Atomic, Molecular and Optical Physics Seminar

Fall Semester 2009

Birefringence and Dichroism — From Gas-phase to Vacuum

國立清華大學
National Tsing Hua University

Hsien-Hao Mei
梅 賢 豪

Nov 24 2009 14:00 @ Rm 620, Phys Bldg

Q & A

- **Who**
- **Why**
- **What**
- **How**
- **When**

Q & A Collaboration

- Center for Gravitation and Cosmology:
  - Wei-Tou Ni (Dept. of Phys, National Tsing Hua Univ.)
  - Hsien-Hao Mei (Dept. of Physics, National Tsing Hua Univ.)
- Coordinate with:
  - Sheau-shi Pan (Center for Measurement Standards, ITRI)
  - Sheng-Jui Chen (Center for Measurement Standards, ITRI)
- Former member:
  - Jeah-Sheng Wu (Innolux Display Corp→Chimei Innolux Corp)
- Location:
  - Rm 005 & Rm 006, Dept. of Physics, NTHU, Hsinchu, Taiwan
- Contact:
  - Tel: +886-5715131(ext. 33211) / Fax: +886-5723052
  - E-mail: mei@phys.nthu.edu.tw / wtni@phys.nthu.edu.tw

Q & A

- **Who**
  - **Q & A Collaboration**
- **Why**
- **What**
- **How**
- **When**

Motivation: Q(ED) & A(xion) experiment

(i) QED

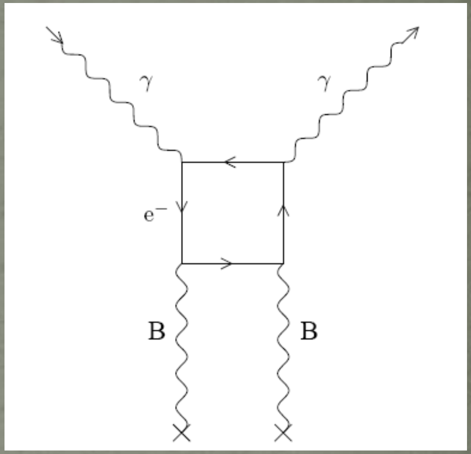
(ii) (Pseudo)scalar-Photon Interaction

- Bottom Up Approach:

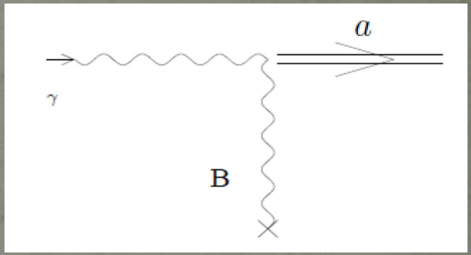
CP violation {
Pecci & Quinn: *PRL* **38** 1440 (1977)
Weinberg: *PRL* **40** 233 (1978)
Wilczek: *PRL* **40** 279 (1978)

invisible {
Kim: *PRL* **43** 103 (1979)
Dine *et al.*: *PL*B **104** 1999 (1981)
Shifman *el al.*: *NP*B **166** 493 (1980)

- Top Down Approach:
  String
- **Phenomenological Study Approach**
  From analysis of Equivalence Principles (1973-1977)



Delbruck scattering



Primakoff effect

(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

VOLUME 38 | 14 FEBRUARY 1977 | NUMBER 7

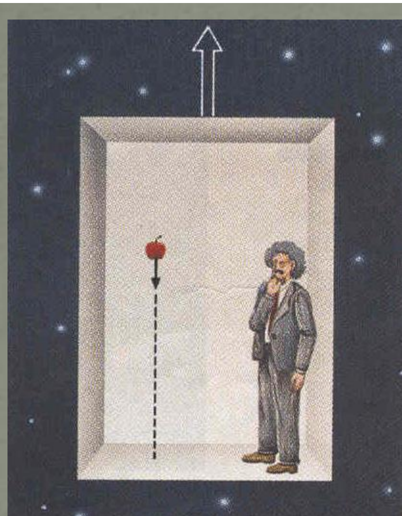
Equivalence Principles and Electromagnetism*

Wei-Tou Ni

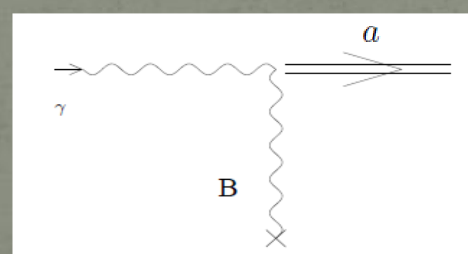
Department of Physics, Montana State University, Bozeman, Montana 59715, and Department of Physics, National Tsing Hua University, Hsinchu, Taiwan, Republic of China†

(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



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

$$F \equiv A_{j,i} - A_{i,j}$$

$$e^{0123} = 1$$

Modified Maxwell Equations → Polarization Rotation in EM Propagation

Constraints from CMB polarization observation → **Ni: *Chin Phys Lett* 22 33 (2005)**

Q & A

- **Who**
  - **Q & A Collaboration**
- **Why**
  - **QED & Axion/(Pseudo-)scalar Field from WEP/EEP**
- **What**
- **How**
- **When**

Axion / Axion-Like-Particles (ALPs)

pseudo-scalar $\phi^{(-)}$

$$\mathcal{L}_{\text{int}}^{(-)} = -\frac{1}{4} g\phi^{(-)} F_{\mu\nu}\tilde{F}^{\mu\nu} = g\phi^{(-)}(\vec{E}\cdot\vec{B})$$

$\vec{E}_\gamma \cdot \vec{B} \neq 0$

scalar $\phi^{(+)}$

$$\mathcal{L}_{\text{int}}^{(+)} = -\frac{1}{4} g\phi^{(+)} F_{\mu\nu}F^{\mu\nu} = \frac{1}{2} g\phi^{(+)}(\vec{E}^2 - \vec{B}^2)$$

$\vec{B}_\gamma \cdot \vec{B} \neq 0$

$$L = \frac{1}{M}(\mathbf{E}\cdot\mathbf{B}_{\text{ext}})a$$

$$L = \frac{1}{2M_s}(\mathrm{E}^2 - \mathrm{B}^2)\phi_s$$

⇩

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu a\partial^\mu a - m_a^2 a^2) + \frac{1}{4M}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

$$F_{\mu\nu} = F_{\mu\nu}^{\text{ext}} + \partial_\mu A_\nu - \partial_\nu A_\mu$$

⇩

$$(\Box + m_a^2)a - \frac{1}{M}\dot{\mathbf{A}}\cdot\mathbf{B}_{\text{ext}} = 0\ ,$$

$$\Box\mathbf{A} + \frac{1}{M}\dot{a}\mathbf{B}_{\text{ext}} = 0\ ,$$

$\nabla\cdot\mathbf{A} = 0$ $A^0 = 0$ transverse

$$\begin{bmatrix} \omega^2+\partial_z^2 & 0 & 0 \\ 0 & \omega^2+\partial_z^2 & -iB_{\text{ext}}\omega/M \\ 0 & +iB_{\text{ext}}\omega/M & \omega^2+\partial_z^2-m^2 \end{bmatrix} \begin{bmatrix} A_o \\ A_p \\ a \end{bmatrix} = 0$$

⇩

Dichroism

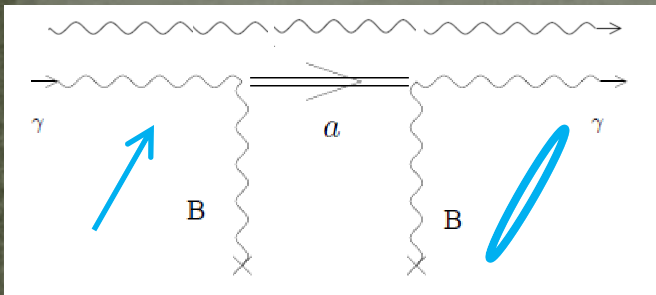
$$\varepsilon = \left(\frac{B_{\text{ext}}^2\omega^2}{M^2 m_a^4}\right)\sin^2\left(\frac{m_a^2 l}{4\omega}\right) \approx \frac{B_{\text{ext}}^2 l^2}{16M^2}$$

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

Birefringence

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

ALPs: Birefringence vs Dichroism



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

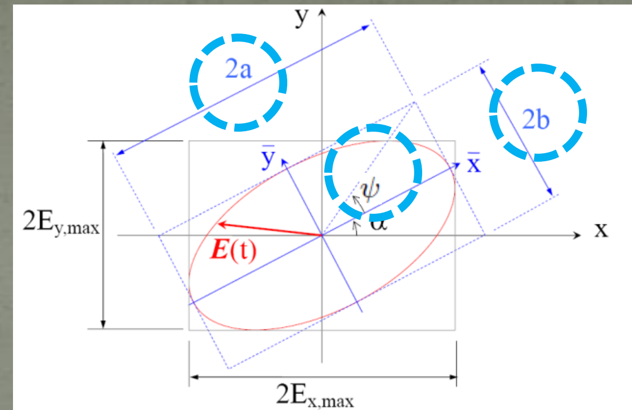
Birefringence

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

Phase retardation

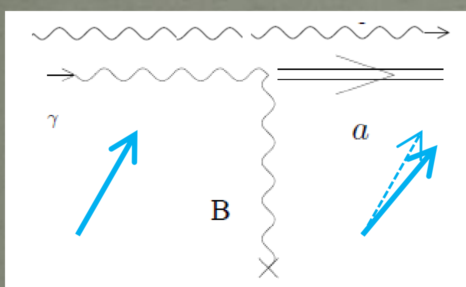
$\frac{\delta}{2} \sin 2\theta = \psi_0 \sin 2\theta$

Ellipticity $\psi = b/a$

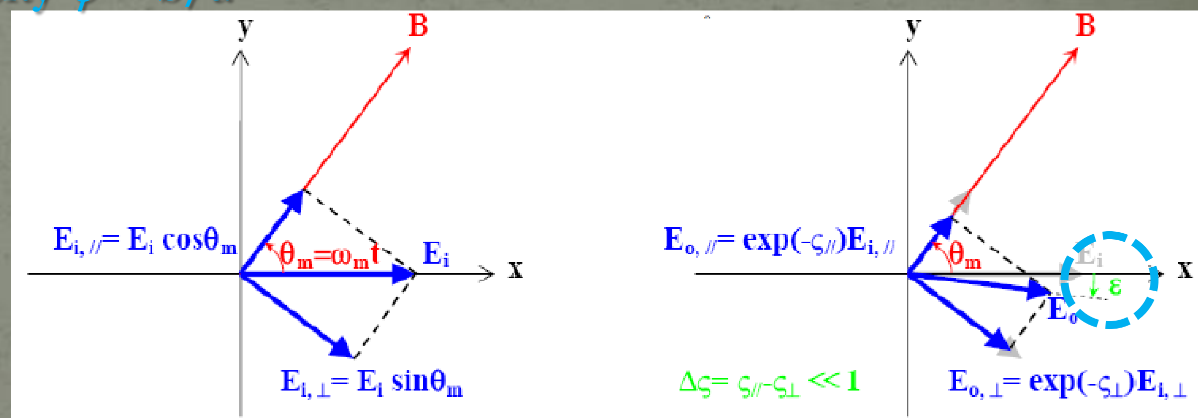


Constraining
m_a: mass of a/ϕ
M ($=g_{a\gamma\gamma}^{-1}$): coupling scale

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



Dichroism



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

Polarization Rotation ε

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

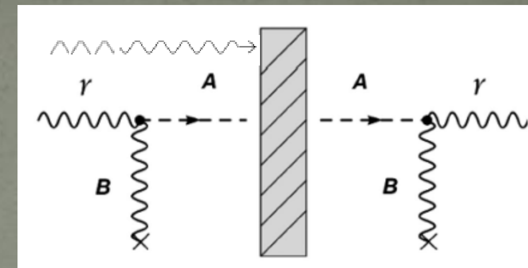
$m_a^2 < 2\pi\omega/l$

2007 ALPs & MCPs results from dichroism

T_{int} = 18.9 hr

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

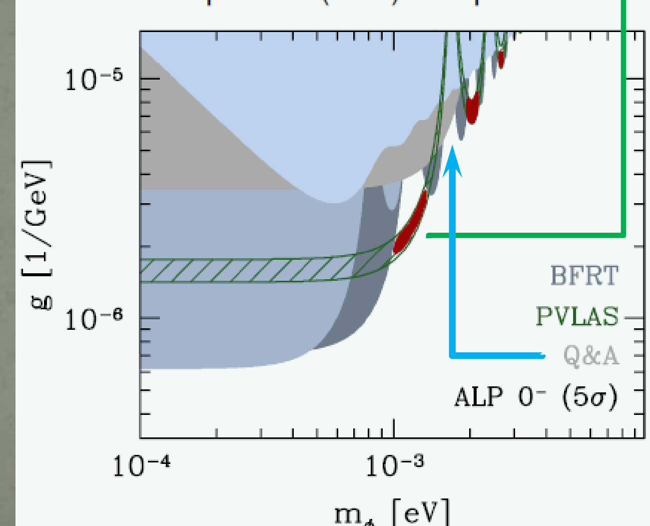
MCP search comp. in 2007 Experiment	BFRT (λ: 514 nm)	PVLAS (λ: 1,064 nm)	Q & A (λ: 1,064 nm)
Magnetic field B (T)	2.63–3.87	5	2.3
Magnetic region length L (m)	8.8	1	0.6
Effective number N of reflections	254	44,000	18,700
Effective $NB^{2/3}L$ $(\omega/\omega_0)^{-1/3}$ ($T^{2/3}m$)	2,650	123,500	18,600
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: Light Shining through a Wall

PVLAS excluded their earlier result in 2008:
6.5 ± 10 (2σ) @ 2.3 T
9.1 ± 12 (2σ) @ 5 T   Phys. Rev. **D77** 032006 (2008)

Axion-like particle (ALP) interpretation:



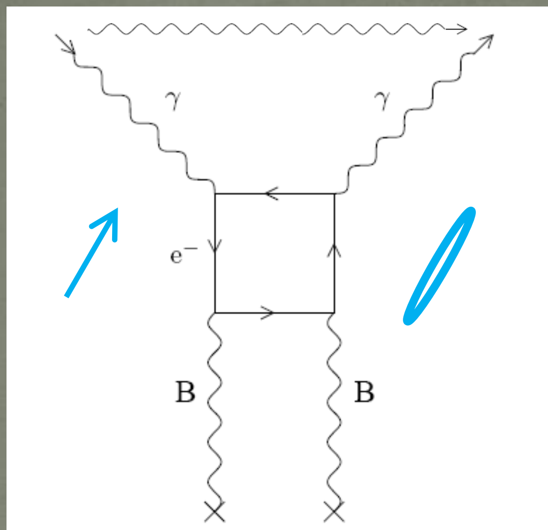
Mod. Phys. Lett. A 22 2815 (2007)

Laser experiments: History & Presence

Experiment	Reference	$\Delta\theta$	ψ	LSW
ALPS (DESY/D) "**A**xion-**L**ike **P**article **S**earch"	arXiv:0905.4159	✘	✘	✔
BFRT (**B**NL-**F**ermilab-**R**ochester-**T**rieste)	Phys.Rev.**D47**(1993)	✔	✔	✔
⇨ **BMV** (LULI/F) "**B**iréfringence **M**agnétique du **V**ide"	Phys.Rev.Lett.**99** (2007) Phys.Rev.D**78** (2009)	✘	✘	✔
GammeV (Fermilab/USA) "**Gamm**a to **meV** particle search"	Phys.Rev.Lett.**100** (2008) Phys.Rev.Lett.**102** (2009)	✘	✘	✔
LIPSS (Jefferson Lab/USA) "**LI**ght **P**seudoscalar or **S**calar particle **S**earch"	Phys.Rev.Lett.**101** (2008) arXiv:0810.4189	✘	✘	✔
OSQAR (CERN/CH) "**O**ptical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration"	Phys.Rev.D**78** (2008)	✘	✘	✔
⇨ **PVLAS** (INFN/I) "**P**olarizzazione del **V**uoto con **LAS**er"	Phys.Rev.Lett.**96** (2006) Erratum-ibid.**99** (2007) Phys.Rev.D**77** (2008)	✔	✔	(✔)
⇨ **Q&A** (Hsinchu/Taiwan) "**Q**ED & **A**xion"	Mod.Phys.**A22** (2007)	✔	✘	✘

Probing QED effect

QED vs Gaseous CME (Cotton-Mouton Effect)



Euler & Heisenberg (1936):

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

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

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

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

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

11

$$\Delta n_u = -2.66 \times 10^{-13}$$

Normalized CME birefringence of N_2 (under 1 atm & 1 T)

Cotton & Mouton (1905); Buckingham & Pople (1967):

$$U(\tau, E, B) = U_0 - \mu_p^e E_p - \frac{1}{2}\alpha_{pq}E_pE_q - \frac{1}{2}\chi_{pq}B_pB_q - \frac{1}{2}\xi_{pq,r}E_pB_qB_r - \frac{1}{4}\eta_{pq,rs}E_pE_qB_rB_s + O[(E,B)^3]$$

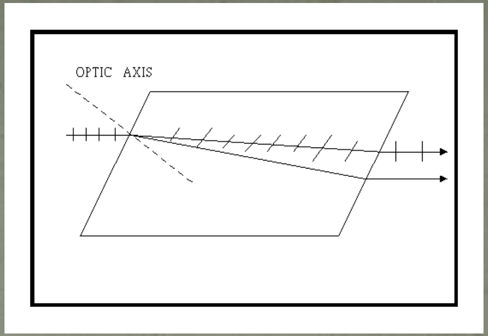
$$\frac{\partial^2 U}{\partial E^2} \Rightarrow n^2 \approx \varepsilon = 1 + 4\pi\frac{N_A}{(4\pi\varepsilon_0)V_m}\left(\alpha_{pi} + \frac{1}{2}\eta_{pq,rs}B_rB_s + \cdots\right)$$

$$\Delta n = \frac{\pi B^2 P}{4\pi\varepsilon_0}\left(\frac{\Delta\eta}{kT} + \frac{2}{15(kT)^2}\Delta\alpha\Delta\chi\right)$$

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

***P* ~ 10^{-9} torr**

Historical Review of CME



- A. Cotton & H. Mouton: first discover/separate this effect from axial Faraday rotation in 1905.
  - **Faraday**: B//k, linear (∝BL); **CME**: B⊥k, nonlinear ($\propto B^2L$).
- Analogy: **Kerr** birefringence under transverse E ($\propto E^2L$).
- Voigt: treated as interactions between electrons & **B** in 1908.
- Born: Introduced the magnetic hyper-polarizability or 2nd order susceptibility to explain the source of CME in 1933.
- Buckingham & Pople: developed the fundamental model for CME in 1956, and systematically and quantitatively measured CME over 40 gases in 1967.
- C. Rizzo, A. Rizzo, D. M. Bishop: Reviewed and Summarized all theoretical models with measurements before 1997.

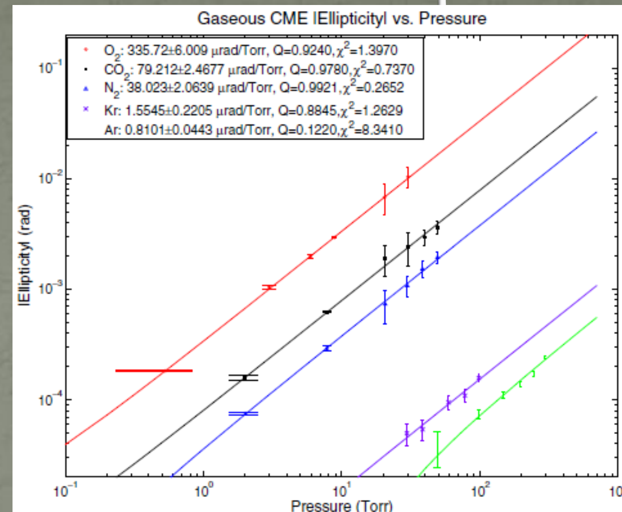
2009 CME measurement at 1064 nm

Gas	Normalized Cotton-Mouton birefringence Δn_u at P = 1 atm and B = 1 T
N_2	$(-\,2.02 \pm 0.16^{\S} \pm 0.08^{\P}) \times 10^{-13}$
O_2	$(\,-1.79 \pm 0.34^{\S} \pm 0.08^{\P}) \times 10^{-12}$
CO_2	$(-\,4.22 \pm 0.27^{\S} \pm 0.16^{\P}) \times 10^{-13}$
Ar	$(4.31 \pm 0.34^{\S} \pm 0.17^{\P}) \times 10^{-15}$
Kr	$(8.28 \pm 1.26^{\S} \pm 0.32^{\P}) \times 10^{-15}$

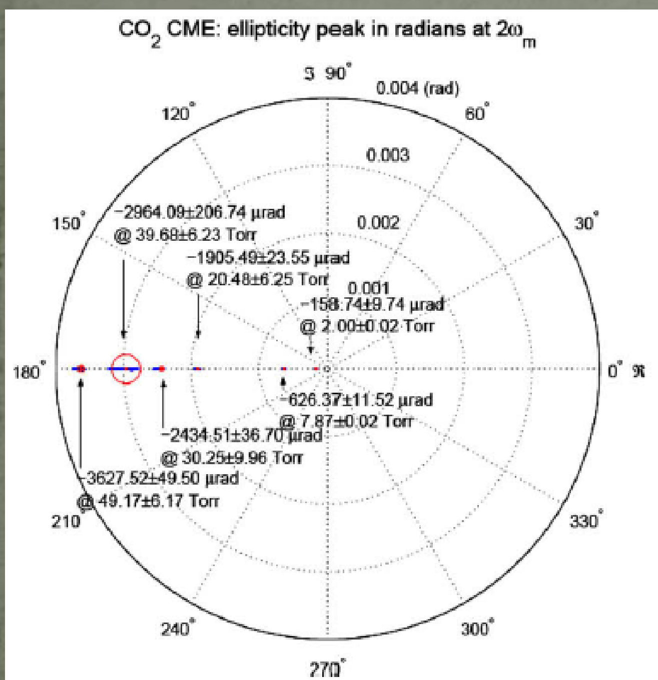
§: Statistical uncertainty
¶: Systematic uncertainty

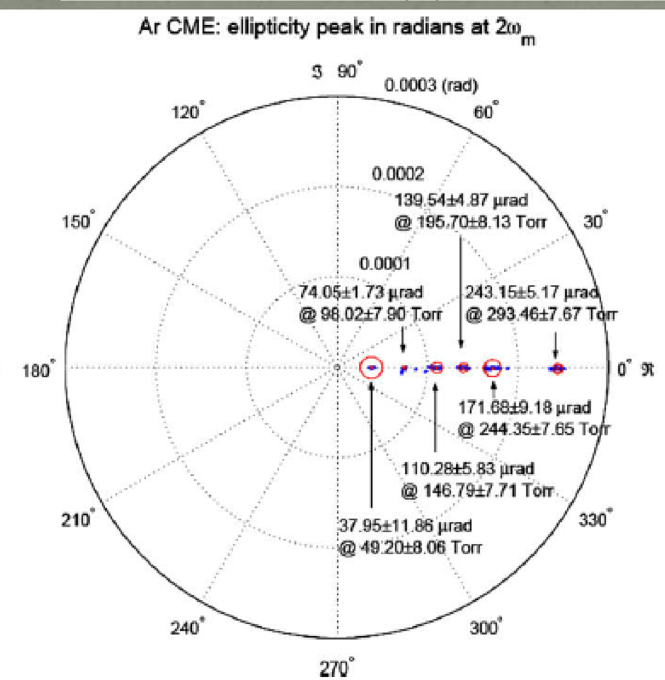
New (pointing to CO_2 and Ar)

Chem. Phys. Lett. 471 216 (2009)



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.

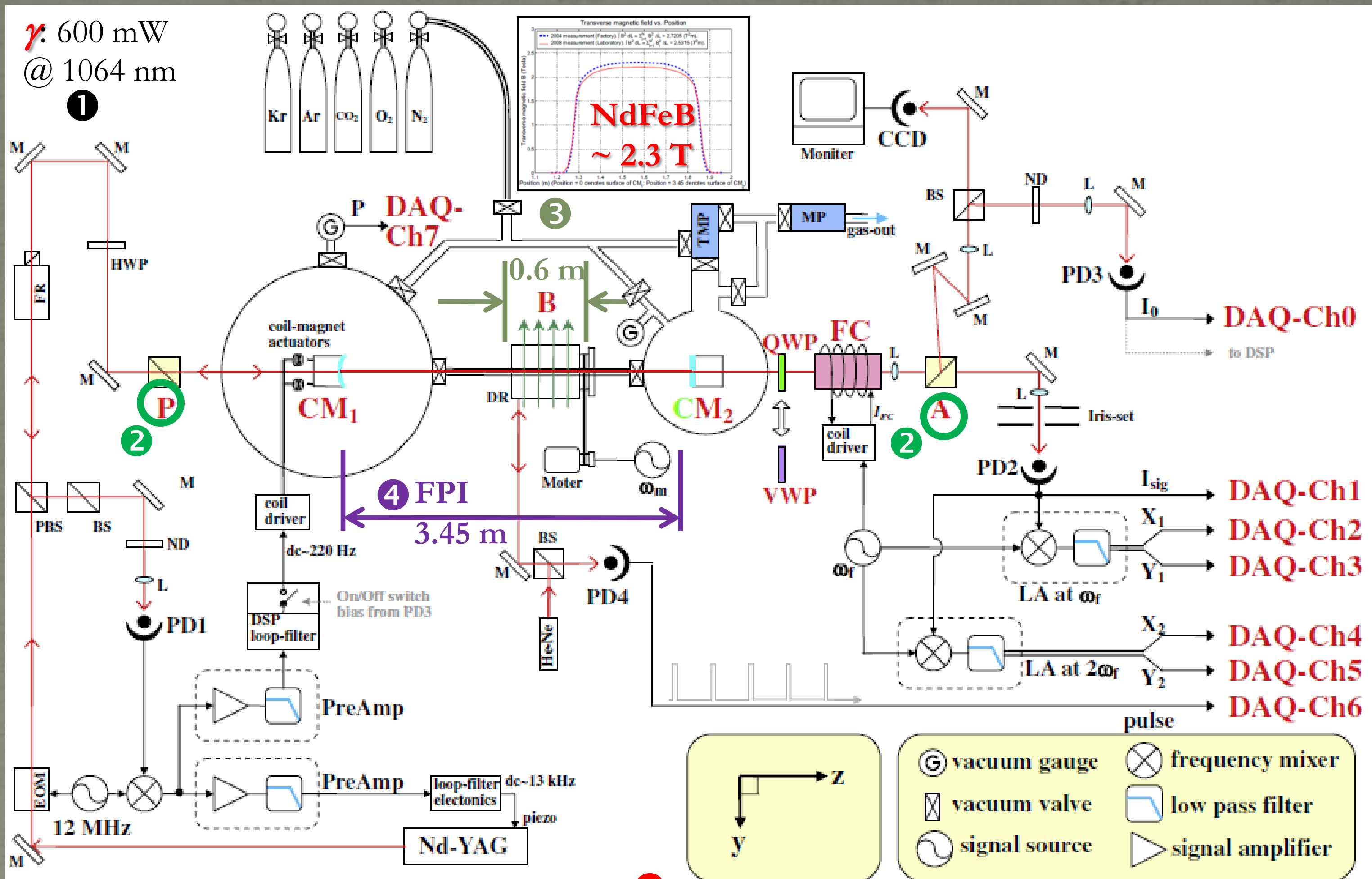
In agreement with the PVLAS results within 1.2σ.

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.

Q & A

- **Who**
  - **Q & A Collaboration**
- **Why**
  - **QED & Axion/[(Pseudo-)scalar Field from WEP/EEP]**
- **What**
  - **Birefringence (ALPs/QED/CME) & Dichroism (ALPs)**
- **How**
- **When**

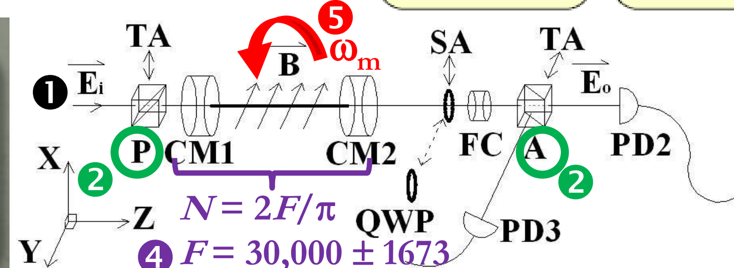
Apparatus for vacuum/CME Lock-in detection



❷ $I_{out} = I_{in}\left(\sigma^2 + \alpha^2\right)$

$$\sigma^2 \equiv \frac{\min(I_{out})}{I_{in}} \cong (5.2 \pm 0.1) \times 10^{-10}$$

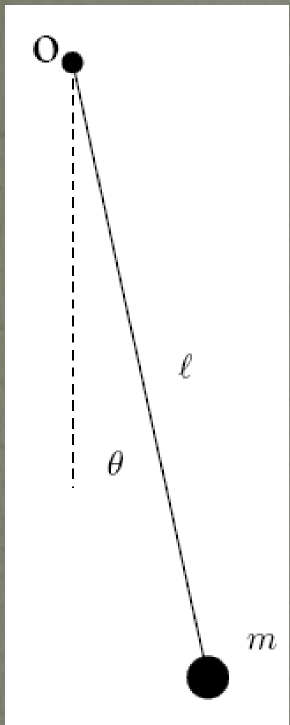
J. Phys.: Conf. Series **32** 236 (2006)

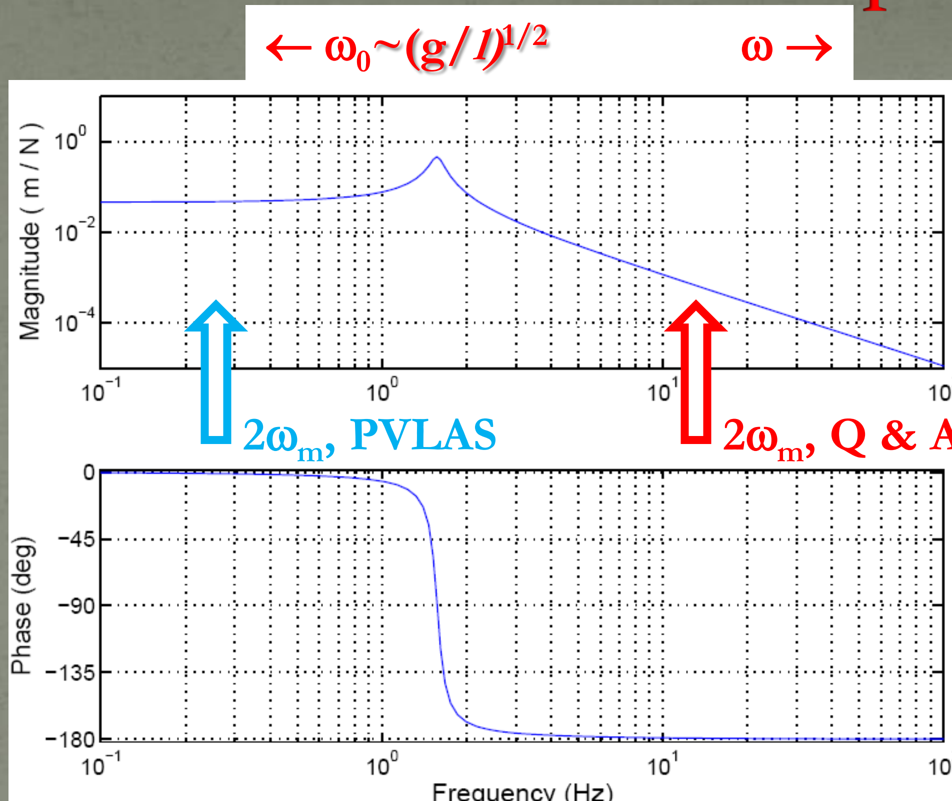


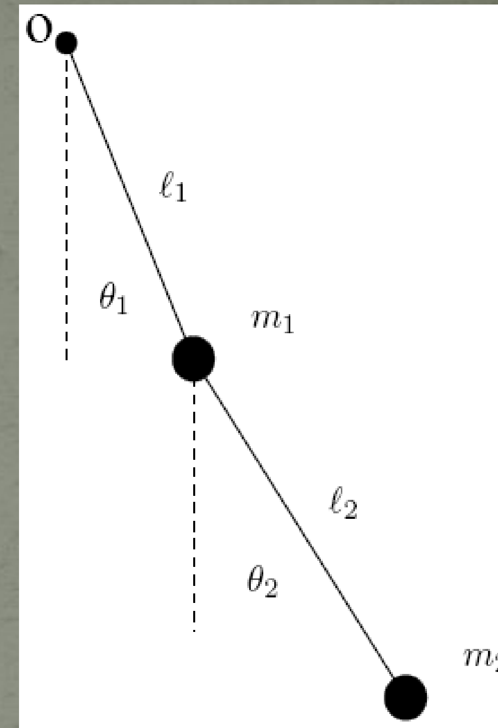
❺ $N\varepsilon(/N\psi)$: signal @ $2\omega_m$

optical signal?
seismic vibration?

❺ Seismic Noise Isolation: Suspension of FPI



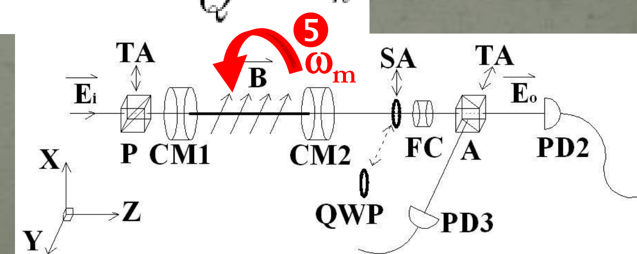




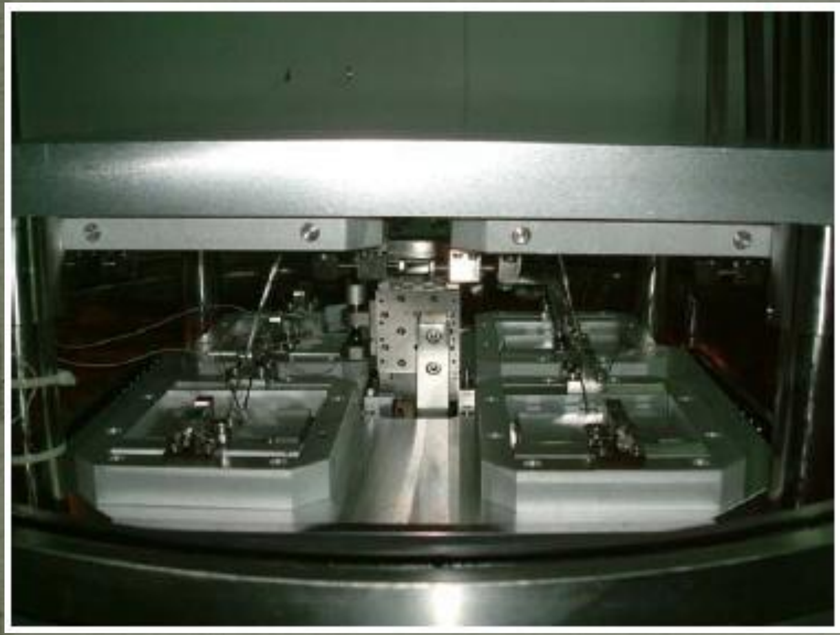
$$\frac{X(\omega)}{X_0(\omega)} = \frac{\omega_0^2}{-\omega^2 - i\frac{b}{m}\omega + \omega_0^2}$$

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

Ground Based GW Observatory

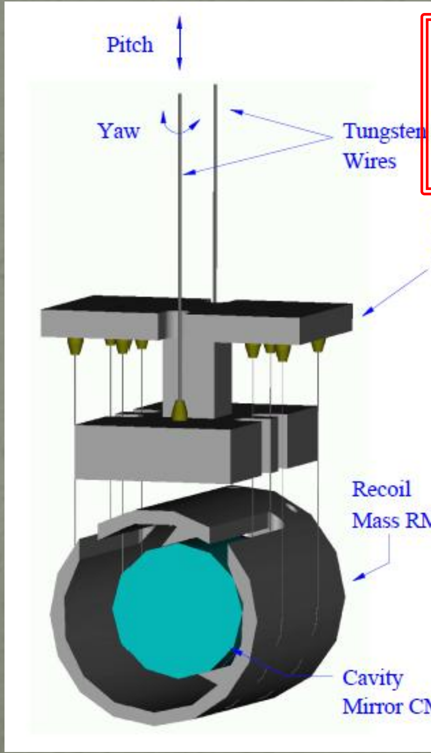


❺ Q & A Suspension of FPI cavity mirrors



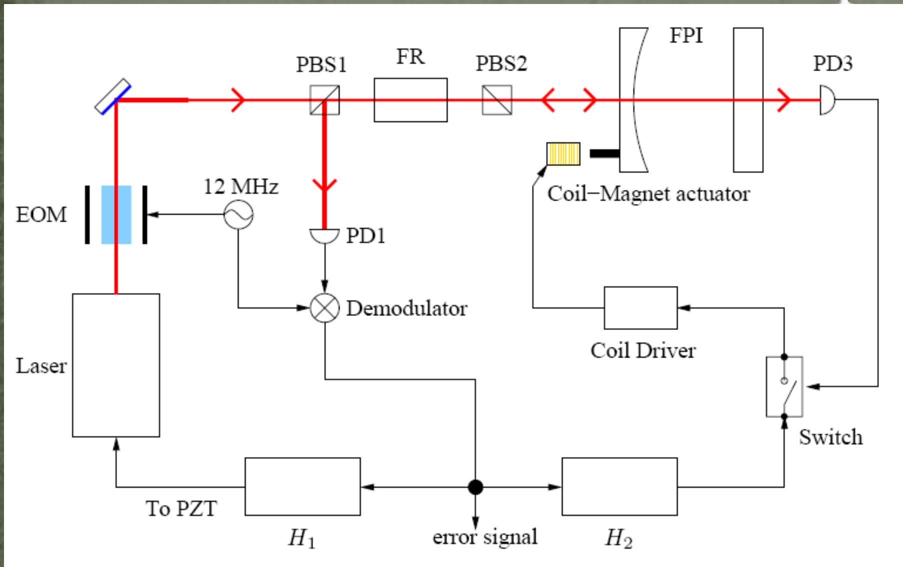
X-pendulum (Cross-wired-pendulum):
Designed by TAMA Collaboration
Simulate simple pendulum with long wire
Resonance: **0.24 Hz** & **0.29 Hz**
Displacement: 80 μm (no damping)
→3 μm (eddy current) ≈ 6 *FSR*
Isolation ratio (by X-pendulum): 27 & 72

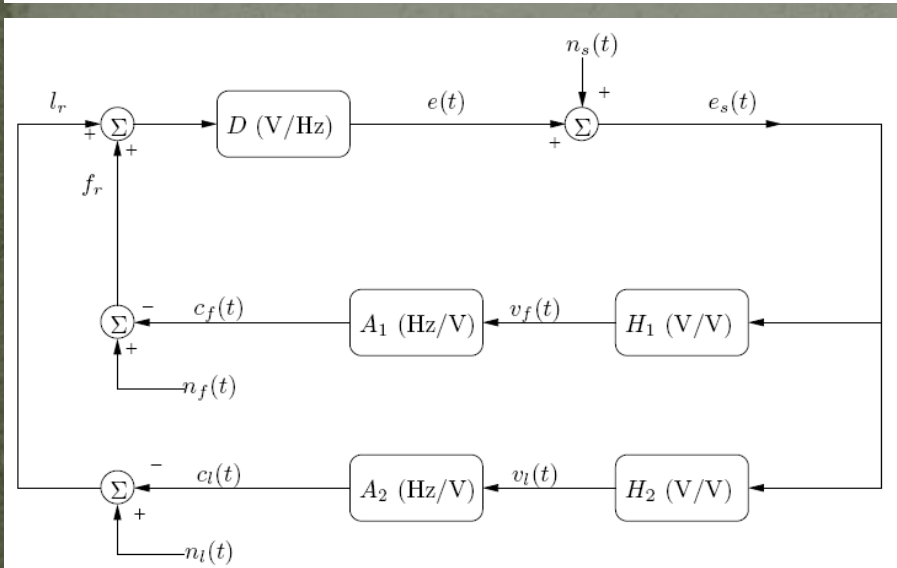
Double pendulum:
Upper layer: Intermediate mass (IM)
Bottom layer: Cavity mirror (CM), Recoil mass (RM)
Main Resonance: **1.53 Hz** & **4 Hz**
Pound-Drever-Hall locking of FPI cavity-length

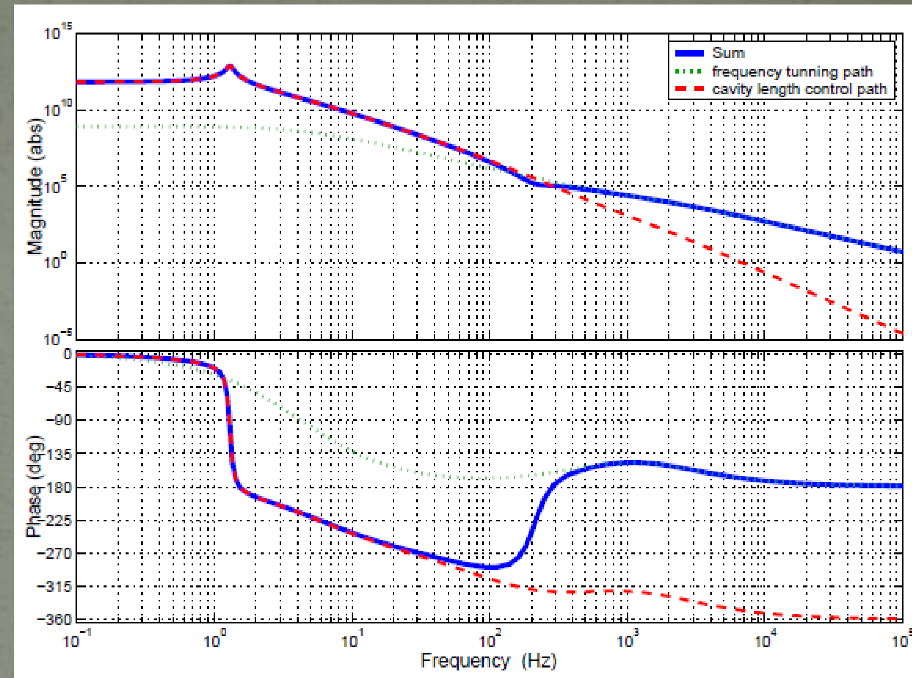


Optical signal is isolated from environmental seismic noise at $2\omega_m$ (10-20 Hz).

❺ PDH Control loop







Laser frequency H_1A_1:

Dynamic range ± 200 MHz

Control band width 13 kHz

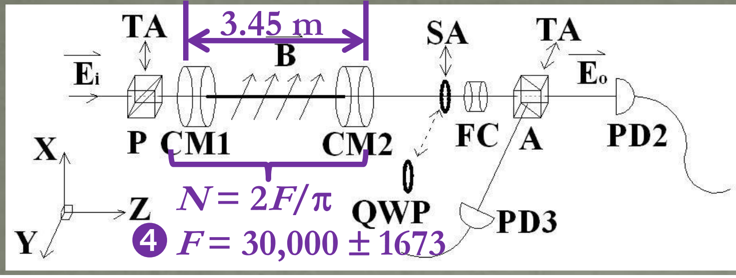
FPI cavity length H_2A_2:

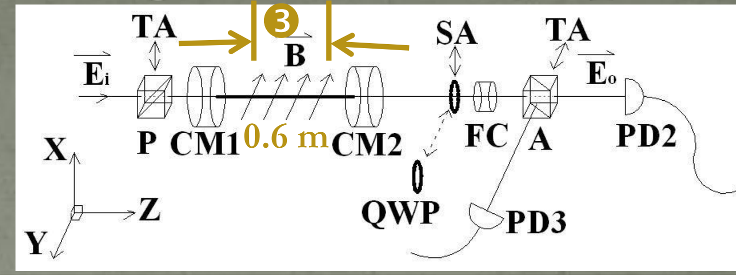
Dynamic range ± 1 mm

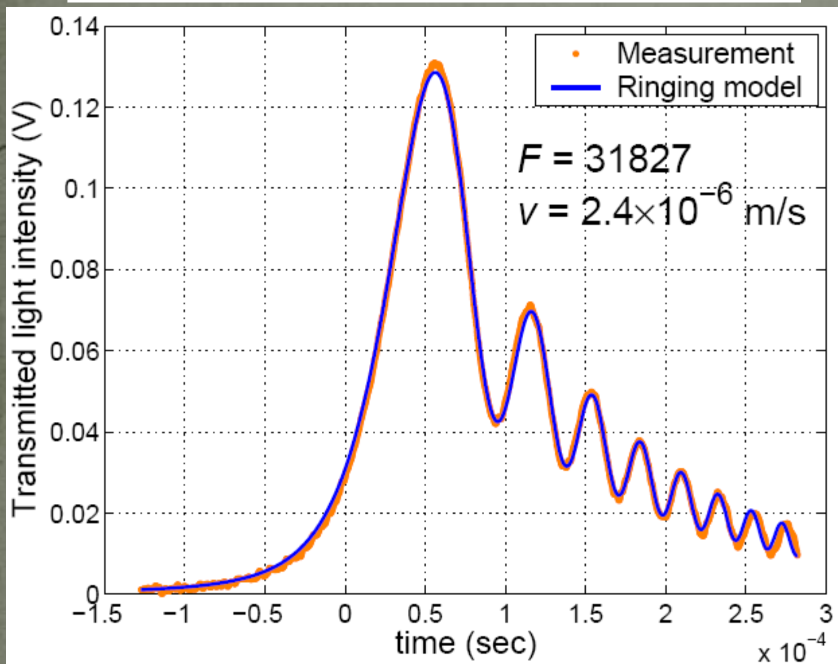
Control band width 220 Hz

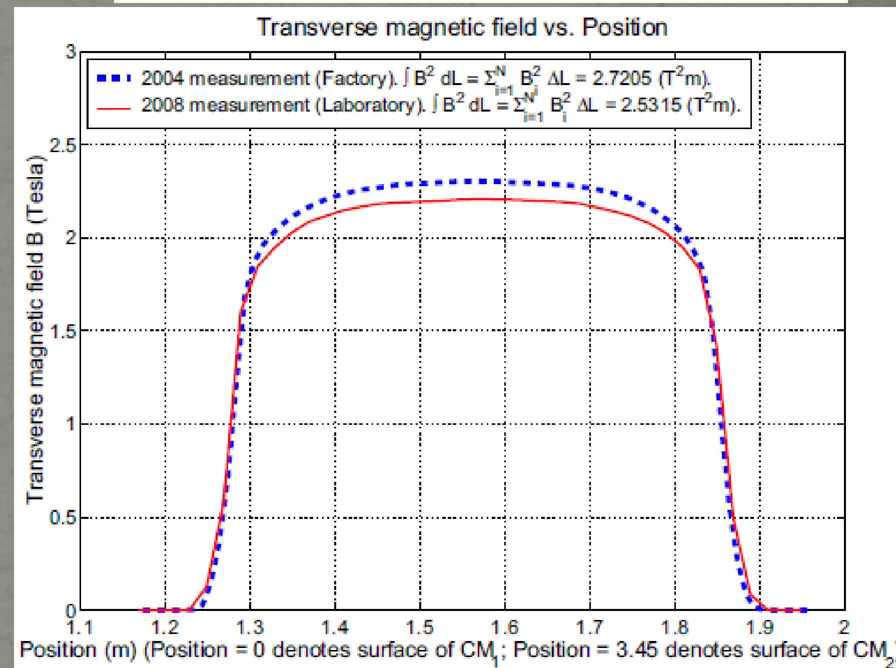
Best performance: $H_1A_1 >> H_2A_2$

❹ Finesse fitting of FPI / ❸ Magnetic field profile









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

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

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

B_T (T)	≥ 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

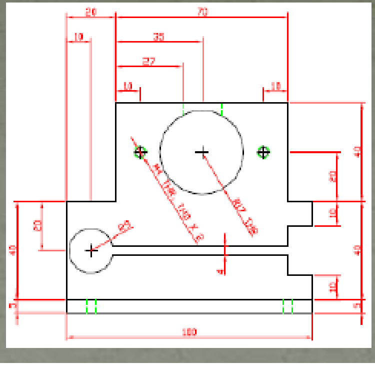
❷ Ellipsometry & σ^2

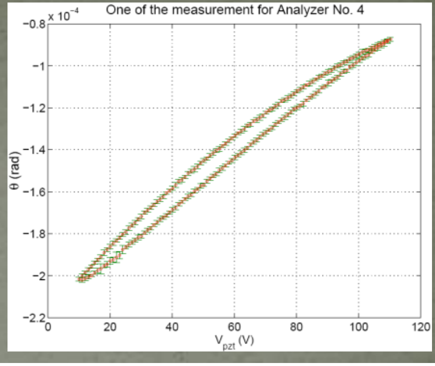
$$\sigma^2 \equiv \frac{\min(I_{out})}{I_{in}}$$

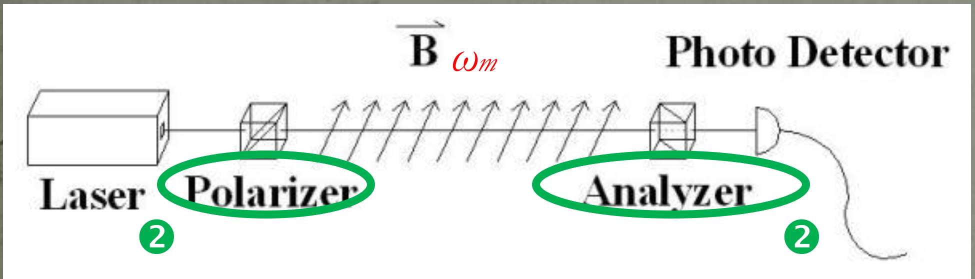
$$\sigma^2 + \tfrac{1}{2}\varepsilon^2 \qquad \tfrac{1}{2}\varepsilon^2 \sin 2\omega_m t$$

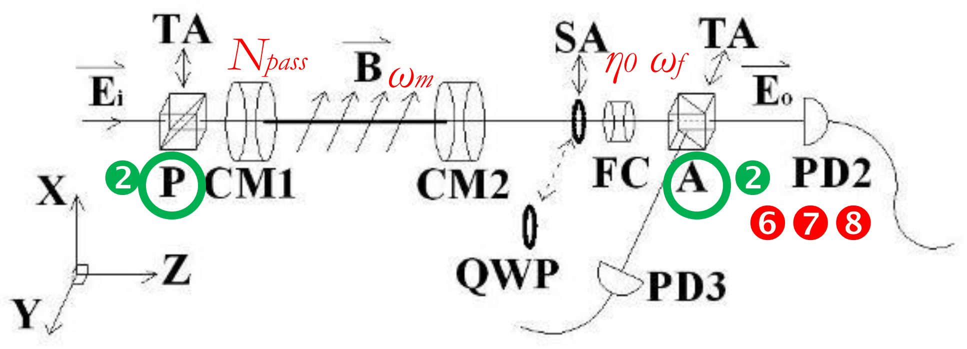
Malus Law: $I_{out} = I_{in}\,(\sigma^2 + \alpha^2)$

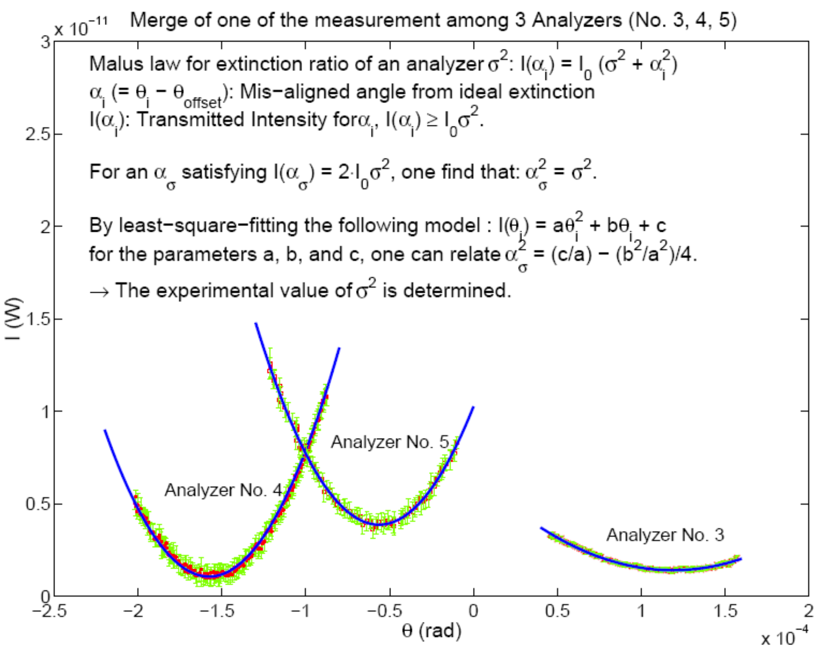
$$\varepsilon \geq \sqrt{2\sigma^2}$$











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

$$\sigma^2 + \tfrac{1}{2}\eta_0^2$$

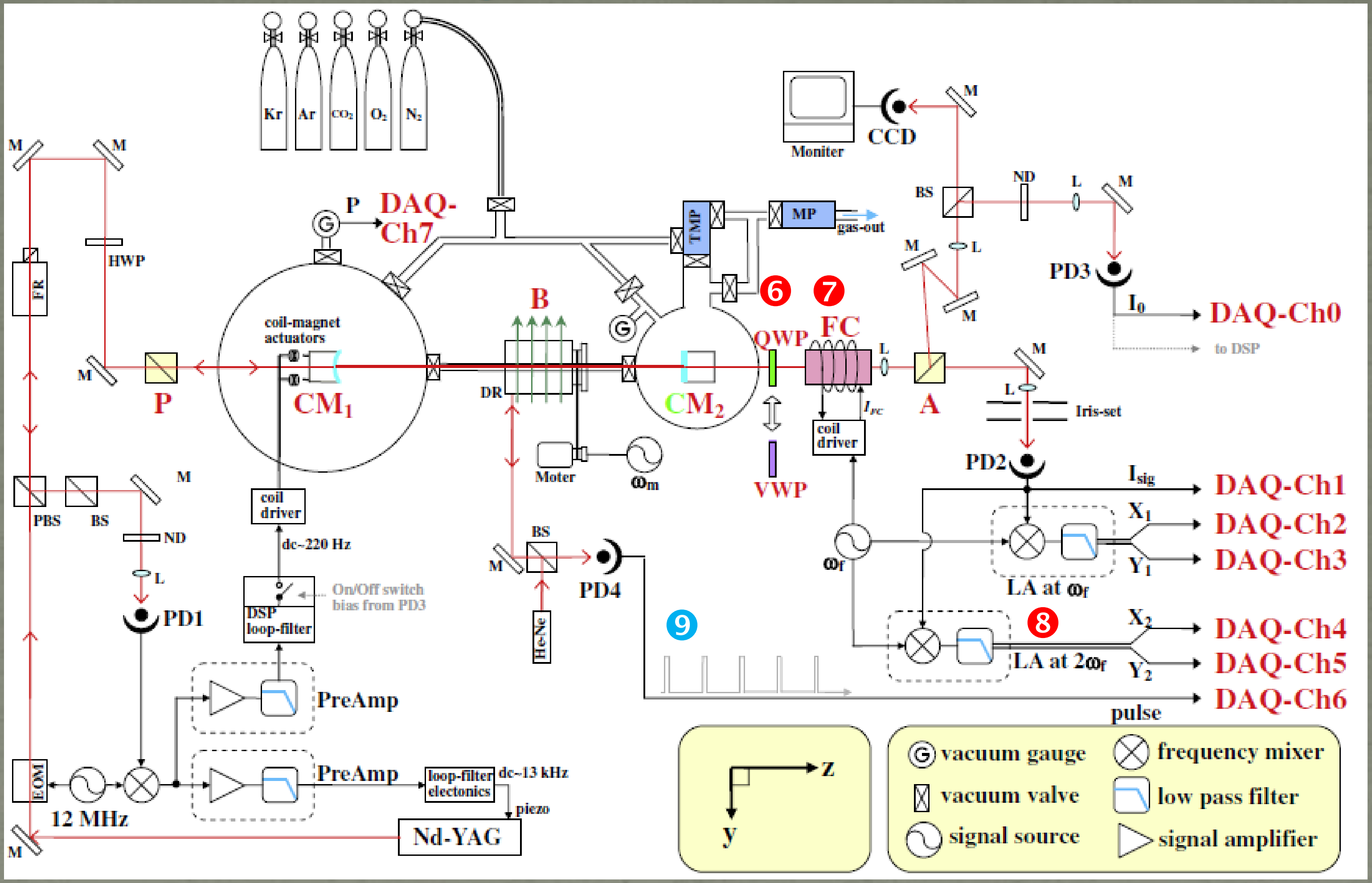
$$\tfrac{1}{2}\eta_0 N_{pass}\varepsilon \cdot \sin(\omega_f \pm 2\omega_m)t + \tfrac{1}{2}\eta_0^2 \cdot \sin 2\omega_f t \quad ❻❼❽$$

$$\varepsilon \geq \frac{\eta_0}{N_{pass}} \cdot \frac{1}{N_{Lock-in-Amp}}$$

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

J. Phys.: Conf. Series **32** 236 (2006)

Detection & Integration considerations



❻ **Signal transformation**

QWP(birefringent)/VWP(dichroic)

❼ **Double modulation**($\eta_0 \cong 1$ mrad)

FC (Faraday Cell) @ ω_f (= $2\pi\times 390$ Hz)

Optical signal @ $\omega_f \pm 2\omega_m$

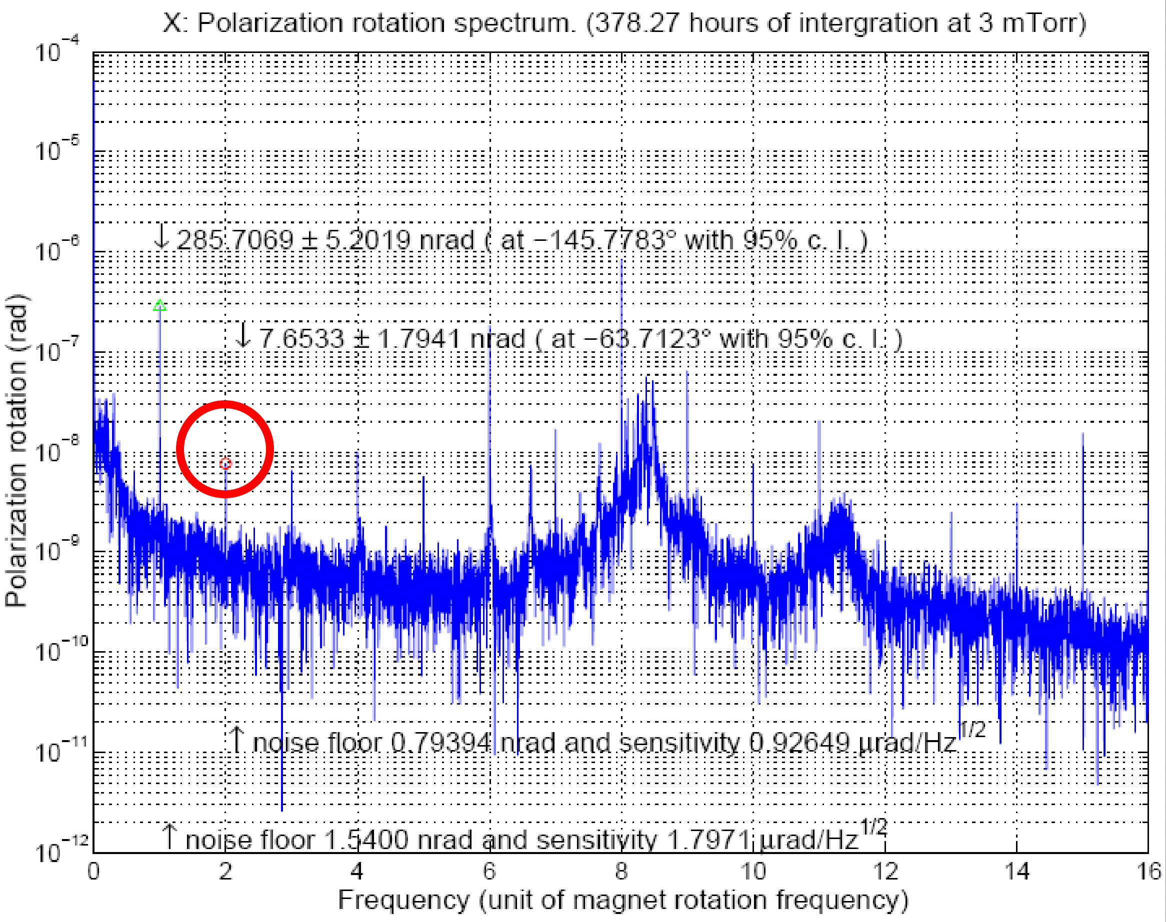
❽ **Lock-in detection**

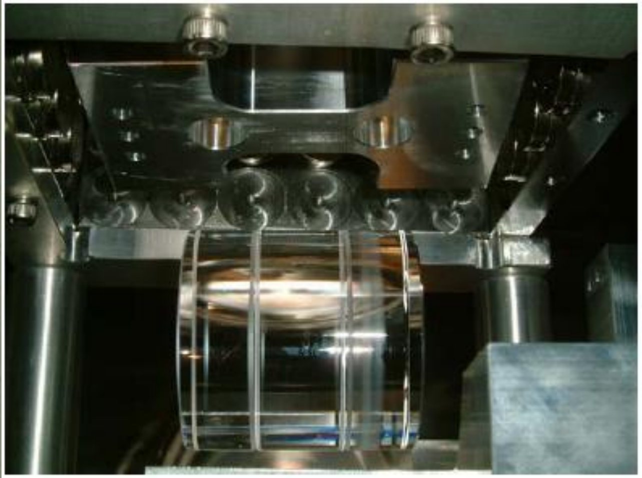
LA_1 ($/LA_2$) demodulating @ ω_f ($/2\omega_f$)

Optical signal recovered @ $2\omega_m$

❾ **Data Resampling** via **Interpolation w. r. t. ω_m**

378.3 hr Polarization Rotation Integration @ 3 mTorr





Stray field contamination at CMs

⇩

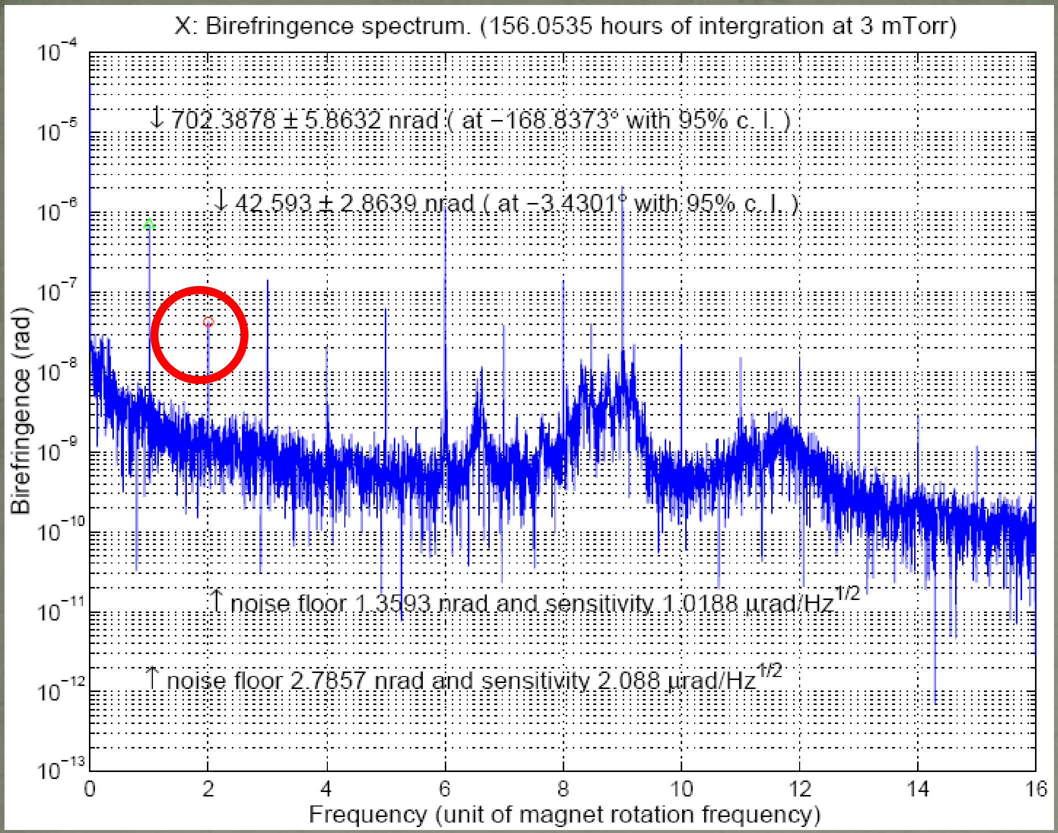
Improved by IM damper field shielding
5 mT → 41.71 μT **(100 times smaller)**

working on $N\varepsilon_0$ ($/\sigma_{N\varepsilon_0}$)

⇩

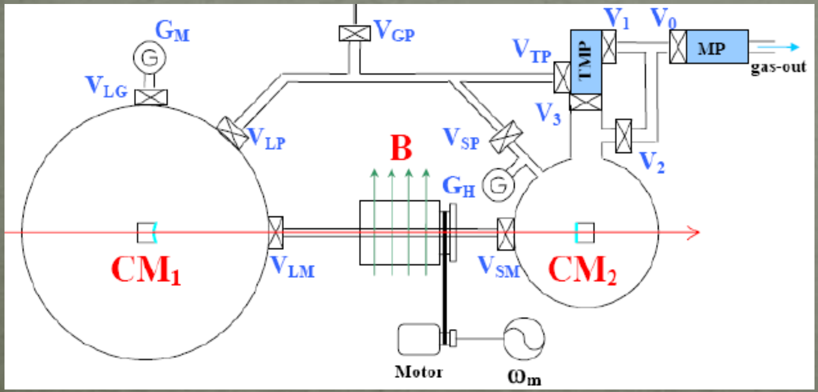
M($=1/g_{a\gamma\gamma}$), m_a

156.05 hr Ellipticity Integration @ 3 mTorr



CME: $\Delta n_u = (7.35 \pm 0.23) \times 10^{-14}$
$\Delta n_u(H_2O)_{theoretical} = 7.5 \times 10^{-15}$

	Alcatel type 2033	Seiko Seiki STP-1000
Type	Mechanical Pump	Turbo Molecular Pump
Exhaust Rate (Lit/s)	9.167	1000
Rotor Speed (rev/min)	1,800	35,000
Allowable $P_{suction}$ (Torr)	760	10^{-4}
Allowable $P_{exhaust}$ (Torr)	760	0.1
Ultimate P (Tor)	10^{-4}	10^{-10}
Auxiliary Pump (Lit/s)		≥ 5.67



$$Q = \frac{d(PV)}{dt}$$

$$C = \frac{Q}{P_1 - P_2}$$

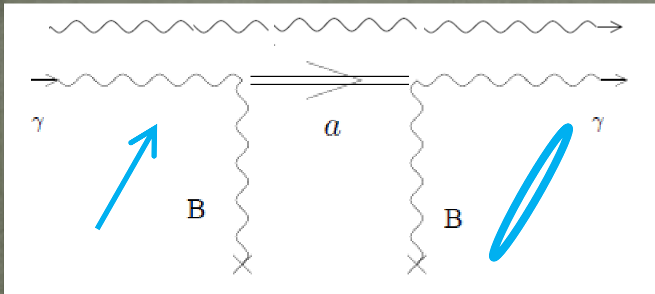
$$V\frac{dP}{dt} = Q - SP$$

$\frac{dP}{dt}$ → 0

SP → Pumping (= Degasing)

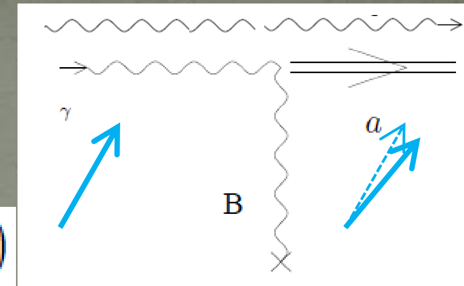
$$C_{Q\&A,exp} = 1.087\ \text{Lit/s}$$

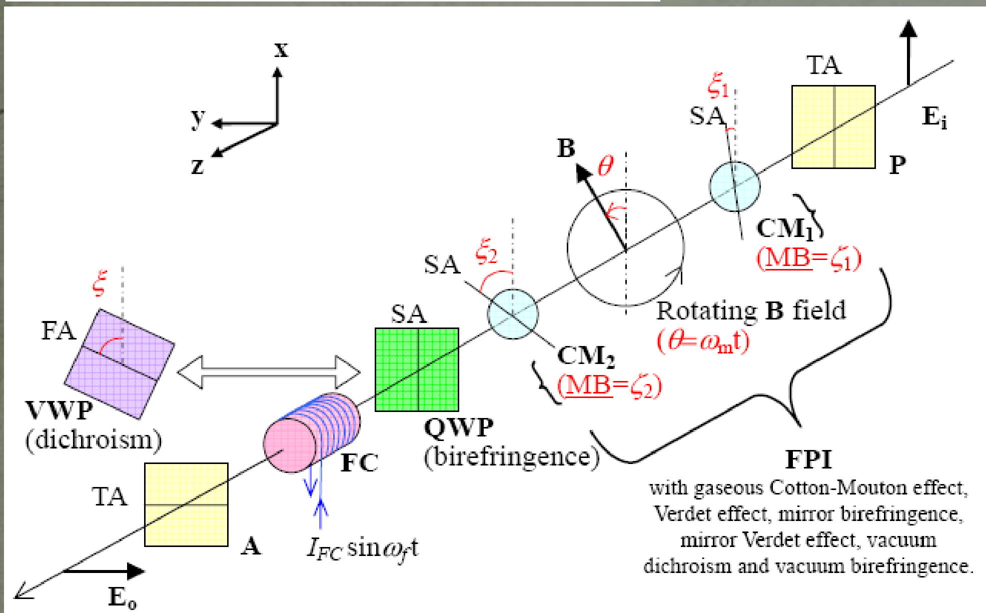
Jones Matrix: Birefringence vs Dichroism



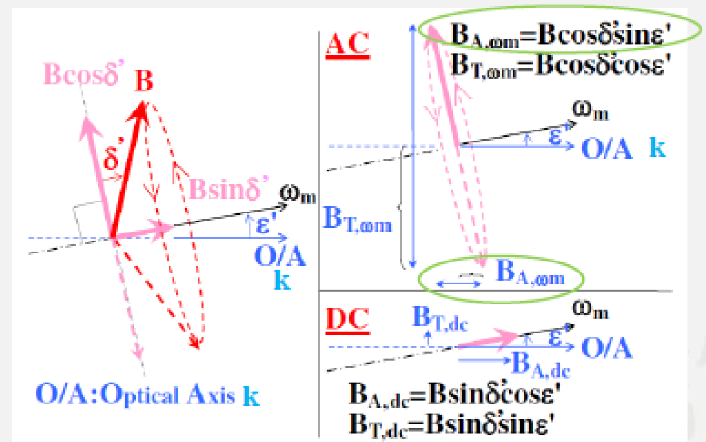
$$J_{WP}\left(\tfrac{\delta}{2},\vartheta\right)=J_R(\vartheta)\begin{bmatrix} e^{i\frac{\delta}{2}} & 0 \\ 0 & e^{-i\frac{\delta}{2}} \end{bmatrix}J_R(-\vartheta)$$

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





Axial stray field (Faraday rotation)



Distortion from $B_{A,\omega m} \rightarrow B_{A,2\omega m}$

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

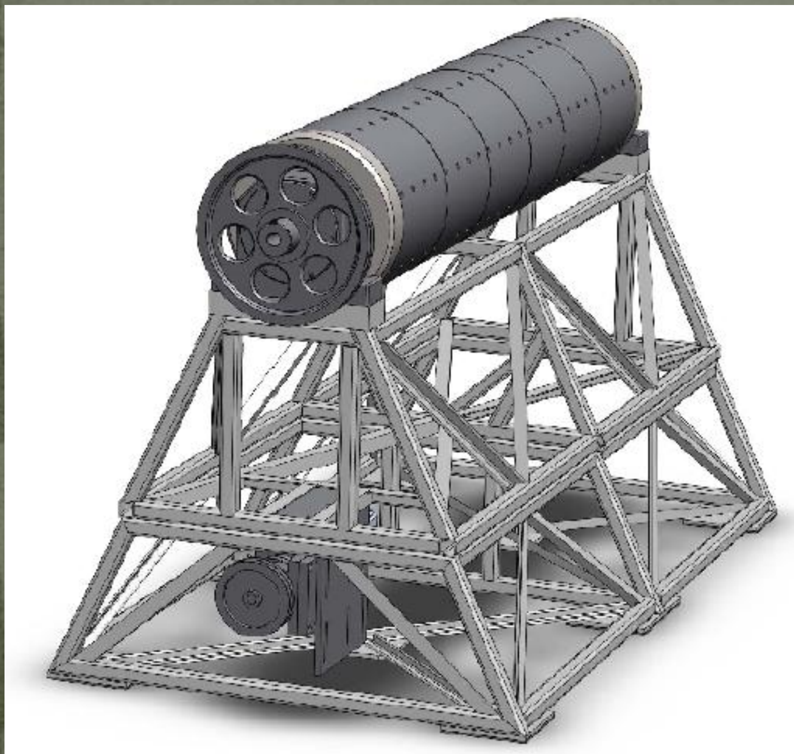
$$E_{out}=\begin{cases} J_A\cdot J_R(\alpha)\cdot J_{FC}\left(\eta_0\sin(\omega_f t+\phi_f)\right)\cdot J_{QWP}\cdot J_{FPI}\cdot J_P\cdot E_0\begin{bmatrix}1\\0\end{bmatrix} \\ J_A\cdot J_R(\alpha)\cdot J_{FC}\left(\eta_0\sin(\omega_f t+\phi_f)\right)\cdot J_{VWP}\cdot J_{FPI}\cdot J_P\cdot E_0\begin{bmatrix}1\\0\end{bmatrix}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

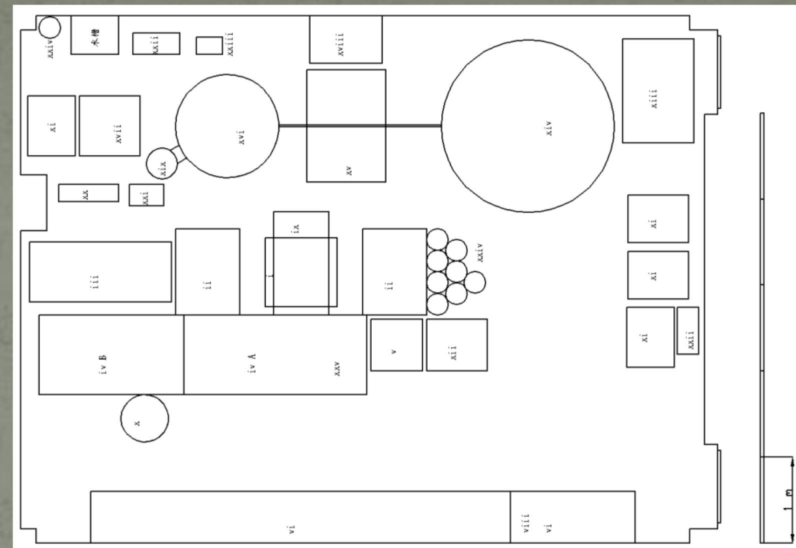
$$\psi(t)\equiv\frac{\eta_0}{4}\cdot\frac{X_1(t)}{Y_2(t)}$$

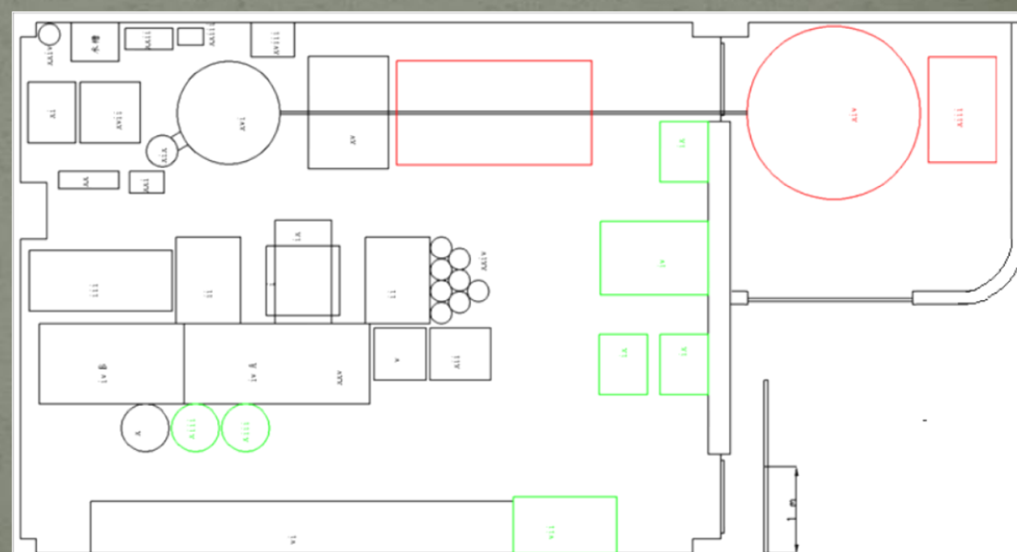
$$\Psi(\omega)\equiv\mathcal{F}(\psi(t))$$

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

Prospect: New magnet after Sept. 2009







Main specs for design:

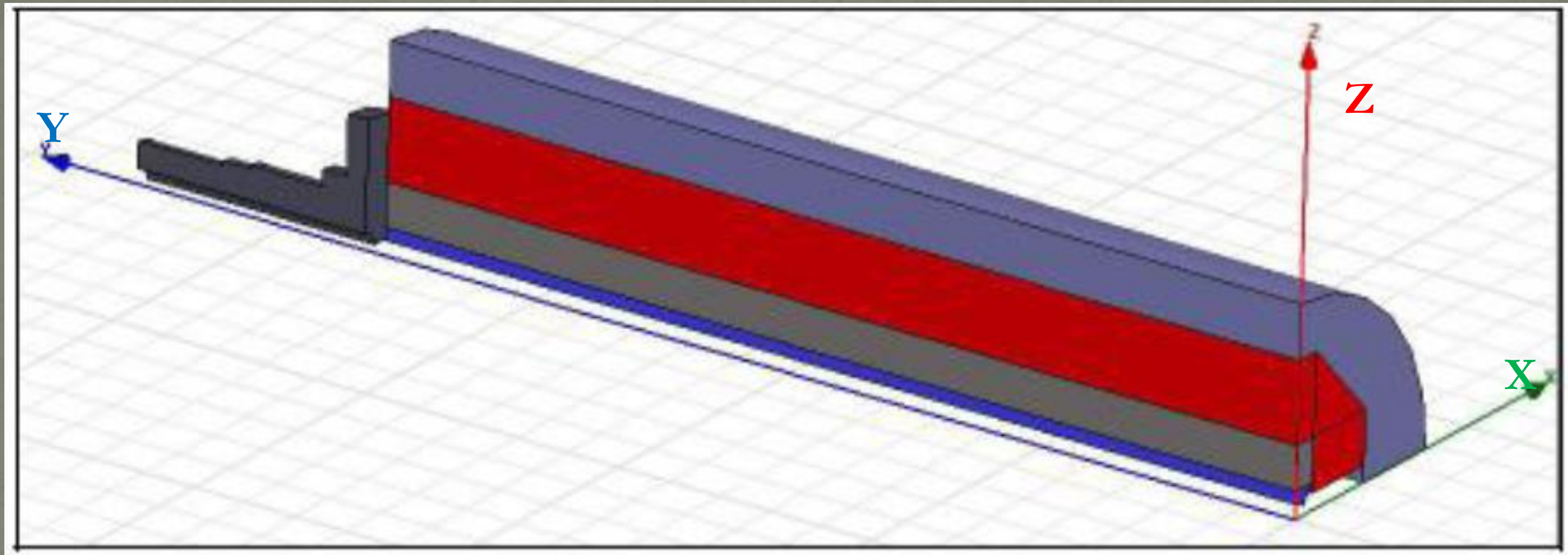
B = 2.3 T

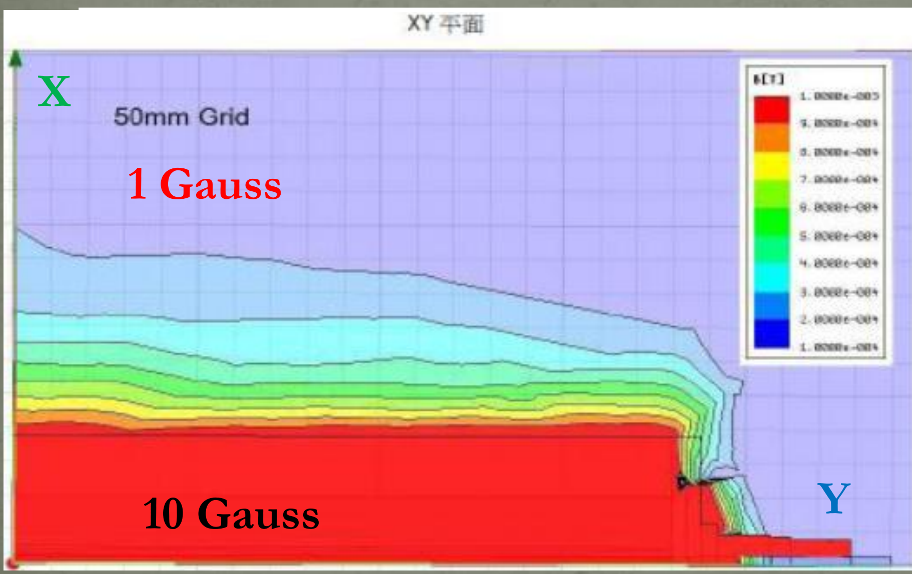
L = 1.8 m

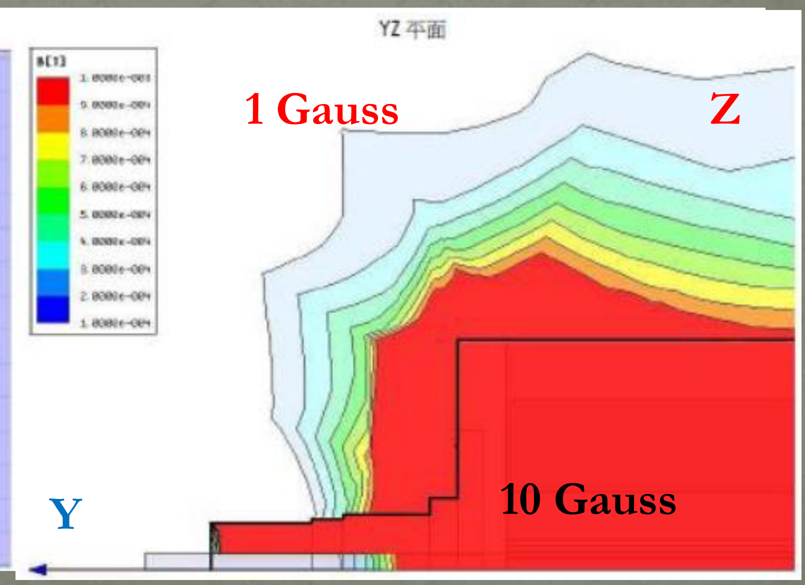
$\omega_m/2\pi$ = 600 rpm

$$\psi_{QED} \propto \lambda^{-1} N B^2 L$$
$$\varepsilon_{Axion} \propto \lambda^{0} N B^2 L^2$$

Simulation for magnetic leakage

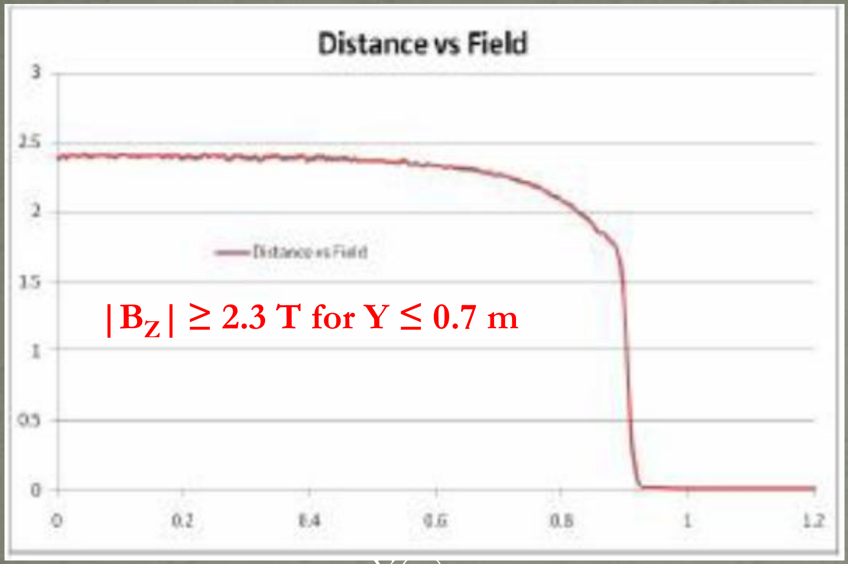






Simulation for transverse(B_Z)/axial(B_Y) fields

B_Z (T)



Y(m)

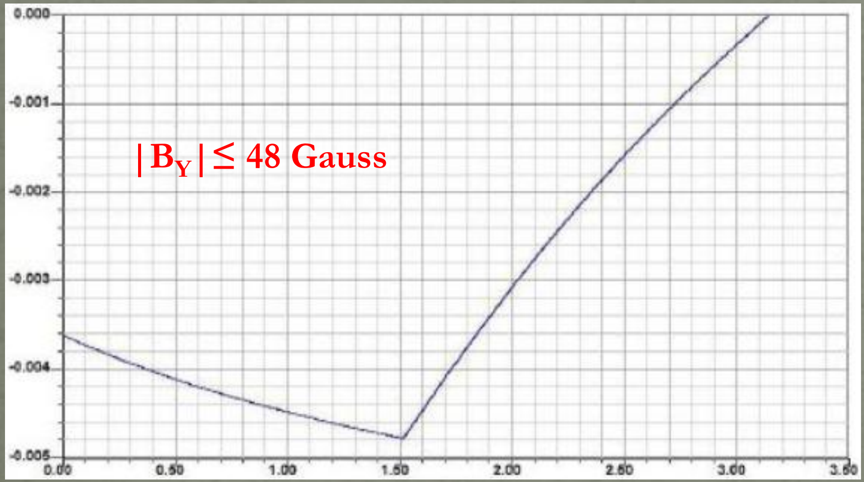
X=Z=0

B_Y (T)

rθ(mm)

Y=450 mm, $r=(X^2+Z^2)^{1/2}=2$ mm, $0<\theta<\pi/2$

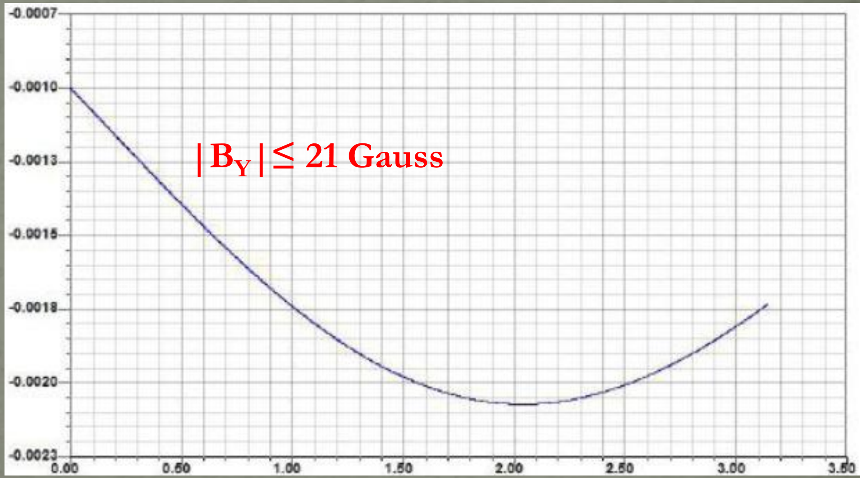
B_Y (T)



rθ(mm)

Y=0 mm, $r=(X^2+Z^2)^{1/2}=2$ mm, $0<\theta<\pi/2$

B_Y (T)



rθ(mm)

Y=800 mm, $r=(X^2+Z^2)^{1/2}=2$ mm, $0<\theta<\pi/2$

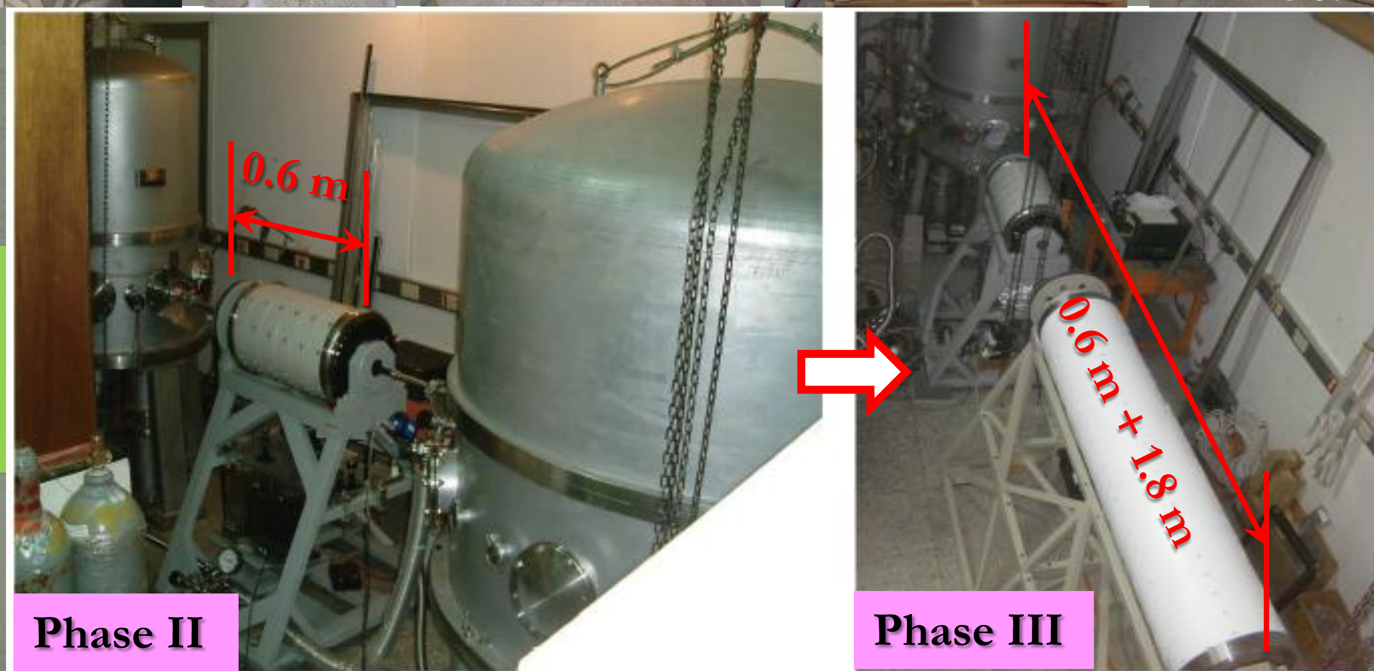
Q & A

- **Who**
  - **Q & A Collaboration**
- **Why**
  - **QED & Axion/[(Pseudo-)scalar Field from WEP/EEP]**
- **What**
  - **Birefringence (ALPs/QED/CME) & Dichroism (ALPs)**
- **How**
  - **Ellipsometry, Vibration Isolation, Lock-in Detection**
  - **Signal Enhancement ($\lambda^{\alpha}NB^{\beta}L^{\gamma}$), Sensitivity Improving**
  - **Calibration, Magnetic Shielding, IBR Compensation**
- **When**

Phase II → Phase III Transition

Phase II → Phase III Transition

L_{FP} : 3.5 m
L : 0.6 m
λ : 1064 nm
F : 30000



L_{FP} : 7 m
L : 2.4 m
λ : 532 nm
F : 10^5

Prospects of Q & A experiment

	achieved (2007 / 2008)	implementing (2009-2010)	next stage (2011?)
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)	29900 / 30000	**10^5**	10^5
Number of passage ($N = 2F/\pi$)	18700 / 19100	**63700**	63700
Magnet's rotational modulation ($f_m = \omega_m/2\pi$)	5 rps / 7 rps	**10 rps**	**20 rps**
Sensitivity ($S_{N\psi_o}$ or $S_{N\varepsilon_o}$)	(1.4 / 0.9) μrad/$Hz^{1/2}$	**10 nrad/$Hz^{1/2}$ ↓ Mirrors' birefringence**	**2 nrad/$Hz^{1/2}$ shot noise limit @ 0.1 W**
Integration time (T_{int})	18.9 hr / 378 hr	**1000 hr (~42 d)**	1000 hr (~ 42 d)
Noise floor after T_{int} ($\sigma_{N\psi_o}$ or $\sigma_{N\varepsilon_o}$)	5.3 nrad/0.8 nrad [$(7\cdot10^3/10^3)N\psi_{o,QED}$]	**5.3 prad ($28\%\times N\psi_{o,QED}$)**	**1.1 prad ($3.3\%\times N\psi_{o,QED}$)**
QED effect in ellipticity ($N\psi_{o,QED} \propto NB^2L/\lambda$)	0.72 prad	**19.1 prad**	33.4 prad
ALPs coupling scale [$M = g_{a\gamma\gamma}^{-1} \sim (BL/4)(N/\sigma_{N\varepsilon_o})^{1/2}$]	§$M > 0.6\times10^6$ GeV for $m_a < 1.7$ meV	**$M > 1.4\times10^8$ GeV for $m_a < 0.8$ meV**	$M > 5.3\times10^8$ GeV for $m_a < 0.8$ meV

§: No results for 2008 due to CMs magnetic field contamination.

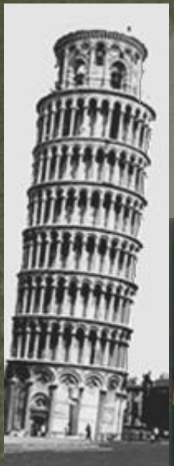
Q & A

- **Who**
  - Q & A Collaboration
- **Why**
  - QED & Axion/[(Pseudo-)scalar Field from WEP/EEP]
- **What**
  - Birefringence (ALPs/QED/CME) & Dichroism (ALPs)
- **How**
  - Ellipsometry, Vibration Isolation, Lock-in Detection
  - Signal Enhancement ($\lambda^{\alpha} N B^{\beta} L^{\gamma}$), Sensitivity Improving
  - Calibration, Magnetic Shielding, IBR Compensation
- **When**
  - Hopefully, 2010-2011

Summary & Outlook

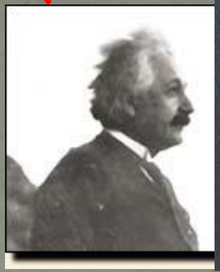
- **Q & A** experiment searches for **QED** or **(pseudo)scalar** predictions through ellipsometer-measured **birefringence** and **dichroism**.
- Cavity mirrors are **suspended** for seismic noise **isolation**.
- **Magnetic field shielding** around cavity mirrors is improved.
- Sensitivity in polarization 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 set up with a rotational speed up to **13 rps** to enhance 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**.

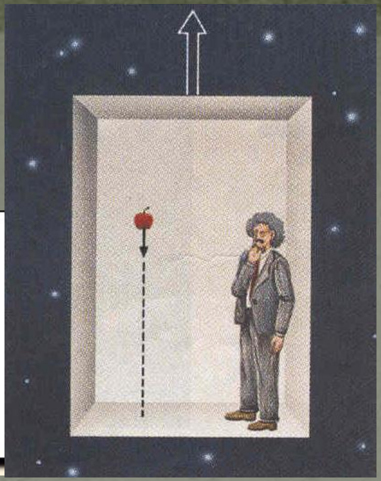
$$L_I = -(1/16\pi)\phi F_{ij} F_{kl} e^{ijkl}$$

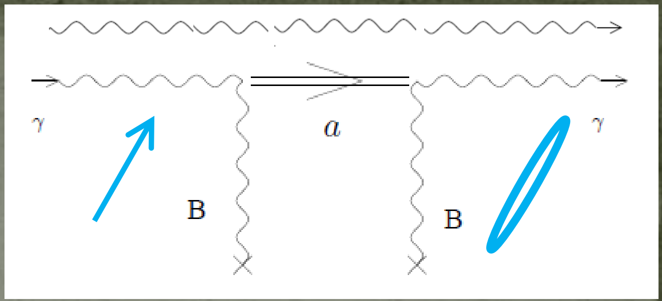


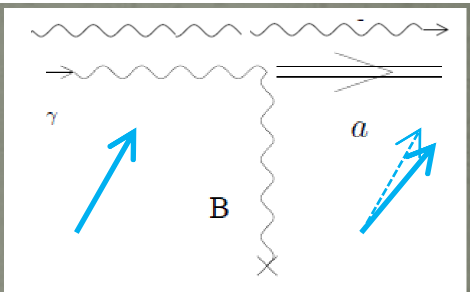
WEP

EEP

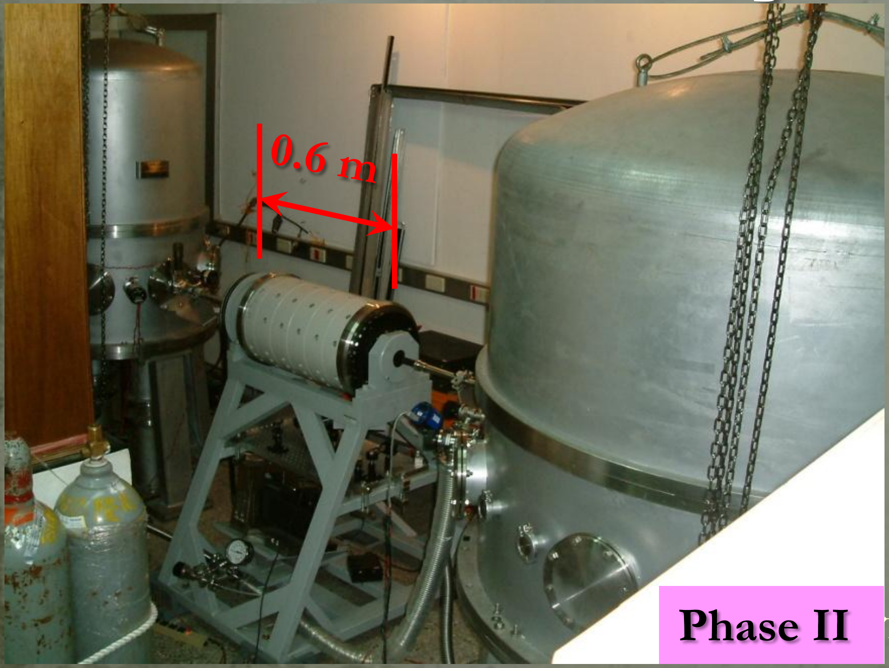




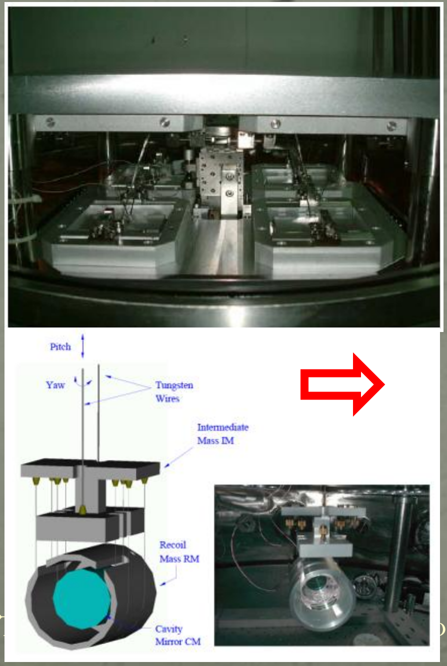


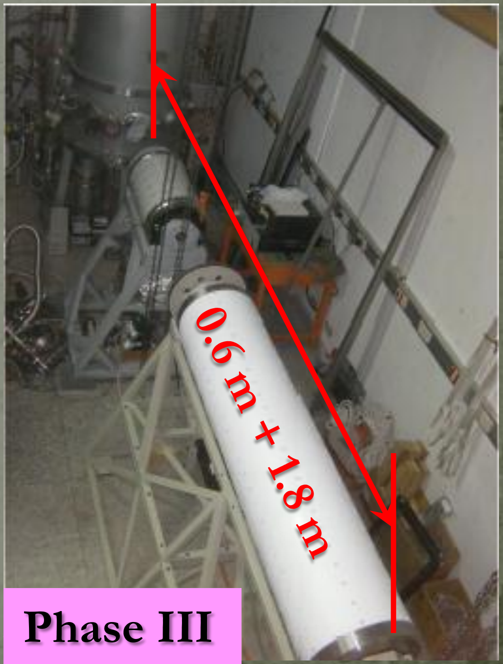


⊡Thank you very much!



Phase II





Phase III