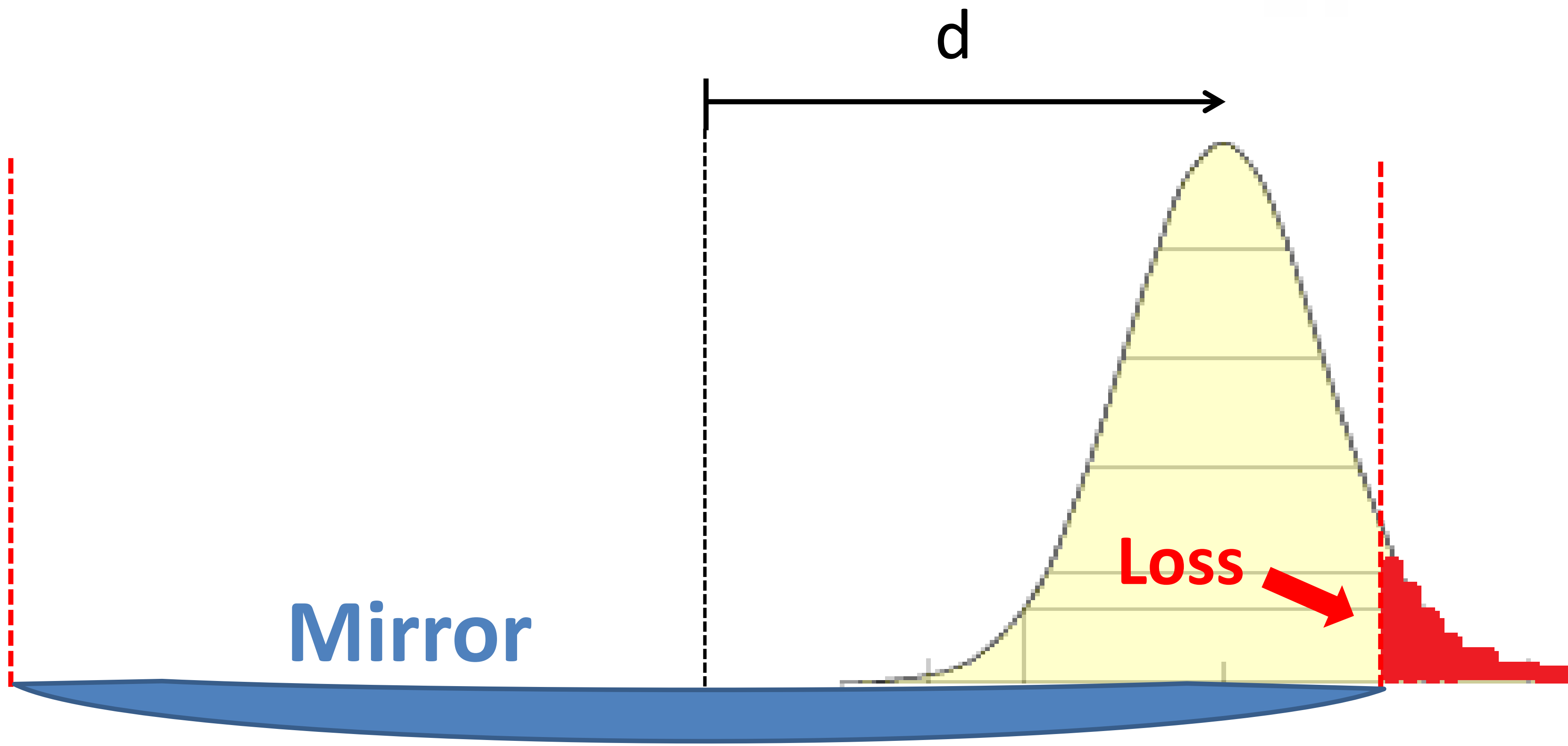


2 Scattering loss



Clipping model : Loss(d)

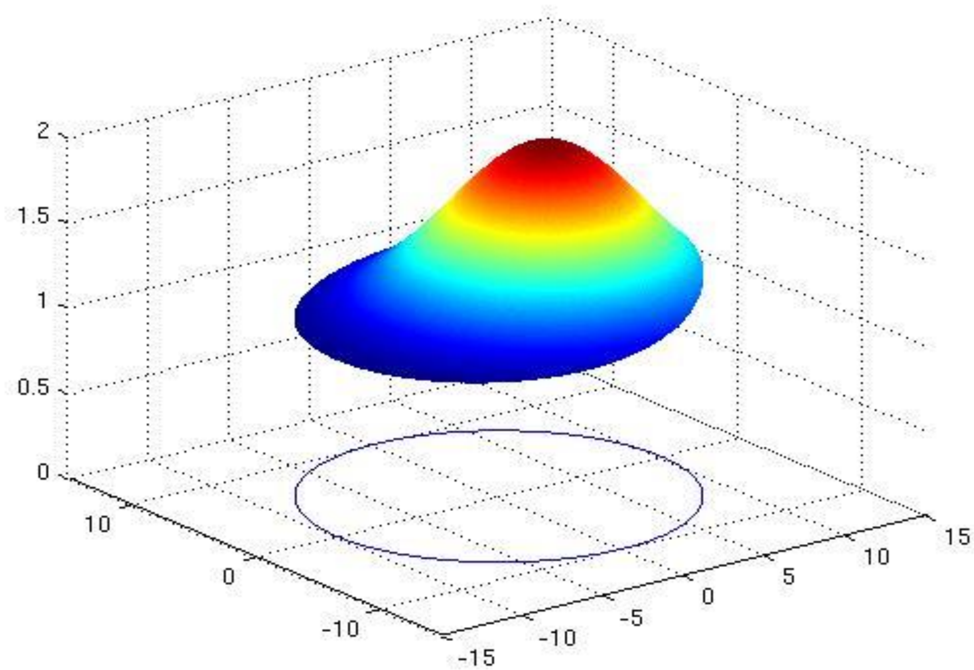
- TEM00 $u(x,y,z) = E_0 \frac{w_0}{w(z)} \exp\left\{ i[kz - \phi(z)] + \left(-\frac{1}{w^2(z)} + i\frac{k}{2R(z)} \right) r^2 \right\}$



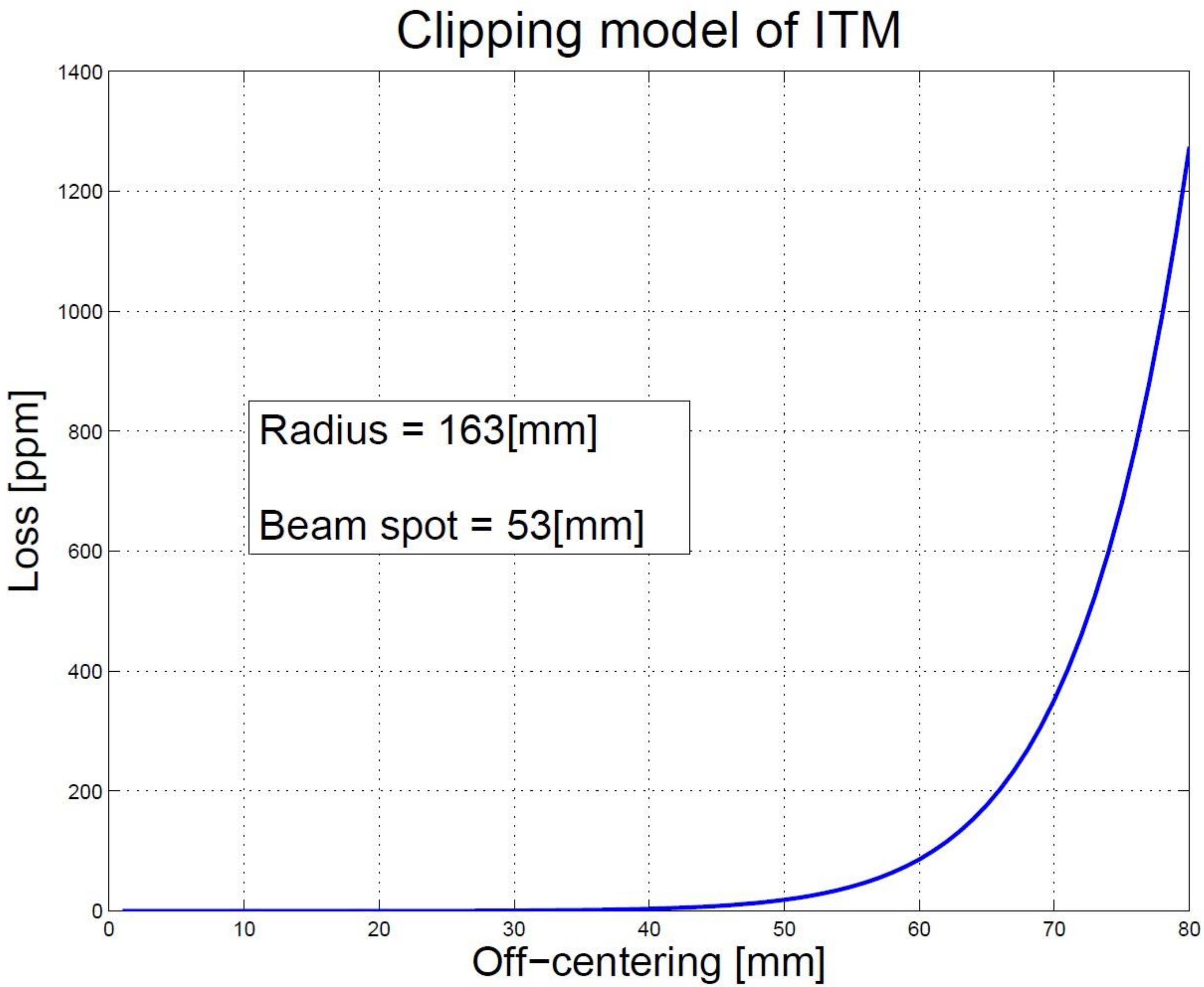
Clipping model : Loss(d)

$$L(d) = 1 - \frac{1}{N}\iint_D dxdy\; e^{-\frac{2}{w^2}\left((x-d)^2+y^2\right)} \quad st \quad D: x^2+y^2 \le R^2$$

$$= 1 - \frac{1}{N}\int_0^R dr \int_0^{2\pi} d\theta\; r\, e^{-\frac{2}{w^2}\left((r cos\theta - d)^2 + (r sin\theta)^2\right)}$$

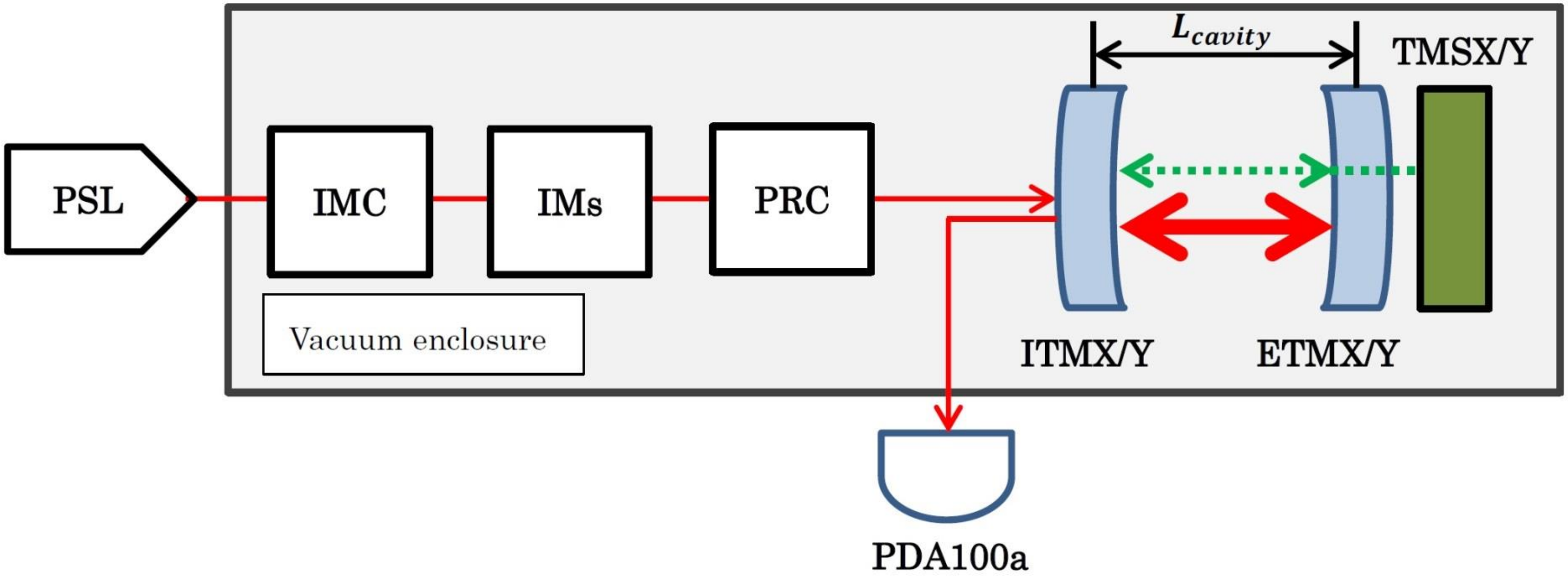


Simulation results

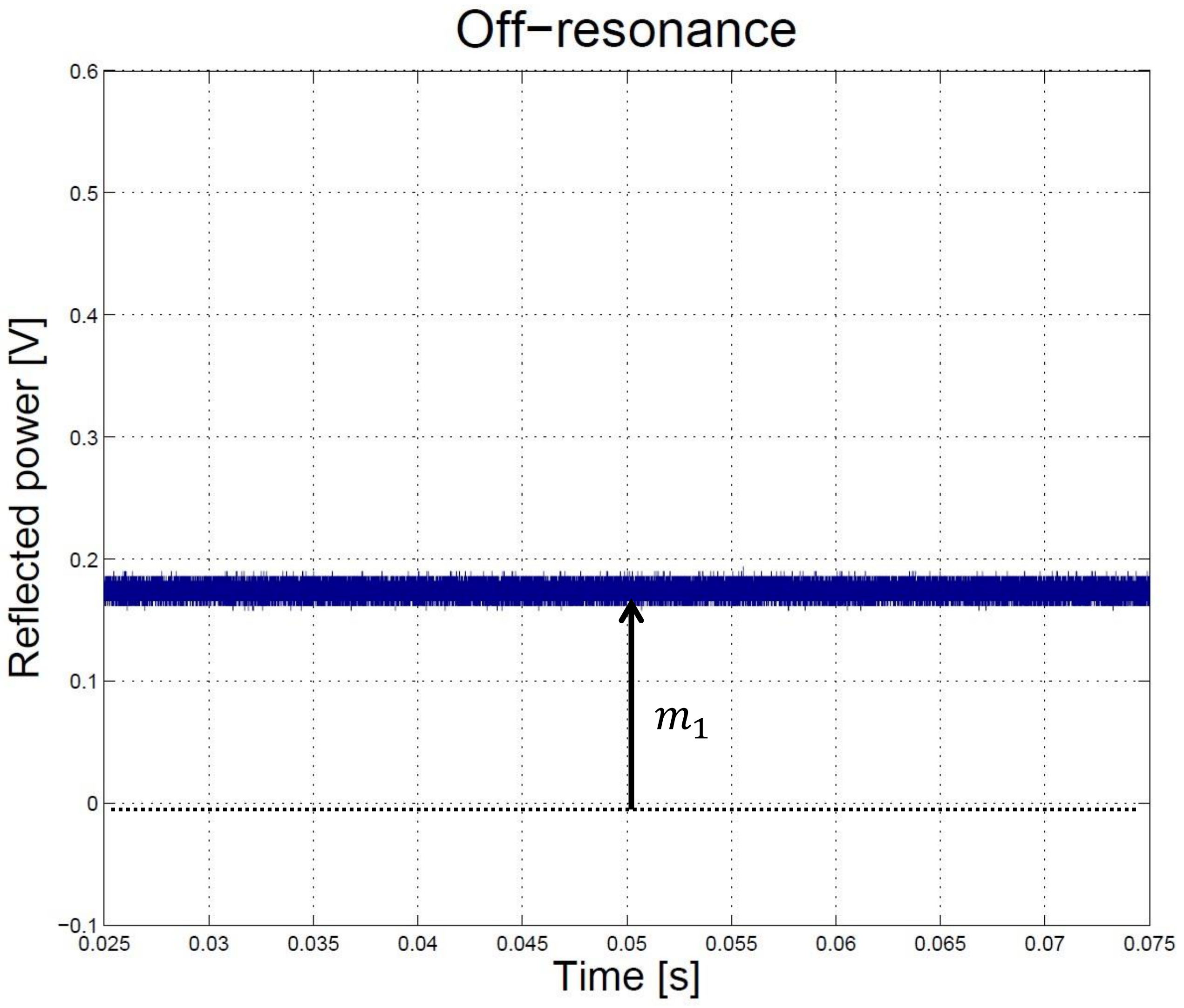


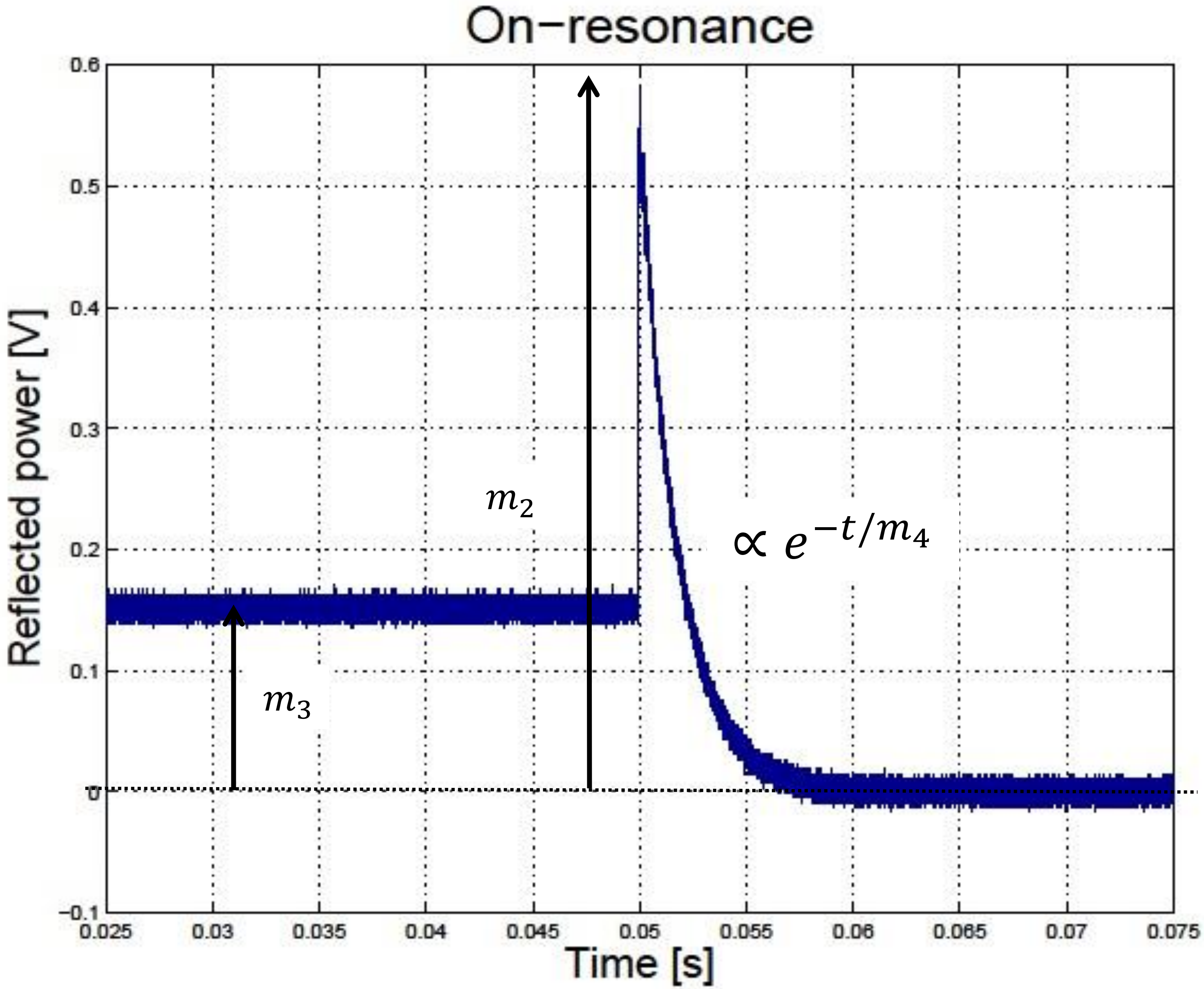
Experiment

- Diagram of optical configuration



Ringdown technique





On−resonance
Reflected power [V]
Time [s]
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
0.025
0.03
0.035
0.04
0.045
0.05
0.055
0.06
0.065
0.07
0.075
m_2
m_3
$\propto e^{-t/m_4}$

Analysis

$$\begin{aligned}
m_1 &= P_0 + P_1 \\
m_2 &= P_0 K T_i^2 R_e \\
m_3 &= P_0 K [r_i - r_e(T_i + R_i)]^2 + P_1 \\
m_4 &= \tau \\
&= \frac{L_{cavity} \times Finesse}{\pi c} = \frac{L_{cavity}}{c} \cdot \frac{\sqrt{r_i r_e}}{1 - r_i r_e} \\
(K &= 1/(1 - r_1 r_2)]^2)
\end{aligned}$$

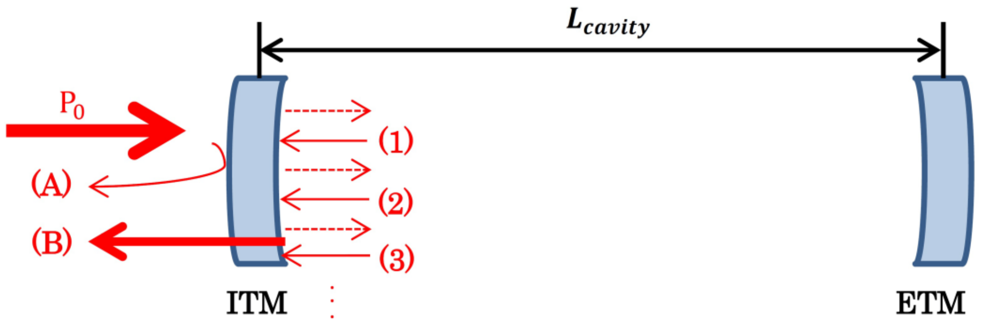
$$* \; R_e = (1 - 5.0 \times 10^{-6}) \quad T_e = 5.0 \times 10^{-6}$$

$$m_1, m_2, m_3, m_4 \Rightarrow T_{ITM}, R_{ITM} \Rightarrow L_{rt} = 1 - T_{ITM} - R_{ITM}$$

(cf. T.Isogai *et al*, Optical Express, Vol.21, No.24(2014))

m_3の式の導出

$$
\begin{aligned}
(A) &= \underset{\sim\sim}{-} E_0 r_i \\
(B) &= t_i((1)+(2)+(3)+\cdots) \\
(1) &= E_0 t_i r_e \\
(2) &= E_0 t_i r_e \cdot r_i r_e \\
(3) &= E_0 t_i r_e \cdot r_i r_e \cdot r_i r_e \\
(B) &= t_i \sum_{n=0}^{\infty} E_0 t_i r_e \cdot (r_i r_e)^n = \frac{E_0 T_i r_e}{1 - r_i r_e} \\
E_{refl} &= E_0 \left(-r_i + \frac{T_i r_e}{1 - r_i r_e} \right) \\
P_{refl} &= E_{refl} E_{refl}^{*} + P_1 = P_0 \left(-r_i + \frac{T_i r_e}{1 - r_i r_e} \right)^2 + P_1 \\
&= P_0 K [r_i - r_e (T_i + R_i)]^2 + P_1
\end{aligned}
$$



各物理量の導出

Finesse

$$F = \frac{\pi c}{L_{cavity}} \cdot m_4$$

ITM field reflectivity

$$r_i = \frac{1}{2} \cdot \left(2 + \frac{\pi^2}{F^2} - \sqrt{4\frac{\pi^2}{F^2} + \left(\frac{\pi^2}{F^2}\right)^2} \right)$$

ITM power transmissivity

$$KR_e \left(\frac{m_3 - m_1}{m_2} \right) T_i^2 = KR_e T_i^2 - 2K(r_i r_e + R_i R_e) T_i - (KR_i(2r_i r_e - R_i R_e - 1) + 1)$$

$$T_i = -B - \sqrt{B^2 - CA}$$

ここで

$$\begin{aligned} A &= KR_e \left(\frac{m_3 - m_1}{m_2} - 1 \right) \\ B &= K(r_i r_e + R_i R_e) \\ C &= KR_i(2r_i r_e - 1 - R_i R_e) + 1 \end{aligned}$$

Mode matching ratio

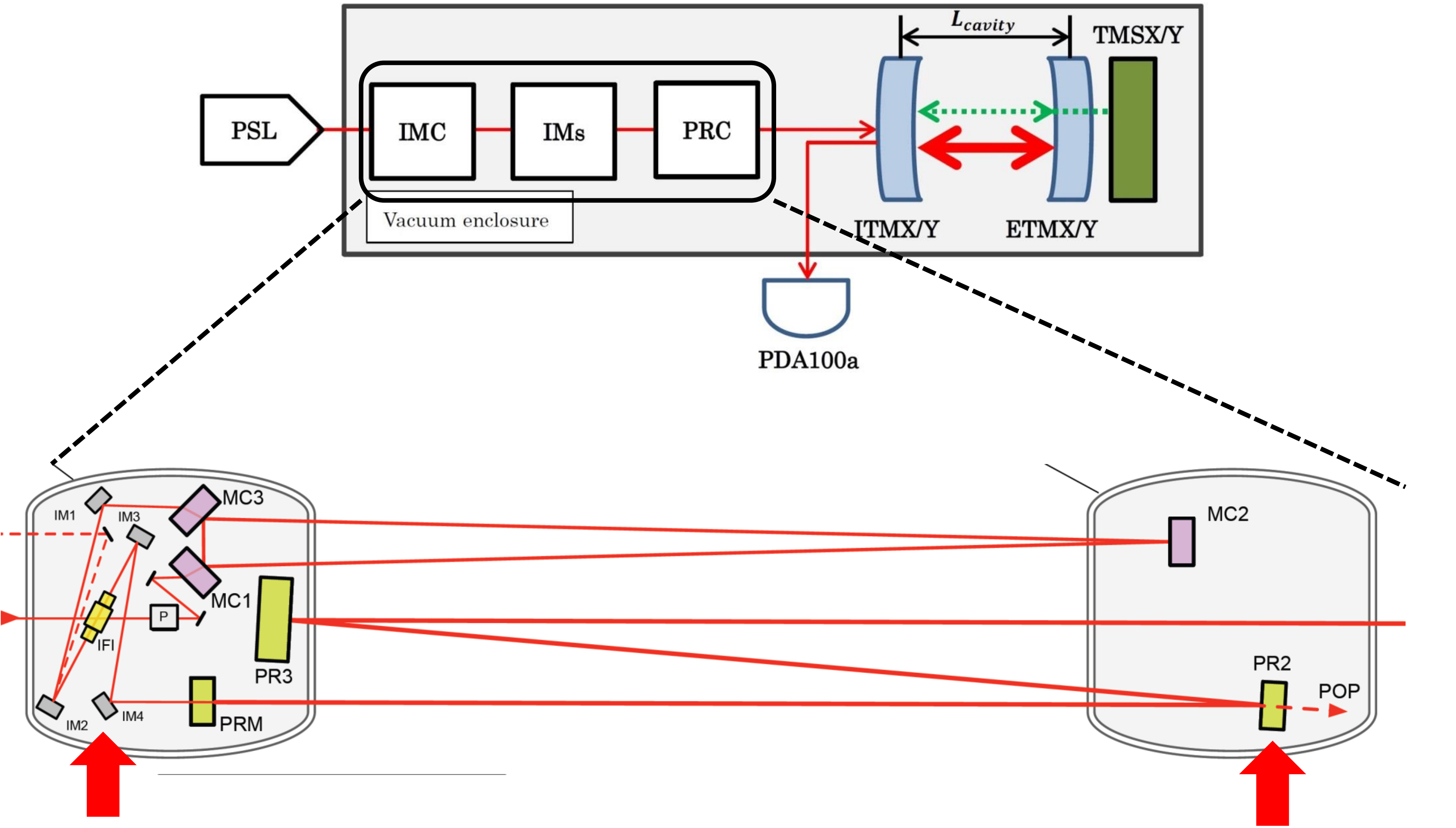
$$\rho_{mm} = \frac{P_0}{P_0 + P_1} = \frac{1}{KT_i^2 R_e} \frac{m_2}{m_1}$$

Round trip loss

$$L_{rt} = 1 - T_i - r_i^2$$

Initial alignment

1.TMS のalignment
→Green beamを目標点におく。
2.ITM,ETMのmisalign
→完璧にscattering
3.ITM のalignment
→Red beamをITMの中心に
4.ETMのalignment
→Red beamを目標点におく
5.IM4とPR2のalignment
→Red beam の波面を最適化
6.目標点をズラして、手順1~5を反復



L_cavity
TMSX/Y
PSL
IMC
IMs
PRC
Vacuum enclosure
ITMX/Y
ETMX/Y
PDA100a
MC3
IM1
IM3
MC1
P
IFI
PR3
IM2
IM4
PRM
MC2
PR2
POP

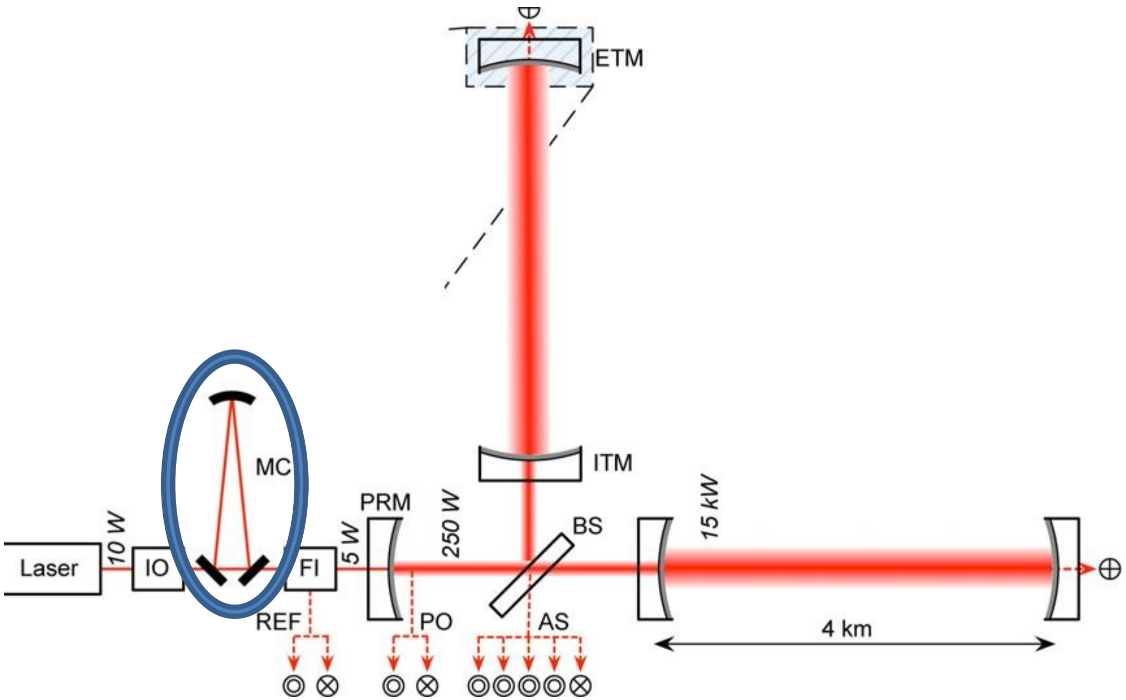

ITMX At 2014-07-21-21-52-54 UTC

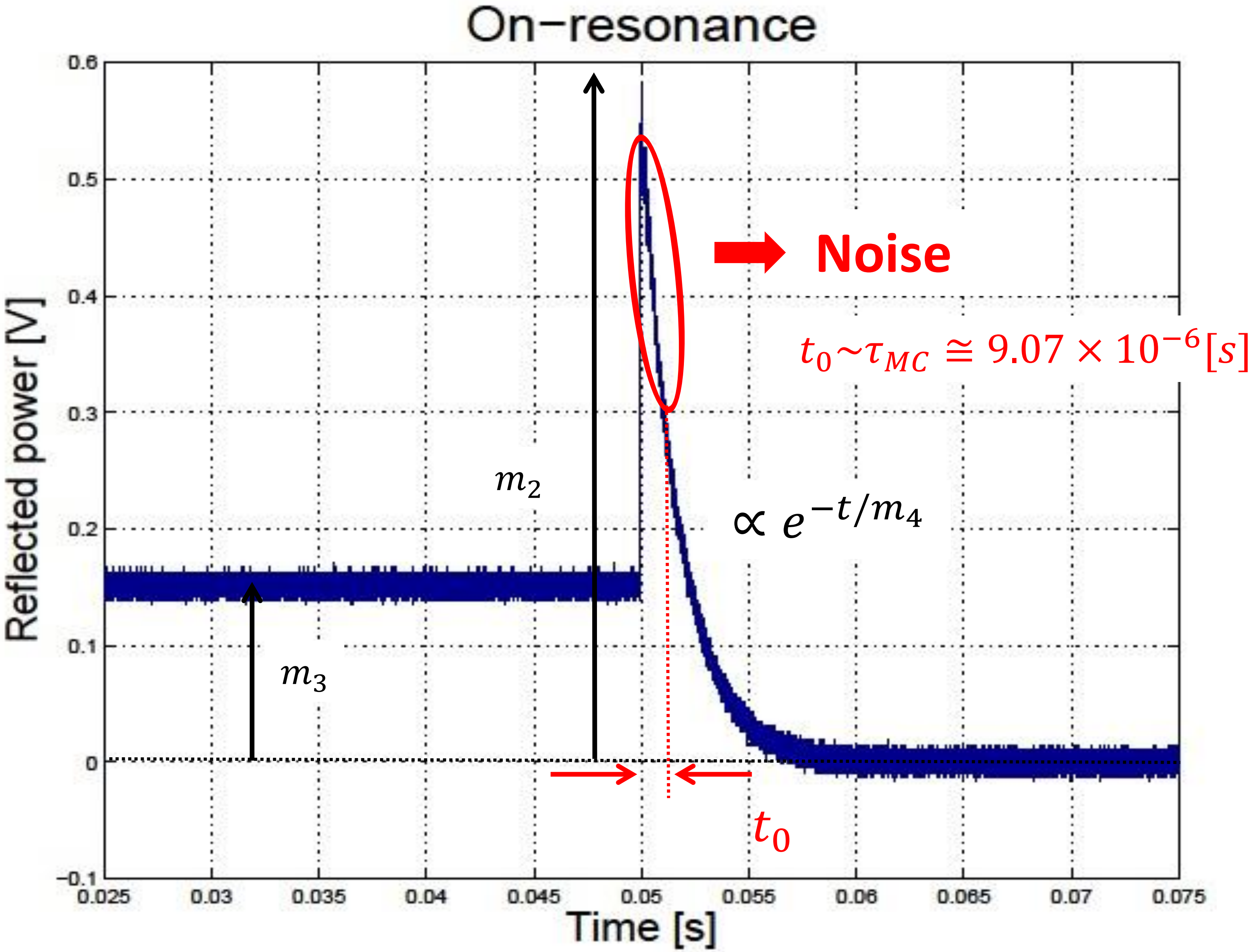

ITMY At 2014-08-16-03-06-43 UTC


'TMY At 2014-08-16-05-11-01 UTC

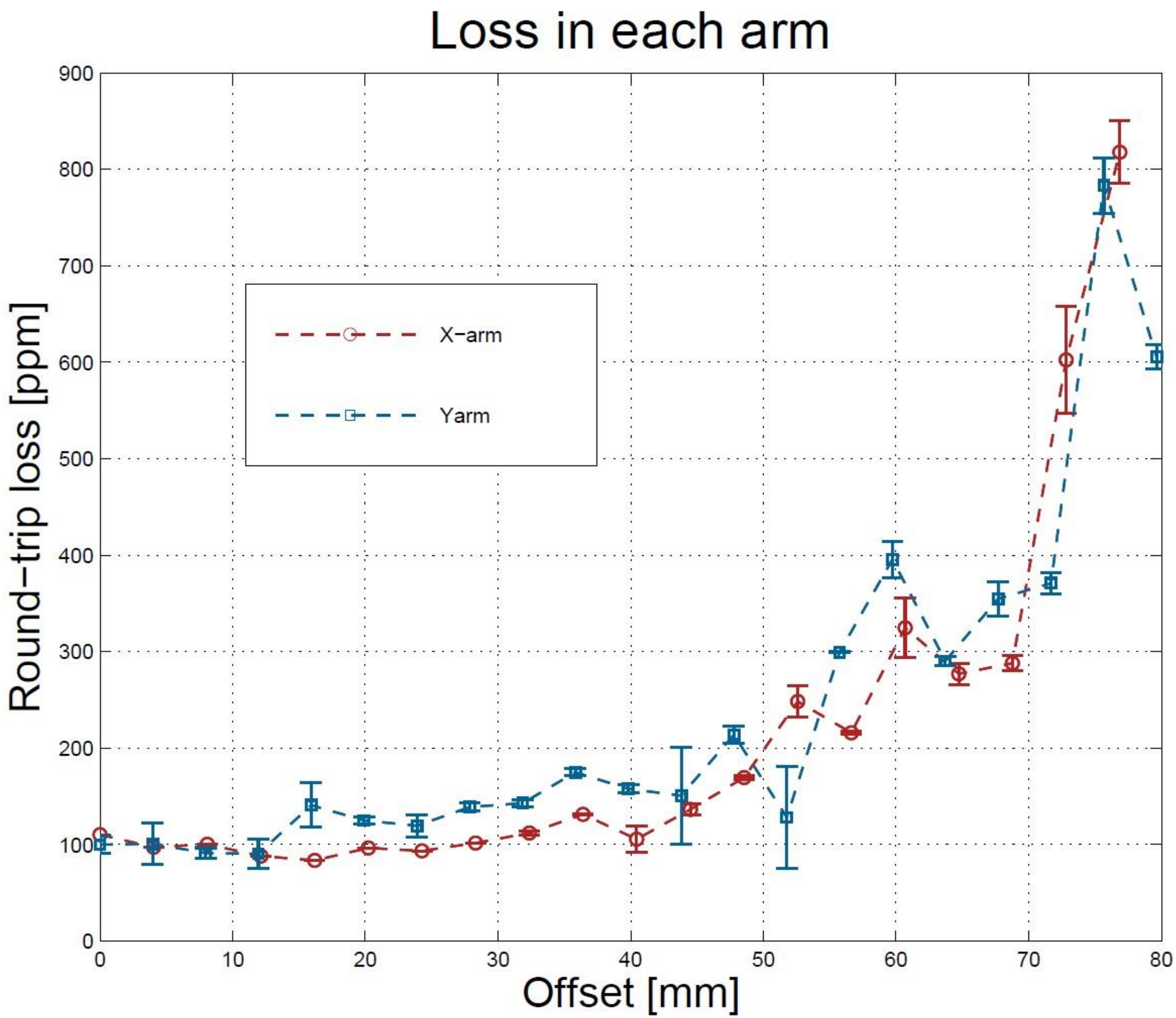
Main noise source

Any cavity ･･･the ringdown speed of τ detertermined by cavity length and finesse





On−resonance
Noise
$t_0 \sim \tau_{MC} \cong 9.07 \times 10^{-6} [s]$
m_2
$\propto e^{-t/m_4}$
m_3
t_0
Reflected power [V]
Time [s]
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
0.025
0.03
0.035
0.04
0.045
0.05
0.055
0.06
0.065
0.07
0.075



Loss in each arm
Round-trip loss [ppm]
Offset [mm]
X-arm
Yarm
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80

誤差の伝搬との不一致

- 誤差の伝搬の公式

$$Loss = L(m_1, m_2, m_3, m_4)$$

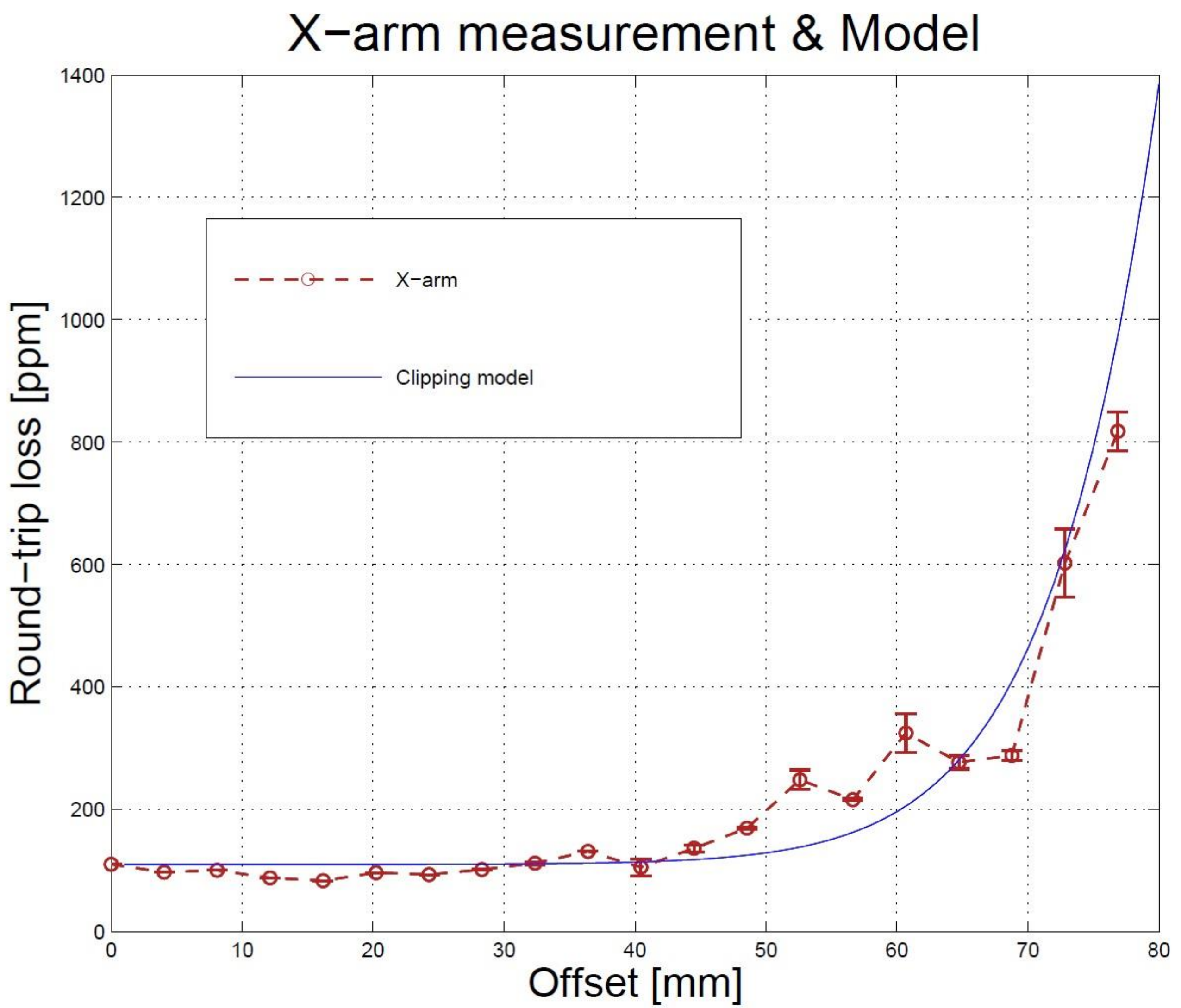
$$\delta L = \sqrt{\left(\frac{\partial L}{\partial m_1}\right)^2 \delta m_1 + \left(\frac{\partial L}{\partial m_2}\right)^2 \delta m_2 + \left(\frac{\partial L}{\partial m_3}\right)^2 \delta m_3 + \left(\frac{\partial L}{\partial m_4}\right)^2 \delta m_4}$$

$$\approx 1\%$$

⇔実験結果

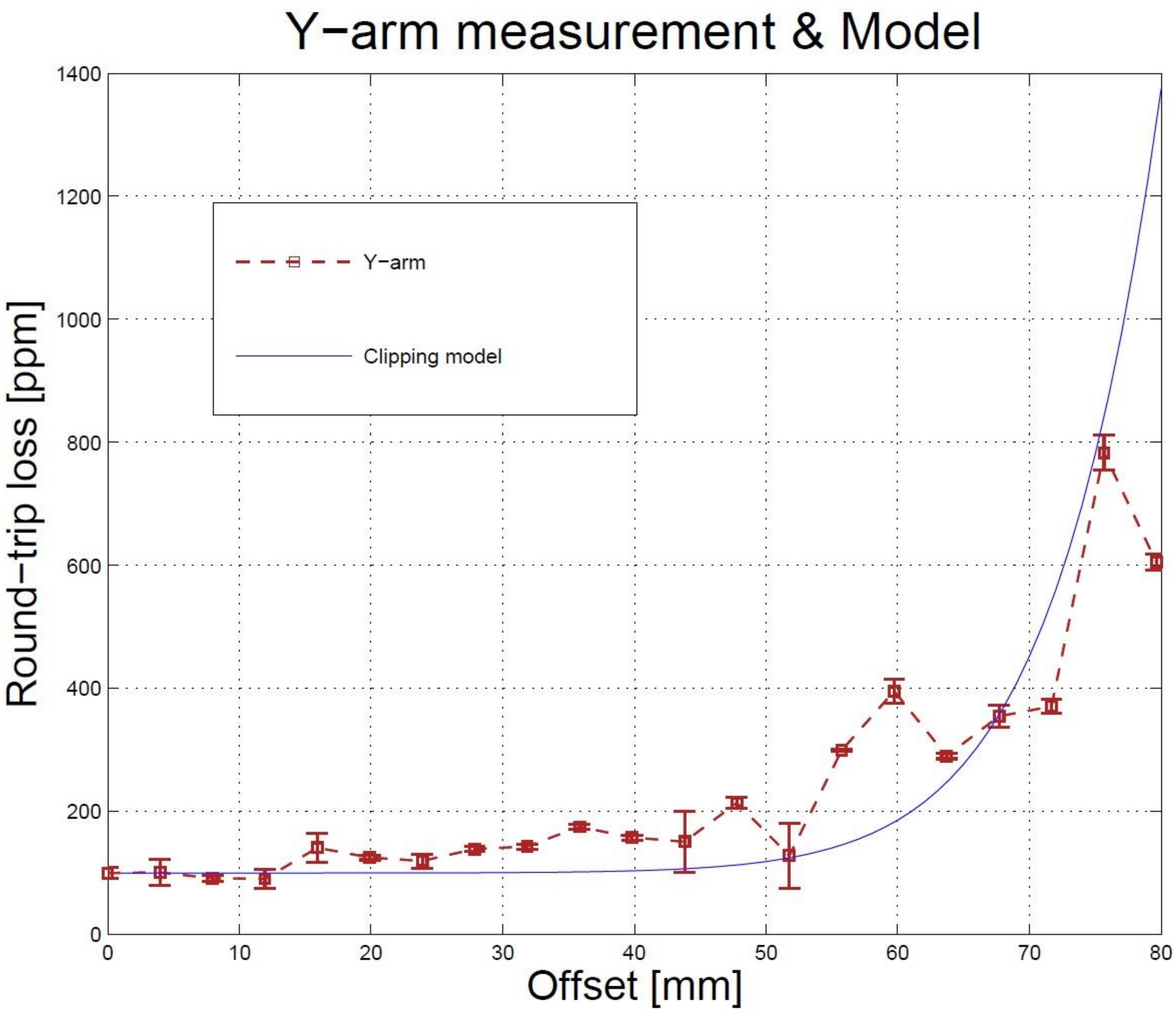
$$\frac{\partial L}{L} \approx 20\text{~}30\%$$

→beam position の揺らぎか？



Scattering loss ITMX:20ppm ETMX:50ppm

→ Where did the other 30 ppm come from?



Scattering loss ITMY: unknown ETMY:36ppm

→ ITMY scattering measurement is needed.

最終的なaLIGO の要請条件

- Round trip loss

50 [ppm]/arm

↓実現するには…

Scattering lossの効果を追求する必要あり

①粗いゆらぎによるモードシフト

②細かいゆらぎによるrandom scattering

③局所的欠陥(ゴミ？)によるscattering

└→ 取り除ければ30～50[ppm]軽減か？

Summary

◎　Round trip lossのbeam off-centeringに対する単調増加性

○　Round trip loss最終目標値の実現可能性

（Hopefully）

Further works

- Statistical error

  More measurement at each beam spot

- 2-dimensional loss measurement

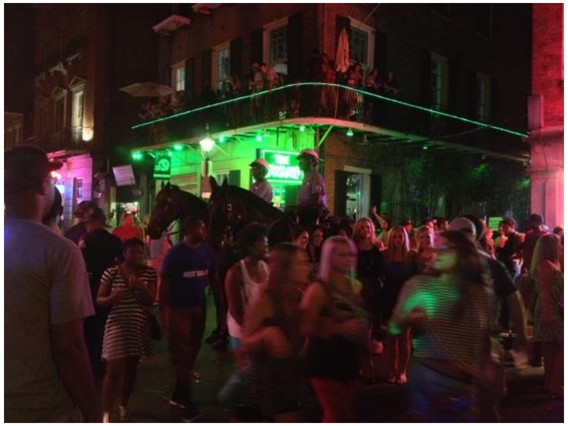
  Measure in other directions from the center

- Scattering error

  ITMY!!

少し休憩…

- New Orleans

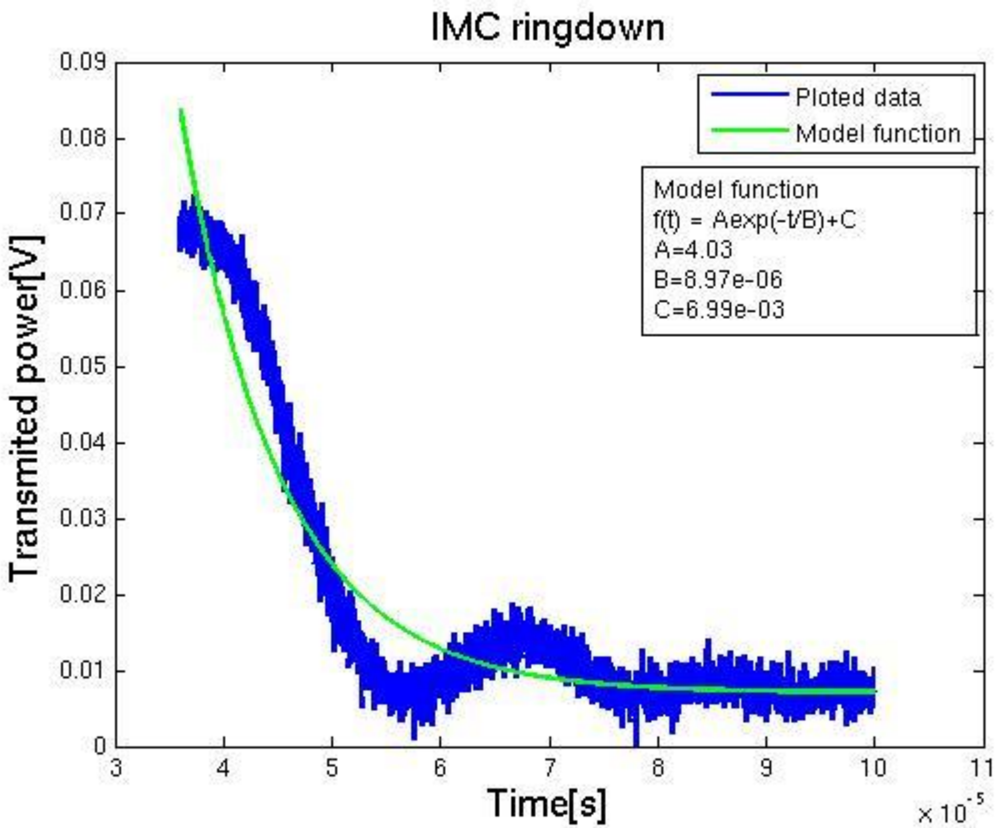


学んだこと

- 研究環境の過酷さ
- 英語でのコミュニケーション
- プログラミング技術の必要性
- <u>ルイジアナには野生のアルマジロがいる！</u>

Thank you for listening!

Time constant of IMC ringdown



Not clean ringdown

⇓

Quicker lock loss?

Mean [s]	Standard error [s]	Standard error per [%]
9.070×10^{-6}	3.0×10^{-8}	0.33

*Reference: $9.095 \times 10^{-6} [s]$

Camera calibration

$$\frac{340[mm]}{640[pc] \times \frac{B}{A}}$$
$$\cong 0.53 \times \frac{A}{B}[mm/pc]$$