PVLAS developments on Fabry-Perot resonators locked to CW lasers and suitable for laser assisted Lorentz stripping of H– beams

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PVLAS collaboration

Summary

- ***Brief*** introduction to PVLAS
- Status of the Optics
  - IR 1064 nm laser at LNL
  - visible 532 nm laser in Trieste
- Original techniques and PVLAS driven developments
- Perspectives

PVLAS

PVLAS collaboration

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PVLAS experiment

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PVLAS principle

Investigate Quantum Vacuum as a "material medium": perturb it with a magnetic field and probe it with a polarised light beam

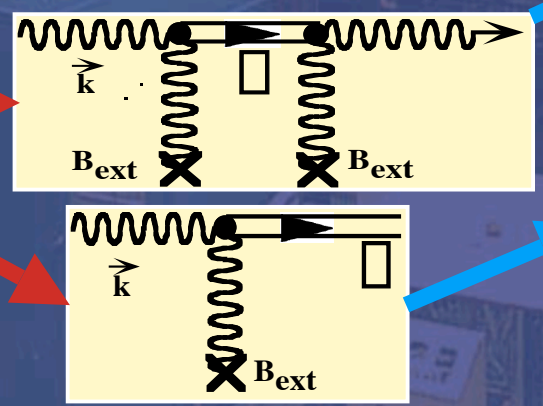
PVLAS physics

Quantum Vacuum as a **birefringent** medium

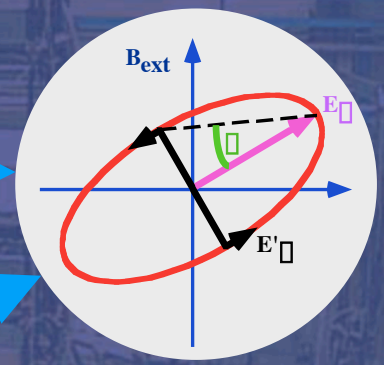
QED and photon-photon scattering

Neutral, light (*axion-like*) particles interacting with two photons (dark matter candidates)

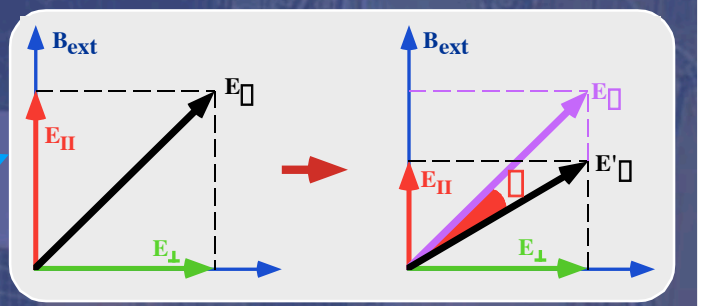
Leading diagrams



Physical effect



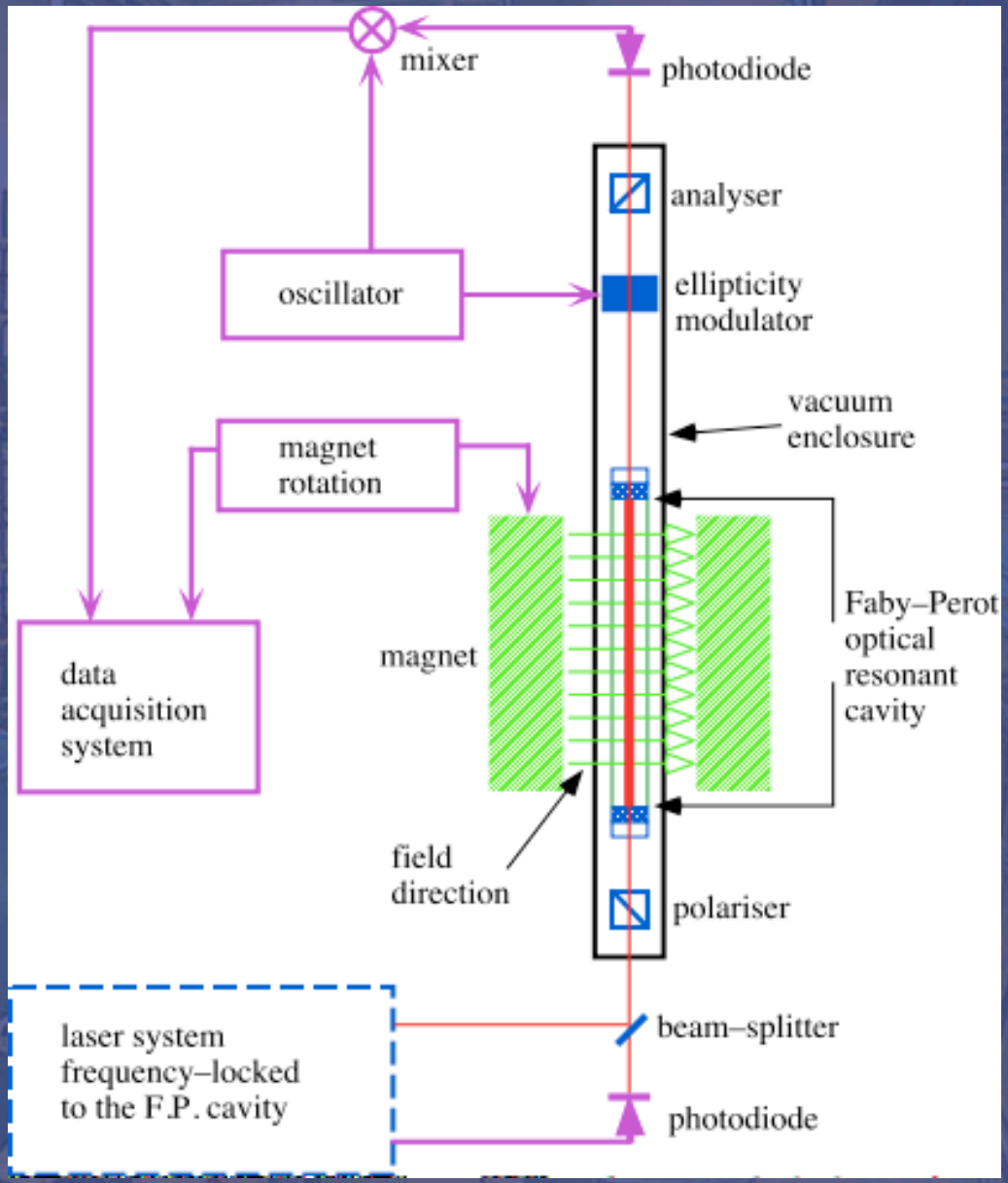
Ellipticity

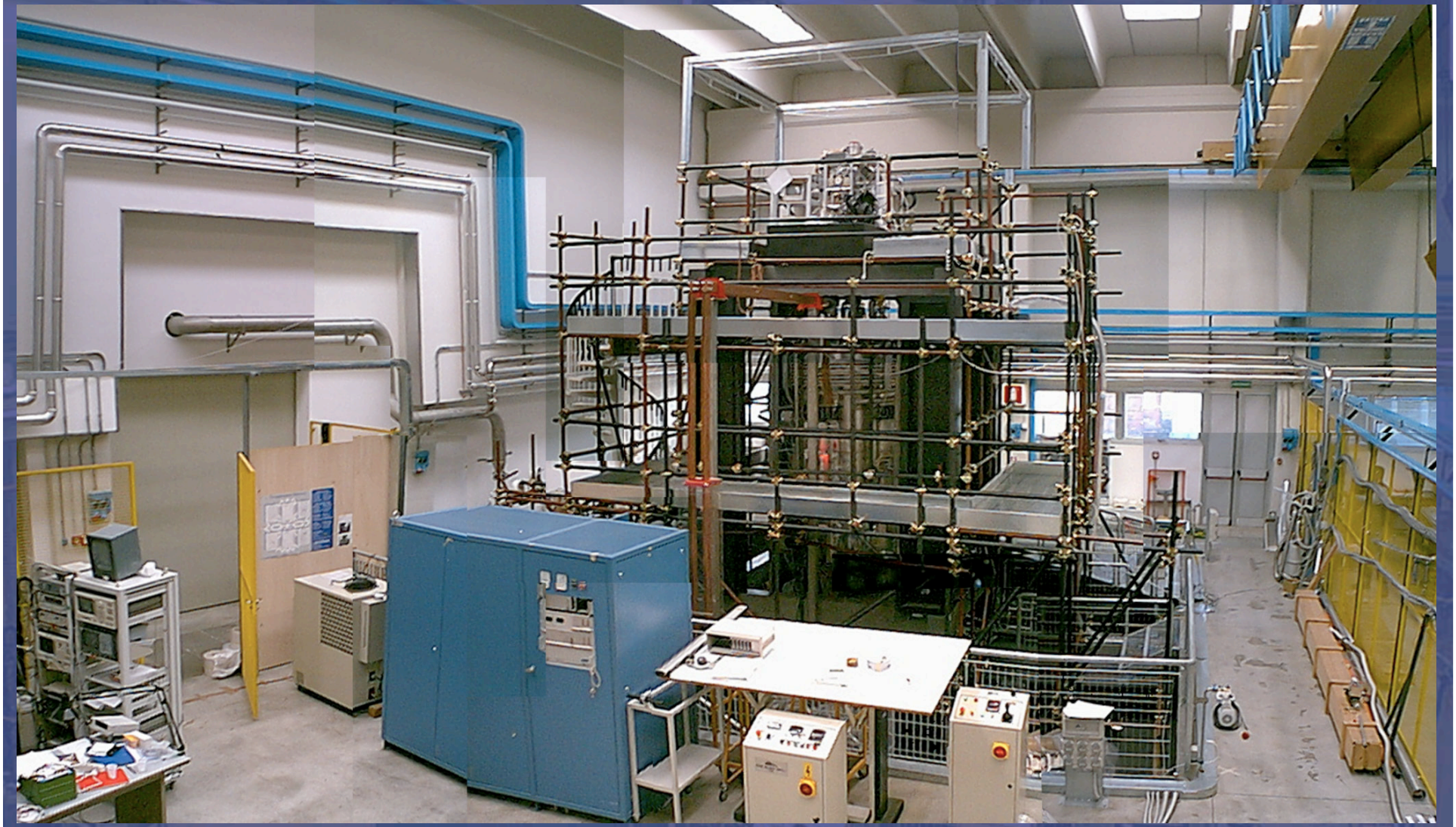


Dichroism

PVLAS principle

- The basic idea is to measure polarization changes induced on a probing light beam by the structure of the vacuum when modified by an external magnetic field
  - A sensitive optical ellipsometer is used to perform heterodyne detection of elliptical polarization: index of refraction differences of about 10^{-22} must be detected
  - A Fabry-Perot cavity increases the optical path in vacuum region, where a superconducting, rotating magnet establishes a time-varying field
  - The vacuum then acts as a birefringent medium changing the light polarization from linear to elliptical





PVLAS status - March 2002

Milestones

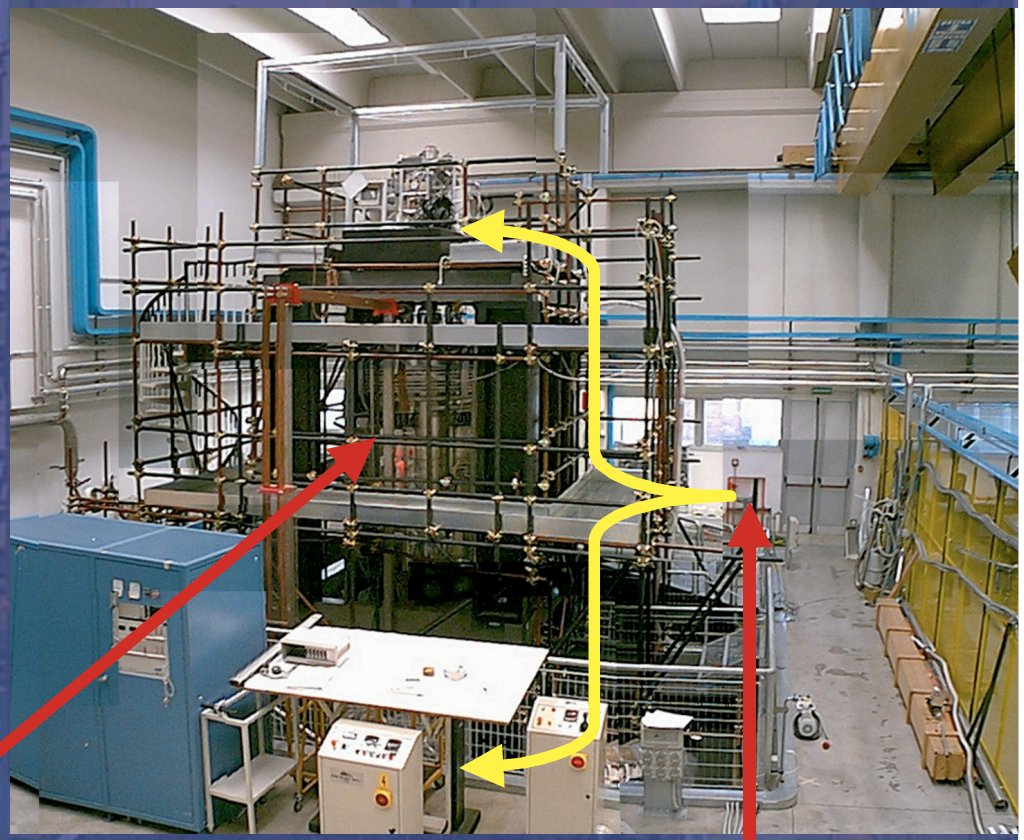
Achieved in 2001

- **installed Stress Optical Modulator (SOM) device (developed within the collaboration)**
- **several hours of data taking**
- **observed a "signal" at the expected frequency**
- **initiated series of tests to clarify the nature of the "signal"**

Projected in 2002

- **prove/disprove that "signal" is of physical origin**
- **upgrade apparatus to visible wavelength**
- **confirm year 2001 results**

INFN Legnaro National Lab. PVLAS site (Padova, Italy)



- Main technologies
  - Superconducting, liquid He, 6 Tesla rotating magnet/cryostat
  - High finesse/high Q (F ~ 100000,Q ~ 10^{12}) **6.4 m long** Fabry-Perot optical resonator

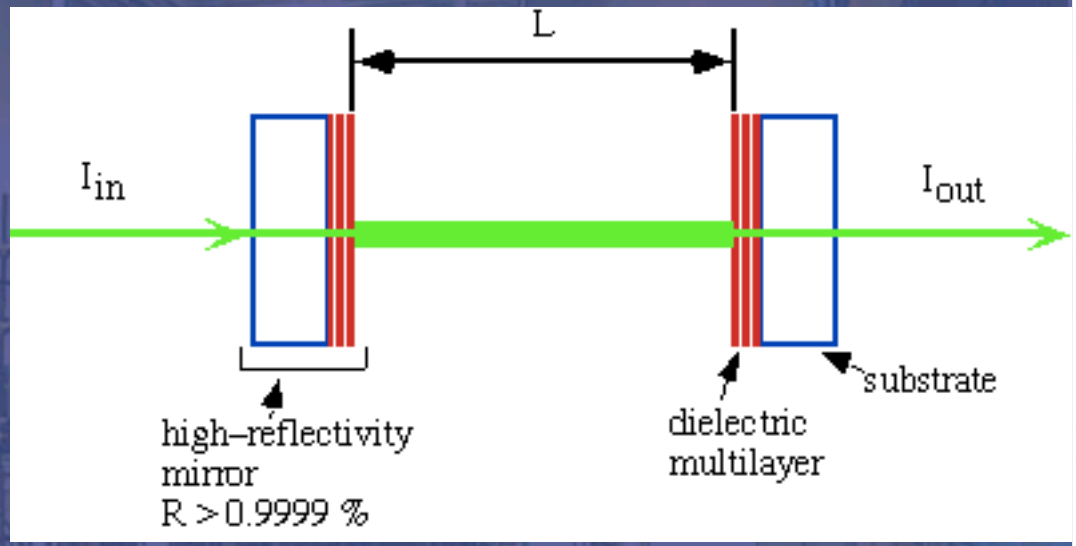
PVLAS - Main results as of March 2002

- Measurement runs have been conducted in the following conditions:
  - interaction region under vacuum ($P < 10^{-7}$ mbar)
    - $B = 0$
    - B from 3 T to 5.6 T
      - two different initial polarization states
  - interaction region filled with N_2, Kr, Xe
    - several pressure values from ~10^{-3} mbar to ~1 mbar
- Results as of February 2002
  - in vacuum
    - when $B = 0$ no signal is observed at the expected frequency
    - when $B \neq 0$ a peak appears in the signal spectrum at the expected frequency
      - preliminary evidence of "correct" dependence from B^2 and the initial polarization state
  - in gas
    - signal peaks at the expected frequency
      - preliminary evidence of "anomalous" peak amplitude in N_2 at low pressures
    - phase calibration of the apparatus
      - the vacuum peak phase appears to lie along the "physical" axis defined by the N_2 and Kr signal peak phases

Status of the Optics

The Fabry-Perot optical cavity

- A Fabry-Perot optical resonator (or "cavity") consists of two facing mirrors set at a distance L apart
- In a Fabry-Perot (FP) light can be "accumulated" by constructive interference when $L = n(\lambda/2)$
- The reflectivity R of the mirrors determines the "Finesse" of the resonator
- The larger F, the longer the optical path and a photon will, on average, bounce between the mirrors for a longer time
- Normally "supermirrors" with R~1 are used for FP's (in PVLAS R ~ 0.99997)



For an "ideal" (i.e. lossless) FP <u>at resonance</u>, when $L = n(\lambda/2)$, one has

$$I_{out} = I_{in}$$

For all FP's (with identical mirrors):

$$\text{Finesse} = \frac{\pi\sqrt{R}}{1-R}$$

$$\text{Optical path length} \approx \frac{2F}{\pi} L$$

Fabry-Perot useful parameters

- **Finesse**
  - the finesse can obtained by measuring the decay time τ of the light intensity transmitted by the cavity once the input light has been switched off

$$I_{TR}(t) = I_0 e^{-t/\tau}$$

$$\tau = \frac{Fd}{\pi c}$$

- **Cavity linewidth**

$$\Delta\nu_c = \frac{c}{2dF}$$

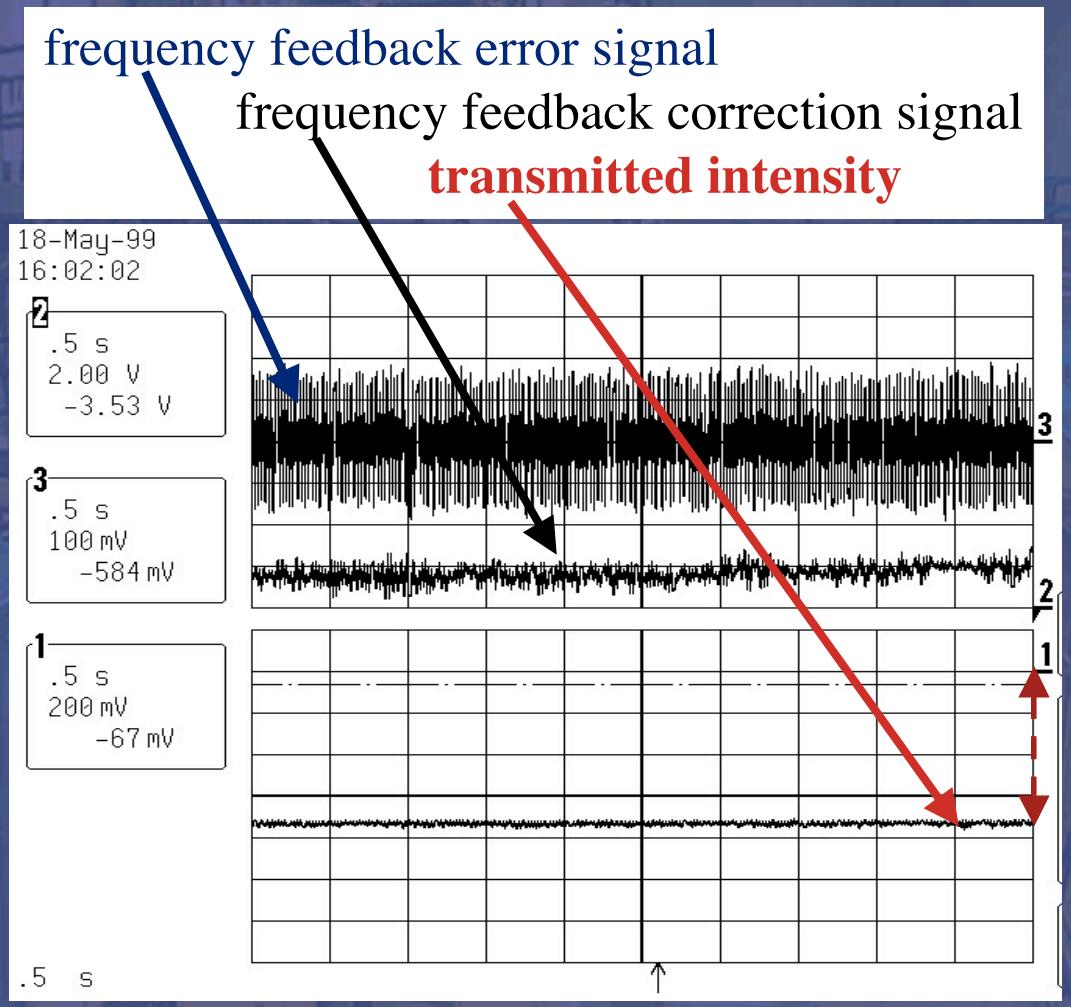
- **Resonator figure of merit**
  (ν_L is the light frequency)

$$Q = \frac{\nu_L}{\Delta\nu_c} = \frac{c}{\nu_L \Delta\nu_c}$$

PVLAS 6.4 m FP cavity

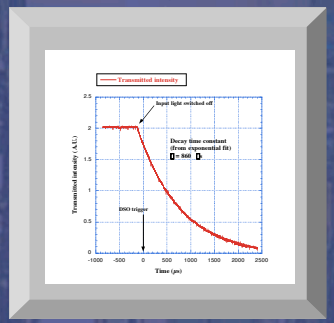
- Signals from the first resonant operation of the 6.40 m PVLAS cavity (L = 6.4 m, □ = 1064 nm) in May 1999

TEM00 mode in the cavity

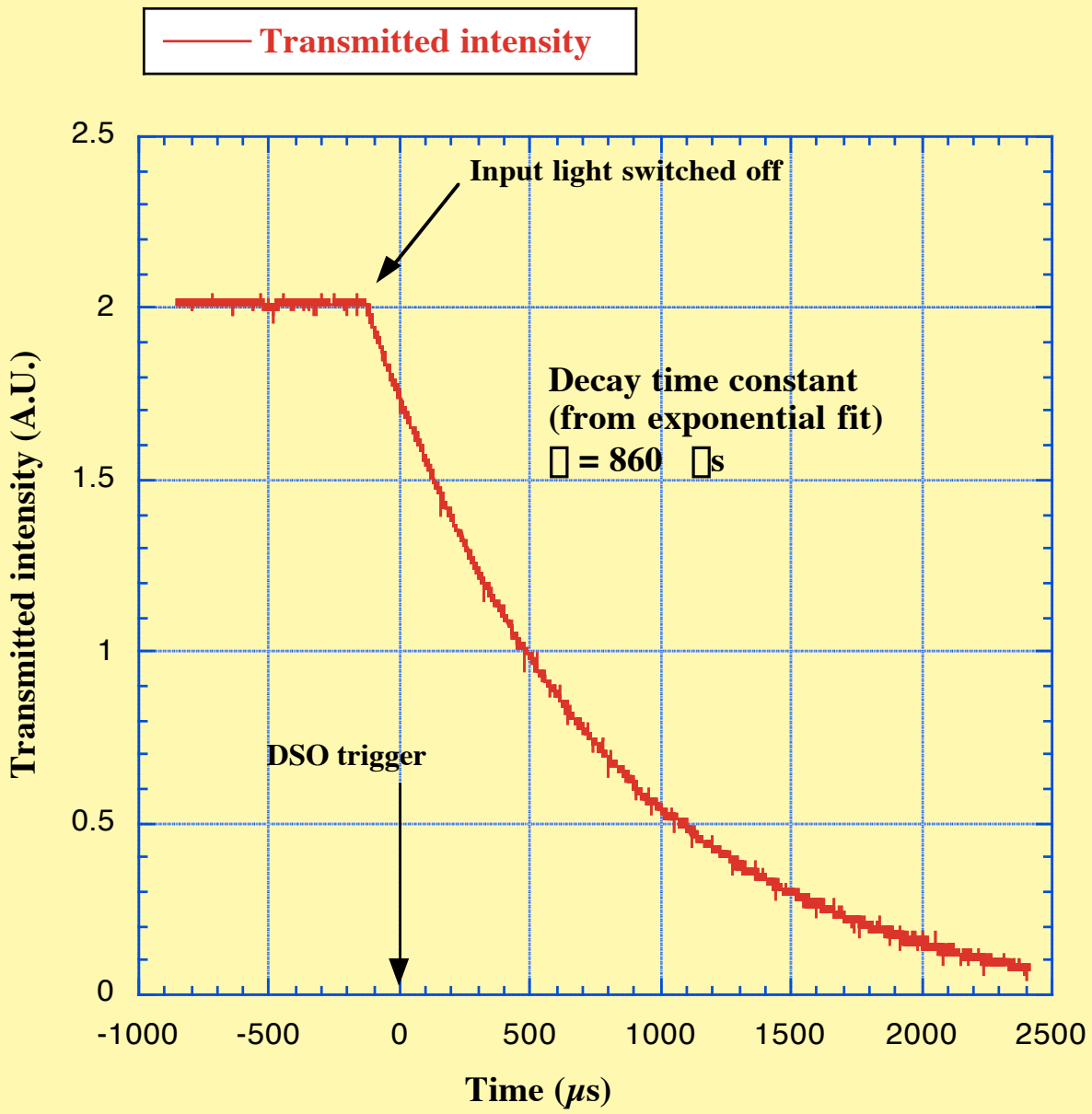


PVLAS FP cavity characterization

- Main parameters
  - L = 6.4 m
  - F > 1.2×10^5
  - N = 2F/□ = 63000 passes in the field region (~400 km !!!)
  - Q = 1.6×10^{12}
- Locking stable for unlimited time while magnet rotates
- Total path length within the magnetic region > 63 km !



Finesse measurement


Transmitted intensity
Input light switched off
Decay time constant
(from exponential fit)
= 860 s
DSO trigger
Transmitted intensity (A.U.)
Time (μs)
2.5
2
1.5
1
0.5
0
-1000
-500
0
500
1000
1500
2000
2500

Figures of merit comparison table

- PVLAS has built and is currently operating a very long, high finesse, Fabry-Perot resonant optical cavity
- This cavity achieved, at the time of first locking, the highest Q factor at that moment

	PVLAS INFN Italy	J. Hall NIST U.S.A.	P. Gill NPL UK	L. Marmet INMS Canada
wavelength	1064 nm	1064 nm	674 nm	674 nm
cavity length	6.4 m	0.47 m	0.10 m	0.25 m
FSR	23.4 MHz	319 MHz	1500 MHz	600 MHz
Finesse	86700	32000	200000	12000
line-width	270 Hz	10 kHz	7.5 KHz	50 kHz
Q	**10^{12}**	**2.8×10^{10}**	**5.9×10^{10}**	**8.8×10^{9}**

	GEO 600 Glasgow UK	Uehara et al. Tokyo Japan	LIGO Caltech U.S.A.	Schiller et al. Konstanz Germany
wavelength	514 nm	1064 nm	514 nm	1064 nm
cavity length	10 m	0.20 m	40 m	0.10 m
FSR	15 MHz	750 MHz	3.75 MHz	1.5 GHz
Finesse	10000	10300	1900	200000
line-width	1.5 kHz	7.3 kHz	2 kHz	7.5 kHz
Q	**10^{11}**	**3.8×10^{10}**	**7×10^{10}**	**3.8×10^{10}**

Original techniques and PVLAS-driven developments

Cavity resonance

- To operate, a Fabry-Perot cavity must be kept at resonance
- In practice, for mirror separations larger than a few cm, resonance can be maintained only by a feedback scheme:
  i. consider the laser wavelength λ fixed, and adjust mirror separation L to achieve the condition $L = n(\lambda/2)$ [n is an integer]
  ii. consider L fixed and tune the laser wavelength to achieve resonance
- In the Pound-Drever-Hall (PDH) locking scheme the instantaneous difference between L and $n(\lambda/2)$ is sensed and the laser wavelength is continuously adjusted to follow variations in L
- The PDH locking method exploits the fact that real cavities (with non-zero losses) reflect part of the light even at resonance

$$\tau_{FP} = \frac{\tau_1 \tau_2}{\left(1 - \sqrt{R_1 R_2}\right)^2}$$

$$R_{FP} = \frac{\left(\tau_1 \sqrt{R_2} - \sqrt{R_1}\right)^2}{\left(1 - \sqrt{R_1 R_2}\right)^2}$$

$T_{FP} + R_{FP} = \tau_1 = 1$-(losses)

$T_{FP} = \tau$ cavity transmittivity

$R_{FP} = r$ cavity reflectivity

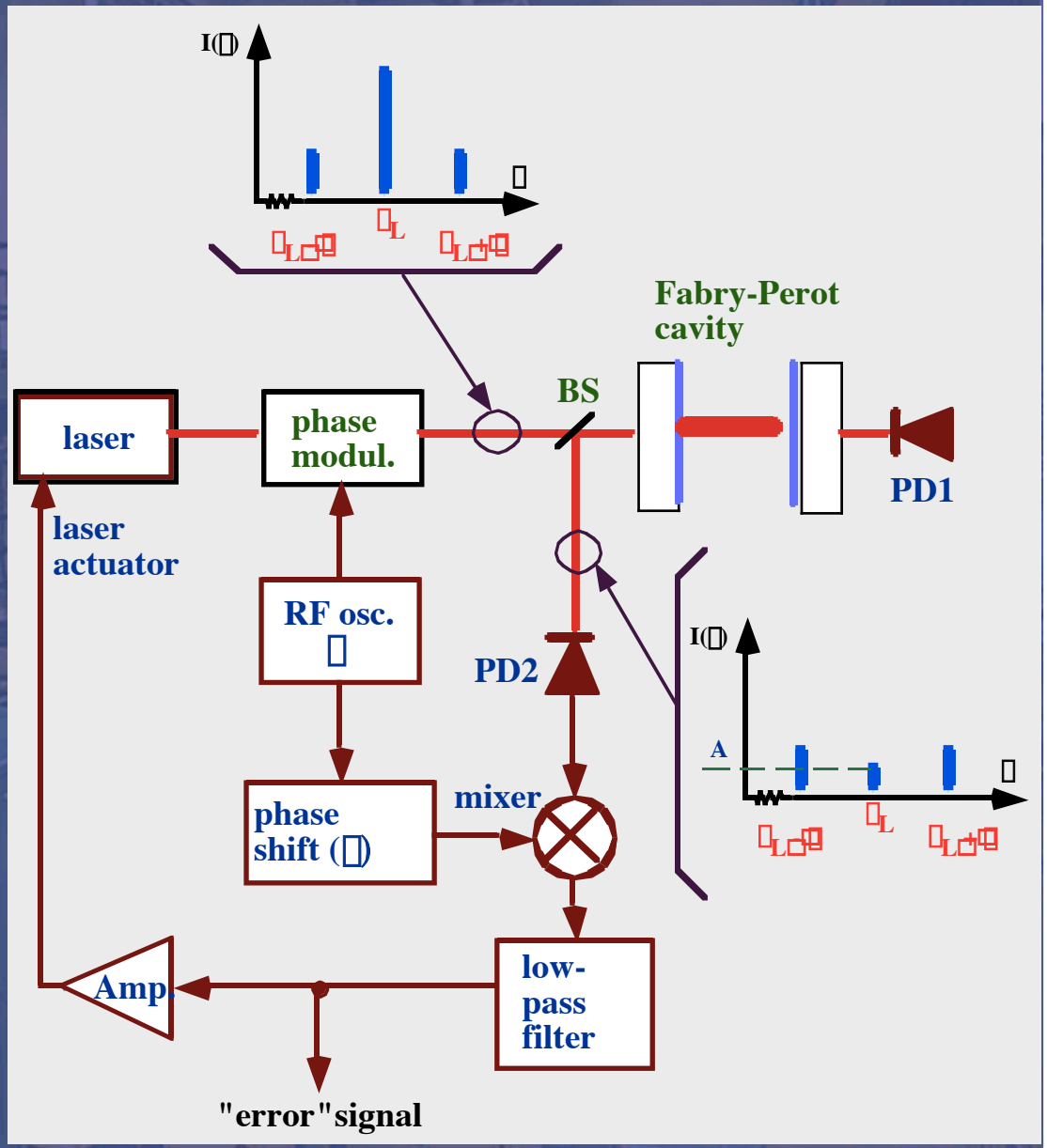
Pound-Drever-Hall frequency locking

- The error signal amplitude contains information on the instantaneous frequency difference between laser and cavity

$$V_{error} \quad (\text{Finesse}) \cdot \left(\nu_{laser} - \nu_{cavity} \right)$$

- The slope of the error signal determines the stability of the feedback loop

$$\frac{\partial V_{error}}{\partial \left(\nu_{laser} - \nu_{cavity} \right)} \quad (\text{Finesse})$$



PVLAS frequency locking

- In phase modulation $E(t) = E_0 e^{i(2\pi\nu_{laser} t + \beta \sin 2\pi\nu t)}\left[1 + (RAM)\cos(2\pi\nu t + \phi)\right]$
  the Residual Amplitude Modulation (RAM) must be kept as low as possible

- The PVLAS locking takes advantage of the laser characteristics:
  - Nd:YAG, Non Planar Ring Oscillator (Lightwave Corp., USA)
  - λ = 1064 nm
  - CW output power = 100 mW
  - frequency tunable with PZT ("fast" ~100KHz BW) and temperature ("slow" ~1 Hz BW) controls acting directly on the laser crystal

- The laser frequency (hence its phase) can be modulated by acting directly on the Nd:YAG NPRO crystal:
  - the need for an external phase modulator is eliminated thereby reducing RAM
  - the frequency difference between laser and cavity can be kept as low as 1 mHz/√Hz at 2 Hz *

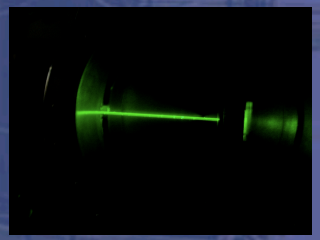
(*) 1 mHz/√HZ means $\Delta L/L = (10^{-3}/\nu_L) \sim 10^{-3}/10^{15} = 10^{-18}$, that is $\Delta L \sim 6\times10^{-18}$ m/√Hz

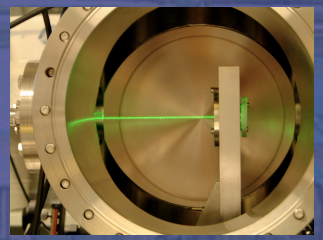
PVLAS driven developments

- Operating at shorter wavelength would be advantageous
  - higher photon energy ➡ larger signal
  - beam is visible ➡ optics easier to operate
  - smaller beam dimensions ➡ reduced noise from optical components
- A frequency doubled Nd:YAG, CW, 100 mW laser, operating at 532 nm has been tested
  - stable locking successfully achieved for the first time to test FP cavity
  - laser ready to be installed on main apparatus and locked to main 6.4 m long, 10000 finesse, PVLAS cavity

Tests on frequency–doubled 532 nm laser

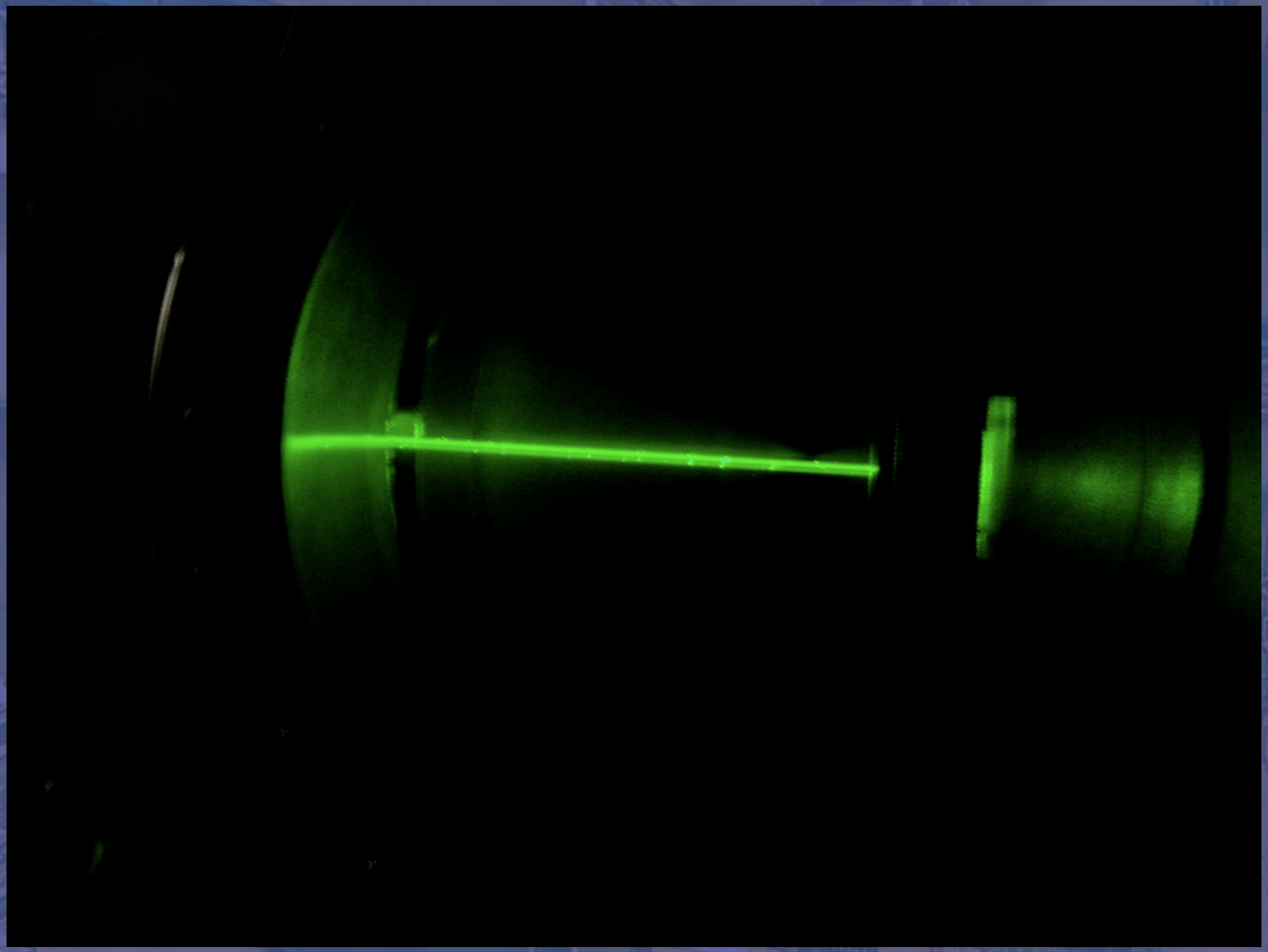
- Tests have been conducted in the INFN Trieste optics laboratory on a frequency–doubled laser with the following characteristics
  - Prometheus mod. made by Innolight, Germany
  - IR emission from a Nd:YAG NPRO, diode pumped, laser is frequency doubled by a single pass through a PPKTP non-linear crystal
  - visible 100 mW CW emission at 532 nm
  - secondary 1 W CW beam at 1064 nm
  - frequency tunable
    - 100 kHz BW piezoelectric “fast” control
    - 1 Hz BW thermal “slow” control

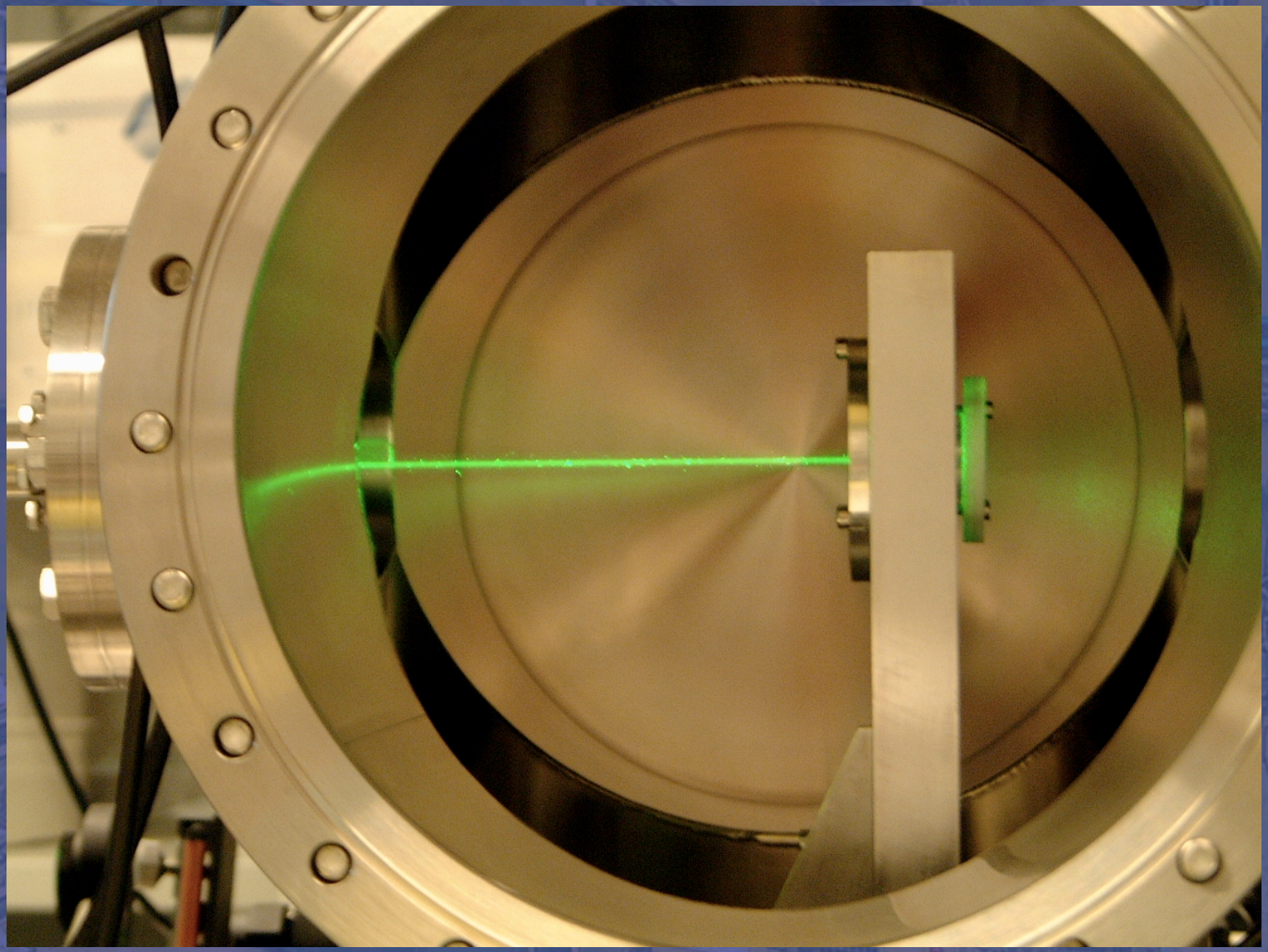




- The laser has been frequency–locked to a test FP cavity
  - cavity length 87 cm
  - cavity finesse ~ 45000

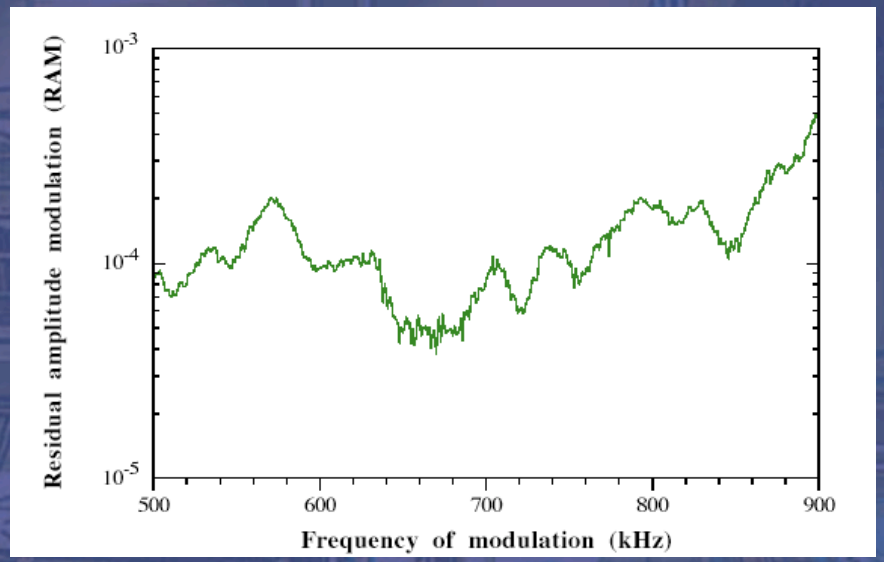
(for more details see hep-ex/0202046)

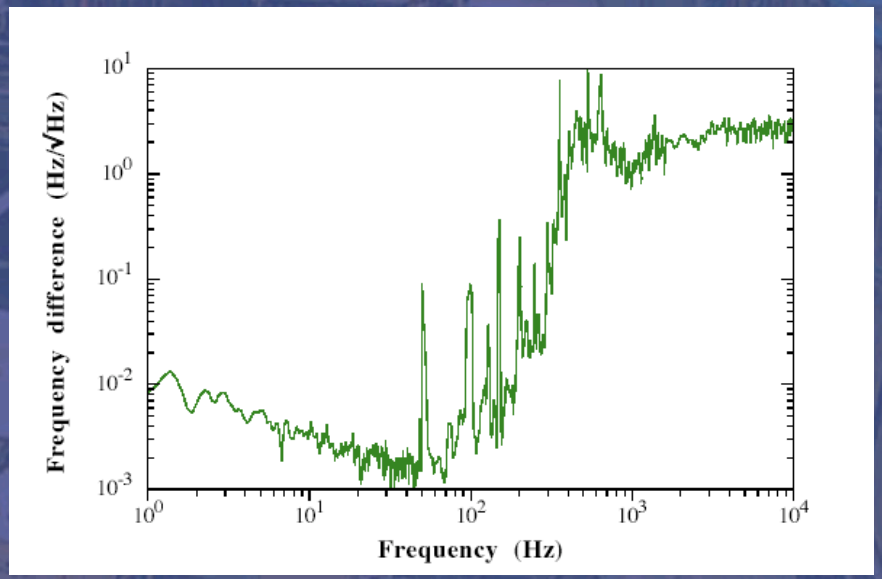




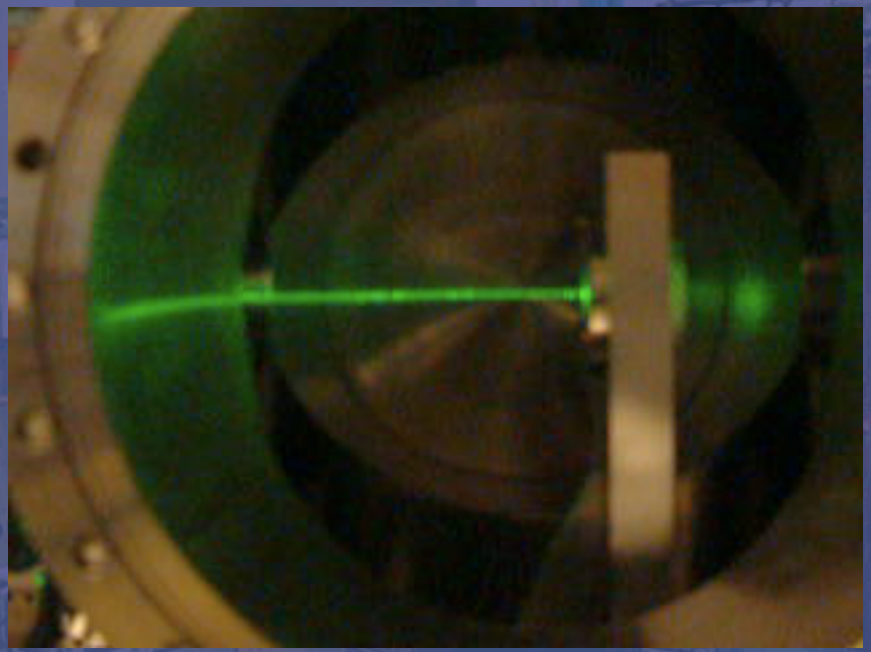
532 nm locking test results

- achieved locking for extended time periods to a L = 87 cm and F ~ 45000 Fabry–Perot cavity
- locking is kept by acting directly on the laser without the need for an external modulator
- visible laser and test feedback loop characteristics comparable to main PVLAS IR laser-6.4 m long FP cavity system
  - Residual Intensity Noise
  - Residual Amplitude Modulation
  - cavity/laser instantaneous frequency difference

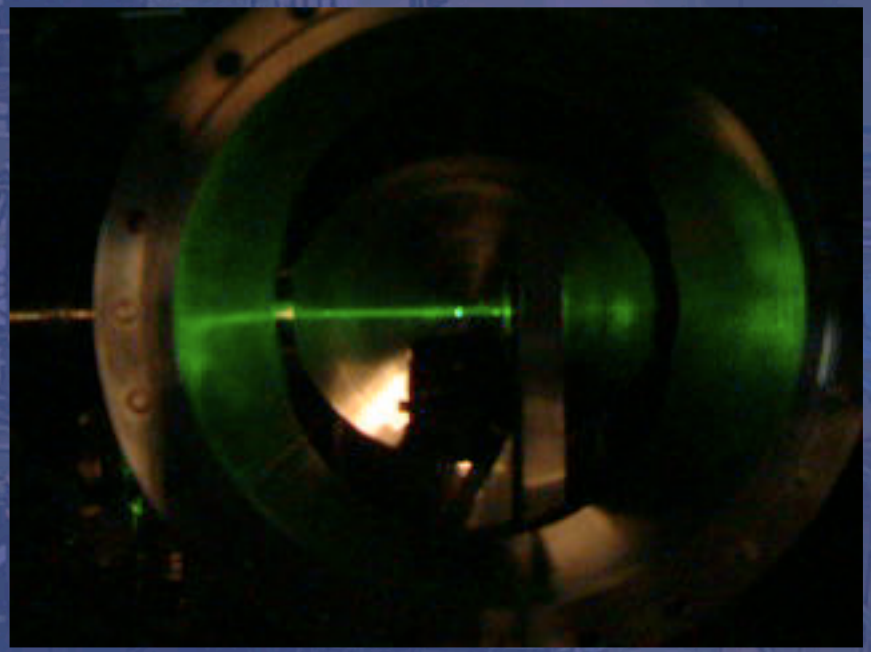




“Live” FP resonance ...



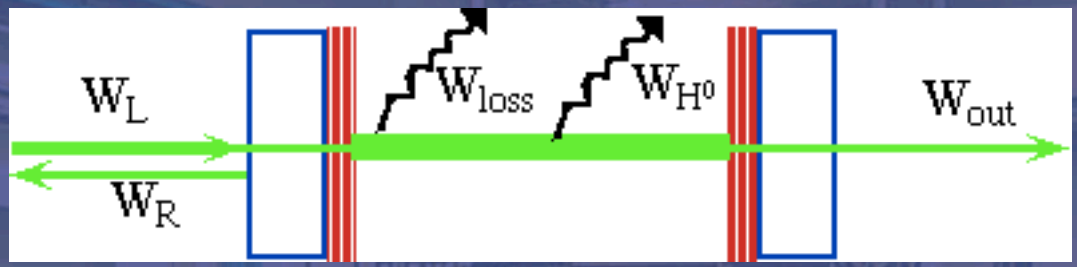
On–Off locking



Stable locking

Perspectives

Cavity power budget



- W_L = laser output power
- W_R = reflected power
- W_{out} = transmitted power
- W_{loss} = cavity losses
- W_{H^0} = losses due to H^0 excitation

Fabry-Perot cavity power budget

$$W_L = W_{out} + W_R + W_{loss} + W_{H^0}$$

cavity transmission ratio

$$\Box = \frac{W_{out}}{W_L}$$

Light power in the cavity at resonance is

$$W_C = \left(\frac{F}{\Box}\right) W_{out}$$

and **light power density** in given by
(S is the beam cross-section)

$$DW_C = \left(\frac{F}{\Box}\right)\frac{W_{out}}{S} = \frac{\Box F}{\Box S} W_L$$

Power requirements

- Minimum power density for laser assisted stripping = 10 kW/cm^2
- If 10^{16} H^0/s must be stripped, then 10^{16} photons/s are lost, leading (assuming λ = 532 nm, i.e. 2 eV photons) to a "stripping" loss given by

$$W_{H^0} = 10^{16} \left[\frac{H^0}{s}\right] \cdot 2 \left[\frac{eV}{ph}\right] \cdot 1.6 \cdot 10^{-19} \left[\frac{J}{eV}\right] = 3 \text{ mW}$$

Beam size requirements

- The required beam cross section is **S = 1 cm²,** leading to a beam radius (beam waist) $\square_0$ **= 0.56 cm**
- Using gaussian beam propagation equations one can estimate the necessary mirror radius of curvature R from

$$\square_0 = \sqrt{\frac{\square}{\square}\sqrt{d(R \square d)}}$$

where **d** is half the cavity length

Summary table

	PVLAS test	PVLAS upgrade	Projected	
Laser model	Innolight	Innolight		
Pout	100 mW	100 mW	**5-10 W**	nominal power
W_L	20 mW	20 mW	**1.6 W**	power input
$\square$	0.07	0.13	0.2	transm. ratio
F	45000	100000	100000	Finesse
$\square_0$	0.7 mm	0.92 mm	5.6 mm	beam waist
L	0.87 m	6.4 m	6.4 m	cavity length
$\square$	532 nm	532 nm	532 nm	wavelength
DW_C	1200 W/cm^2	700 W/cm^2	10 kW/cm^2	power density
W_{H^0}	3 mW	3 mW	3 mW	stripping losses
R	11 m	11 m	**110 m**	mirror radius
W_{H^0}/W_C	2×10^{-4}	2×10^{-4}	3×10^{-7}	stripping loss ratio
T	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	optical losses

Conclusions

- Technical challenges ("show stoppers")
  - visible, tunable lasers in the 5-10 W power range
  - "supermirrors" with long radii of curvature (>100 m)
- Feasibility of laser assisted , Fabry-Perot enhanced, H^- stripping

⇒ YES