Experimental observation of magnetically induced: LINEAR DICHROISM ON VACUUM.

by

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and myself.

These results have been obtained at the PVLAS APPARATUS built and operating at the:

LABORATORI NAZIONALI DI LEGNARO (L.N.L.);
LEGNARO, PADOVA ITALY

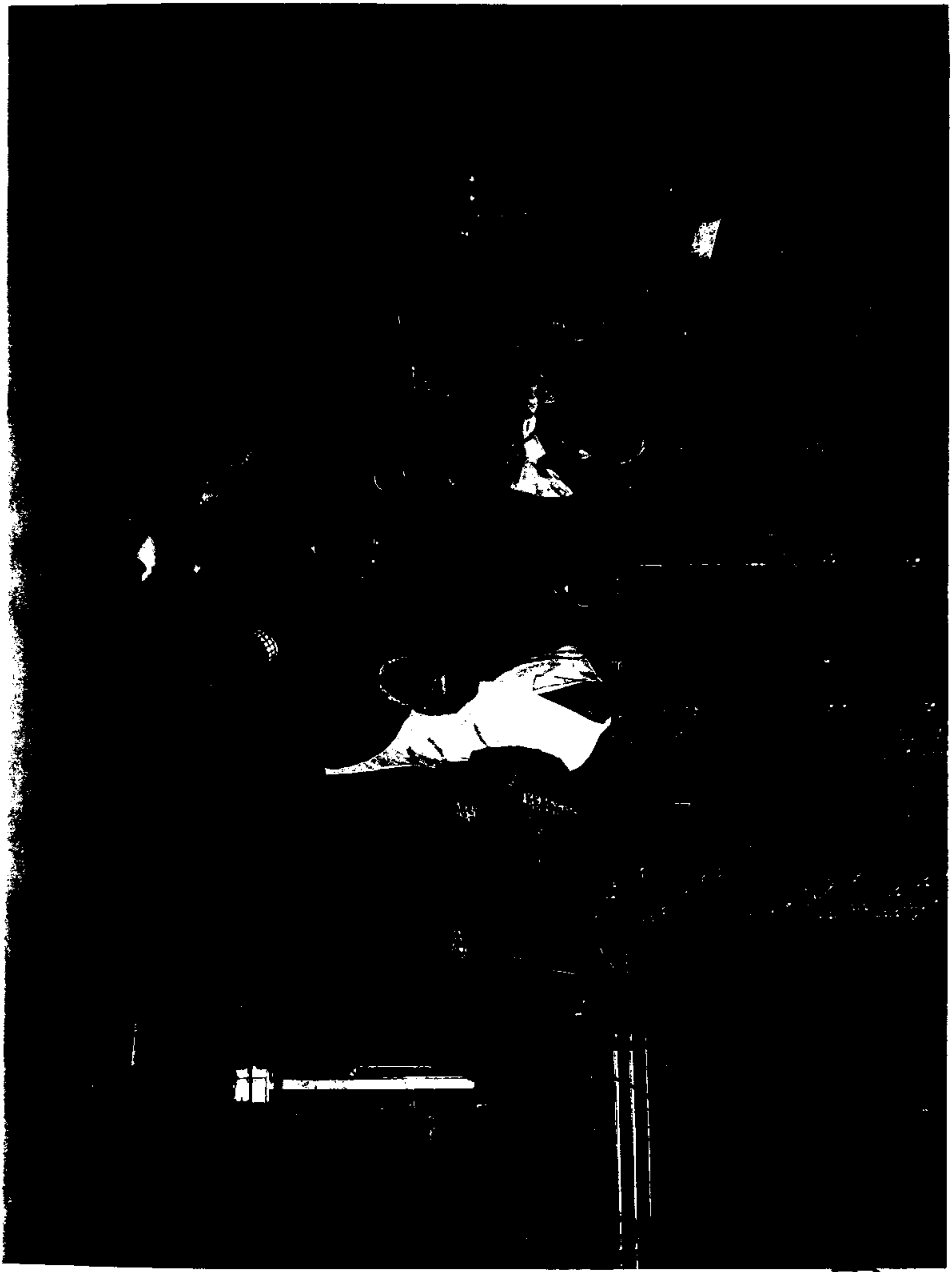


FIG 2 → + Breeait

(2)

P. V. L. A. S

Specifically built in order to obtain significative experimental informations on VACUUM using optical Techniques

Our full experimental program is to detect and measure the two following properties (eventually) acquired by VACUUM due to the presence of a magnetic field ($\vec{B}_0$):

1) Linear Birifraugence

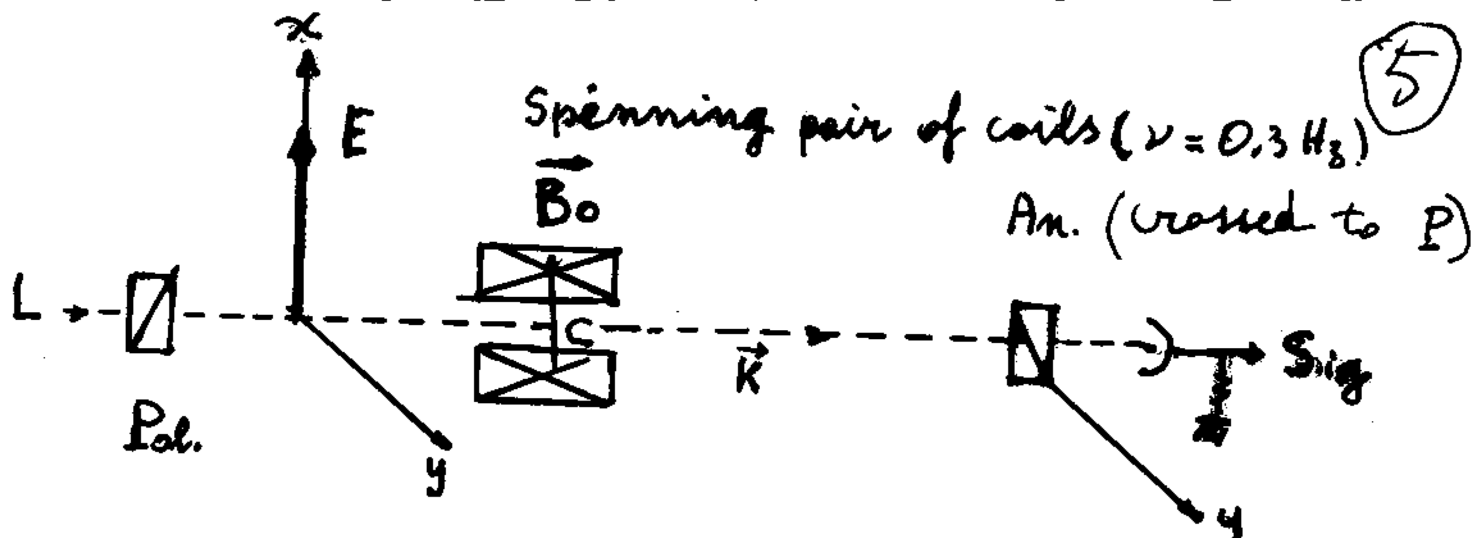
2) Linear dicroism.

In this communication I report experimental results on

Linear dichroism induced on Vacuum by a static magnetic field ($\vec{B_0}$).

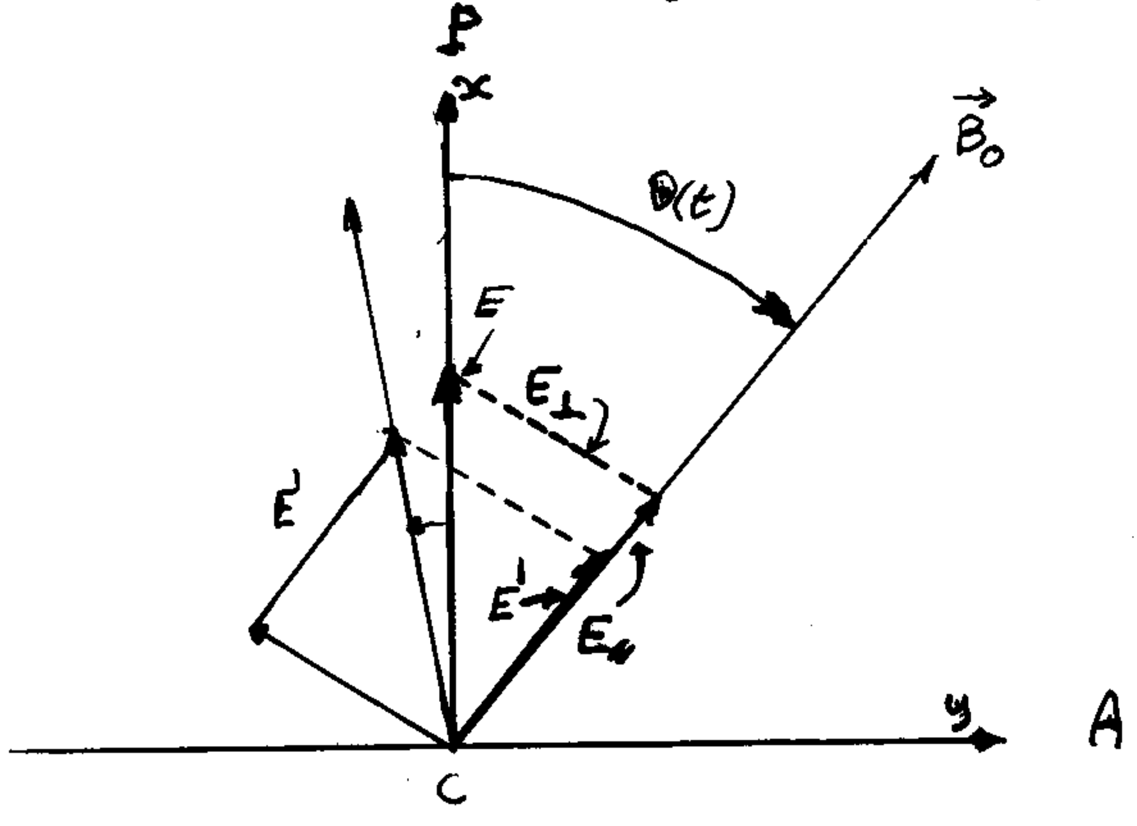
↓

Selective absorption (by the magnetized Vacuum) of polarized light, according to its polarization-orientation with respect to the $\vec{B}_0$ direction.



if $|\vec{B}_0| = 0 \longrightarrow Sig = 0$: beam in vacuu

for $\vec{B}_0 \neq 0$ $\vec{B}_0$ stays in X Y plane



Suppose there is a selective absorption of the $E_\parallel$ component: (average value q)

$$E_\parallel \longrightarrow q E_\parallel = E' = E' \quad q < 1$$

FIG. 6

Initially
-no absorption-

$$E e^{-i\xi}\begin{pmatrix}1\\0\end{pmatrix} \longrightarrow \begin{pmatrix}P\\A\end{pmatrix}$$

With absorp.

$$E \bar{e}^{i\xi}\begin{pmatrix}(q-1)\cos^2\theta(t)+1\\ \frac{q-1}{2}\,\mathrm{Sen}\,2\theta(t)\end{pmatrix}$$

$$\mathrm{Sig}\,A = \frac{q-1}{2} E\,\mathrm{Sen}\,2\theta(t)$$

So max. rot. signal = $\boxed{\Delta\alpha = \frac{q-1}{2}\ \text{rad.}}$

Notice $\Delta\alpha \neq \leftrightarrows q \not\approx 1$

Therefore observing a magnetically induced dichroism in VACUUM means detect a (rotational) signal of a linearly polarized radiation beam that goes through the "magnetized Vacu with its propagation vector $\vec{K}$ ortogon to $\vec{B_0}$.

$\downarrow$

OUR experim. results $\longrightarrow$

With

$$\left\{\begin{array}{l} L = 110 \text{ cm} \\ \vec{B}_0 = 5.51 \text{ Tesla} \end{array}\right\} \text{ We find}$$

① $$\boxed{\frac{9-1}{2} = -(3.7 \pm 0.4)\, 10^{-12} \text{ rad/Pass}}$$

putting $\bar{N}$ of passes $= 52000$ gives:

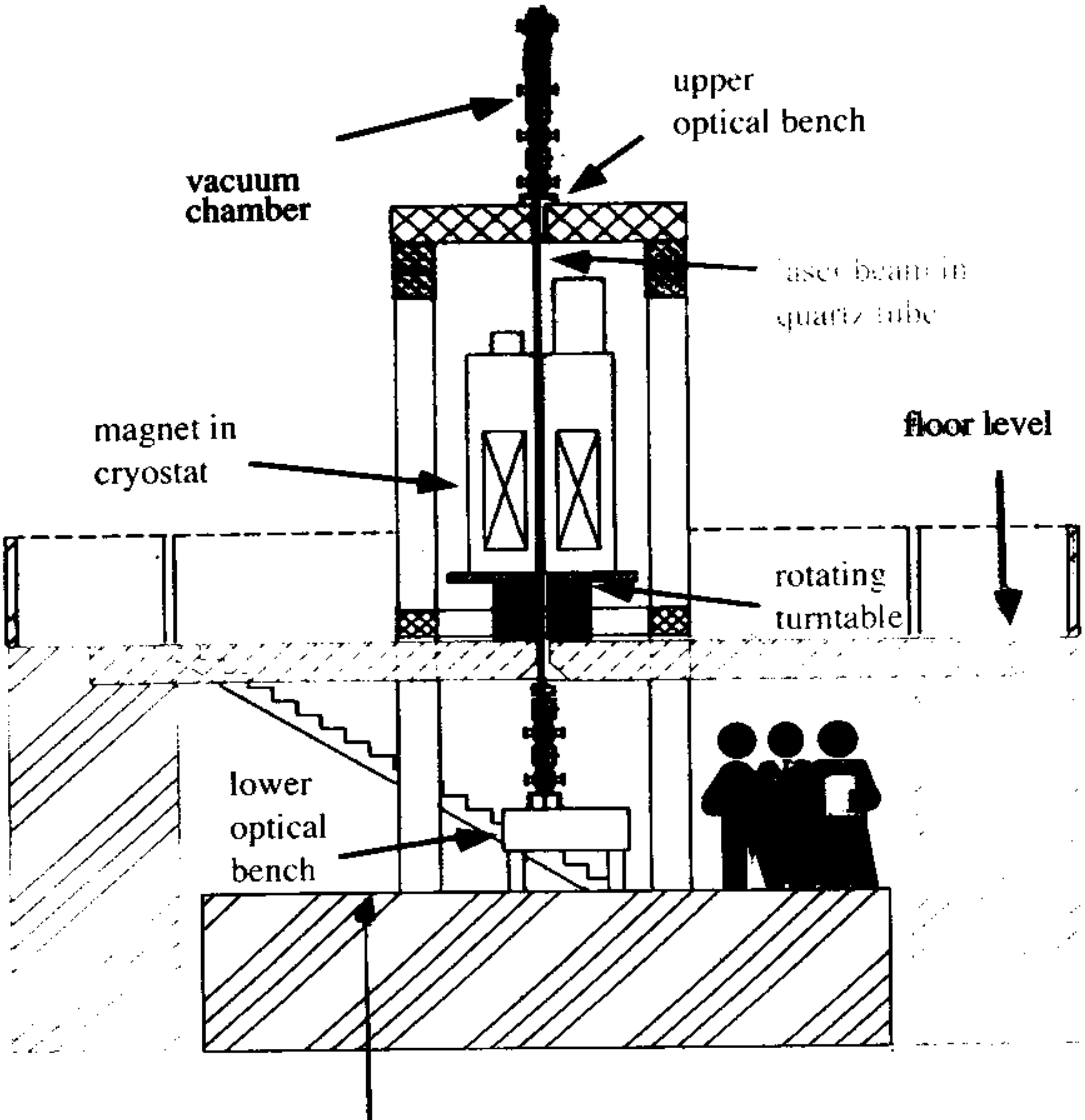
$\Longrightarrow$ ① $\boxed{\text{rot. signal} = \Delta\alpha = (2.2 \pm 0.2)\, 10^{-7} \text{ ra}}$

i.e. We observe a change in the amplitu of the polarization component parallel to the $\vec{B}_0$ field (in fact a decrease).

What happened to the missing part?

+ At this point, before speaking of additional experimental results
+ compare our to others results,
+ how to proceed to understand what is happening
+ near future plans, etc

let me breifly present the P.V.L.A.S. apparatus.



- The floor of the pit was constructed to be seismically isolated from the rest of the building. It lays on 15 meter pylons sunk i sand.

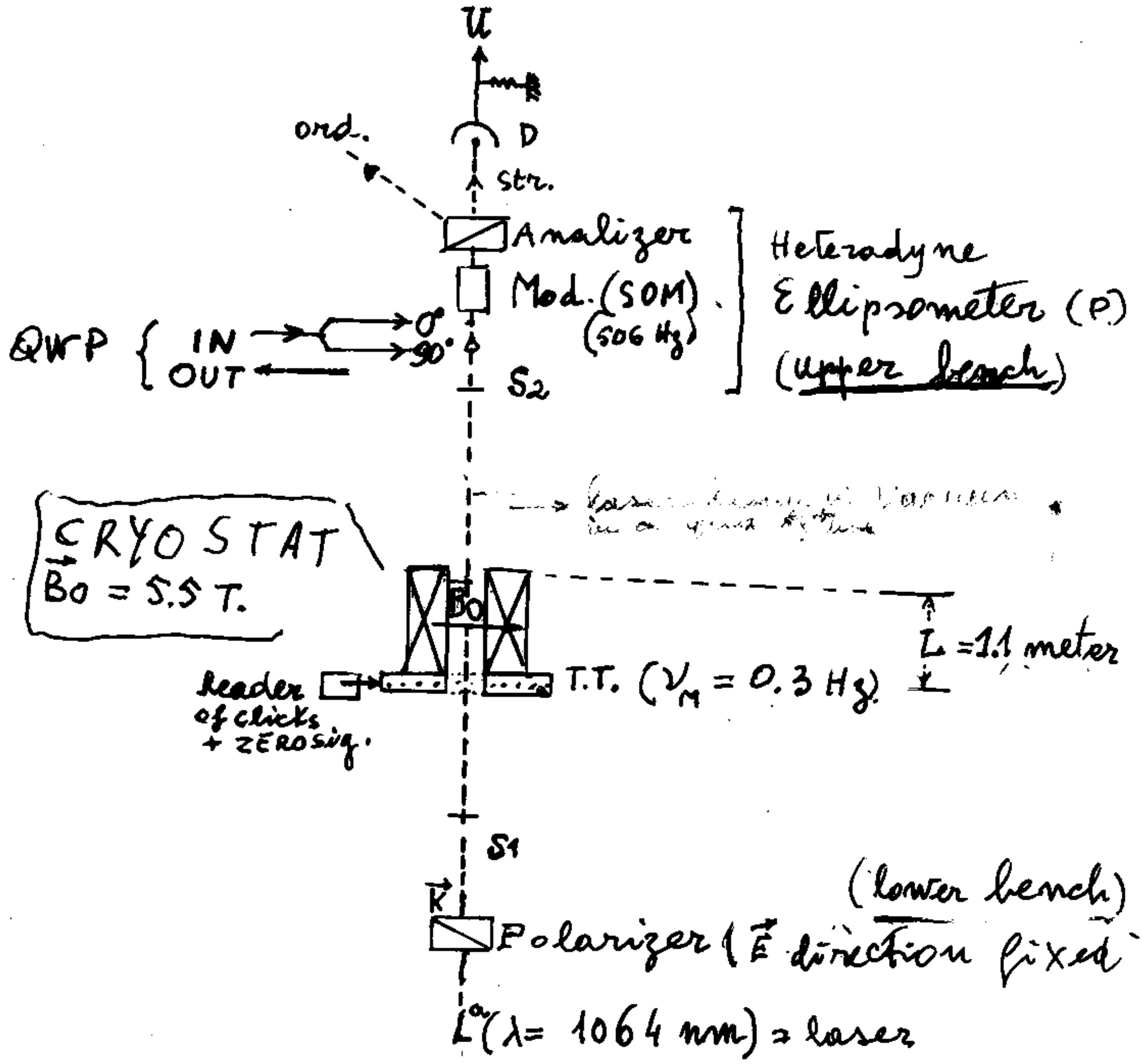
- The optics is mounted on two granite optical tables: the lowe one on the floor of the pit and the upper one on top of a granit structure 8 meters high also resting on the floor of the pit.

- The cryostat containing the superconducting magnet is fixed o a rotating turntable which in turn is fixed to a reinforced concret beam laying across the pit but resting on the building floor: whe the platform is rotating the field B_0 of the superconducting magne rotates remaining always on a horizontal plane. $\nu = 0{,}3$ Hz.

- As a result the concrete beam and cryostat are mechanicall decoupled from all the optical parts.

⑨ DICHROISM (of VACUUM+

↑ vertical direction : $\vec{B}_0$ contained in horizontal plane
while T.T. table rotates.



- [SOM STRESS_OPT. MOD.
- [S1 S2 → F. P. cavity locked with laser
  640 cm long
- [T.T. Turning Table
  (with hole center).
- Laser beam in Vacuum < 5.10^{-8} mb.
- L ~ "Interaction region.. cm. 100.

fig 10

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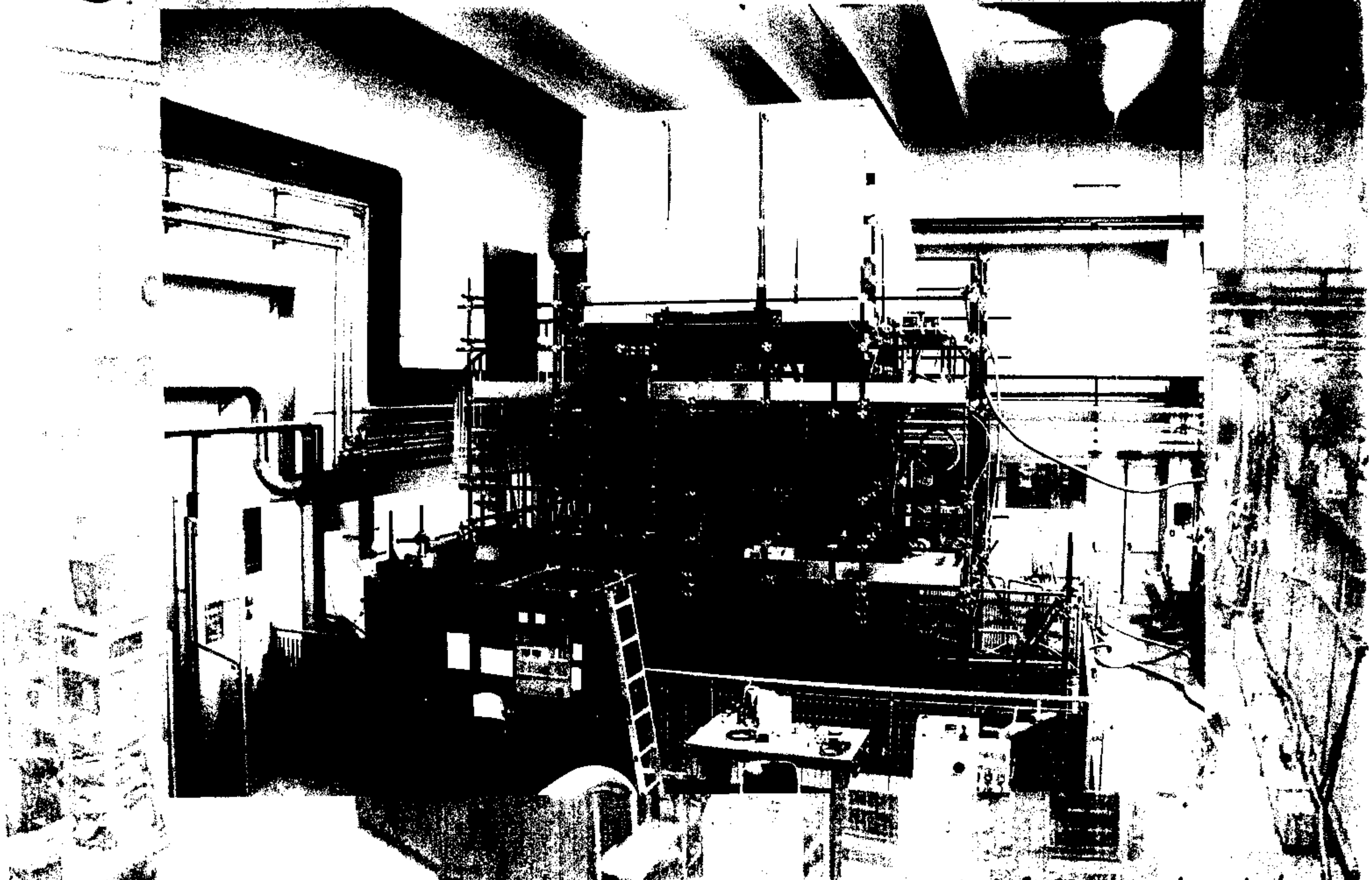
PVLAS hall at LNL



MAIN PARAMETERS OF THE PVLAS APPARATUS

- MAGNET

  VERY IMPORTANT

  DIPOLE, 6T, Temp. 4.2 K, 1 m FIELD ZONE = L_M

  $\vec{B}_0 \rightarrow$ HORIZONTAL

- CRYOSTAT

  ROTATION FREQ. (TYPICAL) ~300 mHz, SLIDING CONTACTS, WARM BORE

- LASER

  1064 nm, 100 mW, FREQUENCY-LOCKED TO THE FABRY-PEROT CAVITY

- FABRY-PEROT OPTICAL CAVITY $\boxed{S1 \quad S_2}$

  6.4 m LENGTH, FINESSE ~10^5, OPTICAL PATH IN THE INTERACTION REGION ~60 Km

- HETERODYNE ELLIPSOMETER

S.O.M.=ELLIPTICITY MODULATOR, QUARTER WAVE PLATE (ON-OFF), HIGH EXTINCTION (~10^{-7})

- SOM TIME-MODULATION OF THE EFFECT
  provides ellipticity carrier for Heterodyne
- DETECTION CHAIN.

  PHOTODIODE WITH LOW-NOISE AMPLIFIER

- DAQ

  DEMODULATED AT LOW FREQUENCY AND PHASE-LOCKED TO THE MAGNETIC FIELD INSTANTANEOUS DIRECTION

  HIGH SAMPLING FREQUENCY (8.2 KHz) DIRECT ACQUISITION

- DICROISM CONFIGURATION QWP in $\begin{cases} \rightarrow 0^\circ \\ \rightarrow 90^\circ \end{cases}$
- Ellipticity " " QWP out

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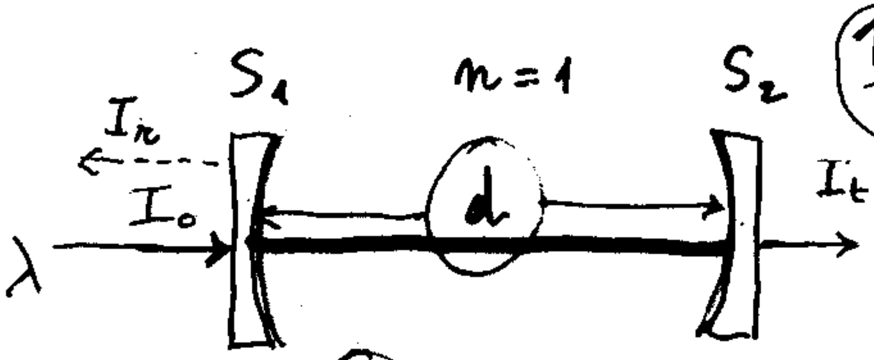
FABRY·PER



$\left(\frac{2d}{\lambda} = \text{intero}\right)$ ↔ résonan

$(T, R, q, \boxed{R_c})$

$$\left(\frac{I_t}{I_0}\right) = \eta_t^0 \frac{1}{1+\left(\frac{2F}{\pi}\right)\text{sen}^2\delta}, \left(\frac{I_r}{I_0}\right)$$

$$\delta = 2\pi \frac{2d}{\lambda}$$

$$\eta_t^0 = \left(\frac{TF}{\pi}\right)^2$$

$\lambda = 1060$ nm $\quad \nu = 3\,10^{14}$ Hz

$F = \frac{2\pi c}{2d}\boxed{\tau}$ finesse ($\gtrsim 10^5$) ⇢ ≃ reflec

$= R \Rightarrow \frac{2}{\pi}F$ -

$\boxed{\eta_t^0} = \left(\frac{TF}{\pi}\right)^2$ ratio I_t/I_0 at reson. $> 10\%$

$\underset{\text{(curva Airy)}}{\Delta\nu_c} = \frac{1}{2\pi\boxed{\tau}}$ Cavity linewidth (~ 300 Hz $\div 400$ Hz)

$Q = \frac{\nu_{light}}{\Delta\nu_c}$ quality factor ($\sim 10^{12}$)

$\nu_{FSR} = \frac{c}{2\boxed{d}}$ free spectral range (25 MHz)

} experi

$$\text{Th.}\begin{cases} F = \frac{\pi\sqrt{R}}{1-R} \\ \eta_t^0 = \left(\frac{TF}{\pi}\right)^2 \end{cases}$$

$$\overset{\sim 10^{-5}}{T} + R + \overset{\text{perdite}}{q} = 1$$

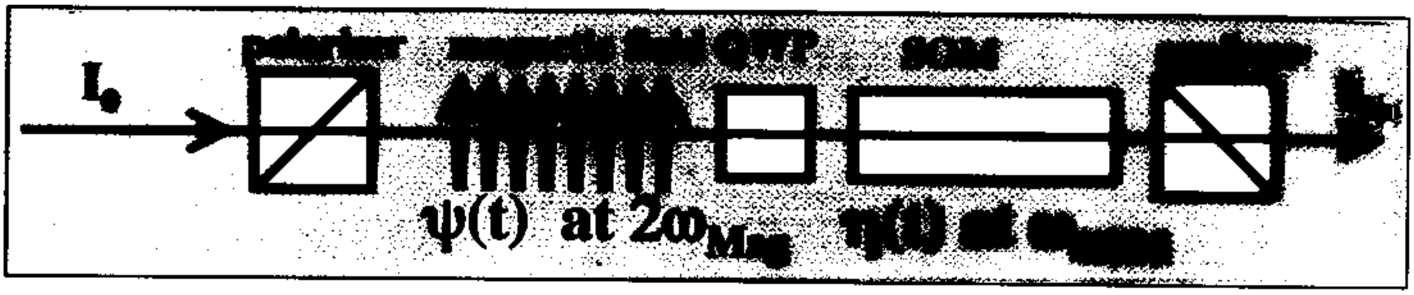
$$N_{refl.} \simeq \frac{2}{\pi}F \simeq \frac{2}{1-}$$

$\sim \frac{2}{3}$

For Dichroism CONFIGURATION

Measurement principle

- Static measurement is excluded.
- Modulate the field and add a carrier signal with a modulator at ω_{SOM}
- Rotating the field at Ω produces an ellipticity at 2Ω X (B² dependence) and Δα at 2Ω x



Ideally

$$I_{Tr} = I_0\left[\sigma^2 + \left(\Psi(t) + \eta(t)\right)^2\right] =$$

$$= I_0\left[\sigma^2 + \left(\Psi(t)^2 + \eta(t)^2 + 2\Psi(t)\eta(t)\right)^2\right]$$

Main frequency components:

- $2\omega_{SOM}$ from $\eta(t)^2$
- $\omega_{SOM} \pm 2\,\Omega_{Mag}$ from $2\Psi(t)\eta(t)$

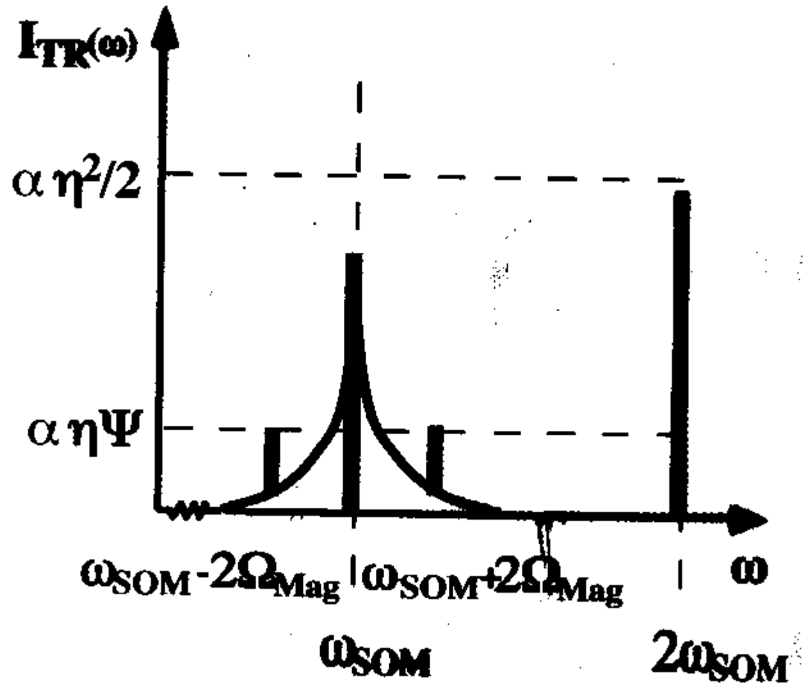
$$2\sin a \sin b = [\cos(a-b) - \cos(a+b)]$$

$$I_{Tr} = I_0\left[\sigma^2 + \left(\Psi(t) + \eta(t) + \alpha_s(t)\right)^2\right]$$

$$= I_0\left[\sigma^2 + \left(\underbrace{\eta(t)^2}_{\text{Normalization}} + \underbrace{2\Psi(t)\eta(t)}_{\text{Desired signal}} + \underbrace{2\alpha_s(t)\eta(t)}_{\text{Birefringence noise}} + \ldots\right)\right]$$

$$\boxed{\begin{array}{l} \Psi(t) = \Psi_0 \sin\left(2\Omega_{Mag} t\right); \quad \eta(t) = \eta_0 \sin\left(\omega_{SOM} t + \varphi\right) \\ 2\Psi(t)\eta(t) = \Psi_0\eta_0\left\{\cos\left(\left(\omega_{SOM} - 2\Omega_{Mag}\right)t + \varphi\right) - \cos\left(\left(\omega_{SOM} + 2\Omega_{Mag}\right)t + \varphi\right)\right\} \end{array}}$$

A small, time-varying signal can be extracted from a large noise background with the heterodyne technique.



In order to verify that everything is working as due (even under controle) we measured the birifrengenze of same gasses (N_2, Ne) and found in agreement to where to appear in a polar plot, as far as regards their PHASES

Notic $\underline{\underline{N_2}}$ appont to $\underline{\underline{Ne}}$

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→ELLEPTICITY CONFIGURATION

Measurement principle

- Static measurement is excluded.
- Modulate the field and add a carrier signal at ω_{SOM}
- Rotating the field at Ω produces an ellipticity at 2Ω

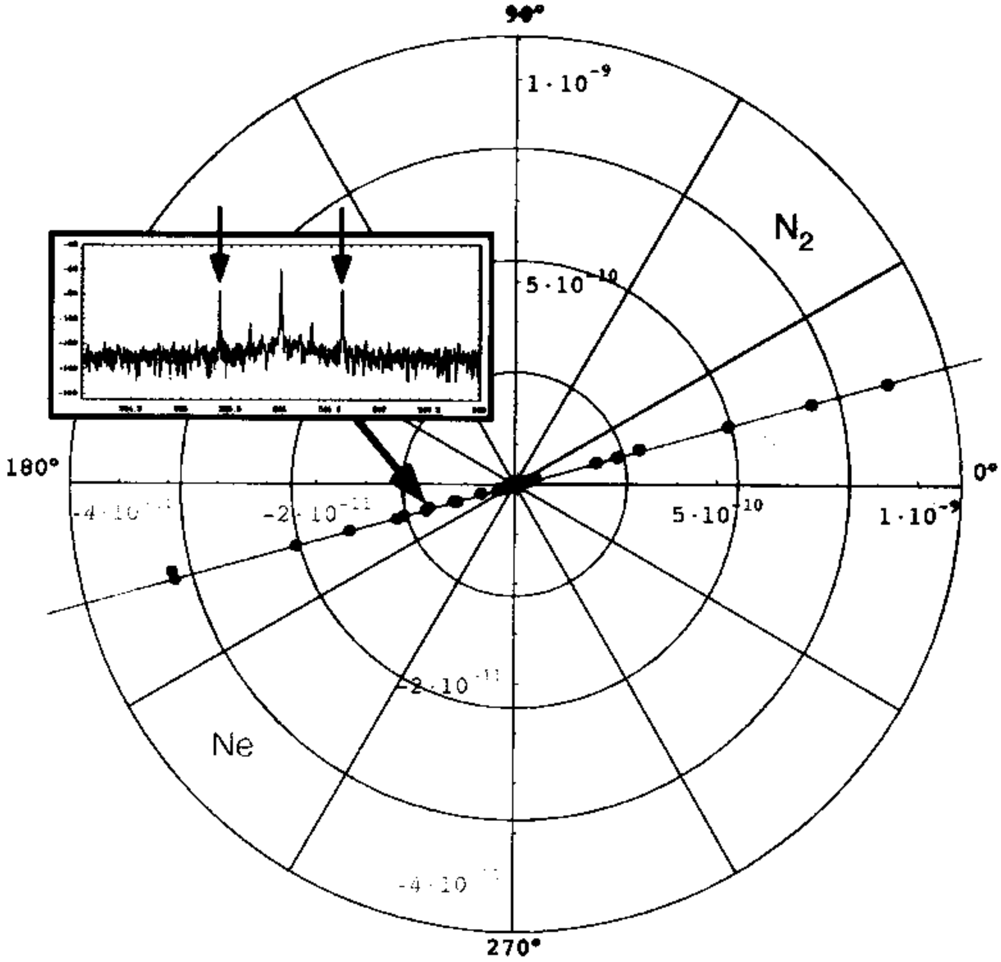
Ideally,

$$I_{Tr}=I_0\left[\sigma^2+(\Psi(t)+\eta(t))^2\right]=I_0\left[\sigma^2+\left(\Psi(t)^2+\eta(t)^2+2\Psi(t)\eta(t)\right)^2\right]$$

Main frequency components at $\omega_{\mathrm{SOM}}\pm 2\,\Omega_{\mathrm{Mag}}$ and $2\omega_{\mathrm{SOM}}$

↑

SOM = STRESS OPTICAL MODULATOR


90°
1·10⁻⁹
5·10⁻¹⁰
N2
180°
0°
-4·10⁻¹¹
-2·10⁻¹¹
5·10⁻¹⁰
1·10⁻⁹
-2·10⁻¹¹
Ne
-4·10⁻¹¹
270°

- PHYSICAL INFORMATION IS EXTRACTED BY ANALYSING AMPLITUDE AND PHASE OF THE FREQUENCY COMPONENTS OF THE LIGHT TRANSMITTED THROUGH THE ELLIPSOMETER

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Sensitivity

Shot noise sensitivity for PVLAS is

$$\sqrt{\frac{\mathbf{4e}}{\mathbf{I_0 q}}} = \mathbf{2 \cdot 10^{-8} / \sqrt{Hz}} \quad \simeq 150 \text{ mW}$$

+ altri (piatti)

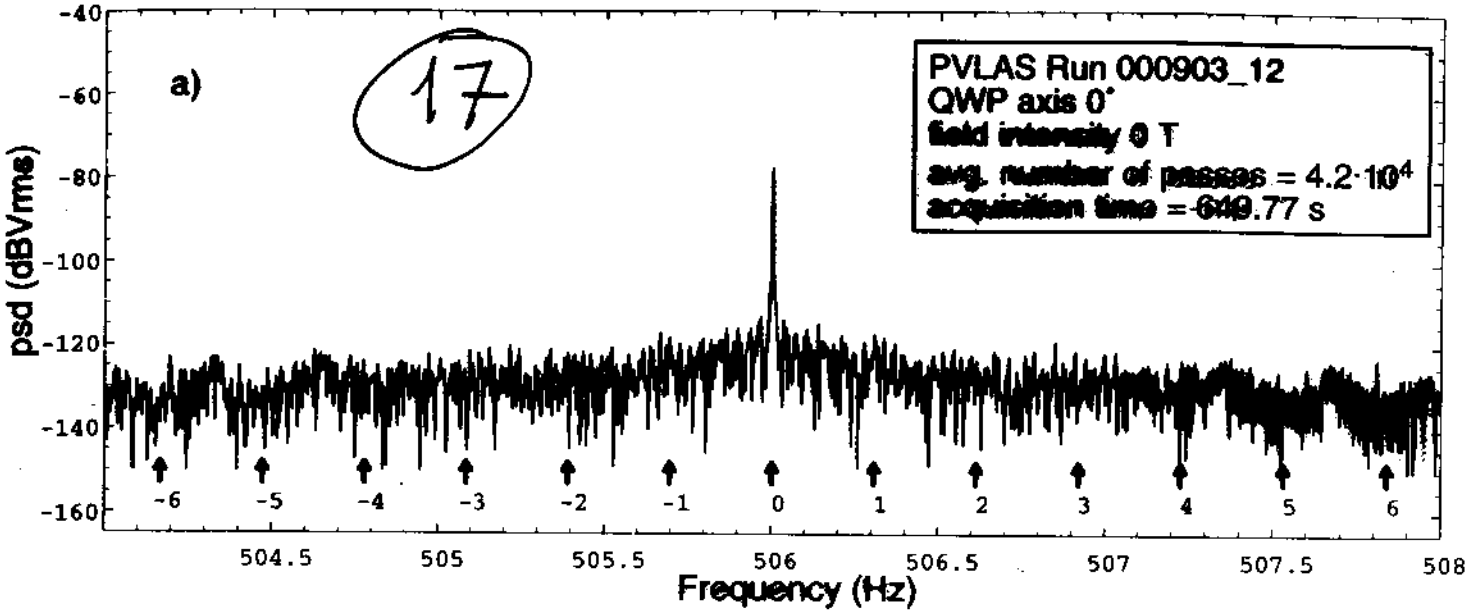
Present sensitivity for PVLAS is

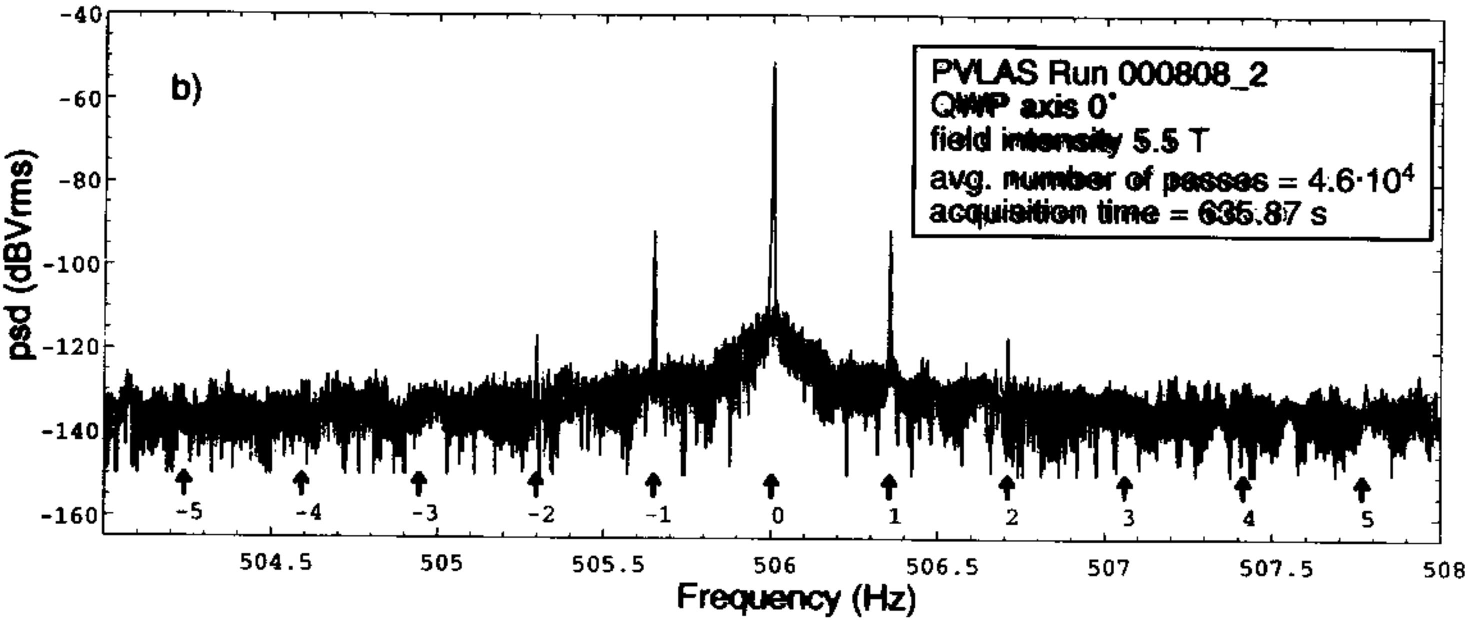
$$\approx \mathbf{2 \cdot 10^{-7} / \sqrt{Hz}}$$

contiene anche 3 dB dovuti al 1/f (½) (½) rumore bianco

Dichroism signal from PVLAS is

$$= \mathbf{(2.2 \pm 0.3) \cdot 10^{-7}\ rad}$$


a)
PVLAS Run 000903_12
QWP axis 0°
field intensity 0 T
avg. number of passes = 4.2·10^4
acquisition time = 649.77 s
psd (dBVrms)
-40
-60
-80
-100
-120
-140
-160
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
504.5
505
505.5
506
506.5
507
507.5
508
Frequency (Hz)


b)
PVLAS Run 000808_2
QWP axis 0°
field intensity 5.5 T
avg. number of passes = 4.6·10^4
acquisition time = 635.87 s
psd (dBVrms)
-40
-60
-80
-100
-120
-140
-160
-5
-4
-3
-2
-1
0
1
2
3
4
5
504.5
505
505.5
506
506.5
507
507.5
508
Frequency (Hz)

Segnali intorno a 506 a destra

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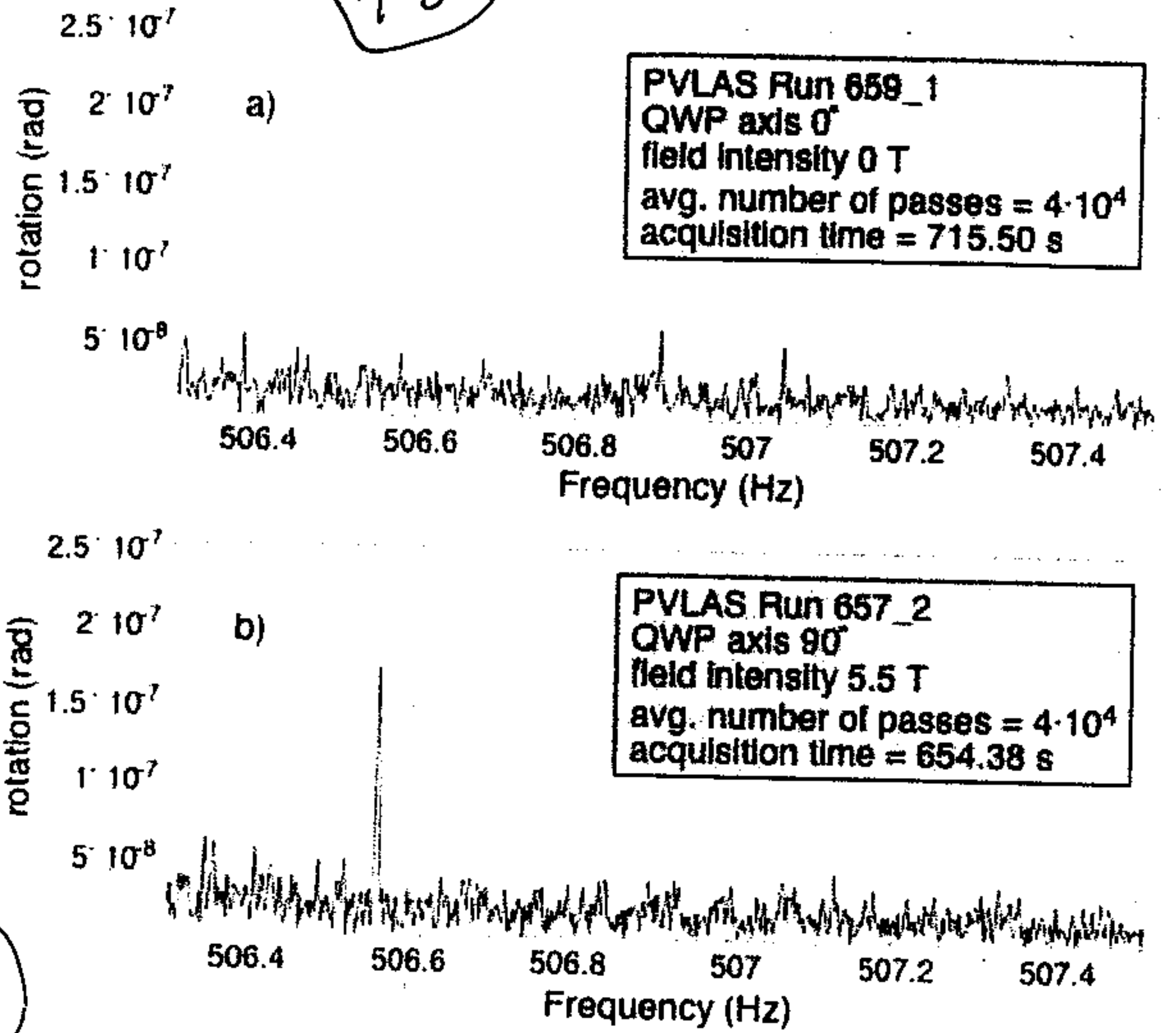

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Results for the measured dichroism in vacuum

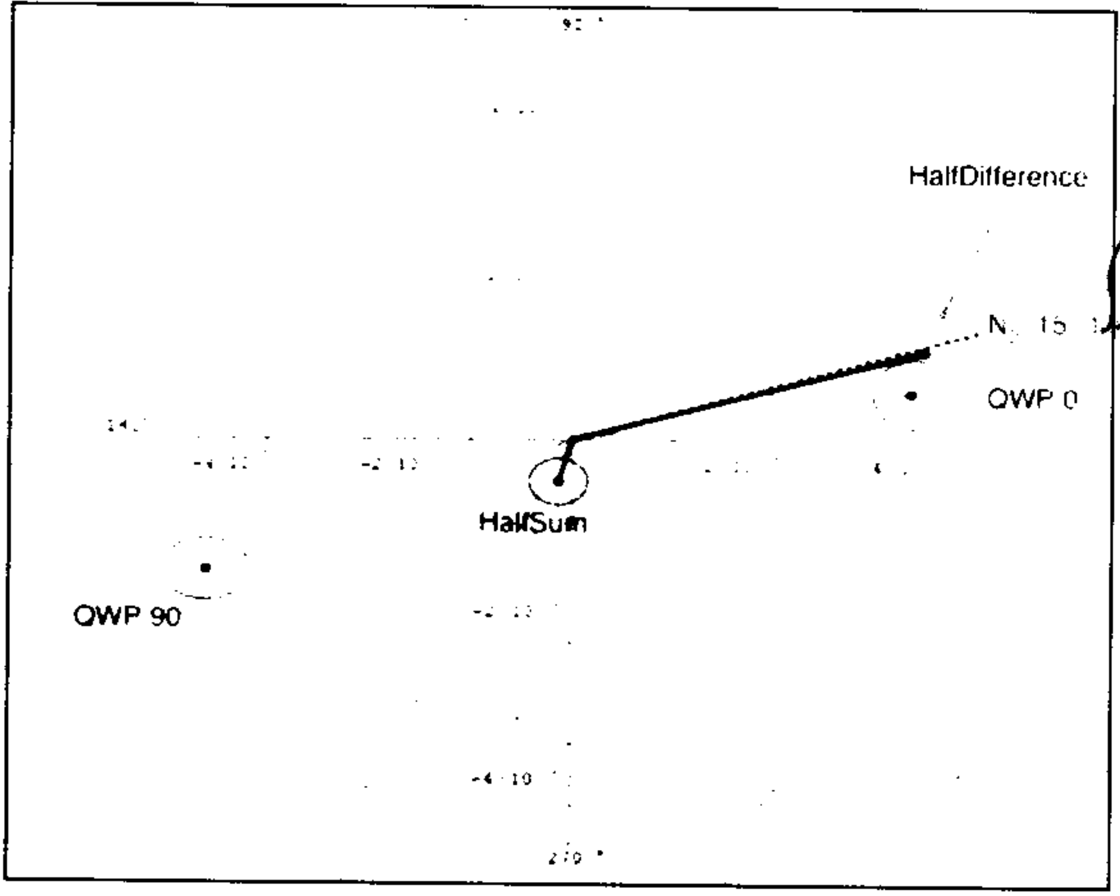
– – QWP 90°: Result of weighted average with the quarter wave plate at 90°

– – QWP 0°: Result of weighted average with the quarter wave plate at 0°

…… N_2: Physical axis defined by measuring the Cotton-Mouton effect in Nitrogen

—— HalfDifference: $\frac{\overline{QWP90^\circ} - \overline{QWP0^\circ}}{2}$ = Dichroism

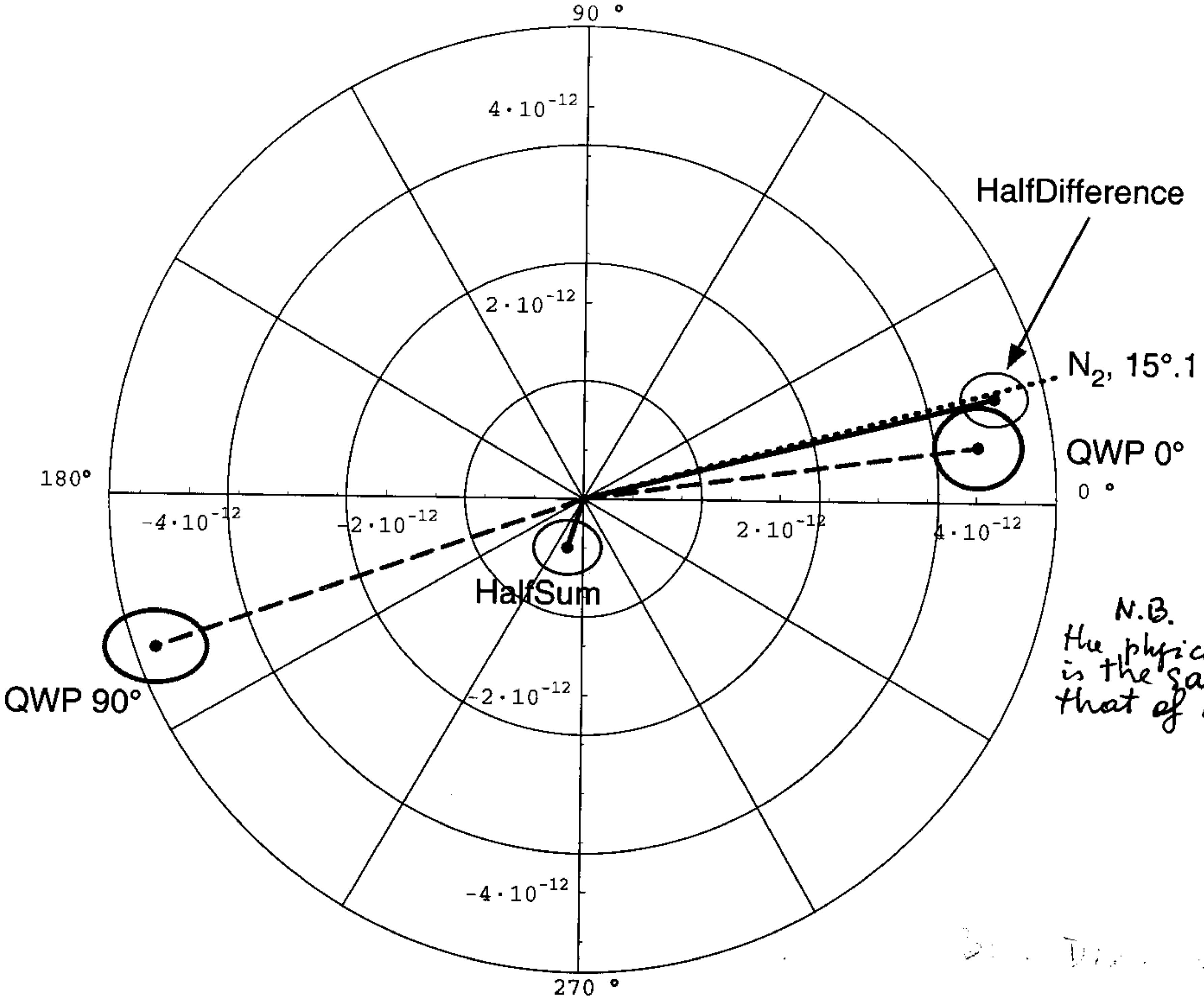
—— HalfSum: $\frac{\overline{QWP90^\circ} + \overline{QWP0^\circ}}{2}$ = Spurious signal



it poin
at N_2

Dichroism signal = (2.2±0.3)·10⁻⁷ rad = $\Delta\alpha$

The phase of the vacuum dichroism equals the phase of the Nitrogen Cotton-Mouton effect: both in turn agree with the expect axis of asymmetry



N.B.
the physical axis
is the same as
that of Neon

Final result

$$\overset{\text{Mor}}{\Delta\alpha} = -\frac{q-1}{2} = (2.2 \pm 0.3)10^{-7} \text{ rad}$$

with the conditions

$l_m = 110$ cm

$|B_0| = 5.51$ Tesla

$N = 52\,000 = \frac{2}{\pi} F$

$F = \frac{\pi c \tau}{d_{Mi}}$: τ measured

$$420 \leqslant \tau \leqslant 620\ \mu s$$

[accenno accordo o disaccordo con B.N.L. ?]

QUESTION what is the origin of $q \neq 1$?

1) Possible unexpected sistematic mistake

2) if real : is it an absorption ? a mixing ? (of photons).

We have planned a "near-future" shut down in order to rebuilt the apparatus correcting same malfunctions that we have learned. Among others:

a) Sismic general insulations
b) correct, via optical feedback, the residual beam movements : improve the housing of the optical pieces
c) $\lambda \to \lambda' = \lambda/2$ (532 nm) "Green" (one can see it !)
d) improve the phonic-shielding

3) May be we seeing a strong QED-QCD interfence - ending with photon splitting -

④ DECIDED The most important thing now is determine $\boxed{m_a}$ To see if our apparatus is O.K

Hypothesis

absorption

mixing (particle of mass $m_b c^2$)

$\downarrow$

We have an expression to which compare the obtained results

However test of coherence

$m_b < \frac{2\pi\omega}{LM}$

$\downarrow$

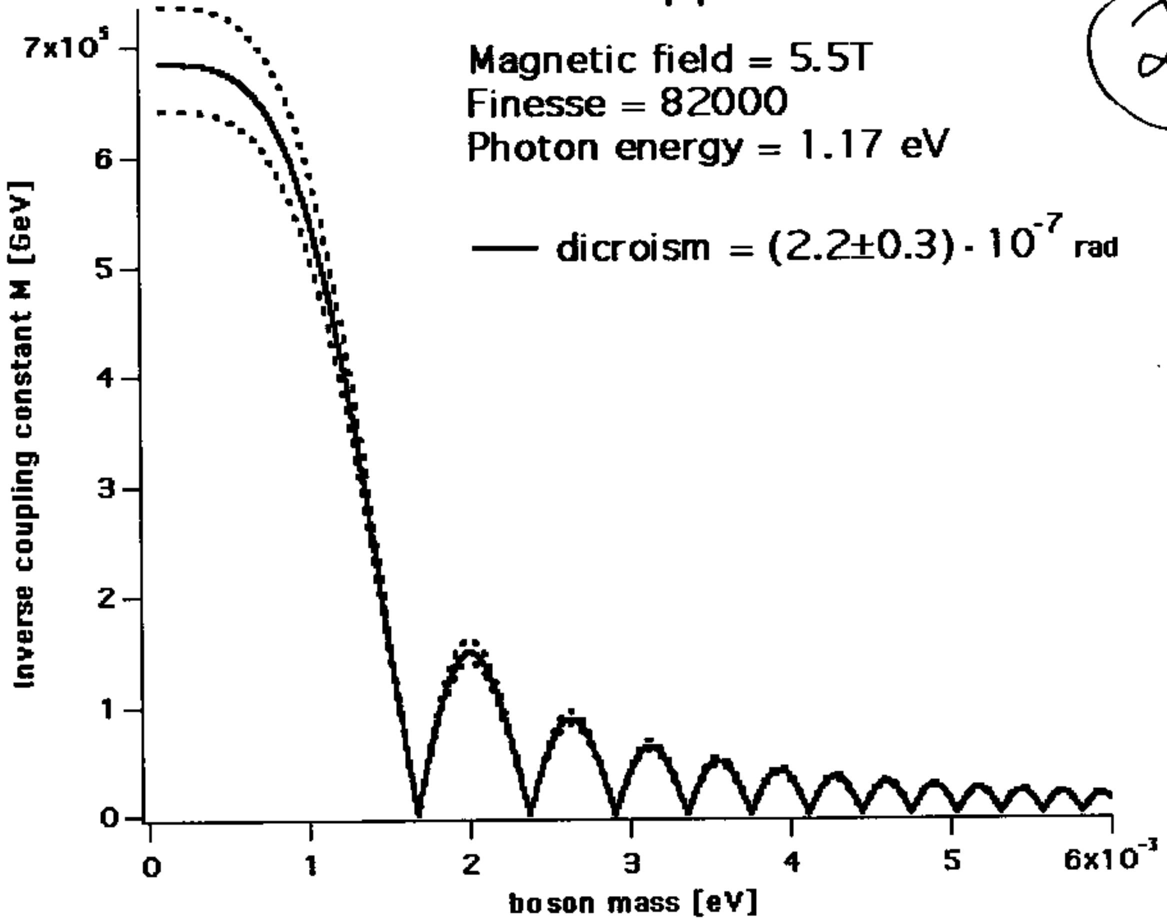
$\sim 1.3\,10^{-3}$ ev

$\downarrow$

method to find $m_b c^2$

Hypothesis : the observed rotation due to a mixing of the photons (of the beam) with a light boson (mass = $m_b c^2$) neutral and with a coupling to two photons $\frac{1}{M}$ GeV^{-1}

㉓



Natural Heaviside-Lorentz units

$$\Delta\alpha = \boxed{\varepsilon = -\sin(2\alpha)\left(\frac{BL}{4M}\right)^2 N\left(\frac{\sin x}{x}\right)^2} \leftarrow$$

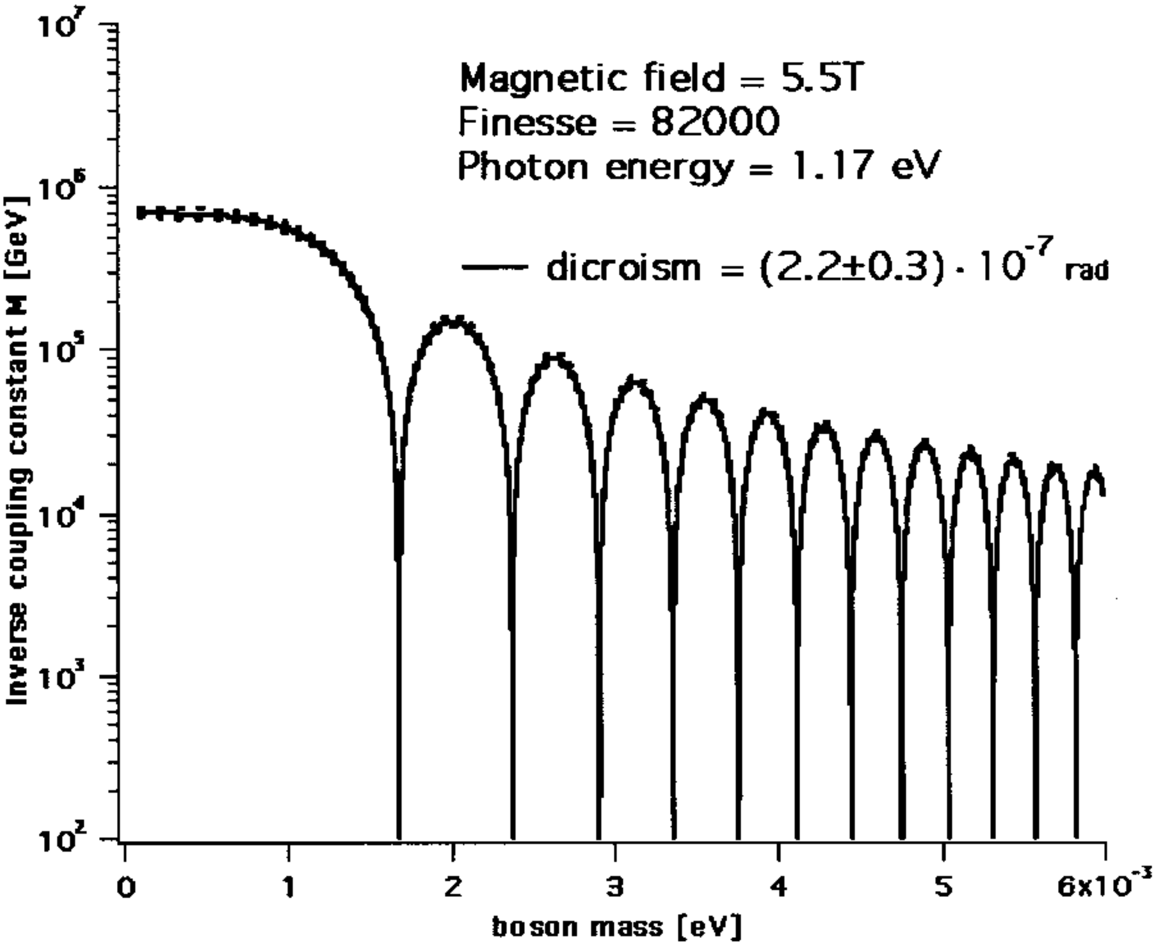
rotation signal

(if)

due to a boson mixing wi a γ

$$\boxed{\begin{array}{l} x = \dfrac{L}{2}\left[\dfrac{{k_m}^2}{2k} + (n-1)k\right] \\ k = \dfrac{2\pi}{\lambda}; \qquad N = \dfrac{2F}{\pi}; \qquad k_m = \dfrac{mc}{\hbar} \end{array}}$$

$m_b c^2$ = mass of the boson.



Nautral Heaviside-Lorentz units

$\bar{N} = \frac{3}{\pi}$ Finesse ≃ 52000

Expecting to finish analyzing data on ellipticity soon.

(1) Adapt expression for $\Delta^{\circ}\alpha$ coming from the Hypothesis of "existing" a light BOSONS (of mass $m_a c^2$), neutral, coupled to two photons with a c.c. $\frac{1}{M}$ gev^{-1}

$$\left.\begin{aligned} \Delta\alpha^{\circ} &= \left(\frac{BL}{4M}\right)^2 \left(\frac{\operatorname{sen} X}{X}\right)^2 \cdot N \\ X &= \frac{L}{2}\left[\frac{K_m^2}{2K} + (n-1)K\right] \end{aligned}\right\} Ⓐ$$

$K = \frac{2\pi}{\lambda}$

$N = \frac{2}{\pi} F$

$K_m = \frac{m c^2}{\hbar c}$

n = index of refraction (1 atm.) of neon

$$\boxed{n-1 = 6.7 10^{-5}}$$

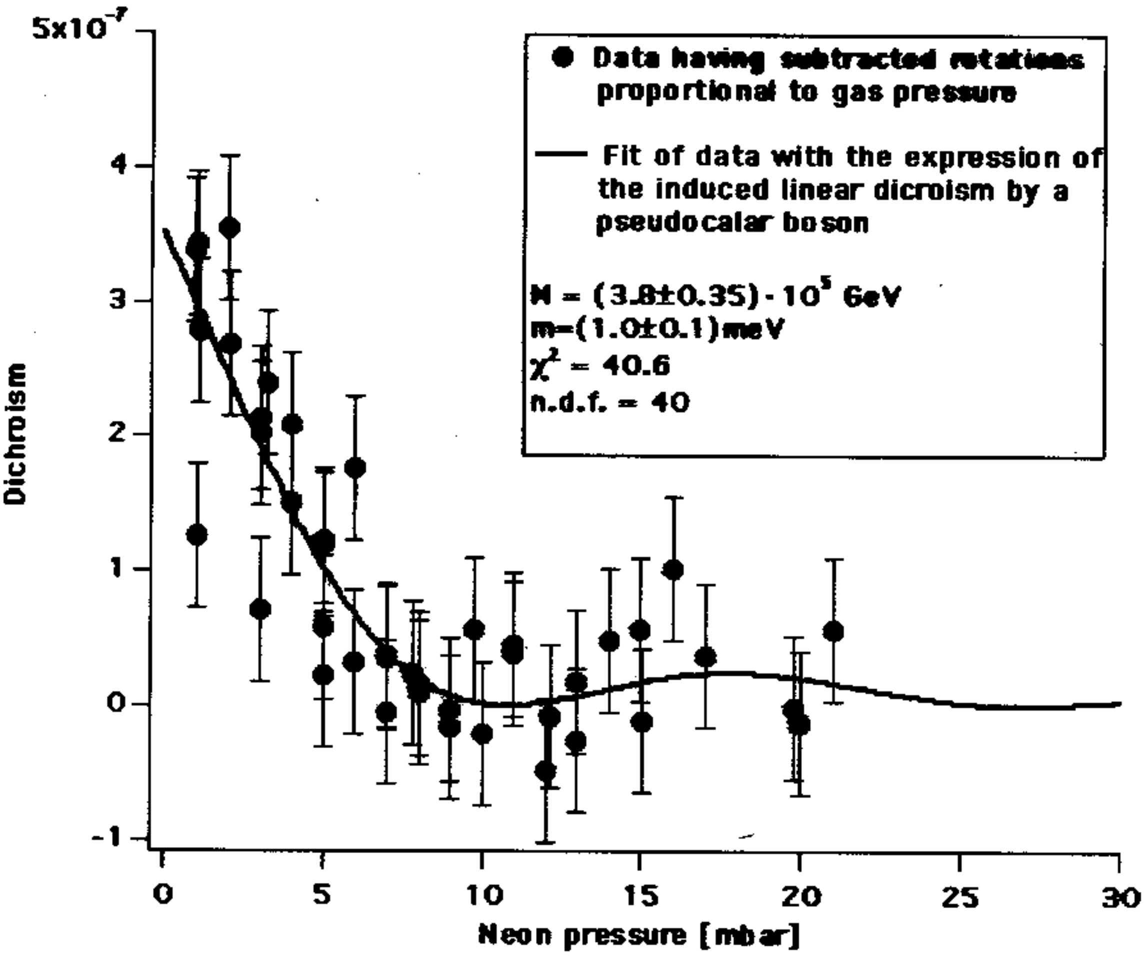
(2) take many data with different pressure of neon

(3) do fits of expression Ⓐ after subtracted the signal due to the Cotton-Mouton effect of neon (component proportional to pression) thus to deduce $m_a c^2$ = mass of the "Hypotetical boson"

→ then produce the test of coherence for our apparatus (see preceding page)

Dichroism Vs. Neon pressure

QWP 0°



$M = (3.8\pm0.35)\cdot10^5$ GeV

$m = (1.0\pm0.1)$ meV $\longrightarrow \left[(1.0 \pm 0.1) < 1.3\right] 10^{-3}$ eV

- O.K. -

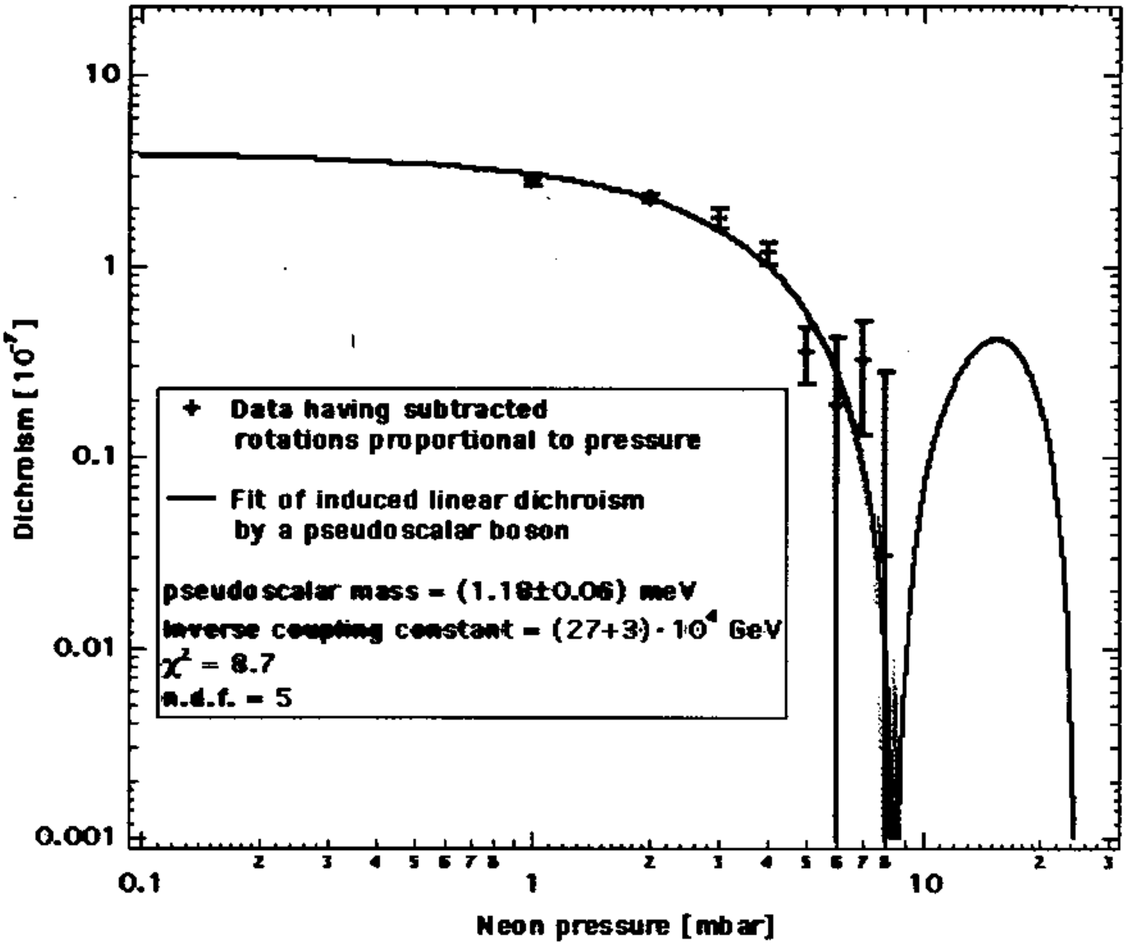
•$P_{Neon} = 0$ => Dichroism = $(2.9\pm0.4)\cdot10^{-7}$ rad

•Vacuum dichroism = $(2.2\pm0.3)\cdot10^{-7}$ rad

all referred to number of passes ≈ 52000.

un surprisingly big!

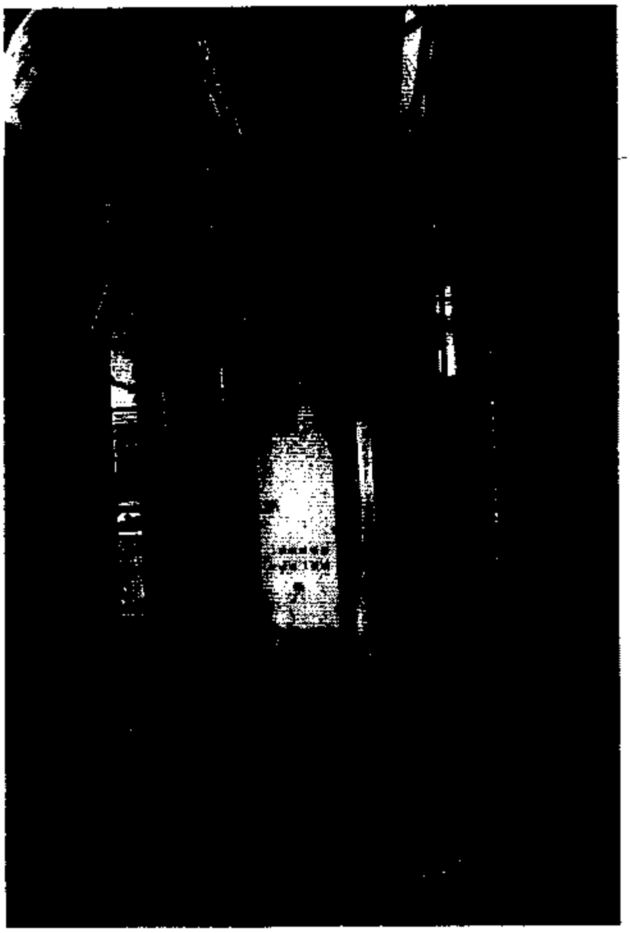
Dichroism Vs. Neon pressure



QWP 0°

- fig 11 d

The cryostat showing the quench protection system.



quench [illegible]

$L_{MAGNET} = 11$

L_M small to preserve the relative phase between the light boson and the photon's field.

$$m_b < m_0^2 = \frac{2\pi\omega}{LM}$$

$$m_0^2 \approx (1{,}3\ 10^{-3} ev)^2$$

$\downarrow$

inequality to be verified.

	m_a [eV]	M [GeV]	$g_{a\gamma\gamma} = \frac{1}{M}$ [GeV^{-1}]
PVLAS Ne DATA	$(1.0 \pm 0.1) \times 10^{-3}$	$(3.8 \pm 0.4) \times 10^{5}$	$(2.6 \pm 0.5) \times 10^{-6}$
PVLAS VACUUM ROTATION	$[(1.0 \pm 0.1) \times 10^{-3}]$	$(5 \pm 1) \times 10^{5}$	$(2.0 \pm 0.4) \times 10^{-6}$
BFRT [PRD 47, 9 (1993)] ELLIPTICITY DATA ONLY	$[(1.0 \pm 0.1) \times 10^{-3}]$	$\geqslant (4 \times 10^{5})$	$\leqslant 2.5 \times 10^{-6}$

- Compatible with a photon-boson mixing mechanism

$m_a c^2 \approx (1.0 \pm 0.1)$ MeV ; $M^{-1} = (3.8 \pm 0.35) 10^5$ geV

International Workshop on "Neutrino Telescopes"

① We observe in vacuum a polarization rotation signal

$\Delta\alpha \neq 0$

② a possible interpretation is to assume the existance of a very light, neutral, pseudoscalar boson coupled to two photons. TEST coherence O.K.

③ With these Hypotheses we obtain

$m_b = 1 \pm 0.1$ meV

$g_{\gamma\gamma} = (2 \div 3) 10^{-6}$ GeV^{-1}

④ We plan to confirm these results in the near future by using energy doubled laser photons.

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