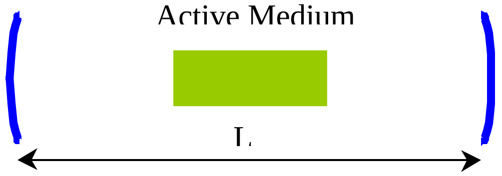
## ***Approaches:***

- Intrinsic stabilization (Lamb dip, mode balance, …)
- Locking to a stable reference Fabry-Perot interferometer
- Locking to an atomic or molecular line

## ***Need to control mirror separation***



Cavity resonances: $\nu \approx (c/2L) \cdot N \rightarrow \delta\nu/\nu = -\delta L/L$

Say we want to stabilize visible light frequency ($\nu \sim 4 \cdot 10^{14}$ Hz) to $\delta\nu < 100$ kHz

$$\delta\nu/\nu \sim 2.5 \cdot 10^{-10}$$

For a typical cavity of $L = 40$ cm, we have $|\delta L| < 10^{-8}$ cm **!**

## ***Two types of problems:***

- Slow drifts (temperature, air pressure, etc.)
- Fast fluctuations: acoustics, dye jet instabilities, etc.

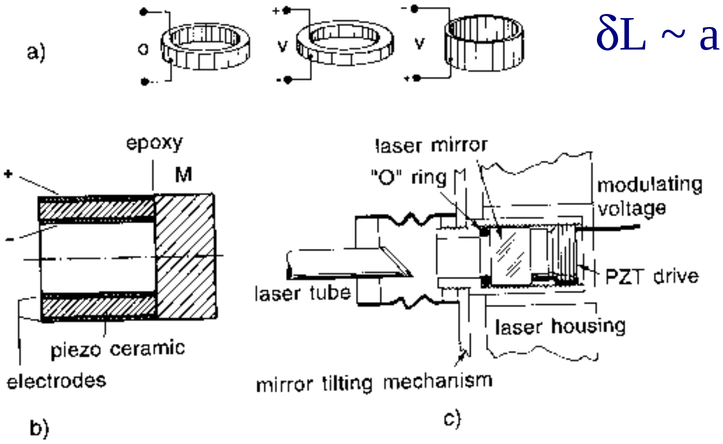
## *Thermal Expansion*

Linear thermal expansion coefficient of some relevant materials at room temperature T = 20° C

| Material | $\alpha$ [$10^{-6}$K$^{-1}$] | Material | $\alpha$ [$10^{-6}$K$^{-1}$] |
|---|---|---|---|
| Aluminum | 23 | BeO | 6 |
| Brass | 19 | Invar | 1.2 |
| Steel | 11÷15 | Soda+glass | 5÷8 |
| Titanium | 8.6 | Pyrex glass | 3 |
| Tungsten | 4.5 | Fused quartz | 0.4÷0.5 |
| $Al_2O_3$ | 5 | Cerodur | < 0.1 |

Also, new glass ultra-low expansion (**ULE**) material

## *Displacing Cavity Mirrors*

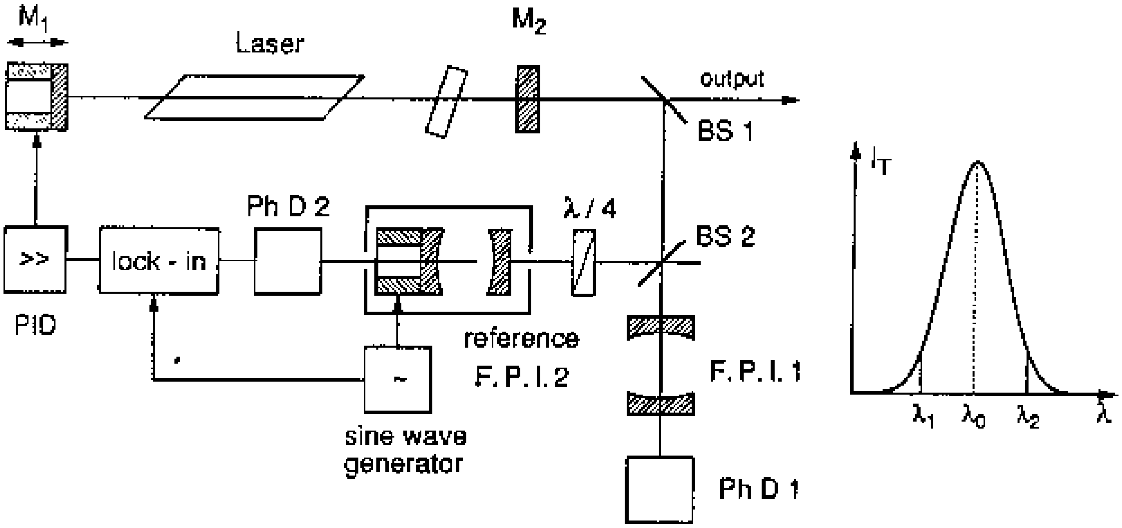


$\delta L \sim$ a few nm/V

(a) Piezo cylinders and their (exaggerated) change of length with applied voltage (b) laser mirror epoxyd on a piezo-cylinder (c) mirror plus piezo mount on a single-mode tunable argon laser

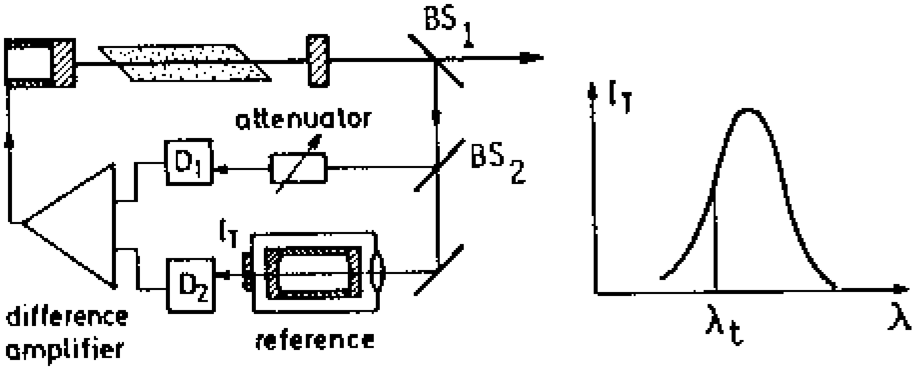
# *Locking to a stable FPI*

- A traditional scheme with PZT dither:



Laser wavelength stabilization onto the transmission peak of a stable Fabry-Perot interferometer as reference

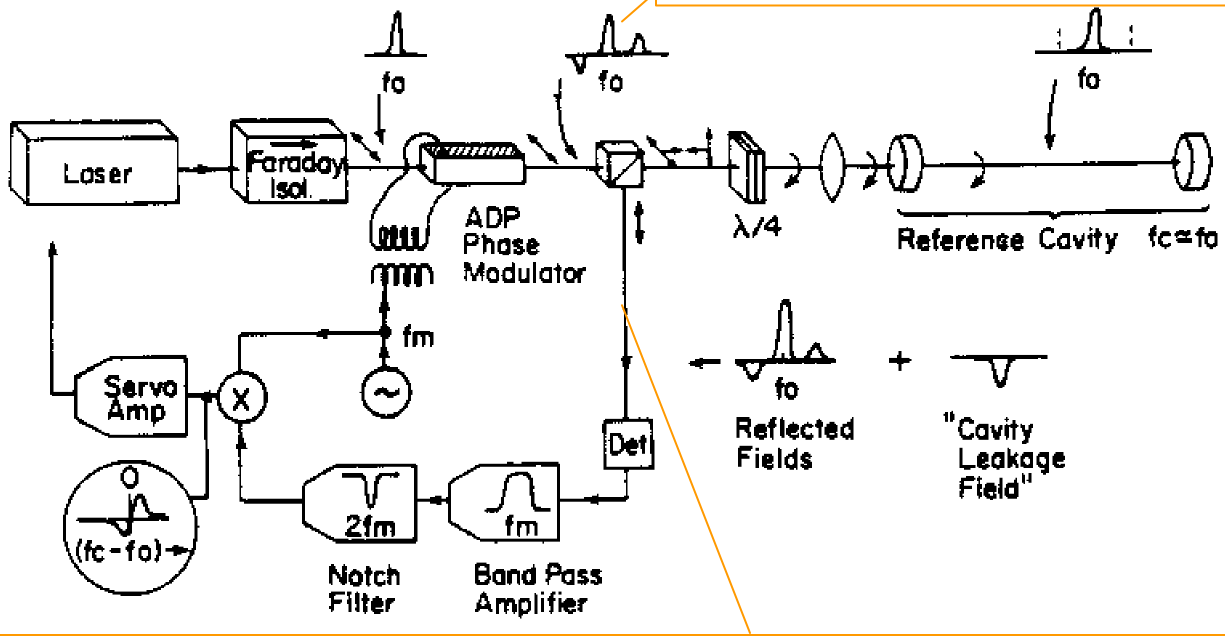
- FPI slope locking:



- The Pound-Drever-Hall method

R. W. P. Drever, J. L. Hall, et al, Appl. Phys. B **31**, 97 (1983).

$a_0 e^{i\omega_0 t} + a_1 e^{i(\omega_0+\omega_m)t} - a_1 e^{i(\omega_0-\omega_m)t}$

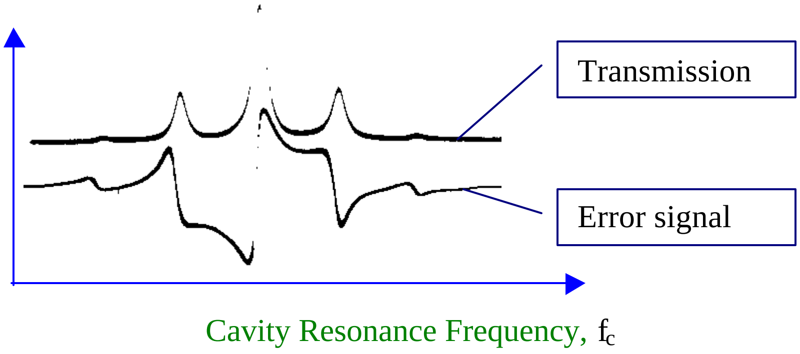


**Light E-field Amplitude:**

$a_0 e^{i\omega_0 t} + a_r e^{i((\omega_0+\omega_m)t+\varphi)} - a_1 e^{i(\omega_0-\omega_m)t}$

**Intensity:**

$a_r^2 + 3a_1^2 - 3a_1^2\cos^2(\omega_m t) + 4a_r a_1 \sin(\varphi)\sin(\omega_m t) + a_1^2\sin^2(\omega_m t)$

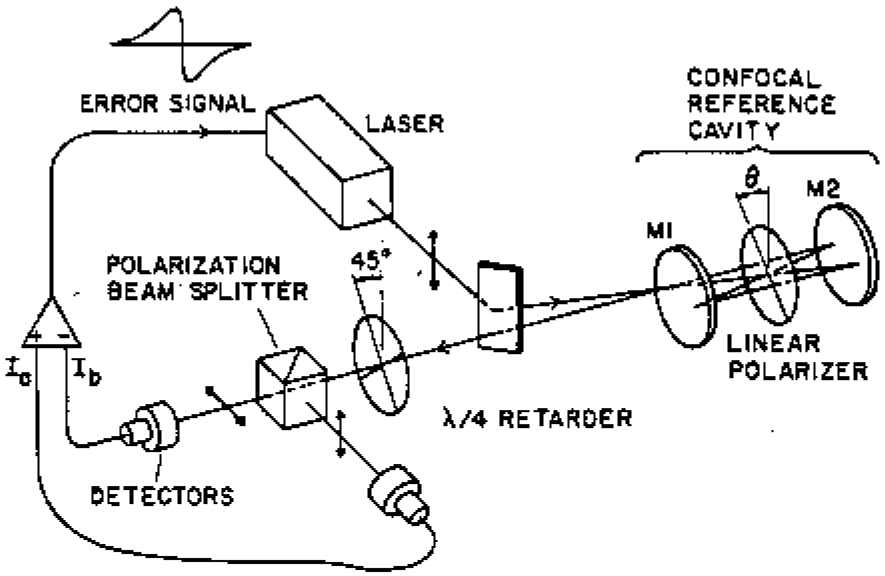


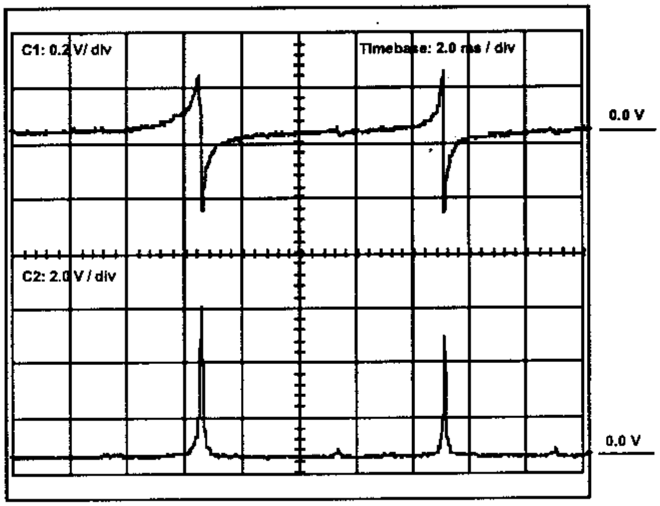
## Advantages:

- Fast
- Large capture range
- Insensitive to power and spatial drifts

## The Hansch-Couillaud method

T. W. Hansch and B. Couillaud, Opt. Commun. **35**(3), 441 (1980).





Wavetrain$^{\text{cw}}$
ring cavity external
frequency doubler

Advantage:

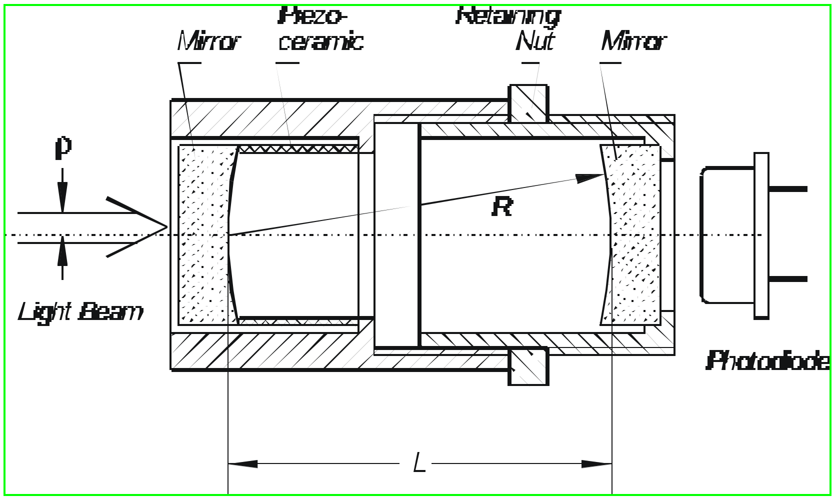
- No modulation

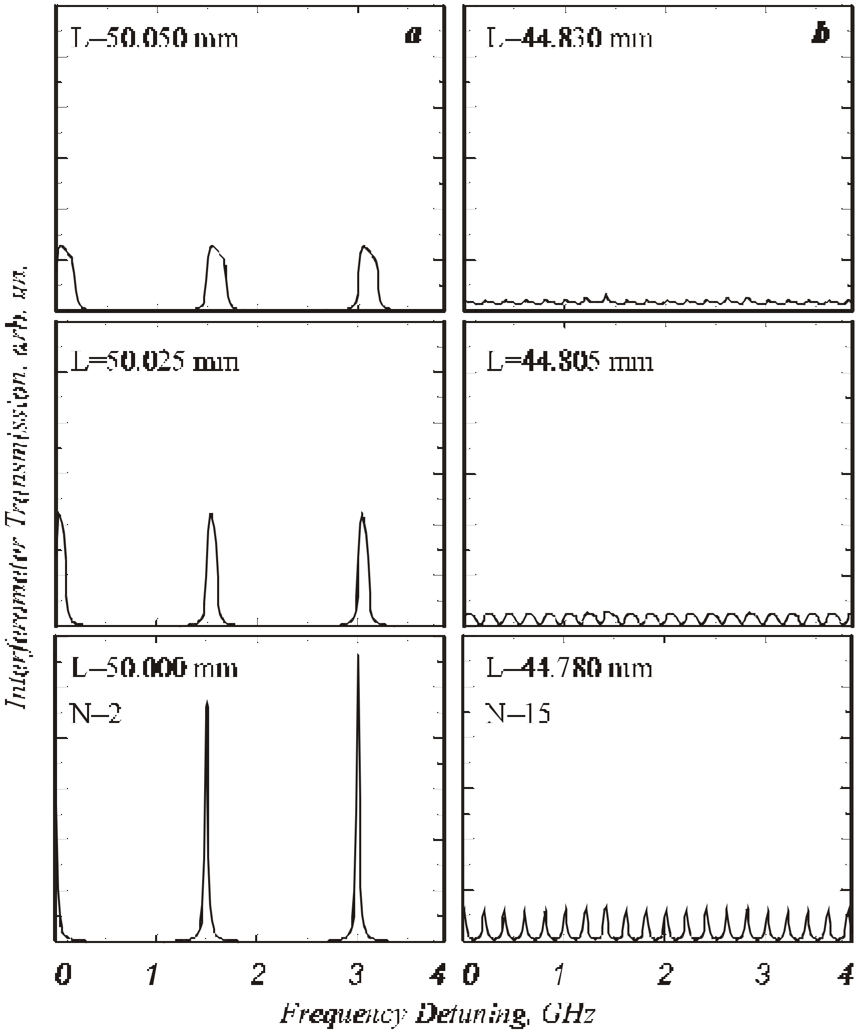
Disadvantage:

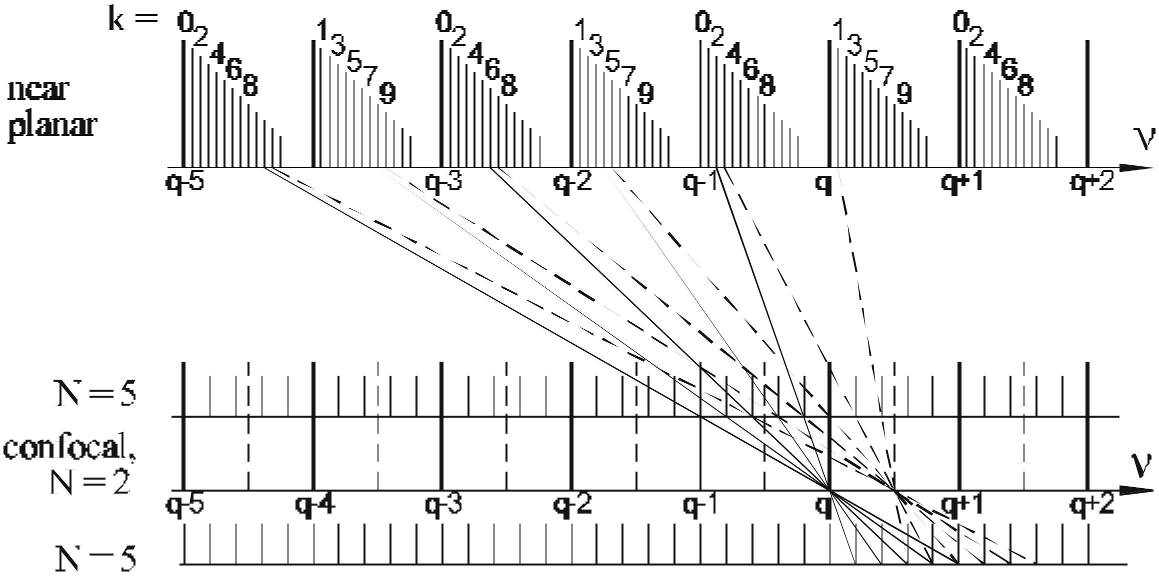
- Need intracavity polarizer

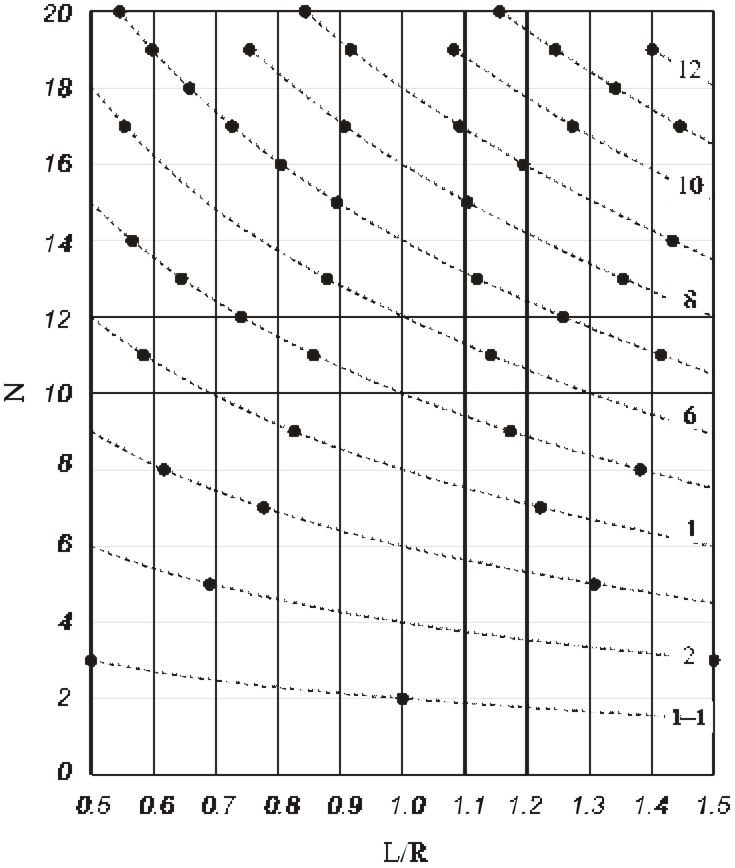
# How to obtain small FSR with a compact FPI ?

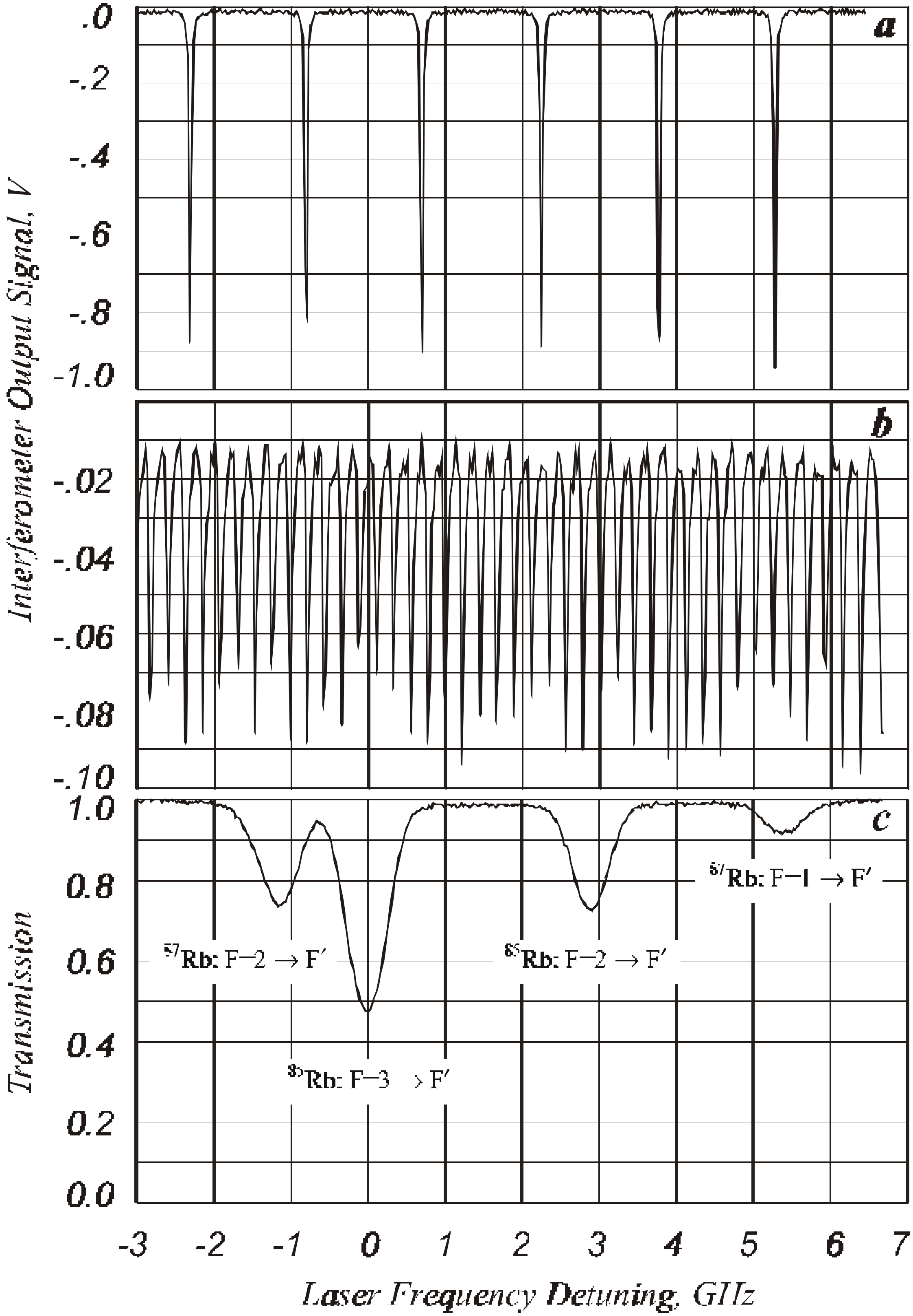
D. Budker, S. M. Rochester, and V. Yashchuk, Submitted to Rev. Sci. Instr.

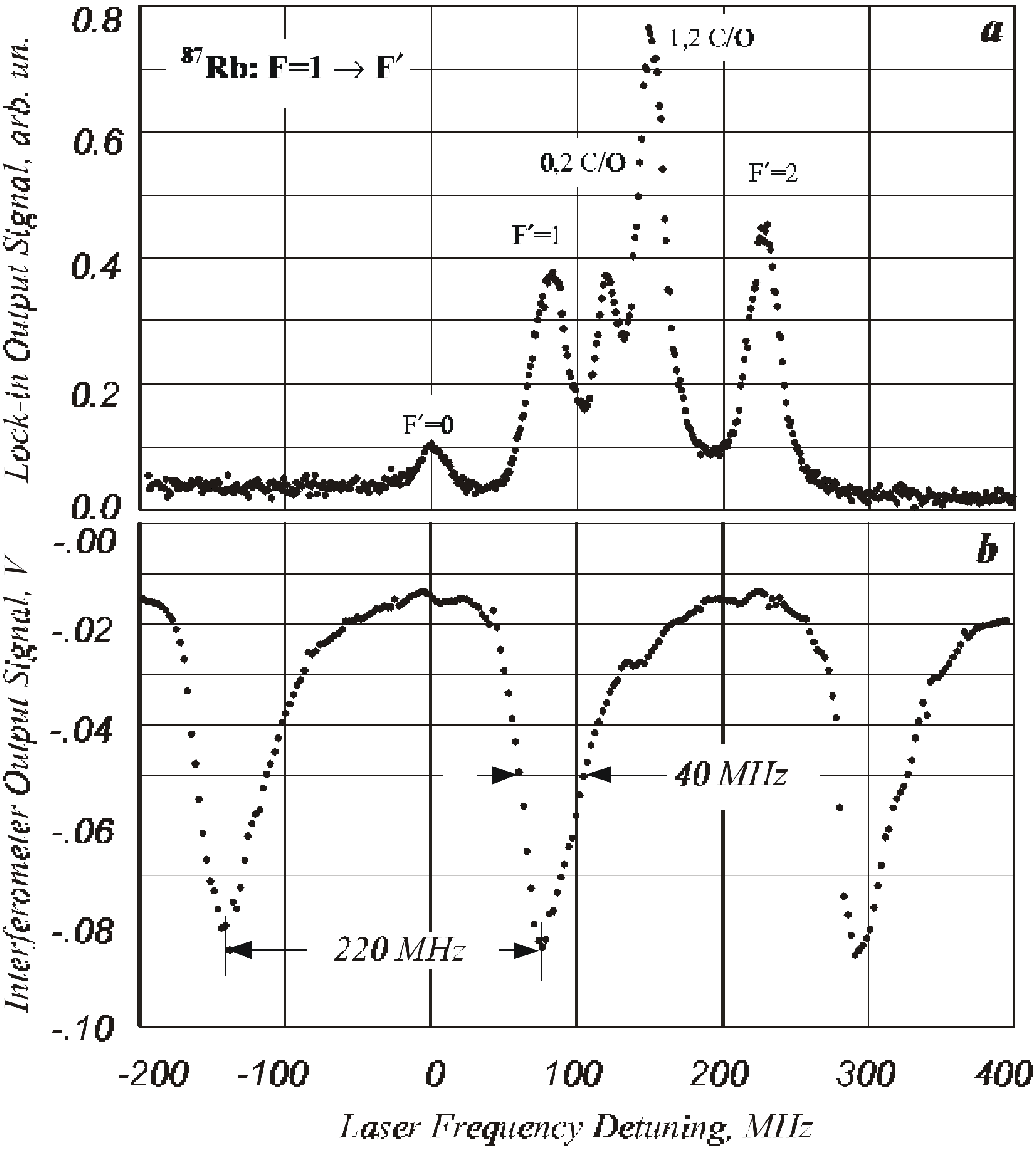





k =
0 2 4 6 8
1 3 5 7 9
near planar
ν
q-5
q-3
q-2
q-1
q
q+1
q+2
N = 5
confocal, N = 2
q-4
N = 5

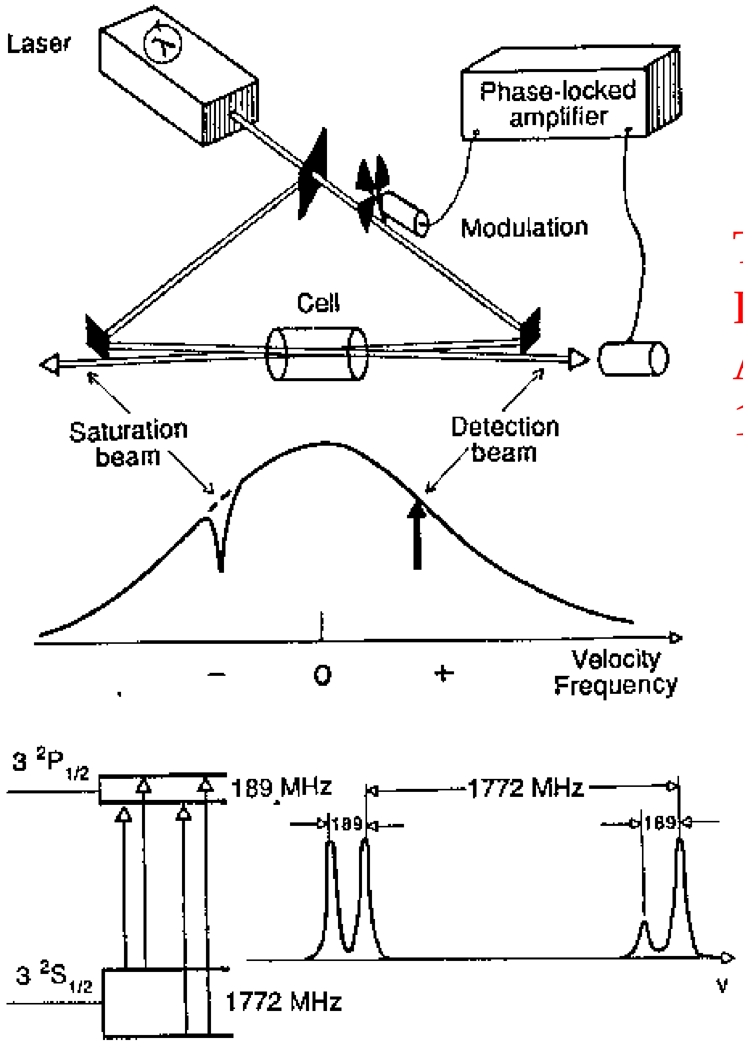

N
0
2
4
6
8
10
12
14
16
18
20
L/R
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
12
10
8
6
1
2
1-1


a
b
c
.0
-.2
-.4
-.6
-.8
-1.0
-.02
-.04
-.06
-.08
-.10
1.0
0.8
0.6
0.4
0.2
0.0
Interferometer Output Signal, V
Transmission
$^{87}$Rb: F=2 → F′
$^{85}$Rb: F=3 → F′
$^{85}$Rb: F=2 → F′
$^{87}$Rb: F=1 → F′
-3
-2
-1
0
1
2
3
4
5
6
7
Laser Frequency Detuning, GHz


a
$^{87}$Rb: F=1 → F′
1,2 C/O
0,2 C/O
F′=2
F′=1
F′=0
0.8
0.6
0.4
0.2
0.0
Lock-in Output Signal, arb. un.
b
-.00
-.02
-.04
-.06
-.08
-.10
Interferometer Output Signal, V
40 MHz
220 MHz
-200
-100
0
100
200
300
400
Laser Frequency Detuning, MHz

# *Locking to an atomic or molecular resonance*

- Saturation spectroscopy:

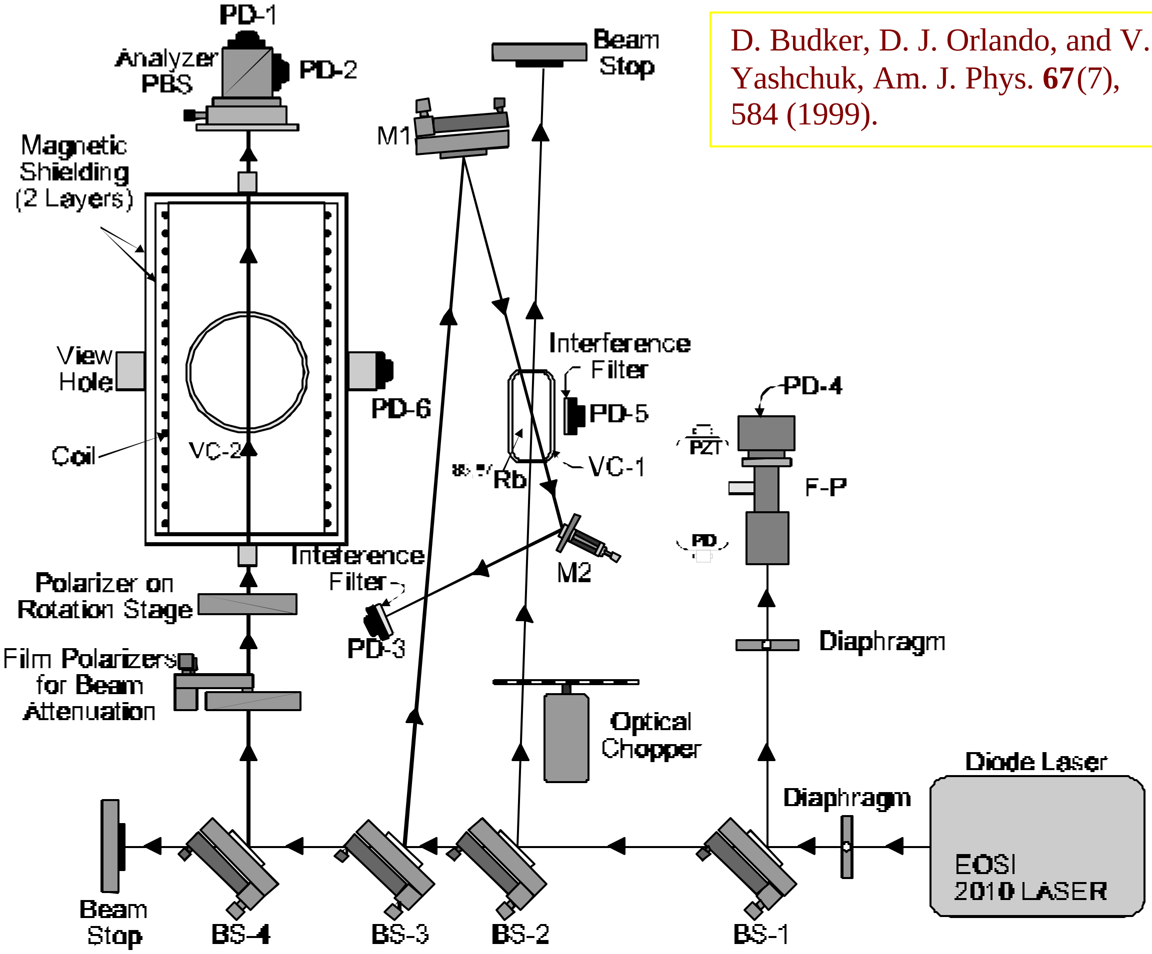


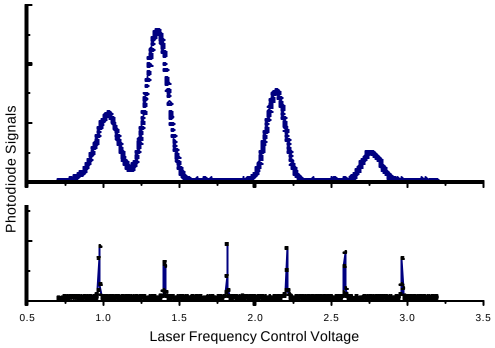
T. W. Hänsch,
I.S. Shahin,
A. L. Schawlow,
1971

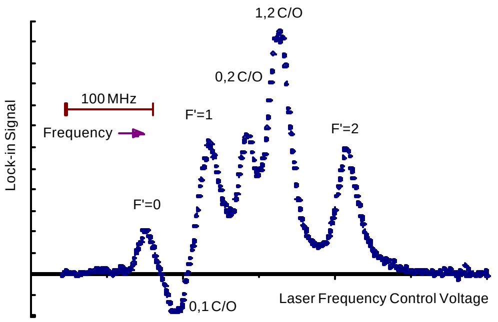
Set-up for saturation spectroscopy of the sodium $D_1$ line . A schematic spectrum is also shown where "cross-over resonances" have been omitted

# The 111 Lab version:

D. Budker, D. J. Orlando, and V. Yashchuk, Am. J. Phys. **67**(7), 584 (1999).

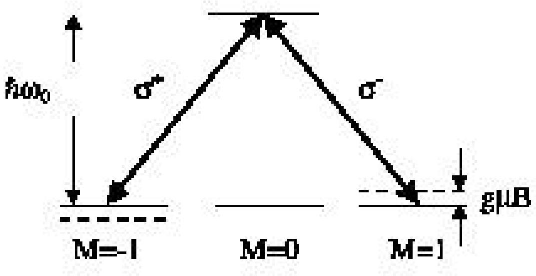


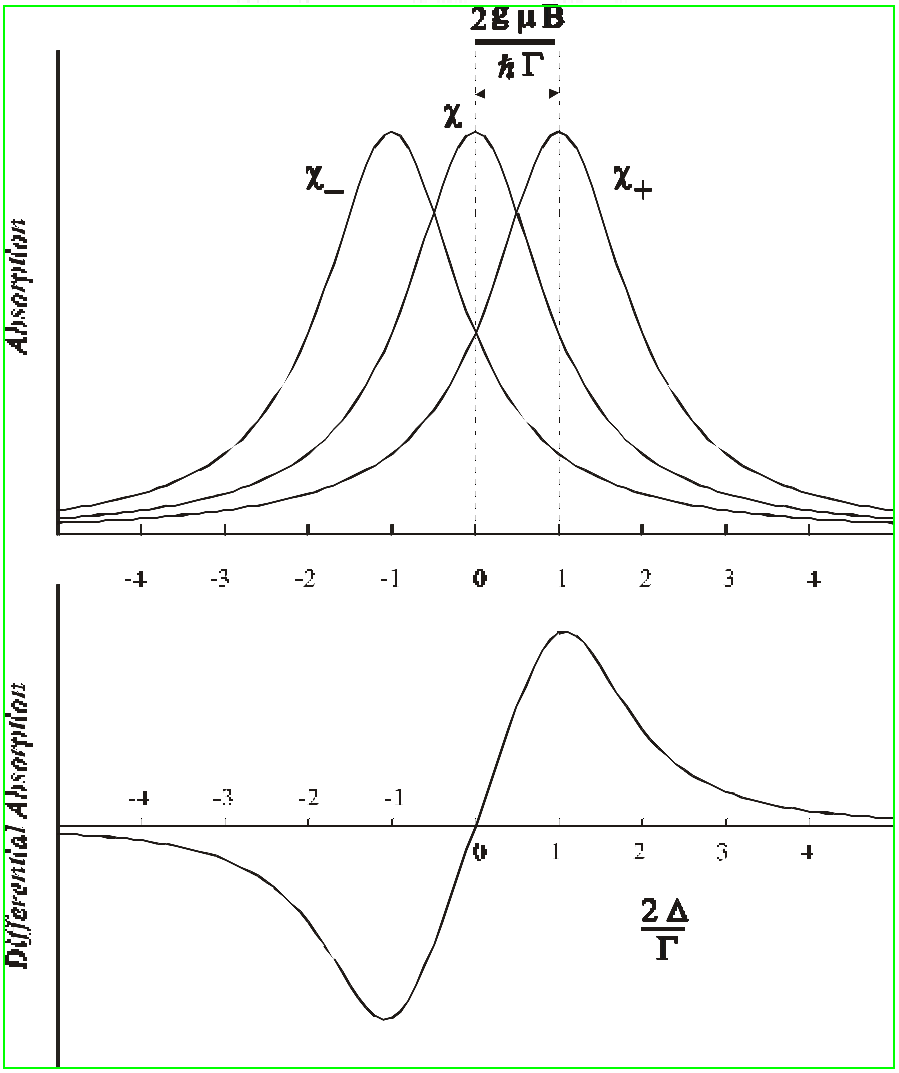


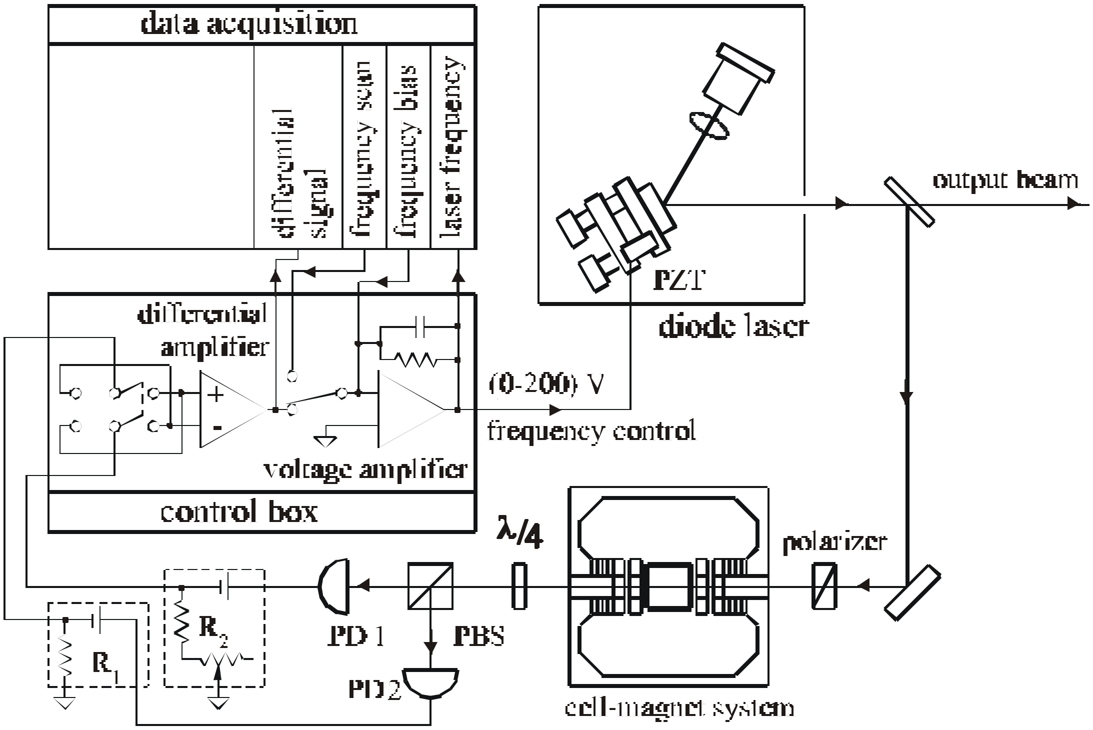


## ➢ Dichroic Atomic Laser Lock (DAVLL):

- B. Cheron, H. Gilles, J. Hamel, O. Moreau, and H. Sorel, J. Phys. III France **4**, 401-406 (1994).
- K. L. Corwin, Z.-T. Lu, C. F. Hand, R. J. Epstain, and C. E. Wieman, Appl. Optics **37**(15), 3295-3298 (1998).
- V. Yashchuk, D. Budker, and J. Davis, Rev. Sci. Instr. **71**(2), 341, 2000.






data acquisition
differential signal
frequency scan
frequency bias
laser frequency
differential amplifier
+
-
voltage amplifier
control box
PZT
diode laser
output beam
(0-200) V
frequency control
λ/4
polarizer
PD 1
PBS
PD 2
R2
R1
cell-magnet system