The status and prospects of the Q & A experiment with some applications

國立清華大學
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Hsien-Hao Mei, Wei-Tou Ni

July 15 2009 9:50 @ Appleby Lecture Theatre

Q & A
Collaboration

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Outline

- **Motivation & Introduction**
  - Pseudoscalar-photon interaction
  - Birefringence vs Dichroism
  - QED vs CME
  - Axion-Like Particles prediction
- **Q & A experiment**
  - Ellipsometry
  - Fabry-Perot Interferometer
  - Suspension and PDH locking
  - Magnet with lock-in
- **Jones Matrix optical model**
  - Wave-plate and Rotation nature
  - FPI and intrinsic birefringence
  - Signal after lock-in detection
- **Current Status & Challenge**
  - Stray field vs gas-line design
  - New magnet for ALP/QED
- **Prospects**
- **Summary & Outlook**

Motivation
Q(ED) & A(xion) experiment

(i) QED

(ii) (Pseudo)scalar-Photon Interaction

- Bottom Up Approach: Markus Ahlers's talk
  - Pecci & Quinn: PRL **38** 1440 (1977)
  - Weinberg: PRL **40** 233 (1978)
  - Wilczek: PRL **40** 279 (1978)
  - Kim: PRL **43** 103 (1979)
  - Dine *et al*.: PLB **104** 1999 (1981)
  - Shifman *el al*.: NPB **166** 493 (1980)
- Top Down Approach: Joseph Conlon's talk
  - String
- **Phenomenological Study Approach**
  - **From analysis of EPs (1973-1977)**

(Pseudo)scalar field: WEP & EEP in EM field

A NON-METRIC THEORY OF GRAVITY*

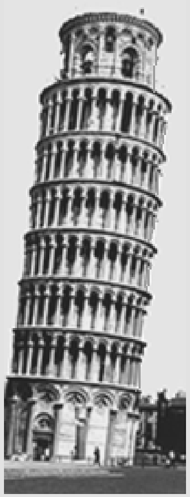
Wei-Tou Ni

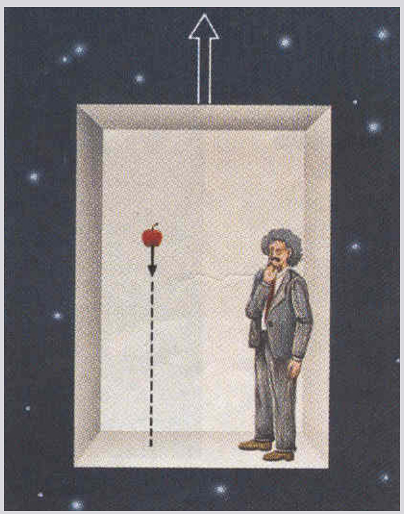
Department of Physics, Montana State University

Bozeman, Montana

59715

December, 1973





PHYSICAL REVIEW LETTERS

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Equivalence Principles and Electromagnetism*

Wei-Tou Ni

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(Received 16 June 1976)

The implications of the weak equivalence principles are investigated in detail for electromagnetic systems in a general framework. In particular, I show that the universality of free-fall trajectories {Galileo weak equivalence principle (WEP[I])} does *not* imply the validity of the Einstein equivalence principle (EEP). However, WEP[I] plus the universality of free-fall rotation states (WEP[II]) *does* imply EEP. To test WEP[II] and EEP, I suggest that Eötvös-type experiments on polarized bodies be performed.

Named as "Axion" after 1978

$$L_I = -(1/16\pi)\phi F_{ij} F_{kl} e^{ijkl}$$

$$F \equiv A_{j,i} - A_{i,j} \qquad e^{0123} = 1$$

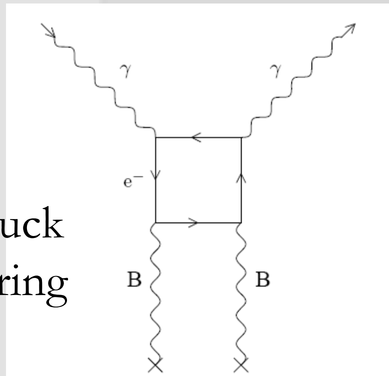
Modified Maxwell Equations → Polarization Rotation in EM Propagaton

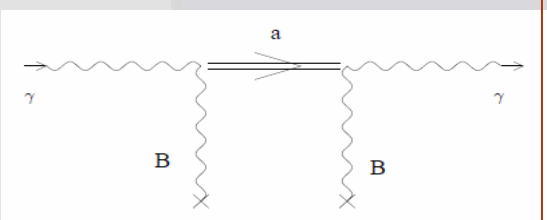
Constraints from CMB polarization observation → **Ni's talk tomorrow**

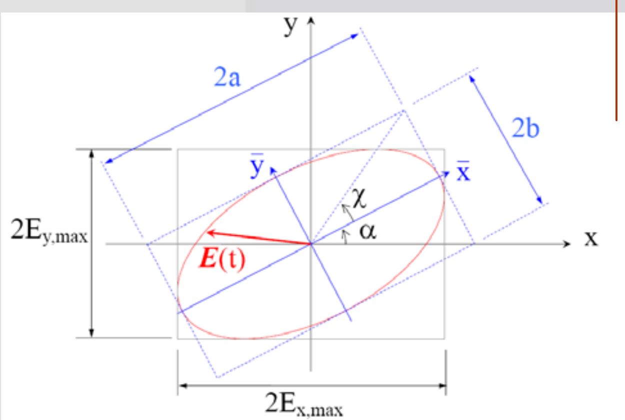
Introduction

Birefringence vs. Dichroism

Delbruck scattering





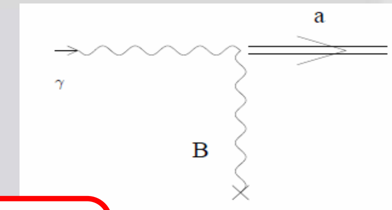


$$\varepsilon \cong \tan\varepsilon = \frac{\Delta\varsigma}{2}\sin 2\theta_m \qquad \theta = \omega_m t$$

Polarization Rotation

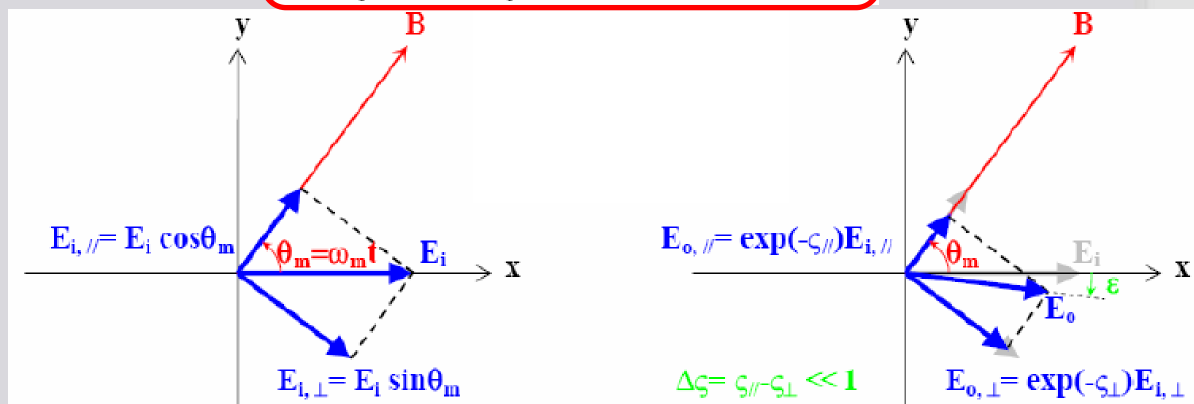
Dichroism

Primakoff effect



ALPs: $$\varepsilon = \left[\frac{B_{ext}^2\omega^2}{M^2 m_a^4}\right]\sin^2\left[\frac{m_a^2 l}{4\omega}\right] \approx \frac{B_{ext}^2 l^2}{16M^2}$$

$$m_a^2 < 2\pi\omega / l$$



$$\Delta n \equiv n_{\parallel} - n_{\perp}$$

Birefringence

$$\delta = 2\pi\frac{L}{\lambda}\Delta n$$

Phase retardation

$$\frac{\delta}{2}\sin 2\theta = \psi_0 \sin 2\theta$$

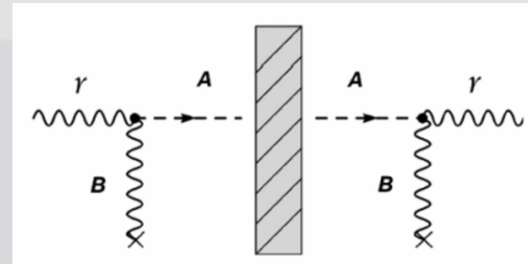
Ellipticity

ALPs: $$\psi = \frac{1}{2}\left[\frac{B_{ext}^2\omega^2}{M^2 m_a^4}\right]\left[\frac{m_a^2 l}{2\omega} - \sin\left[\frac{m_a^2 l}{2\omega}\right]\right] \approx \frac{(B_{ext} m_a)^2 l^3}{96\omega M^2}$$

ALPs & MCPs results from dichroism (comp. in 2007)

ALP search comp. in 2007 Experiment	BFRT (λ: 514 nm)	PVLAS (λ: 1,064 nm)	Q & A (λ: 1,064 nm)
Magnetic field B (T)	2.63–3.87	5	2.3
Magnetic region length L (m)	8.8	1	0.6
Effective number N of reflections	254	44,000	18,700
Effective NB^2L^2 (T^2m^2)	78,700	1,100,000	29,900
Measured dichroism (nrad)	$0.35 \pm 0.30\,(2\sigma)$	$172 \pm 22\,(3\sigma)$	$-0.4 \pm 5.3\,(1\sigma)$
Derived vacuum dichroism (10^{-14} rad $T^{-2}m^{-2}$)	0.45 ± 0.38	15.6 ± 2.0	-1 ± 18
Pseudoscalar mass m_φ (meV)	for $m_\varphi < 0.8$	1–1.5	for $m_\varphi < 1.7$
Coupling energy scale M (10^6 GeV)	> 2.8	0.2–0.6	> 0.6

MCP search comp. in 2007 Experiment	BFRT (λ: 514 nm)	PVLAS (λ: 1,064 nm)	Q & A (λ: 1,064 nm)
Magnetic field B (T)	2.63–3.87	5	2.3
Magnetic region length L (m)	8.8	1	0.6
Effective number N of reflections	254	44,000	18,700
Effective $NB^{2/3}L$ $(\omega/\omega_0)^{-1/3}$ ($T^{2/3}m$)	2,650	123,500	18,600
Measured dichroism (nrad)	$0.35 \pm 0.30\,(2\sigma)$	$172 \pm 22\,(3\sigma)$	$-0.4 \pm 5.3\,(1\sigma)$
Derived vacuum dichroism (rad $T^{-2/3}m^{-1}$)	$(1.3 \pm 1.1) \times 10^{-13}$	$(13.9 \pm 1.8) \times 10^{-13}$	$(-0.2 \pm 2.8) \times 10^{-13}$
Millifermion charge ratio ε (10^{-7})	3.5 (+1.0, −2.3)	8.5 ± 0.4	0 (+4.6, −0)



LSW:
CAST, BMV, PVLAS, LIPSS, GammeV, ALPS, Tokyo axion helioscope, OSQAR, and so on….

6.5 ± 10 (2σ) @ 2.3 T
9.1 ± 12 (2σ) @ 5 T Phys. Rev. **D**77 (2008) 032006

$$\varepsilon = \left[\frac{B_{ext}^2\omega^2}{M^2 m_a^4}\right]\sin^2\left[\frac{m_a^2 l}{4\omega}\right] \approx \frac{B_{ext}^2 l^2}{16M^2}$$

$$m_a^2 < 2\pi\omega/l$$

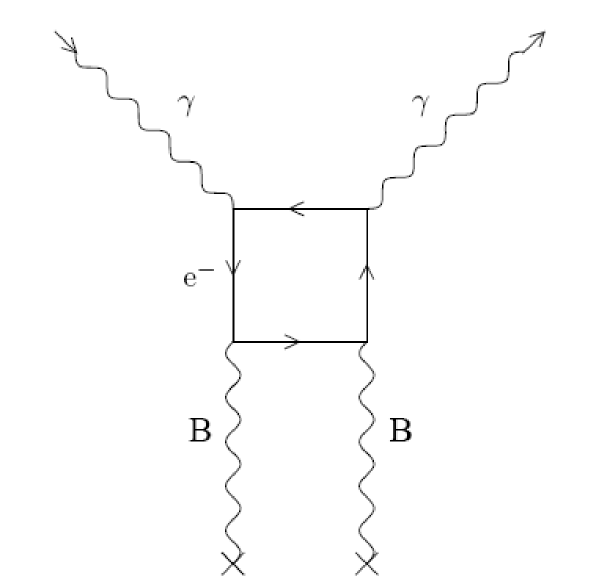
$$\Delta\theta \approx \left(\frac{1}{4}\right)(\kappa_\parallel - \kappa_\perp) \approx 2.1 \times 10^4 \varepsilon^{8/3}\left(\frac{\omega}{\omega_0}\right)^{-1/3} B^{2/3} L_B$$

For $m_\varepsilon < 0.03$ eV, $\chi \gg 1$,

T_{int} = 18.9 hr

Mod. Phys. Lett. A 22 (2007) 2815

Quantum electrodynamics (QED)



Euler and Heisenberg (1936):

$$L_{eff} = \frac{2\alpha^2}{45(4\pi)^2 m_e^4}[(\mathbf{E}^2 - \mathbf{B}^2) + 7(\mathbf{E}\cdot\mathbf{B})^2]$$

$$\Delta n_{QED} = \frac{\alpha}{30\pi B_c^2} B_{ext}^2$$

$$B_c = \frac{m_e^2 c^2}{e\hbar} = 4.42 \times 10^9 \text{ T}$$

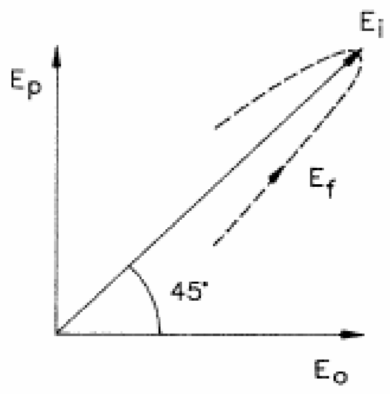
$$\Delta n_{QED} \ll 1; \quad \Delta n_{QED} \propto B_{ext}^2$$

$$\Delta n_{QED,u} = \Delta n_{QED}\,|_{B=1\,\text{T}} \simeq 4 \times 10^{-24}$$

11

Cotton-Mouton effect (CME)

CME of nitrogen: $\Delta n_u = -2.66 \times 10^{-13}$



$$\Delta n \equiv n_{\parallel} - n_{\perp} = \Delta n_u (B/1\text{ T})^2 (P/1\text{ atm})$$

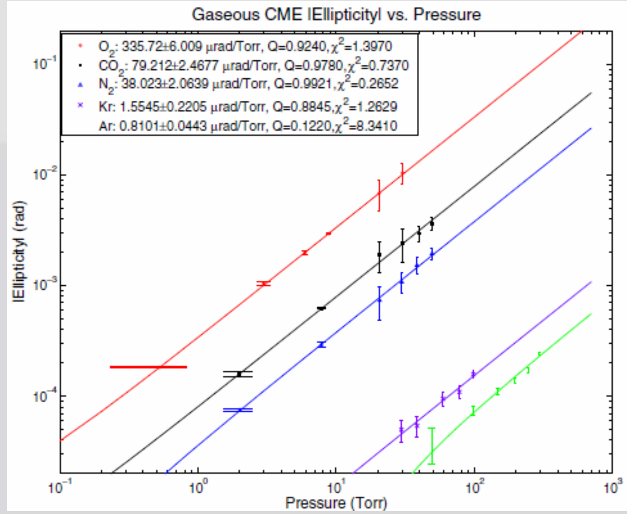
$$\psi = \Delta n_u \left(\frac{2F}{\lambda}\right)\left[\int_{L_B}\left(\frac{B_T(L)}{1\,(T)}\right)^2 dL\right]\left(\frac{P_{gas}}{P_{atm}}\right)$$

2009)

Gas	$C_{CM} = \frac{P_{atm}}{\pi \int_L B^2 dz} \cdot \frac{\Psi_{0,CME}(P)}{NP}$ ($T^{-2}m^{-1}$) for λ = 1064nm
N_2	$(-1.90 \pm 0.15^{\S} \pm 0.08c^{\P}) \times 10^{-7}$
O_2	$(-1.68 \pm 0.32^{\S} \pm 0.08^{\P}) \times 10^{-6}$
CO_2	$(-3.97 \pm 0.25^{\S} \pm 0.15^{\P}) \times 10^{-7}$ ← New
Ar	$(4.05 \pm 0.32^{\S} \pm 0.16^{\P}) \times 10^{-9}$ ← New
Kr	$(7.78 \pm 1.18^{\S} \pm 0.30^{\P}) \times 10^{-9}$

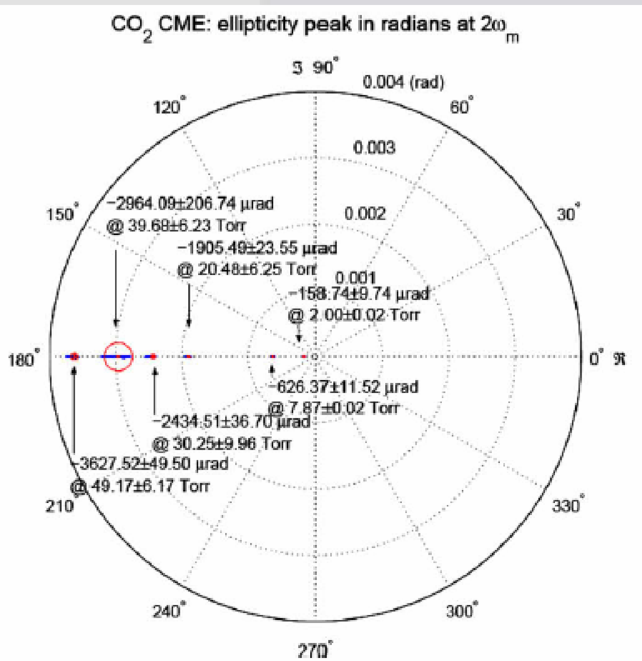
§: Statistical uncertainty from $\chi 2$-fitting of the slope $\Psi_{0,CME}(P)/P$.
¶: Systematic uncertainty (N: 5.6%, B^2: 2.2%, P: 2.5%, η_0: 1.6%).

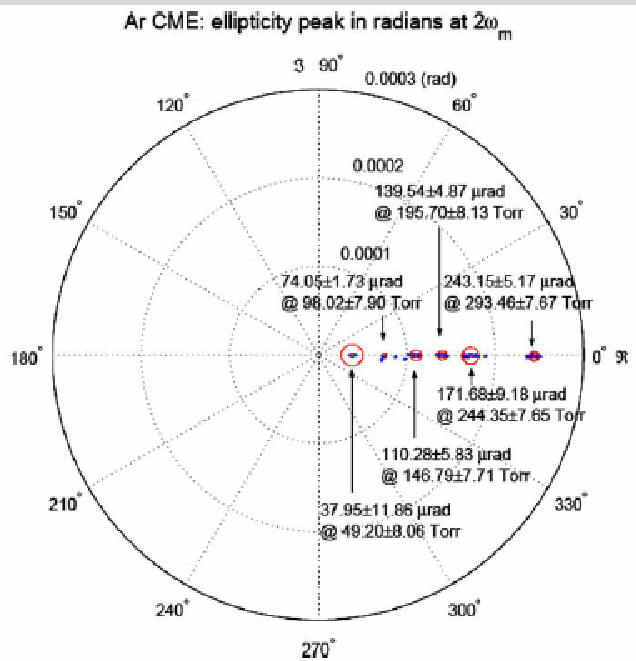
Chem. Phys. Lett. **471** (2009) 216



B: 2.3 T
P: 0.5 – 300 Torr
T: 295 – 298 K

Systematic uncertainty: less than 3.86%.





Statistical uncertainty: limited by pressure gauge readings at the 10 – 100 Torr range.

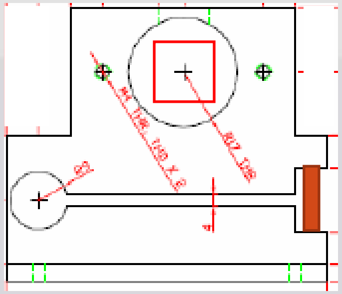
In agreement with the PVLAS results within 1.2σ.

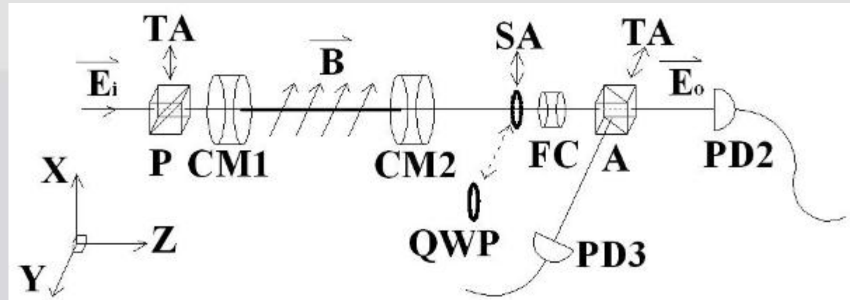
M. Bregant et al., Chem. Phys. Lett. 392 (2004) 276.
M. Bregant et al., Chem. Phys. Lett. 410 (2005) 288.
F. Brandi et al., J. Opt. Soc. Am. B 15 (1998) 1278.

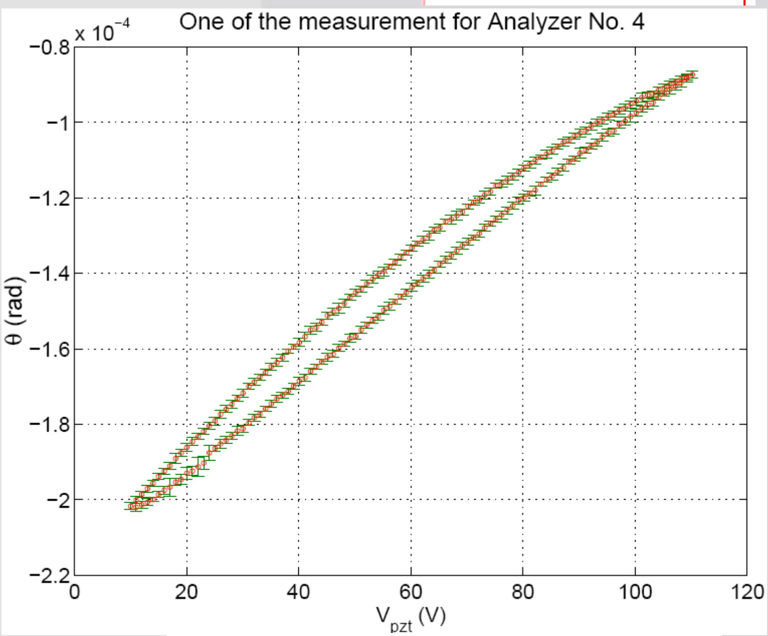
Ellipsometry & extinction ratio (σ^2) measurement

$$I_{out} = I_{in}\,(\sigma^2 + \alpha^2)$$

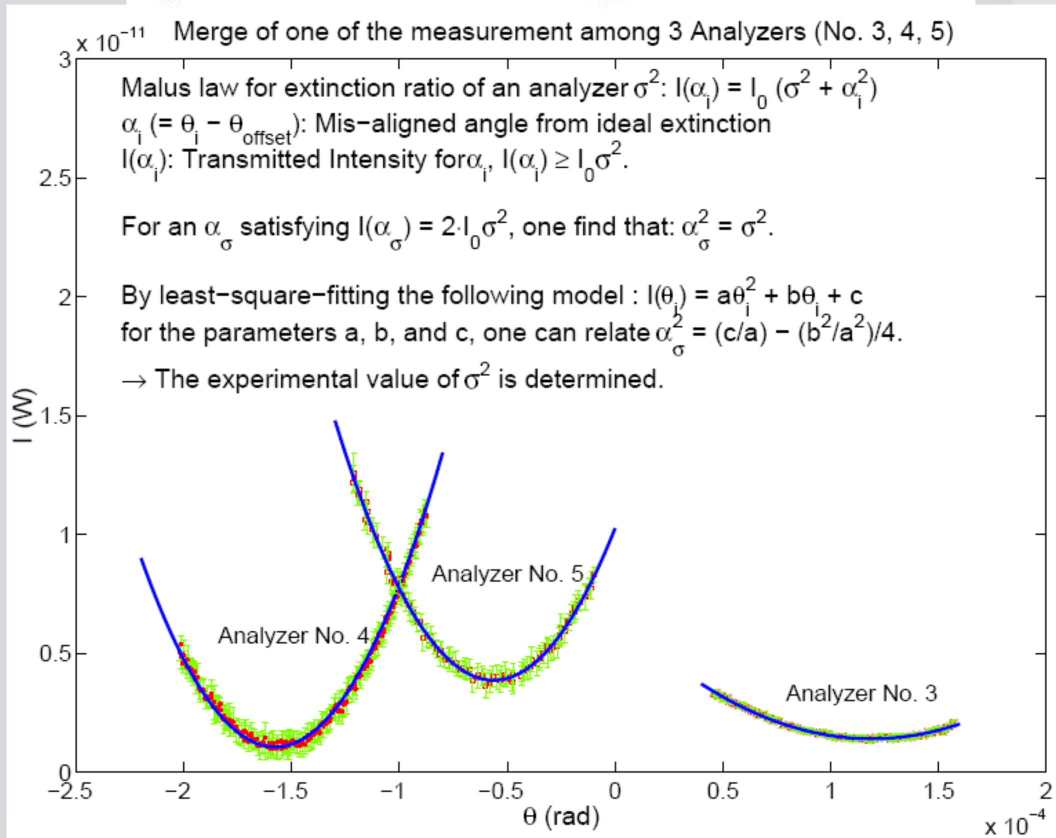
$$\sigma^2 \equiv \frac{\min(I_{out})}{I_{in}}$$



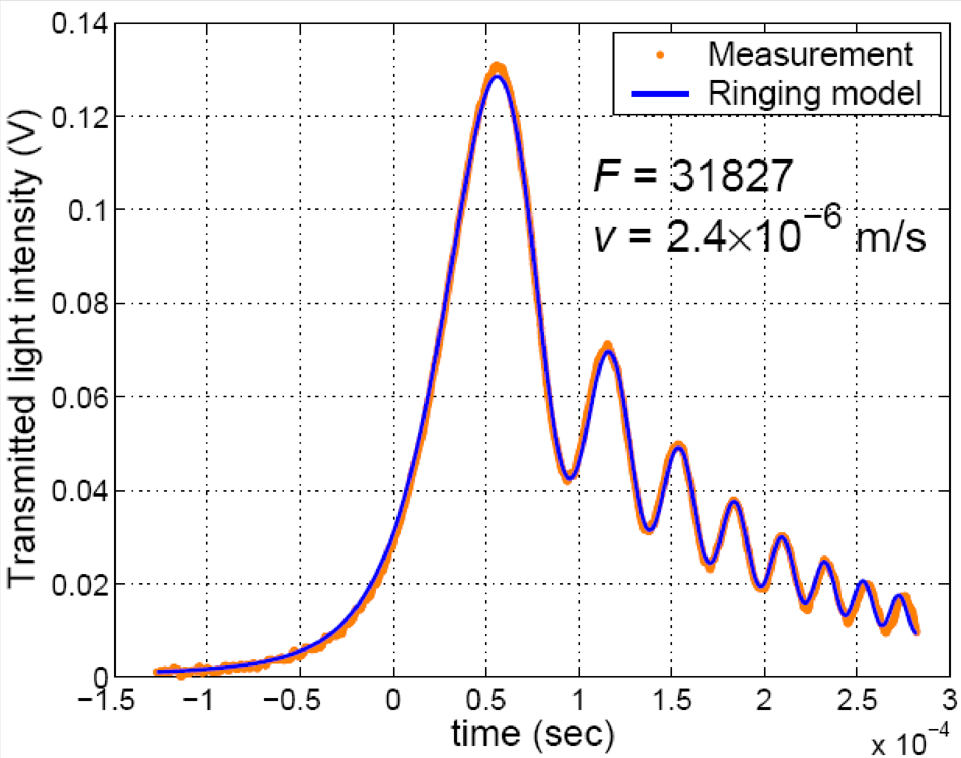




Analyzer	No. 3	No. 4	No. 5
$[\sigma^2] \times 10^{10}$	37.41294	5.16842	18.70794
$\sigma_{[\sigma^2]} \times 10^{10}$	0.99468	0.11864	0.18273



Fabry-Perot Interferometer (FPI) Specs (General Optics)



(Substrate)	Fused Silica
(Dimention)	ϕ50 mm×50 mm
(V-groove)	0.5 mm×2
(V-groove separation)	20 mm
(Radius of curvature)	5 m ∞(flat)
(Coating of inner surface)	High-Reflection
(Reflectivity of inner surface)	$R \simeq 99.99\%$
(Coating of outter surface)	Anti-Reflection
(Reflectivity of outter surface)	$R \lesssim 0.25\%$
(Transmittivity)	$\geq 0.85 \times (1-R)$
(Finesse) F	30,000±1,673
(Cavity Length) L(m)	3.45
(Beam = $\frac{\pi\sqrt{R}}{1-R}$size) w_0(mm)	0.088
(Free Spectral Range) FSR(MHz)	43.478
(Cavity Line-width) $\Delta\nu$(Hz)	1449

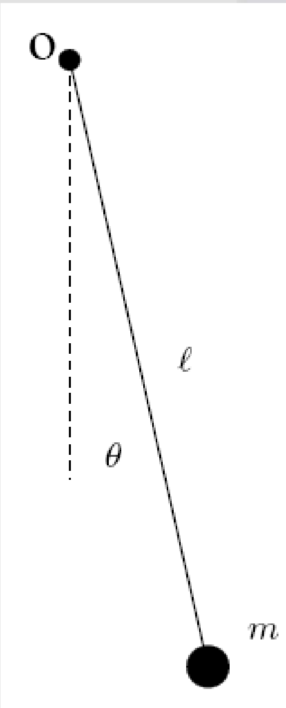
$$I_t(t) = \frac{I_i}{4}\frac{T^2}{R^2}\frac{FSR}{\Omega}\exp\left[-\frac{\pi}{F} - 2\frac{FSR}{\Omega}\frac{\Phi(t)}{F}\right]|\mathrm{erfc}[\Gamma(t)]|^2$$

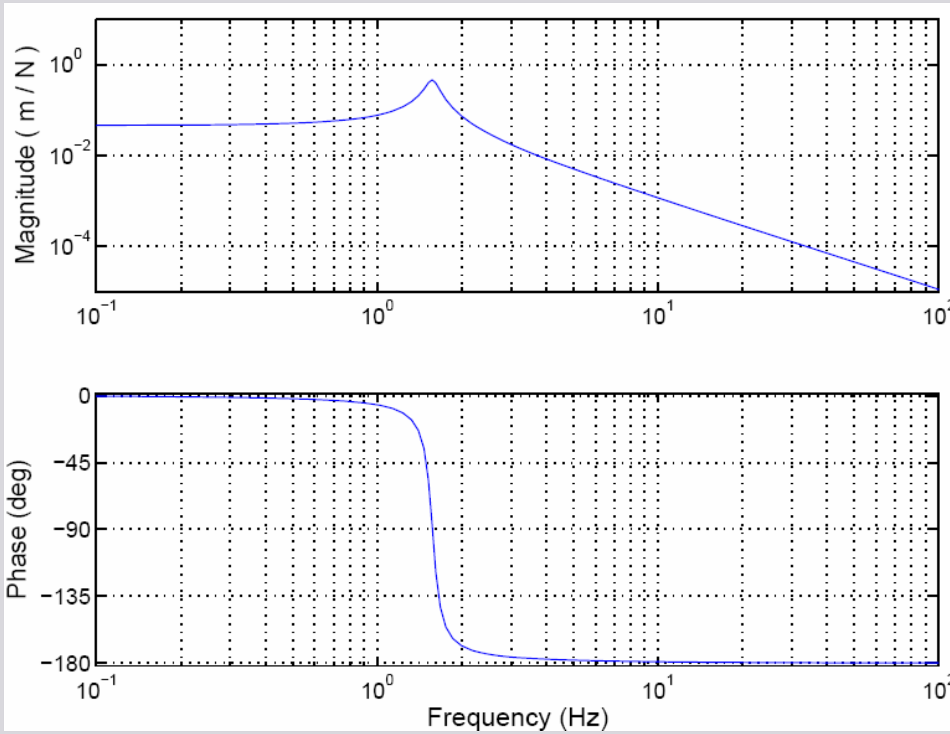
$$\Phi(t) = 2\pi L(t)/\lambda,\ \Omega = 2v/\lambda,\ FSR = c/2L_0,$$

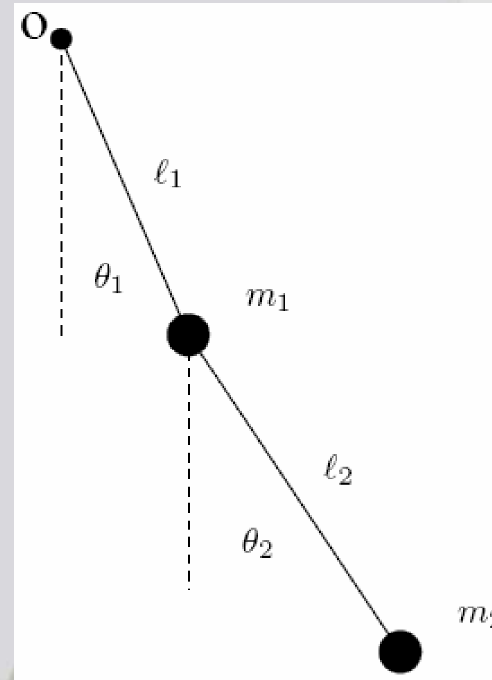
$$\Gamma(t) = \frac{1-i}{2\sqrt{(2)}}\left(\frac{FSR}{\pi\Omega}\right)^{1/2}\frac{\pi}{F} - \frac{1+i}{2\sqrt{2}}\left[\left(\frac{FSR}{\pi\Omega}\right)^{1/2}2\Phi(t) - \left(\frac{FSR}{\pi\Omega}\right)^{1/2}\right]$$

Suspension of FPI cavity mirrors

$\leftarrow (g/l)^{1/2}$



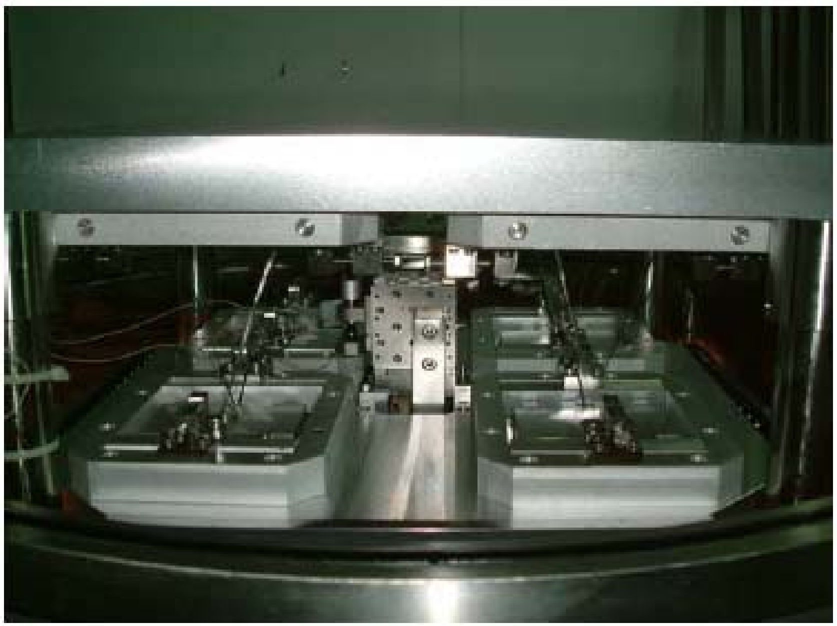




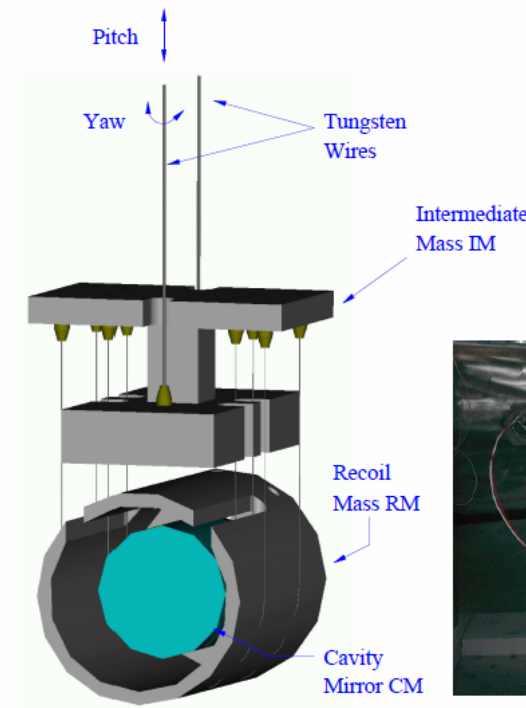
$$\frac{X(\omega)}{X_0(\omega)} = \frac{\omega_0^2}{-\omega^2 - i\frac{b}{m}\omega + \omega_0^2}$$

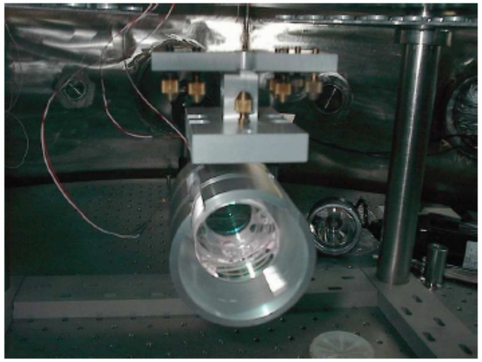
$$\frac{X(s)}{F(s)} = \frac{\frac{1}{m}}{s^2 + \frac{b}{m}s + \frac{g}{\ell}} = \frac{\frac{1}{m}}{s^2 + s\frac{\omega_n}{Q} + \omega_n^2}$$

Suspension system



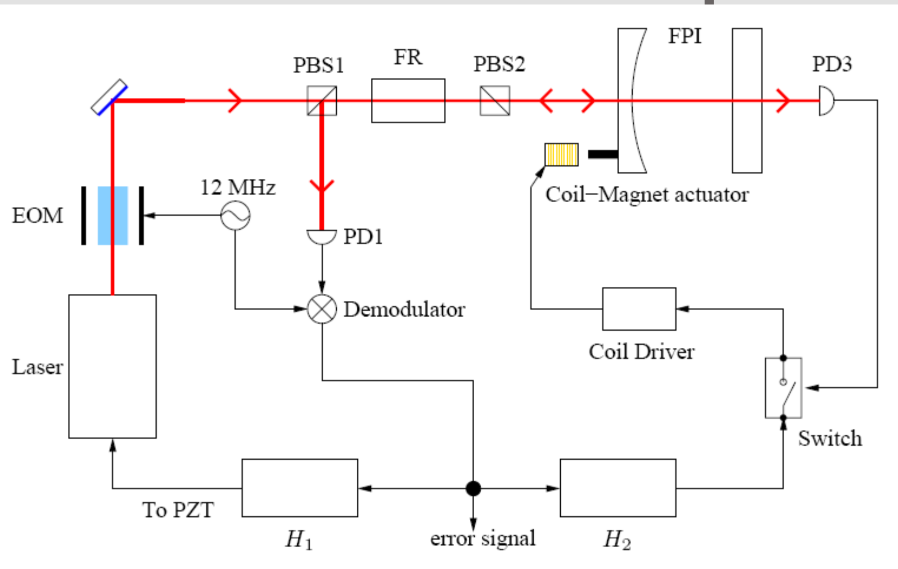
Double pendulum:
Intermidiate mass (IM)
Cavity mirror (CM), Recoil mass (RM)
Main Resonance: 1.53 Hz & 4 Hz
Isolation ratio by (X-pendulum): 27 & 72

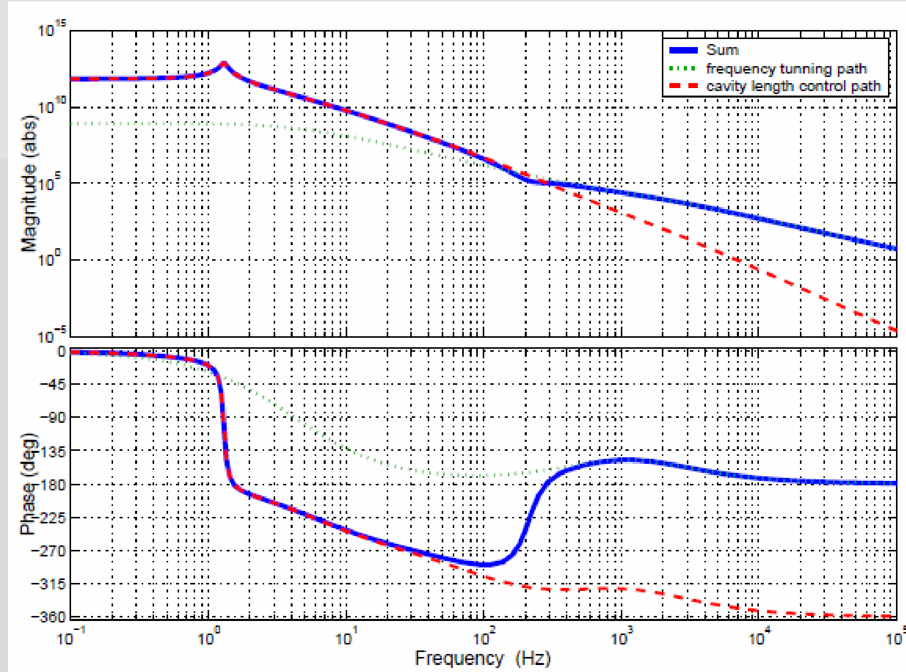


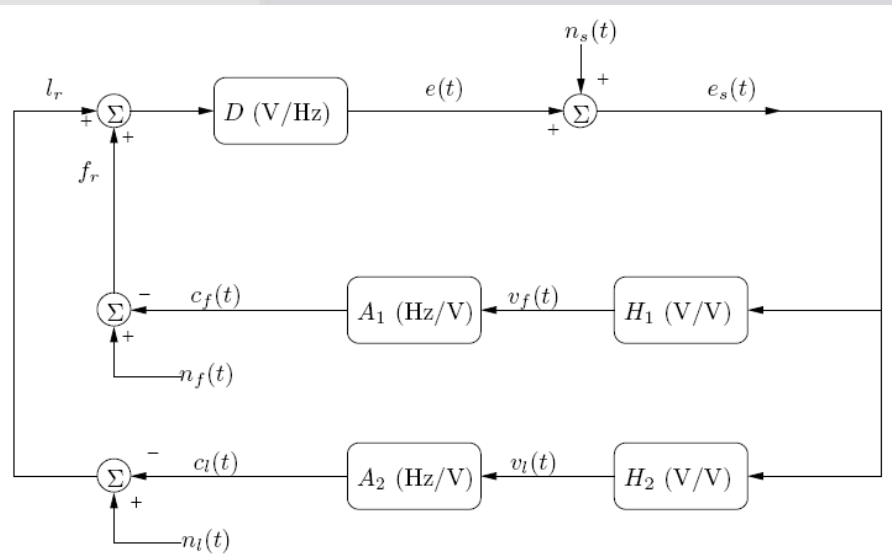


X-pendulum:
Designed by TAMA Collaboration
Simulate simple pendulum with long wire
Resonance: 0.24 Hz & 0.29 Hz (2-dimention)
Displacement: 80 μm (no damping)
→3 μm (eddy current) ≈ 6 *FSR*

Control loop



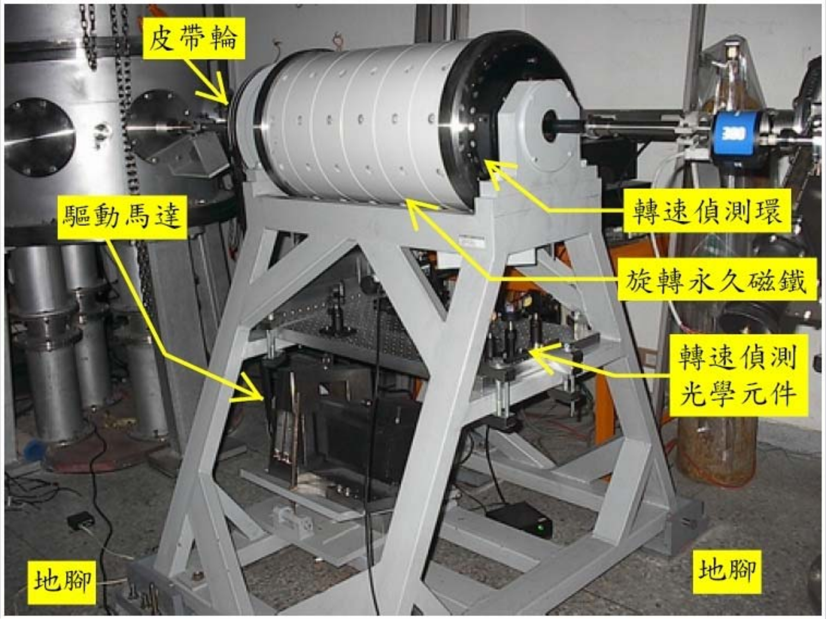


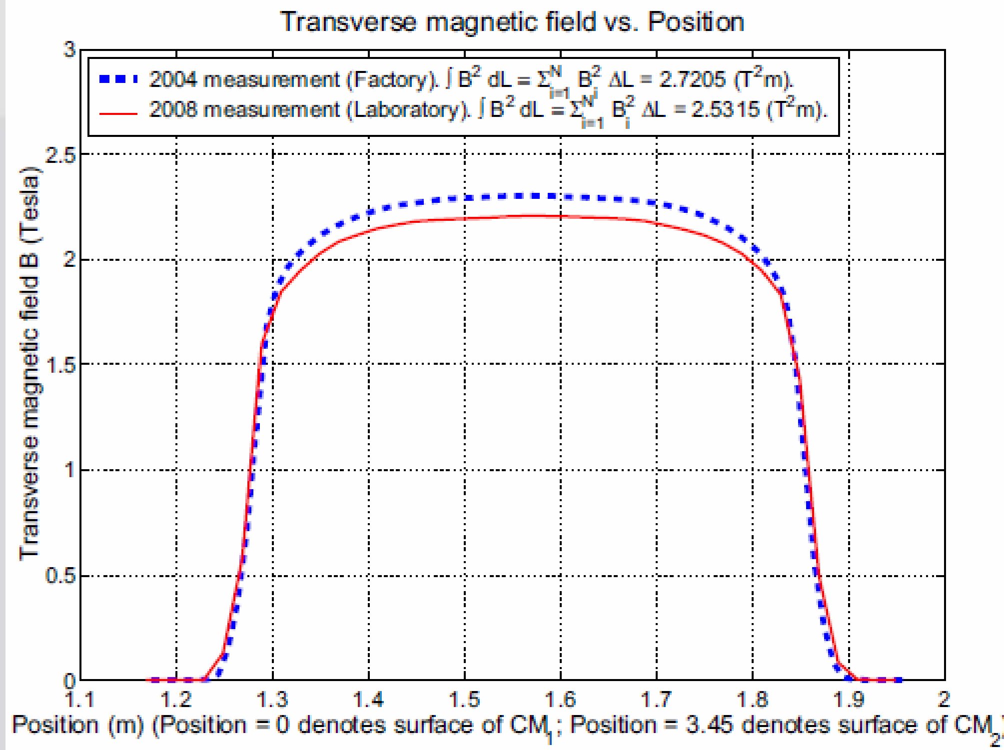


Nd-YAG single mode laser
(λ = 1064 nm, P = 600 mW)
Pound-Drever-Hall locking
(→ D. Tanner's talk: resonant enhanced γ reg.)
Laser frequency H_1A_1:
Dynamic range ± 200 MHz
Control band width 13 kHz
FPI cavity length H_2A_2:
Dynamic range ± 1 mm
Control band width 220 Hz
Best performance: $H1A1 >> H_2A_2$

Lasing of the system (Film)

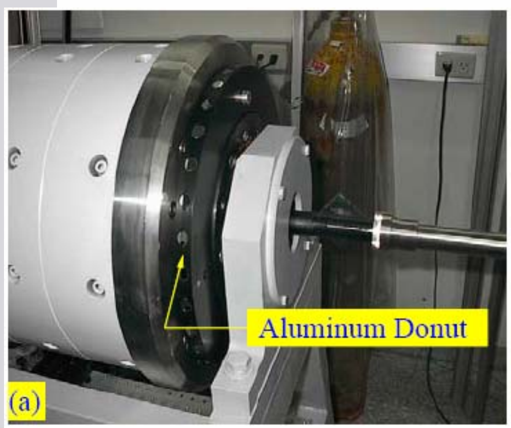
Magnet with motor

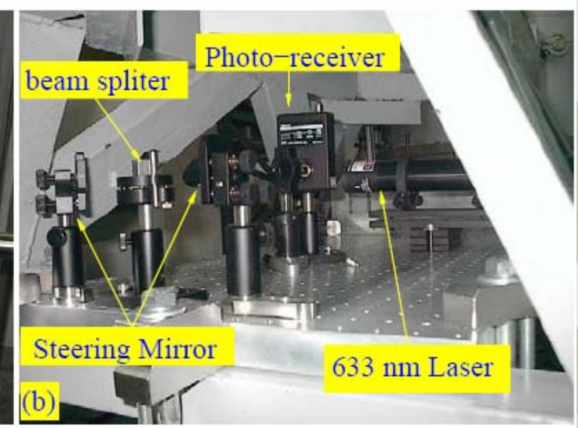




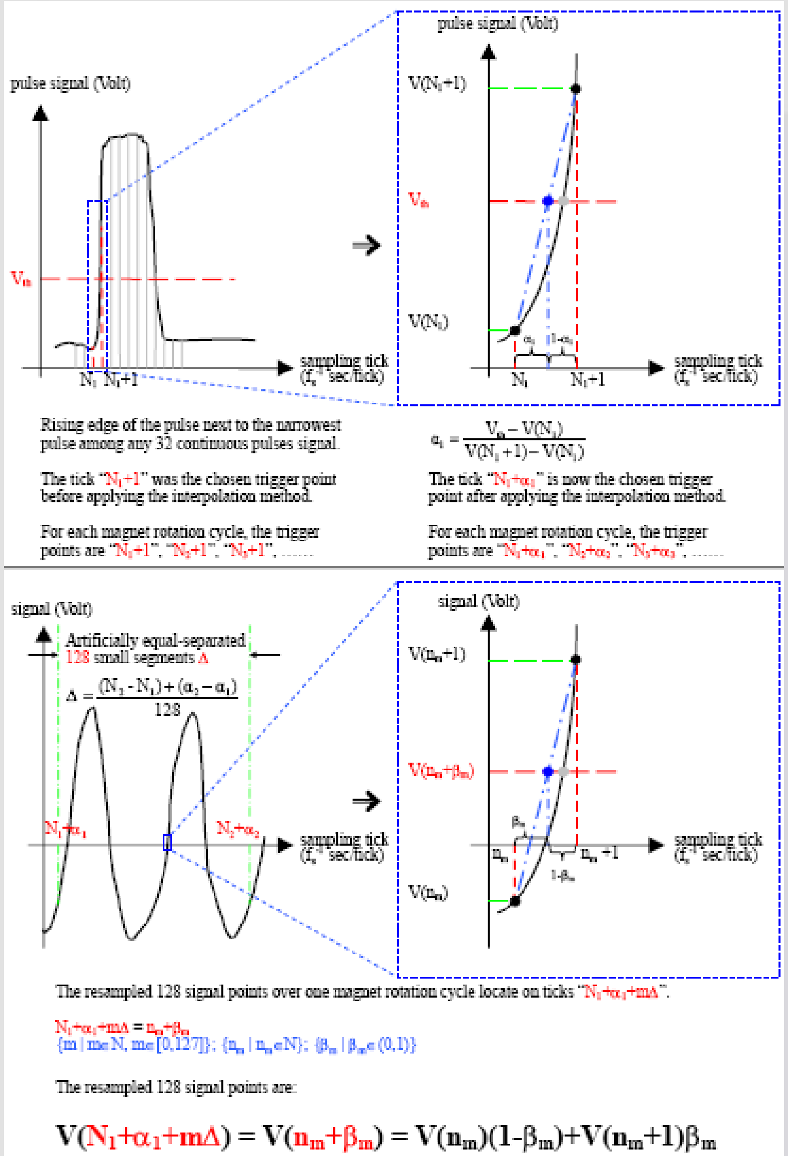
B_T (T)	$\geq$2.0
$\frac{B_A}{B_T}$	$\leq$0.1%
Leakage of B_T or B_A	
at 10 mm away from magnet (T)	$\leq 10^{-4}$
Length L (mm)	600
Height H (mm)	1100
Axial free diameter ϕ (mm)	25.4
Rotating Speed (rev/s)	0-10

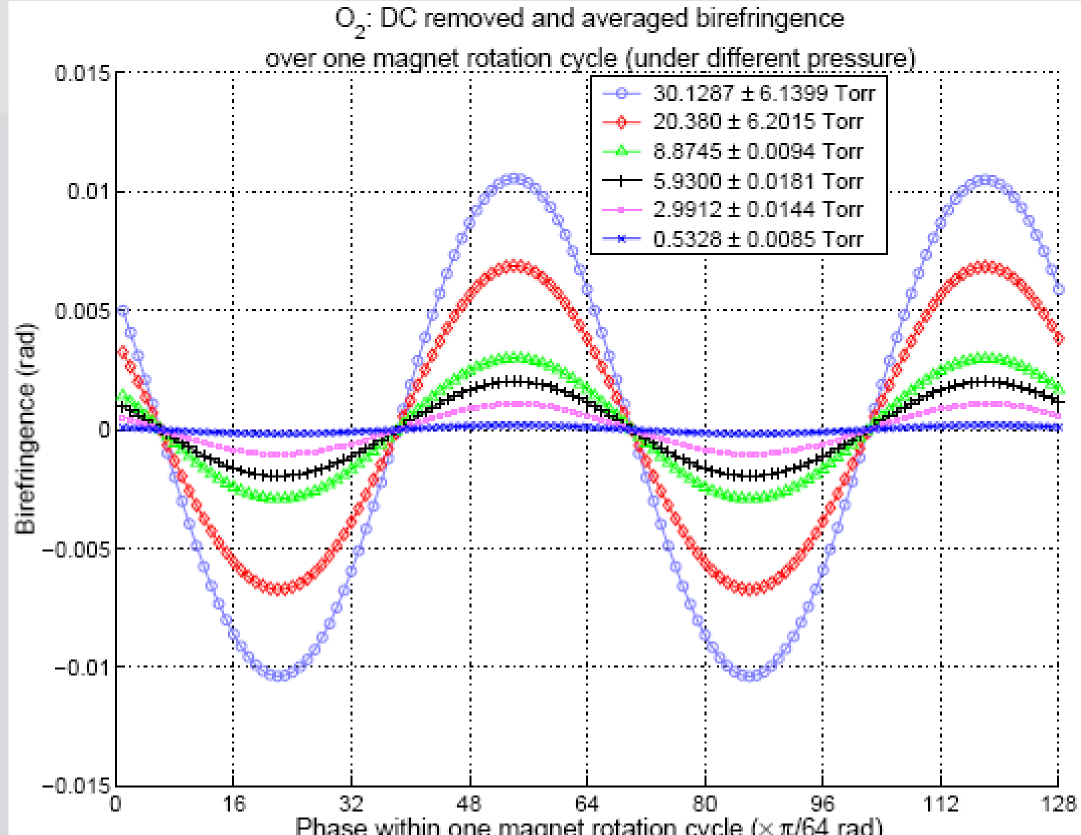
Model	BSM100B-4250
Torgue cont. stall	23 Nm
Rated Speed	1200 RPM
Current Cont. Stall	12 A rms
Peak Current	33 A rms





Interpolation re-sampling





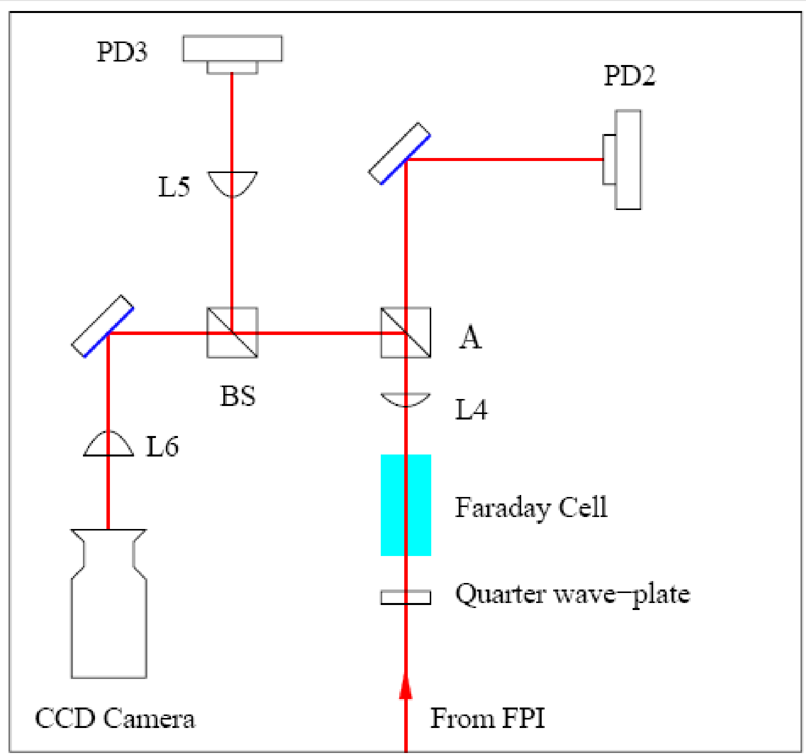
$f_{s\_DAQ} = 20$ kSa/s

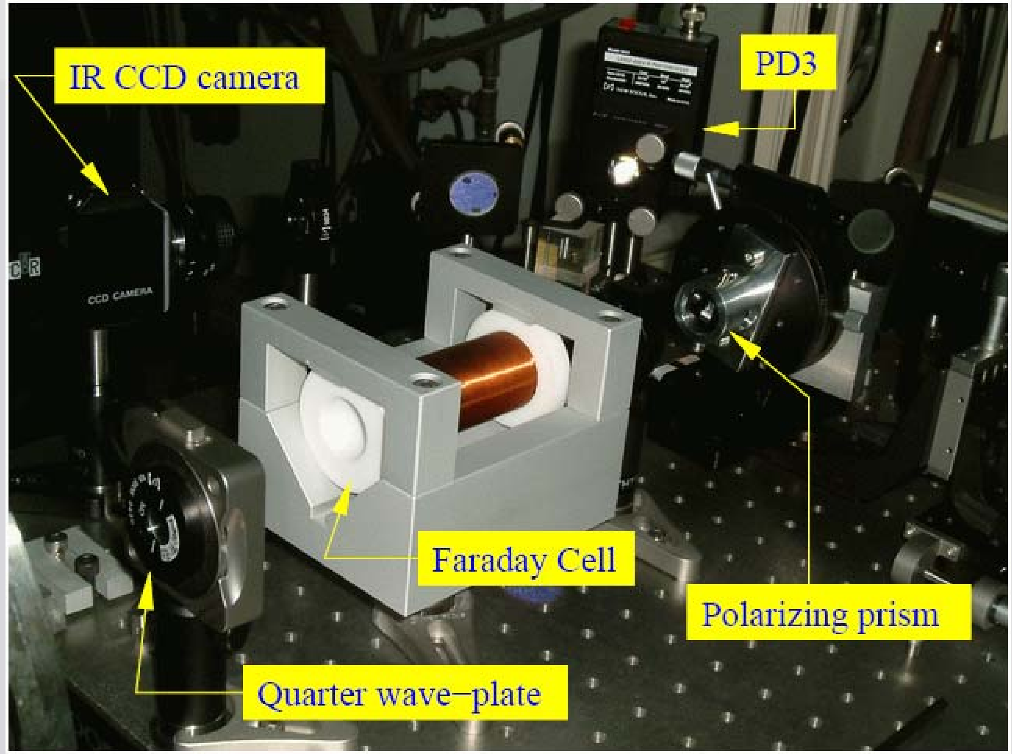
$f_m = 6.7742$ cycle/s ↔ 2952 – 2953 Sa/cycle

$f_{res} = 128 f_m$ ↔ 128 Sa/cycle

$f_{sig} = 2 f_m$

Detection bench elements





FC (Faraday Cell):

modulation depth $\eta_0 = I_{FC} \times 0.019$ rad/A

A (Analyzer):

extinction ratio $\sigma^2 = 92.87$ dB

resolution (roll) = 174.5 μrad

QWP (Quarter wave plate):

resolution (roll) = 200 μrad

VWP (Variable wave plate):

resolution (roll) = 3.5 mrad

resolution (tilt for retardation) = 6.28 mrad

enhanced by νFocus 9852 mount for tilt: 615 μrad

Wave-plate-like & Rotation-like nature

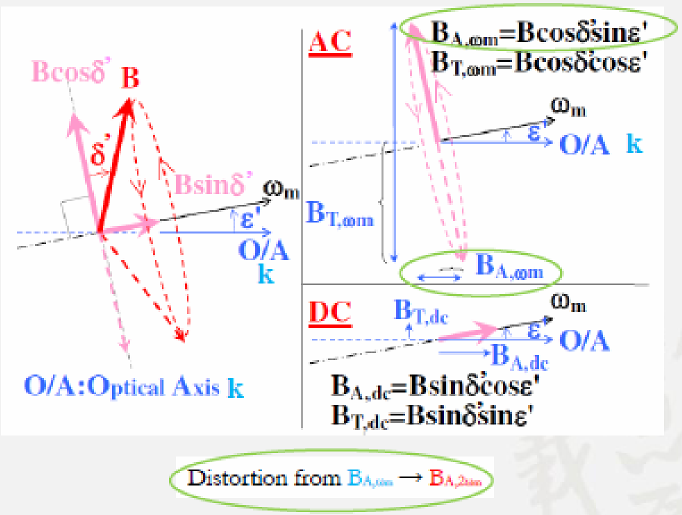
$$J_{WP}\left(\tfrac{\delta}{2},\vartheta\right)=J_R(\vartheta)\begin{bmatrix} e^{i\frac{\delta}{2}} & 0 \\ 0 & e^{-i\frac{\delta}{2}} \end{bmatrix}J_R(-\vartheta)$$

$$\left[J_{WP}\left(\tfrac{\delta}{2},\vartheta\right)\right]^N=J_{WP}\left(N\tfrac{\delta}{2},\vartheta\right)=\cos N\tfrac{\delta}{2}\,I_2+i\sin N\tfrac{\delta}{2}\begin{bmatrix} \cos 2\vartheta & \sin 2\vartheta \\ \sin 2\vartheta & -\cos 2\vartheta \end{bmatrix}$$

$$J_{DIC}\left(\tfrac{\varepsilon}{2},\vartheta\right)=J_{WP}\left(-i\tfrac{\varepsilon}{2},\vartheta\right)$$

$$\left[J_R(\varphi)\right]^N=J_R(N\varphi)$$

Axial stray field (Faraday rotation)

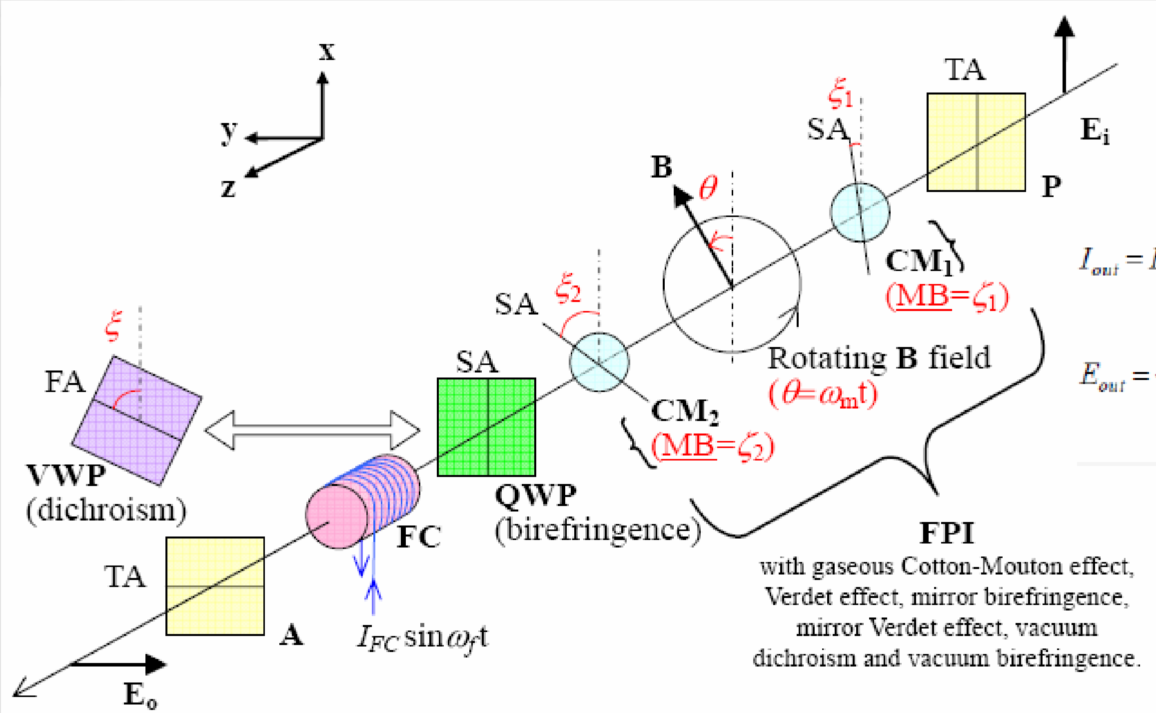


$$\left[J_{WP}\left(\tfrac{\delta}{2},\vartheta\right)\right]^N=I_2+iN\tfrac{\delta}{2}\begin{bmatrix} \cos 2\vartheta & \sin 2\vartheta \\ \sin 2\vartheta & -\cos 2\vartheta \end{bmatrix}+O(N^2\delta^2)+\cdots$$

$$\left[J_R(\varphi)\right]^N=I_2+iN\varphi\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}+O(N^2\varphi^2)+\cdots$$

$$\left[J_{WP}\left(\tfrac{\delta}{2},\vartheta\right)\cdot J_R(\varphi)\right]^N\cong I_2+iN\tfrac{\delta}{2}\begin{bmatrix} \cos 2\vartheta & \sin 2\vartheta \\ \sin 2\vartheta & -\cos 2\vartheta \end{bmatrix}+iN\varphi\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\cong\left[J_R(\varphi)\cdot J_{WP}\left(\tfrac{\delta}{2},\vartheta\right)\right]^N$$

$N\delta << 1$ and $N\varphi << 1$



$$I_{out} = E_{out}^* \cdot E_{out}$$

$$E_{out} = \begin{cases} J_A \cdot J_R(\alpha) \cdot J_{FC}\left(\eta_0 \sin(\omega_f t + \phi_f)\right) \cdot J_{QWP} \cdot J_{FPI} \cdot J_P \cdot E_0 \begin{bmatrix} 1 \\ 0 \end{bmatrix} \\ J_A \cdot J_R(\alpha) \cdot J_{FC}\left(\eta_0 \sin(\omega_f t + \phi_f)\right) \cdot J_{VWP} \cdot J_{FPI} \cdot J_P \cdot E_0 \begin{bmatrix} 1 \\ 0 \end{bmatrix} \end{cases}$$

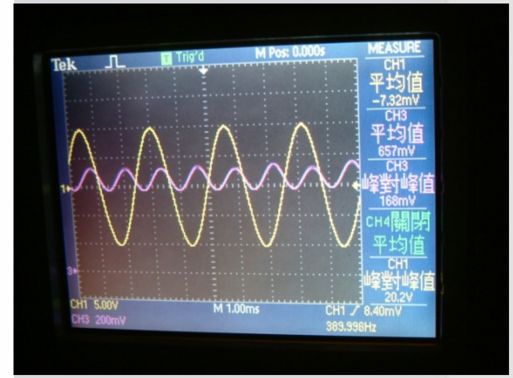
Optical component / Effect	Jones matrix representation
P/*A*: polarizer with transmitting axis at **x**/**y**	$J_P = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}; J_A = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$
BIR: birefringence nature of CME, vacuum (ψ,θ), or mirrors (ζ,ξ)	$J_{BIR}(\psi, \theta) = J_{WP}(\psi, \theta)$
DIC: dichroism nature of vacuum (β,θ)	$J_{DIC}(\beta, \theta) = J_{WP}(-i\beta, \theta)$
S: Faraday rotation or Verdet effect ($\upsilon \sin(\theta + \phi_s)$) from stray field	$J_S(\upsilon \sin(\theta+\phi_s)) = J_R(\upsilon \sin(\theta+\phi_s))$
FC: polarization rotation modulator ($\eta_0 \sin(\omega_f t + \phi_f)$)	$J_{FC}(\eta_0 \sin(\omega_f t+\phi_f)) = J_R(\eta_0 \sin(\omega_f t+\phi_f))$
QWP: quarter wave-plate	$J_{QWP}(\pi/4, 0) = J_{WP}(\pi/4, 0)$
VWP: variable wave-plate to compensate intrinsic birefringence	$J_{VWP}(-\zeta, \xi) = J_{WP}(-\zeta, \xi)$
R: misalignment of the analyzer with angle α	$J_R(\alpha)$

Detected intensity

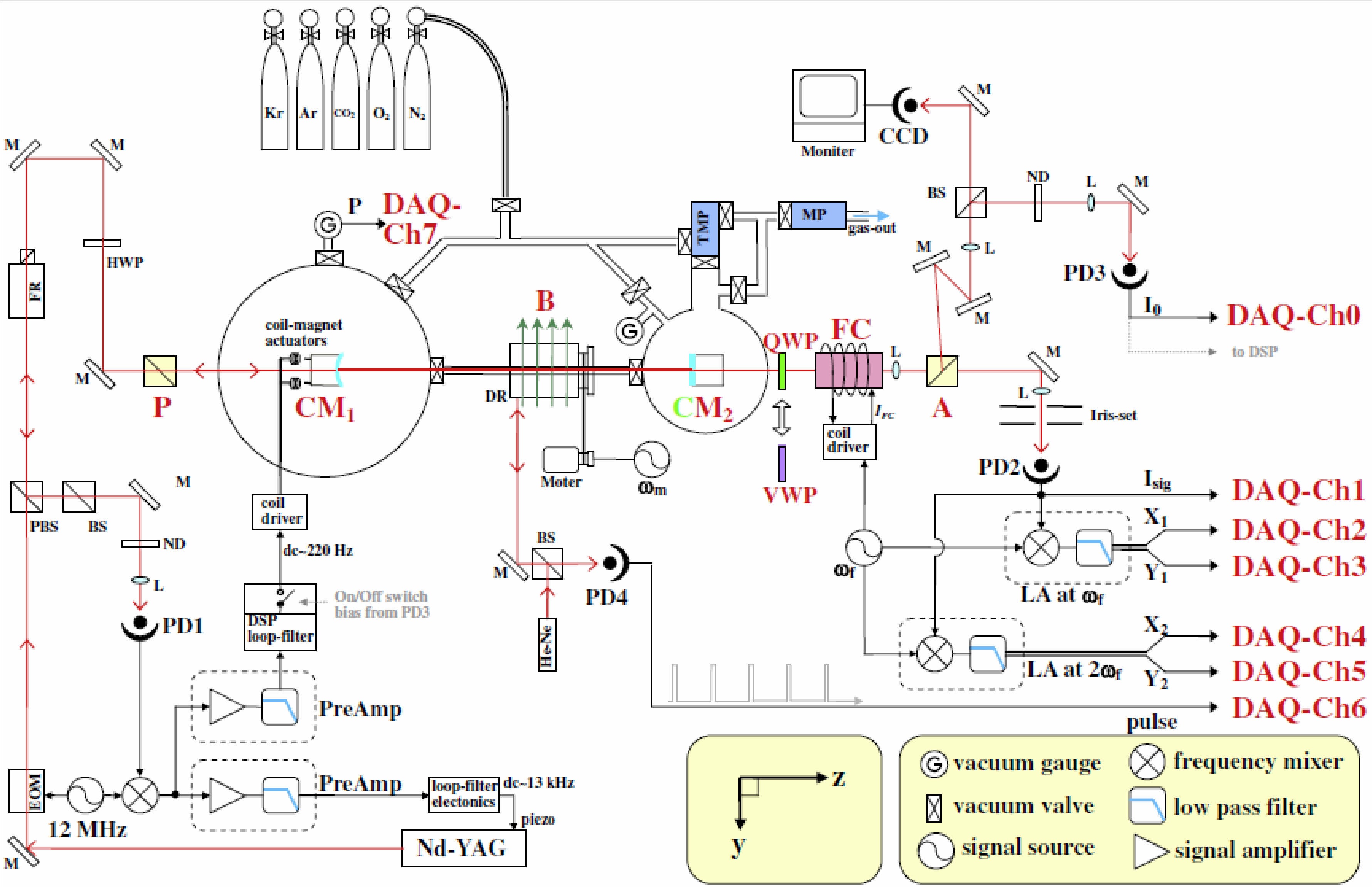
Table 2. Detected I_{out} components at major frequencies preserved to ρ^3 where ρ^n denotes for combinations of the products generated from ψ_0, β_0, ζ_0, υ_0, υ_2, and υ_{M2} to order n.

I_{out}	Birefringence detection at PD2 with QWP
I_{dc}	$I_0\left[\sigma_{ext}^2+\frac{1}{2}\left[\eta_0^2+N^2\left(\psi_0^2+\beta_0^2+\upsilon_0^2+\upsilon_2^2\right)+\upsilon_M^2+\upsilon_{M2}^2\right]+\left(\alpha+N\zeta_0\sin 2\xi\right)^2\right]$
$I_{\omega_f\pm\omega_m}$	$I_0\eta_0\left(N\upsilon_0+\upsilon_M\right)\begin{bmatrix}\pm N\zeta_0\cos 2\xi\cos\left((\omega_f\pm\omega_m)t+(\phi_f\pm\phi_s)\right)\\ \mp\frac{1}{2}N\psi_0\cos\left((\omega_f\pm\omega_m)t+(\phi_f\mp\phi_s)\right)\end{bmatrix}$
$I_{\omega_f\pm2\omega_m}$	$I_0\eta_0\begin{bmatrix}\mp N\psi_0\cos\left((\omega_f\pm2\omega_m)t+\phi_f\right)\pm N\beta_0N\zeta_0\cos\left((\omega_f\pm2\omega_m)t+(\phi_f\pm2\xi)\right)\\ \pm\left(N\upsilon_2+\upsilon_{M2}\right)N\zeta_0\cos 2\xi\cos\left((\omega_f\pm2\omega_m)t+(\phi_f\pm2\phi_s)\right)\end{bmatrix}$
I_{ω_f}	~~$2I_0\eta_0\left(\alpha+N\zeta_0\sin 2\xi\right)\sin\left(\omega_f t+\phi_f\right)$~~ $\rightarrow$ 0
$I_{2\omega_f}$	$-\frac{1}{2}I_0\eta_0^2\left[\cos(2\omega_f t+2\phi_f)\right]$

I_{out}	Dichroism detection at PD2 with VWP
I_{dc}	$I_0\left[\sigma_{ext}^2+\frac{1}{2}\left[\eta_0^2+N^2\left(\psi_0^2+\beta_0^2+\upsilon_0^2+\upsilon_2^2\right)+\upsilon_M^2+\upsilon_{M2}^2\right]\right]$
$I_{\omega_f\pm\omega_m}$	$I_0\eta_0\left(N\upsilon_0+\upsilon_M\right)\begin{bmatrix}\mp\cos\left((\omega_f\pm\omega_m)t+(\phi_f\pm\phi_s)\right)\\ \mp\frac{1}{2}N\beta_0\cos\left((\omega_f\pm\omega_m)t+(\phi_f\mp\phi_s)\right)\end{bmatrix}$
$I_{\omega_f\pm2\omega_m}$	$I_0\eta_0\begin{bmatrix}\mp N\beta_0\sqrt{1+4\alpha^2}\cos\left((\omega_f\pm2\omega_m)t+(\phi_f\pm\tan^{-1}2\alpha)\right)\\ \mp\left(N\upsilon_2+\upsilon_{M2}\right)\cos\left((\omega_f\pm2\omega_m)t+(\phi_f\pm2\phi_s)\right)\end{bmatrix}$
I_{ω_f}	~~$2I_0\eta_0\alpha\sin\left(\omega_f t+\phi_f\right)$~~ $\rightarrow$ 0
$I_{2\omega_f}$	$-\frac{1}{2}I_0\eta_0^2\left[\cos(2\omega_f t+2\phi_f)\right]$



Lock-in CME measurement



Lock-in detection

Source	Channel	Birefringence detection lock-in amplified signal
LA_1	X_1	$\kappa_{LA}\cdot I_0\eta_0\left[N\psi_0\sin 2\omega_m t - N\zeta_0\left[\begin{array}{l} N\beta_0\sin(2\omega_m t+2\xi)+(N\upsilon_2+\upsilon_{M2})\cos 2\xi\sin(2\omega_m t+2\phi_s) \\ +(N\upsilon_0+\upsilon_M)\cos 2\xi\left[\cos(\omega_m t+\phi_s)-\frac{1}{2}N\psi_0\cos(\omega_m t-\phi_s)\right]\end{array}\right]\right]$
LA_1	Y_1	0
LA_2	X_2	0
LA_2	Y_2	$\kappa_{LA}\cdot\frac{1}{4}I_0\eta_0^2$

Source	Channel	Dichroism detection lock-in amplified signal
LA_1	X_1	$\kappa_{LA}\cdot I_0\eta_0\left[\begin{array}{l} N\beta_0\sqrt{1-4\alpha^2}\sin(2\omega_m t+\tan^{-1}2\alpha)+(N\upsilon_2+\upsilon_{M2})\sin(2\omega_m t+2\phi_s) \\ +(N\upsilon_0+\upsilon_M)\left[\sin(\omega_m t+\phi_s)-\frac{1}{2}N\beta_0\sin(\omega_m t-\phi_s)\right]\end{array}\right]$
LA_1	Y_1	0
LA_2	X_2	0
LA_2	Y_2	$\kappa_{LA}\cdot\frac{1}{4}I_0\eta_0^2$

$$\psi(t)\equiv\frac{\eta_0}{4}\cdot\frac{X_1(t)}{Y_2(t)}$$

$$\Psi(\omega)\equiv\mathcal{F}(\psi(t))$$

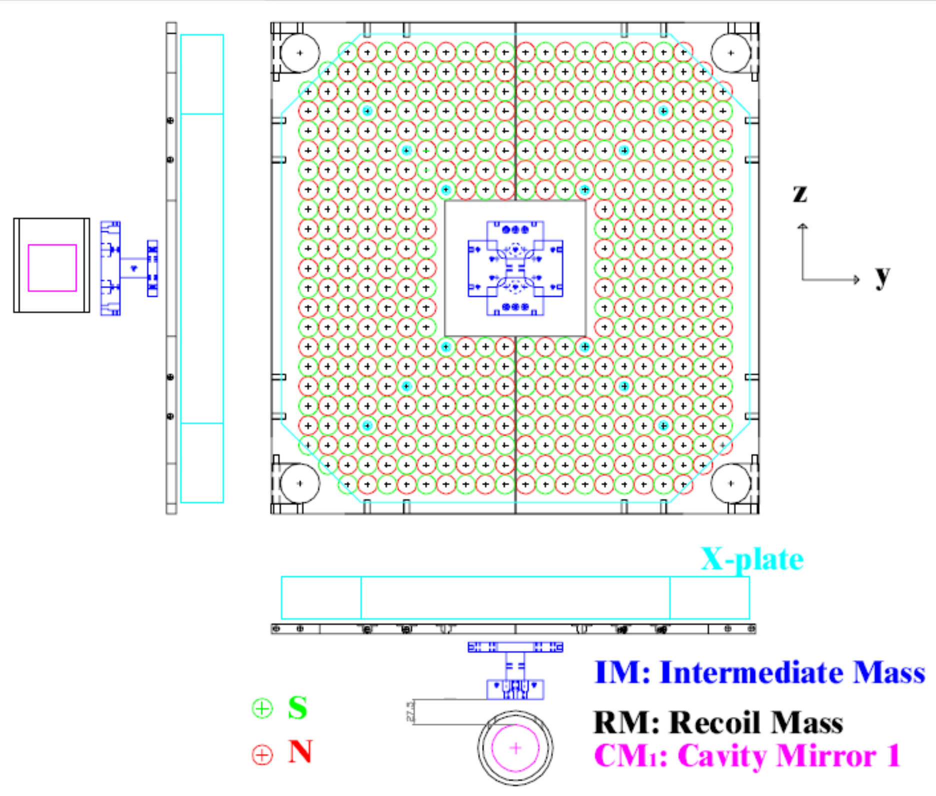
$$\Psi_0\equiv\Psi(2\omega_m)=N\psi_0(\text{or } N\beta_0 \text{ for dichroism detection})$$

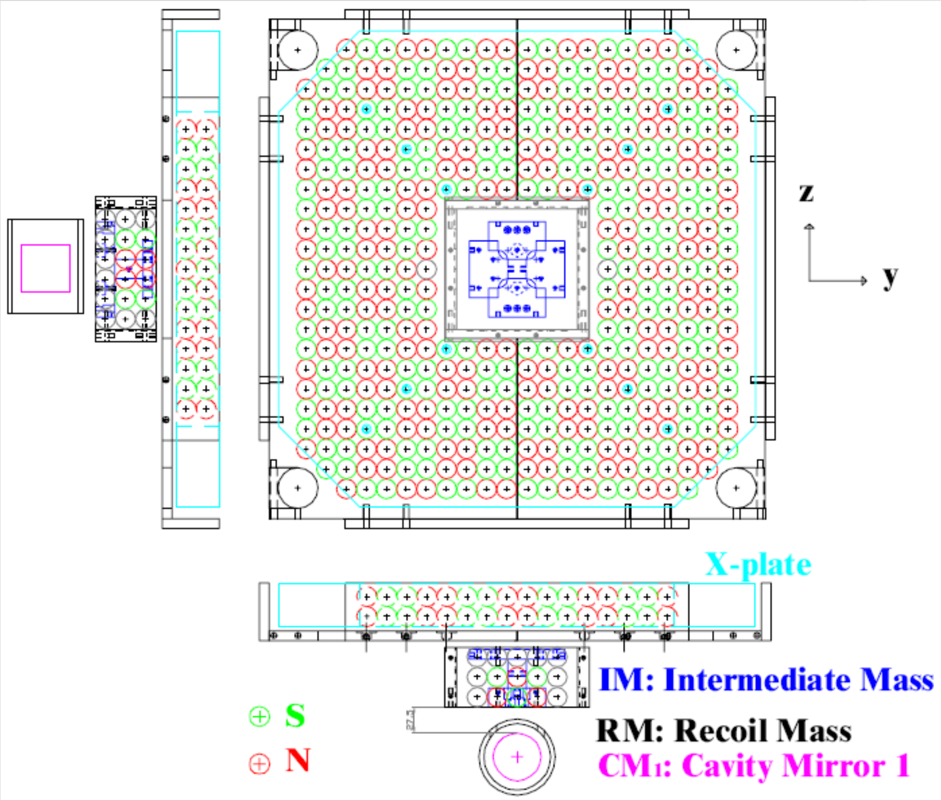
Gas	$C_{CM}=\frac{P_{atm}}{\pi\int_L B^2dz}\cdot\frac{\Psi_{0,CME}(P)}{NP}$ $(T^{-2}m^{-1})$ for $\lambda=1064$nm
N_2	$(-1.90\pm0.15^{\S}\pm0.08c^{\P})\times10^{-7}$
O_2	$(-1.68\pm0.32^{\S}\pm0.08^{\P})\times10^{-6}$
CO_2	$(-3.97\pm0.25^{\S}\pm0.15^{\P})\times10^{-7}$
Ar	$(4.05\pm0.32^{\S}\pm0.16^{\P})\times10^{-9}$
Kr	$(7.78\pm1.18^{\S}\pm0.30^{\P})\times10^{-9}$

§: Statistical uncertainty from χ^2-fitting of the slope $\Psi_{0,CME}(P)/P$.
¶: Systematic uncertainty (N: 5.6%, B^2: 2.2%, P: 2.5%, η_0: 1.6%).

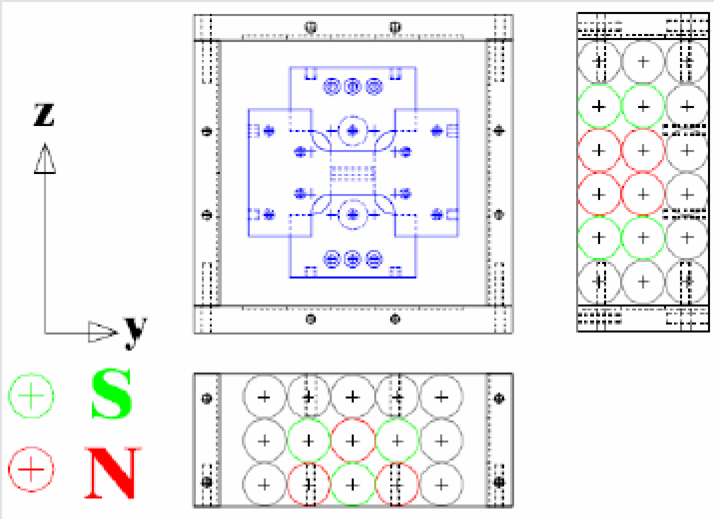
Current Status & Challenge

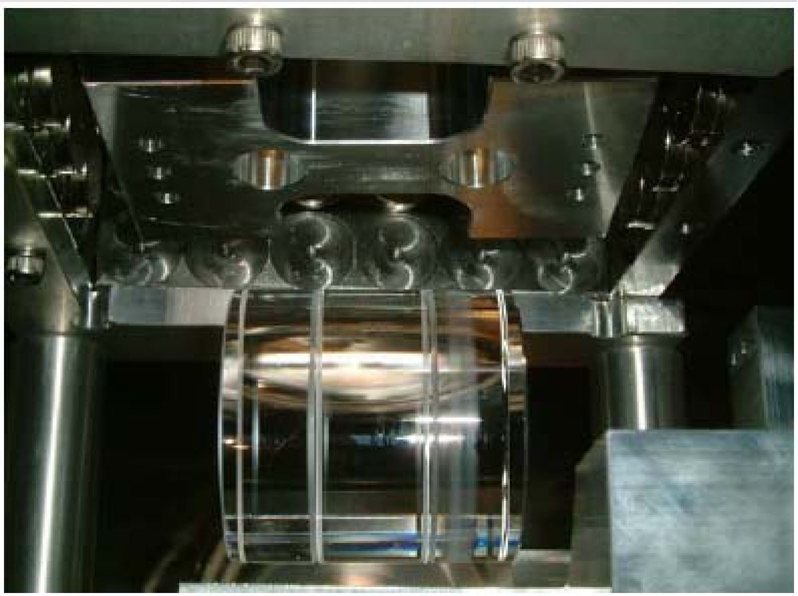
X-plate Damper: Re-arranged

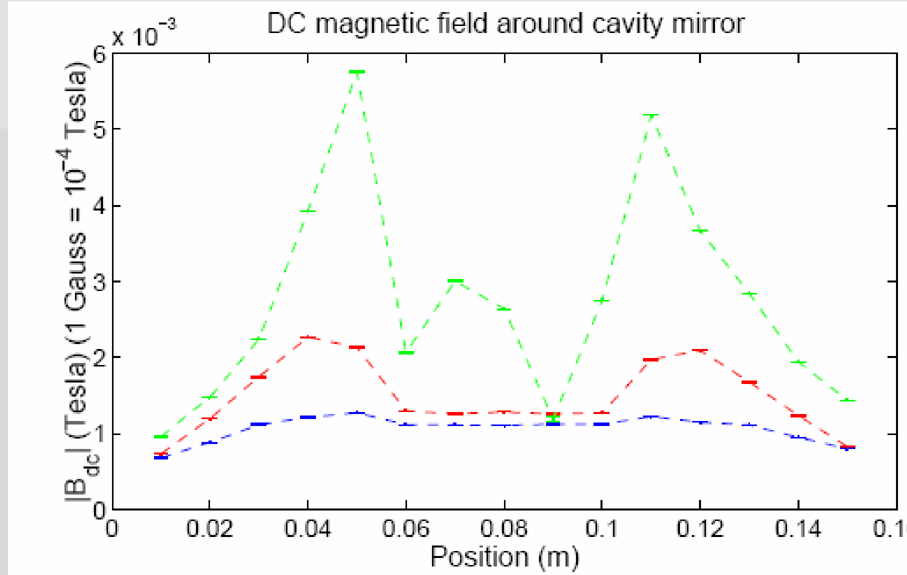


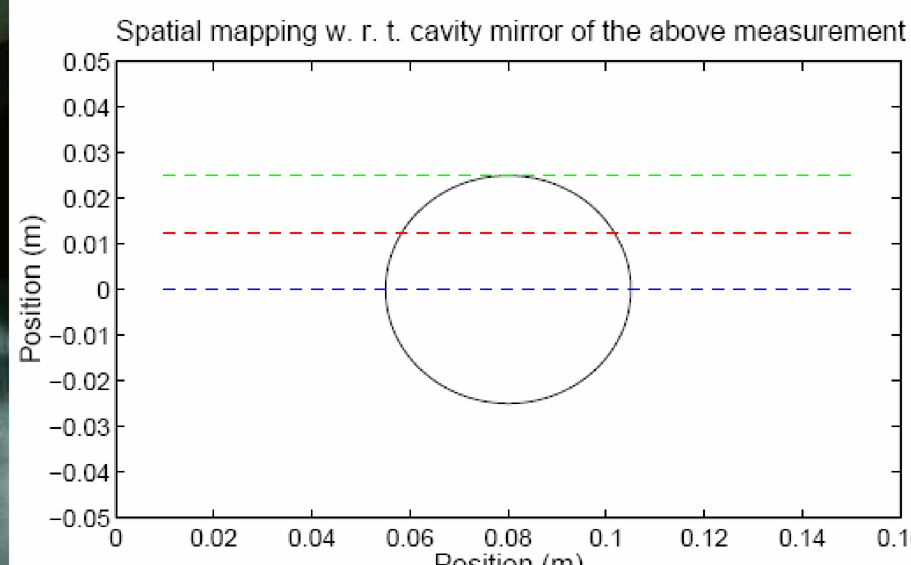


Damper

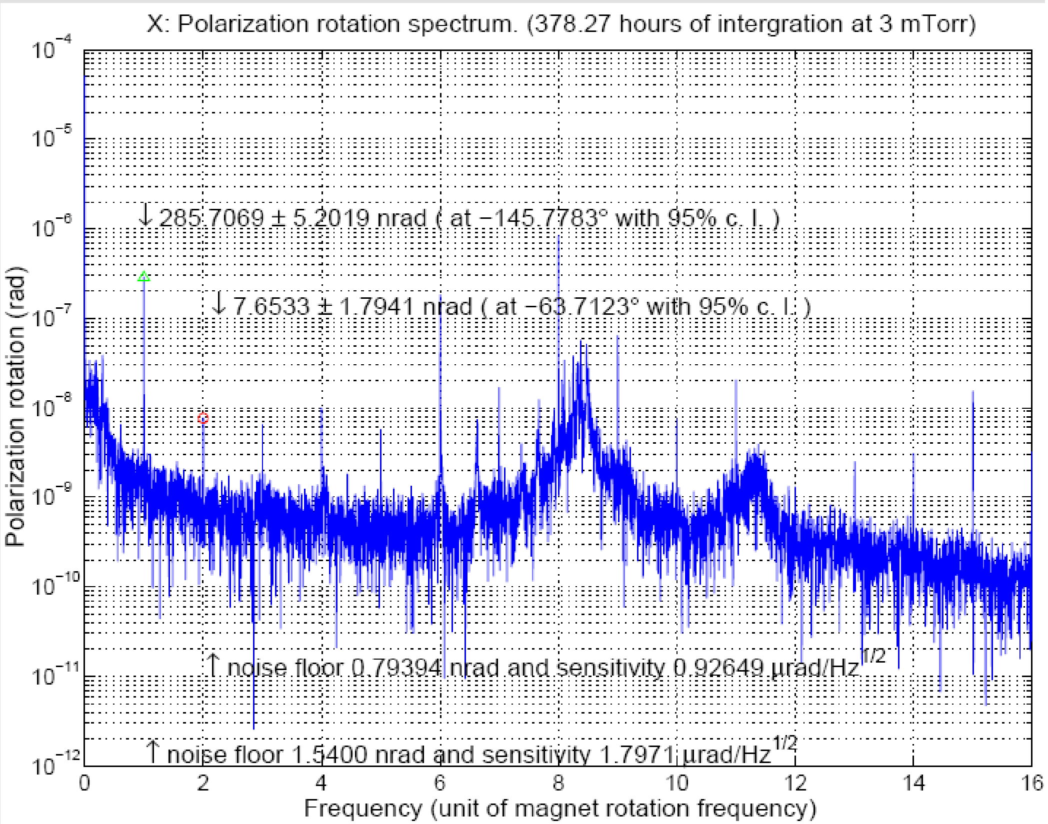

z
y
S
N

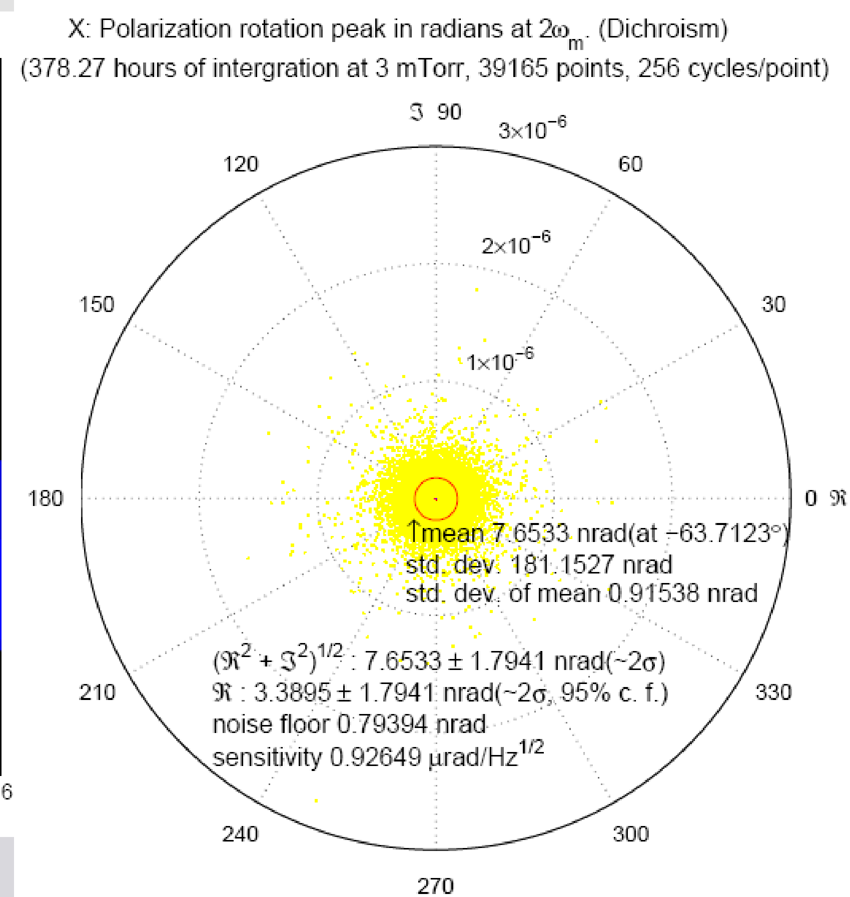



DC magnetic field around cavity mirror
x 10^-3
|B_dc| (Tesla) (1 Gauss = 10^-4 Tesla)
0
1
2
3
4
5
6
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Position (m)


Spatial mapping w. r. t. cavity mirror of the above measurement
Position (m)
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Position (m)

387.27 hr Polarization Rotation





$$\varepsilon = \left(\frac{B_{ext}^2 \omega^2}{M^2 m_a^4}\right) \sin^2\left(\frac{m_a^2 l}{4\omega}\right) \approx \frac{B_{ext}^2 l^2}{16 M^2}$$

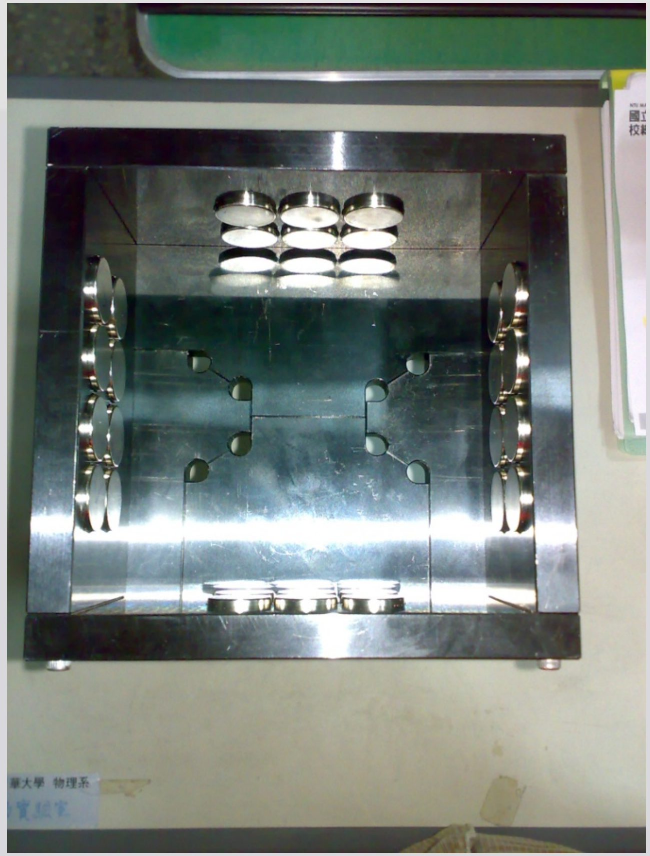
$$m_a^2 < 2\pi\omega / l$$

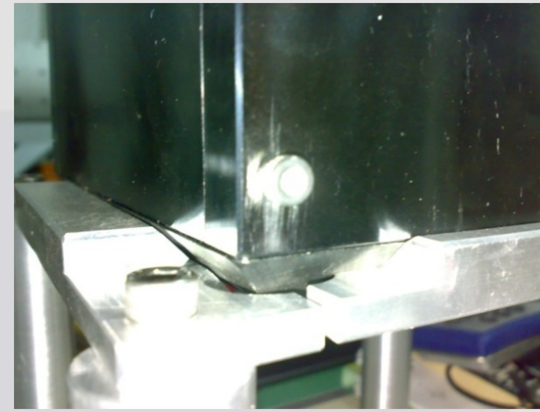
Hold on!

Stray field contamination at cavity mirrors

Enhanced by dc leakage of IM damper field

design



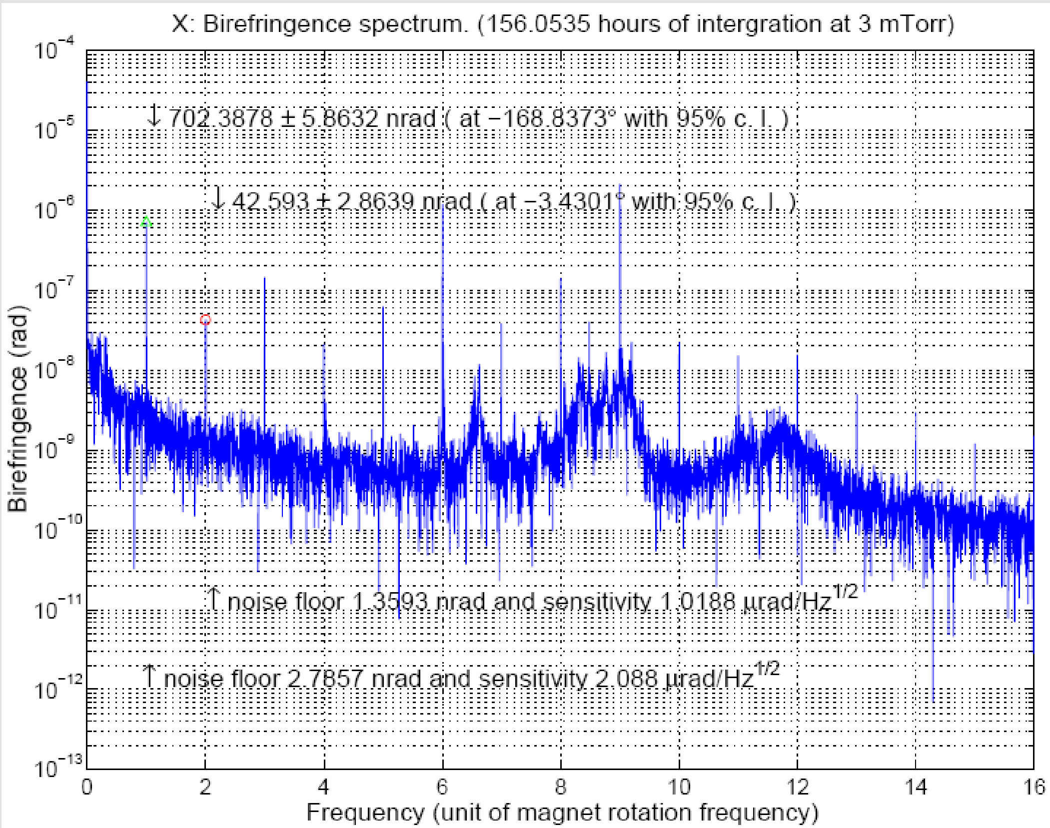


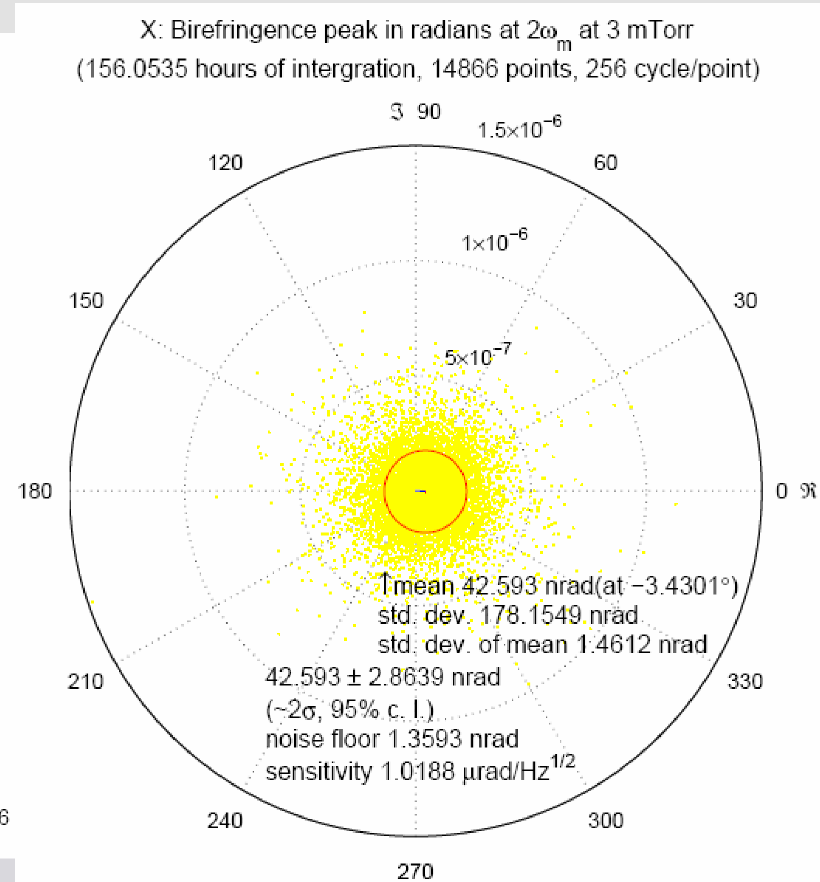
DC magnetic field measured at cavity mirror position:

B_{CM} = 41.71 μT → **100 times smaller** than 5 mT leakage →

B_{EARTH} = 31.63 μT as a comparison using the same probe

156.05 hr Ellipticity





$$\psi = \frac{1}{2}\left[\frac{B_{ext}^2\omega^2}{M^2 m_a^4}\right]\left[\frac{m_a^2 l}{2\omega} - \sin\left[\frac{m_a^2 l}{2\omega}\right]\right]$$

$$Q = \frac{d(PV)}{dt} \qquad C = \frac{Q}{P_1 - P_2} \qquad V\frac{dP}{dt} = Q - SP$$

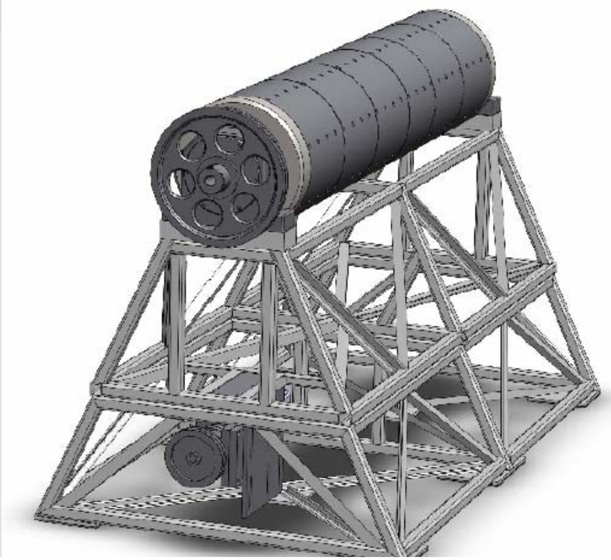
$V\frac{dP}{dt}$ → 0; SP → Pumping (= Degasing)

$$C_{Q\&A,exp} = 1.087 \text{ Lit/s}$$

Not yet! CME: $\Delta n_u = (7.35 \pm 0.23) \times 10^{-14}$

$\Delta n_u(H_2O)_{theoretical} = 7.5 \times 10^{-15}$

1.8 m new magnet ready for shipping:



Main specs for design:

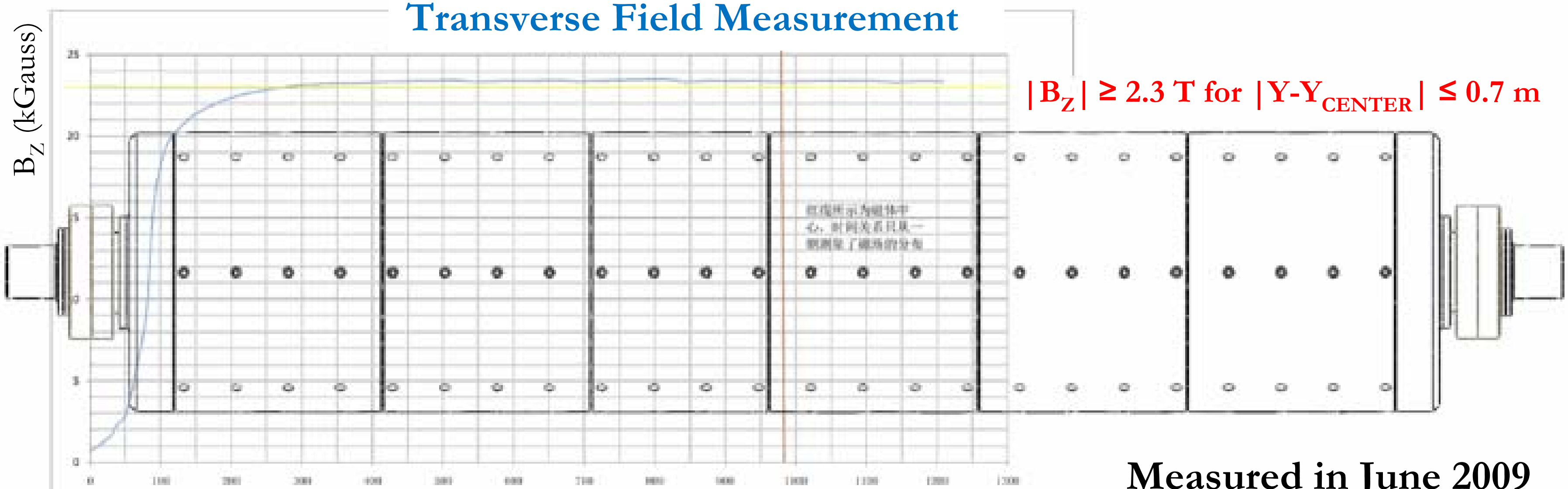
$B = 2.3$ T

$L = 1.8$ m

$\omega_m/2\pi = 600$ rpm

Main body lies on its supporting structure.

Transverse Field Measurement



Measured in June 2009

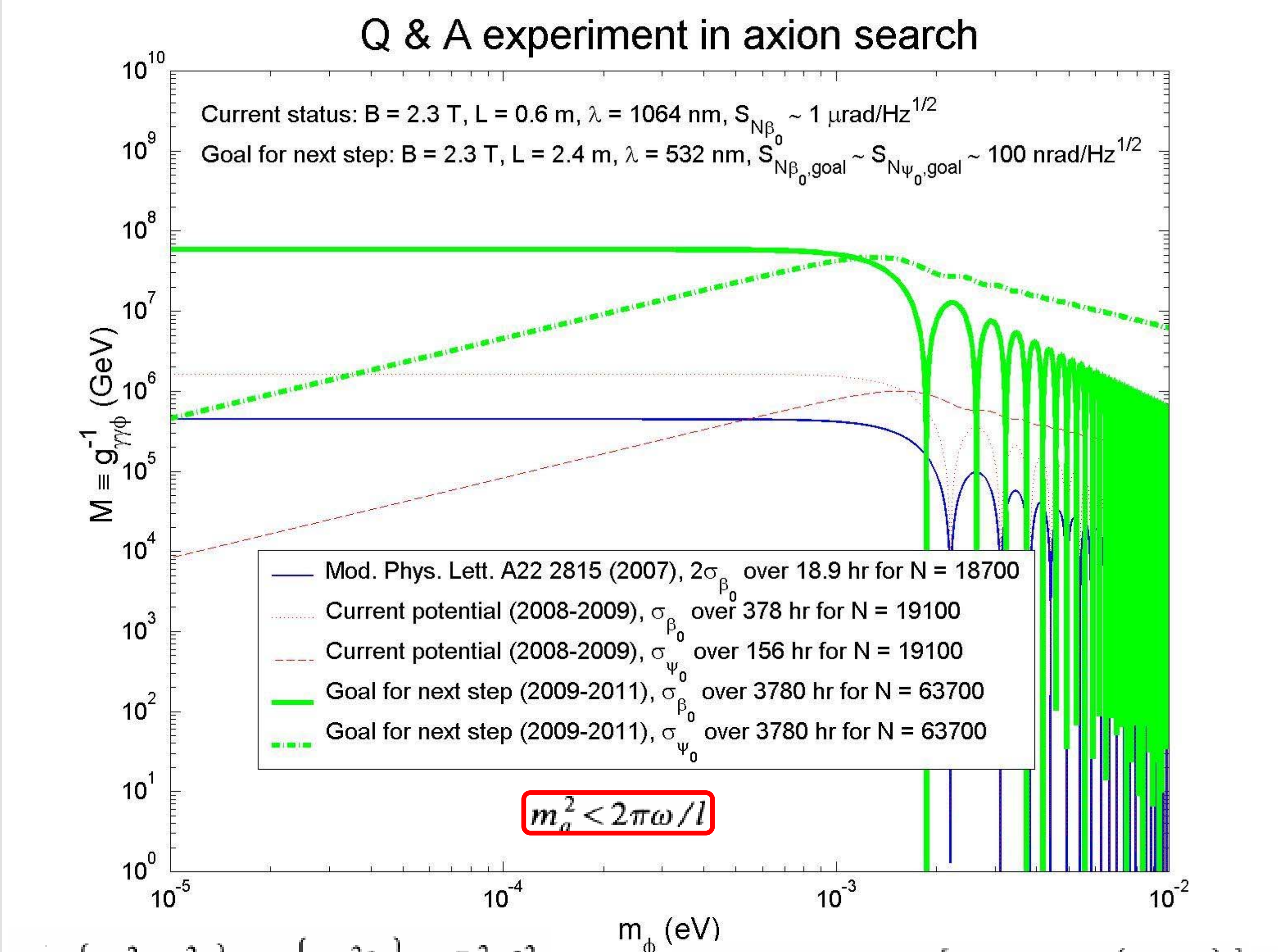
Operation test for 600 rpm (film)

Prospects

Q & A experiment from now on:

	achieved	implementing	next stage
Length of cavity (**L_{FP}**)	3.5 m	**7 m**	7 m
Length of magnetic active zone (**L**)	0.6 m	**2.4 m**	**4.2 m**
Laser wavelength (λ; together with optics)	1064 nm	**532 nm**	532 nm
Finesse of cavity mirrors (***F***)	30000	**10^5**	10^5
Number of passage (**N** = 2***F***/π)	19100	**63700**	63700
Magnet's rotational modulation (**f_m** = $\omega_m/2\pi$)	7 rps	**10 rps**	**20 rps**
Sensitivity (**$S_{N\psi_0}$** or **$S_{N\beta_0}$**)	~ 1 μrad/$Hz^{1/2}$ from the 378 hr integration	**10 nrad/$Hz^{1/2}$ ↓ Mirrors' birefringence**	**2 nrad/$Hz^{1/2}$ shot noise limit @ 0.1 W**
Integration time (**T_{tin}**)	387 hr (~ 16 d)	**1000 hr (~42 d)**	1000 hr (~ 42 d)
Noise floor after T_{int} (**$N\sigma_{\psi_0}$** or **$N\sigma_{\beta_0}$**)	~ 0.8 nrad (~10^3×$N\psi_{0,QED}$)	**5.3 prad (28%×$N\psi_{0,QE}$)**	**1.1 prad (3.3%×$N\psi_{0,QE}$)**
QED effect in ellipticity (**$N\psi_{0,QED}$** ∝ **NB^2L/λ**)	0.72 prad	**19.1 prad**	33.4 prad
ALPs coupling scale (**M** = **$g_{\phi\gamma\gamma}^{-1}$** ~ **BL**/4√$\sigma_{\beta_0}$)	1.6×10^6 GeV	**1.5×10^8 GeV**	2.6×10^8 GeV

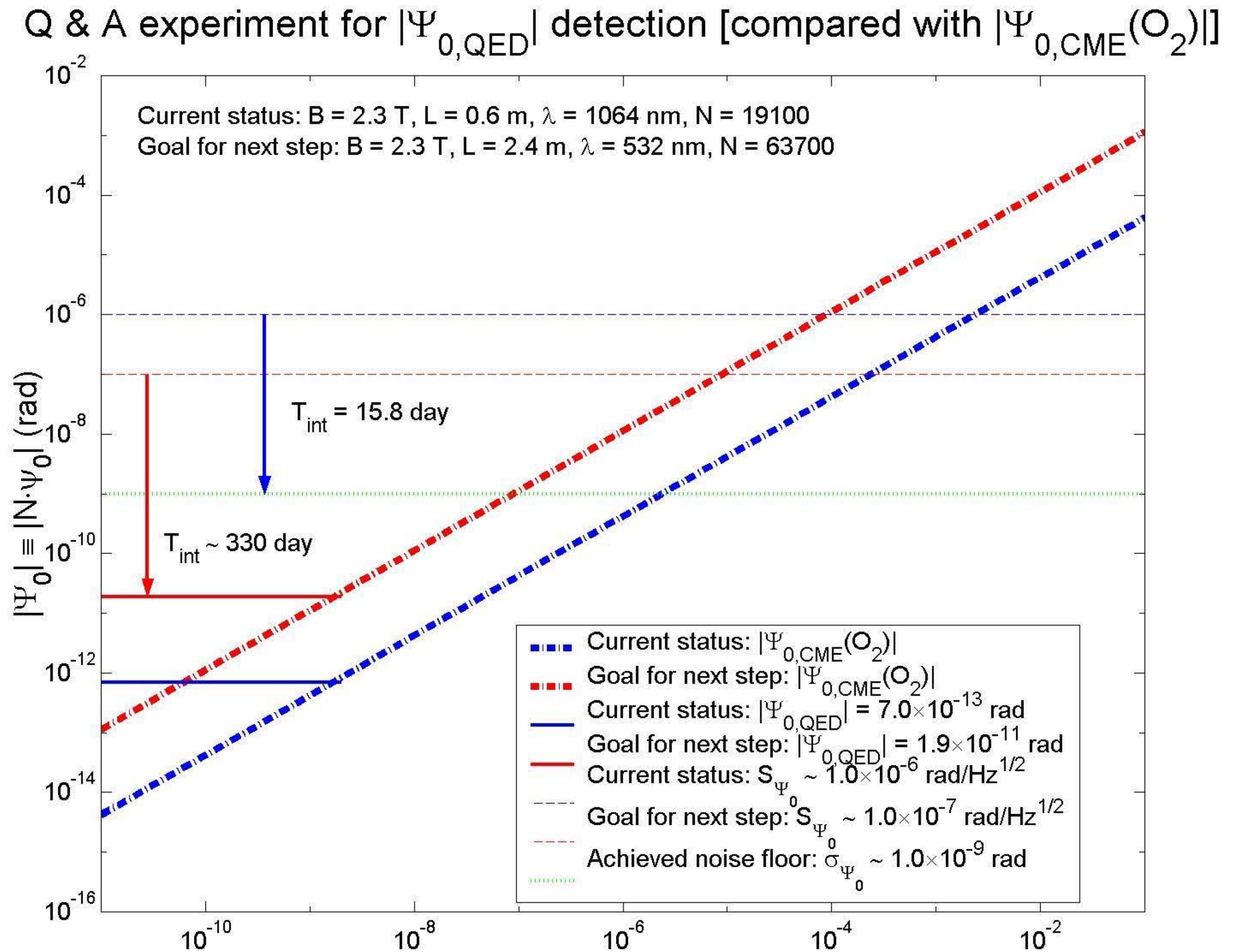
Q & A experiment in ALPs search



$$\varepsilon = \left[\frac{B_{ext}^2\omega^2}{M^2 m_a^4}\right]\sin^2\left[\frac{m_a^2 l}{4\omega}\right] \approx \frac{B_{ext}^2 l^2}{16M^2}$$

$$\psi = \frac{1}{2}\left[\frac{B_{ext}^2\omega^2}{M^2 m_a^4}\right]\left[\frac{m_a^2 l}{2\omega} - \sin\left[\frac{m_a^2 l}{2\omega}\right]\right] \approx \frac{(B_{ext} m_a)^2 l^3}{96\omega M^2}$$

Q & A experiment in QED detection

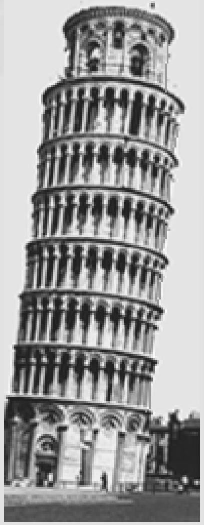


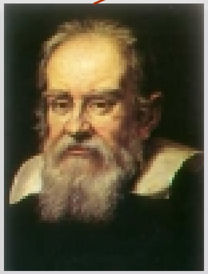
$\Delta n_{QED}\,|_{B=1\,\mathrm{T}} \simeq 4 \times 10^{-24}$ $\delta = 2\pi \frac{L}{\lambda} \Delta n$ $\frac{\delta}{2} \sin 2\theta = \psi_0 \sin 2\theta$

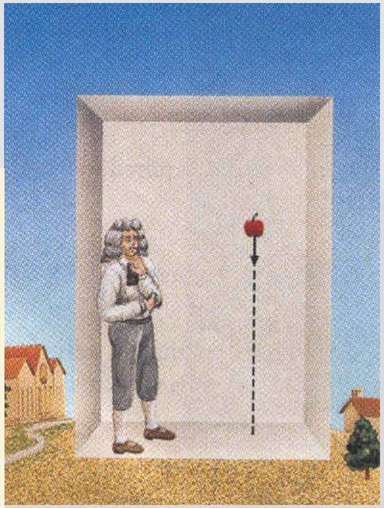
Summary & Outlook

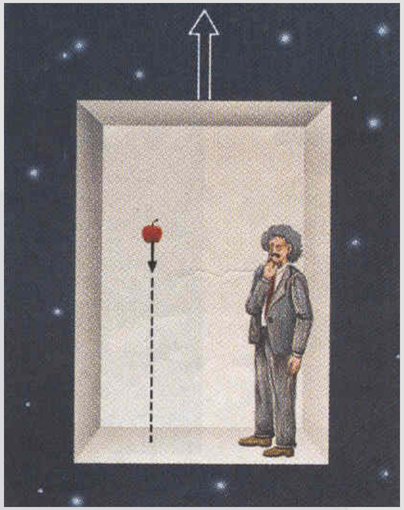
- Q & A experiment searches for QED or (pseudo)scalar predictions through ellipsometer-measured birefringence and dichroism.
- Cavity mirrors are suspended for seismic noise isolation.
- Magnetic field shielding around cavity mirrors is improved.
- Sensitivity in polarization rotation and in ellipticity detection are both around 1 μrad/Hz$^{1/2}$ with a 78% duty cycle within 48 days.
- A new magnet with B = 2.3 T and L = 1.8 m is already made for enhancing the physical effects. A copy will be added in the next stage.
- A 7 m FPI with *F* ~ 10^5 cavity using 532 nm mirrors is under construction.
- We are currently aiming at 10 nrad/Hz$^{1/2}$ sensitivity.
- With these improvement and upgrading of vacuum, **QED** birefringence would be **measured to 28 % in about 50 days**.

$$L_I = -(1/16\pi)\phi F_{ij} F_{kl} e^{ijkl}$$









- Thank you very