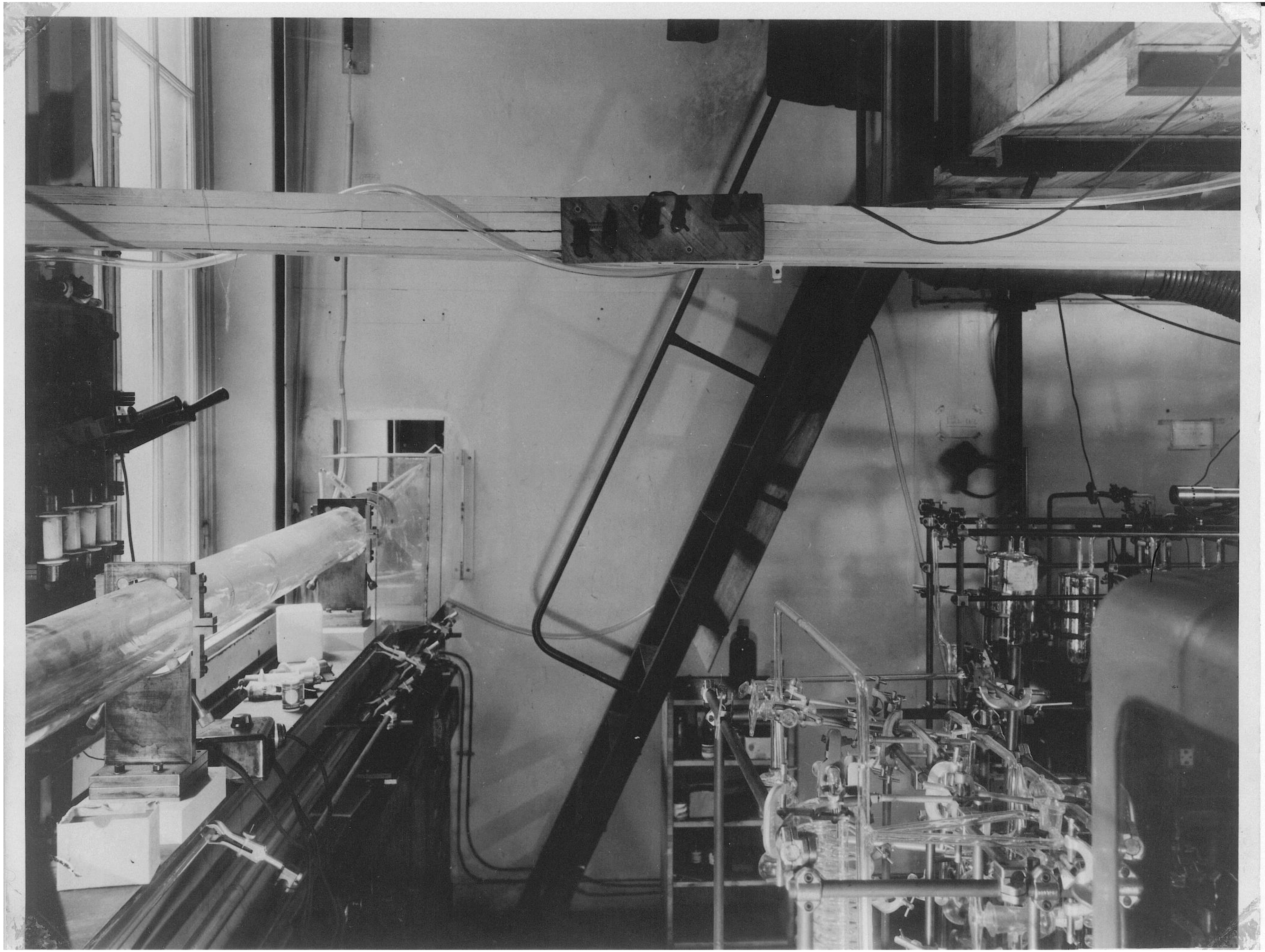
Des premiers lasers à gaz carbonique aux interféromètres atomiques et moléculaires 1965-1994

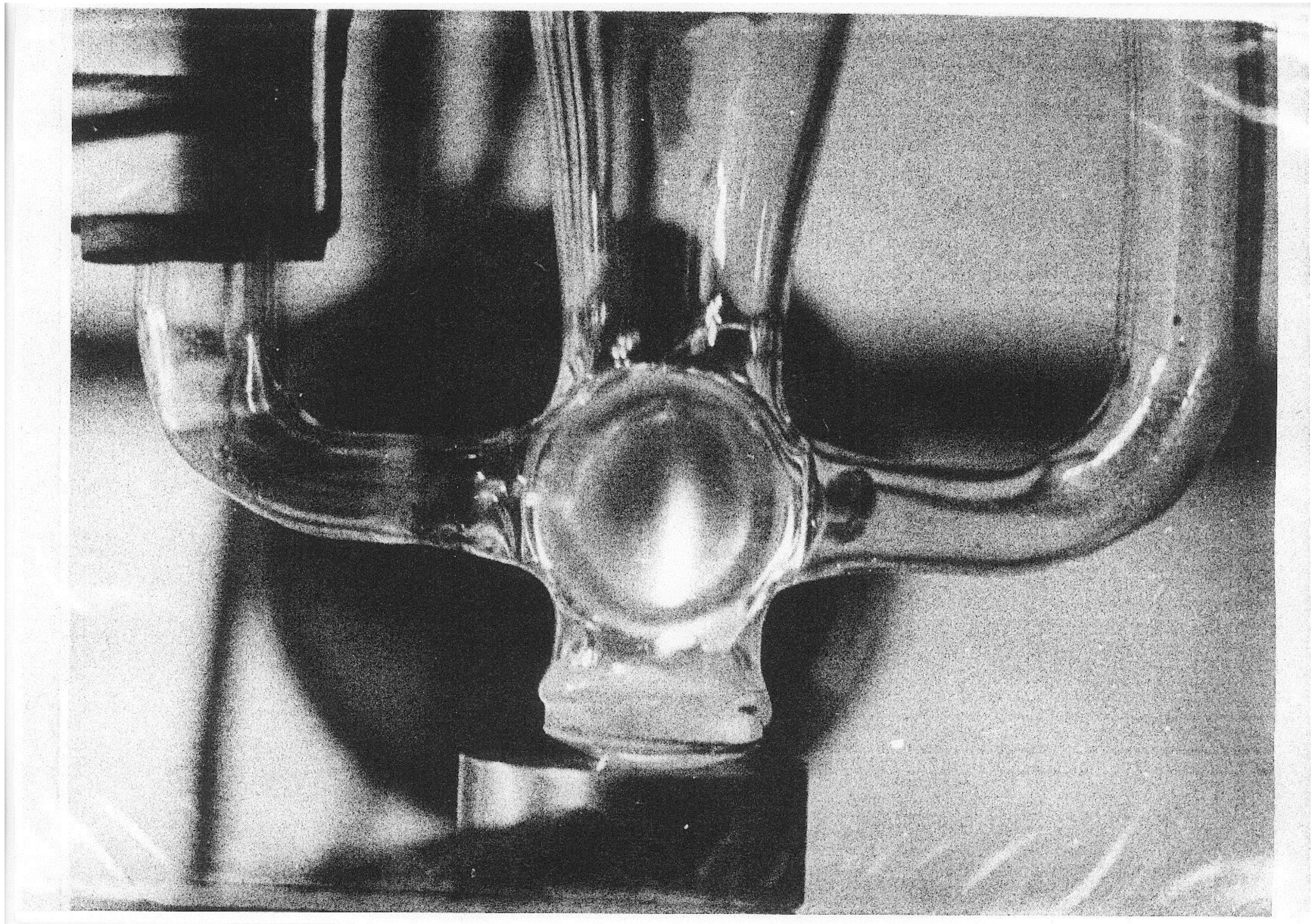
Christian J. Bordé

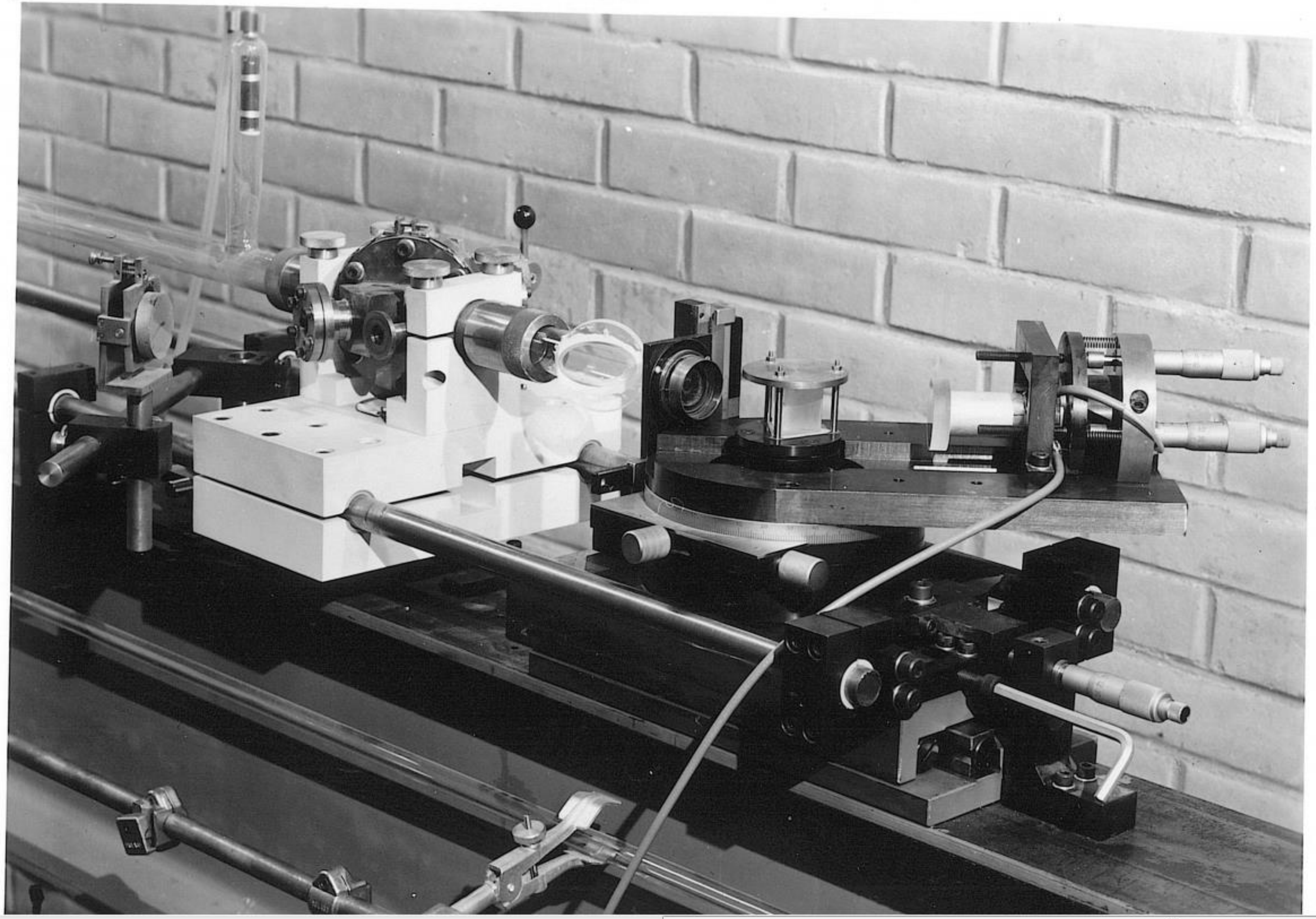
SYRTE et LPL

Académie des Sciences

27 juin 2019

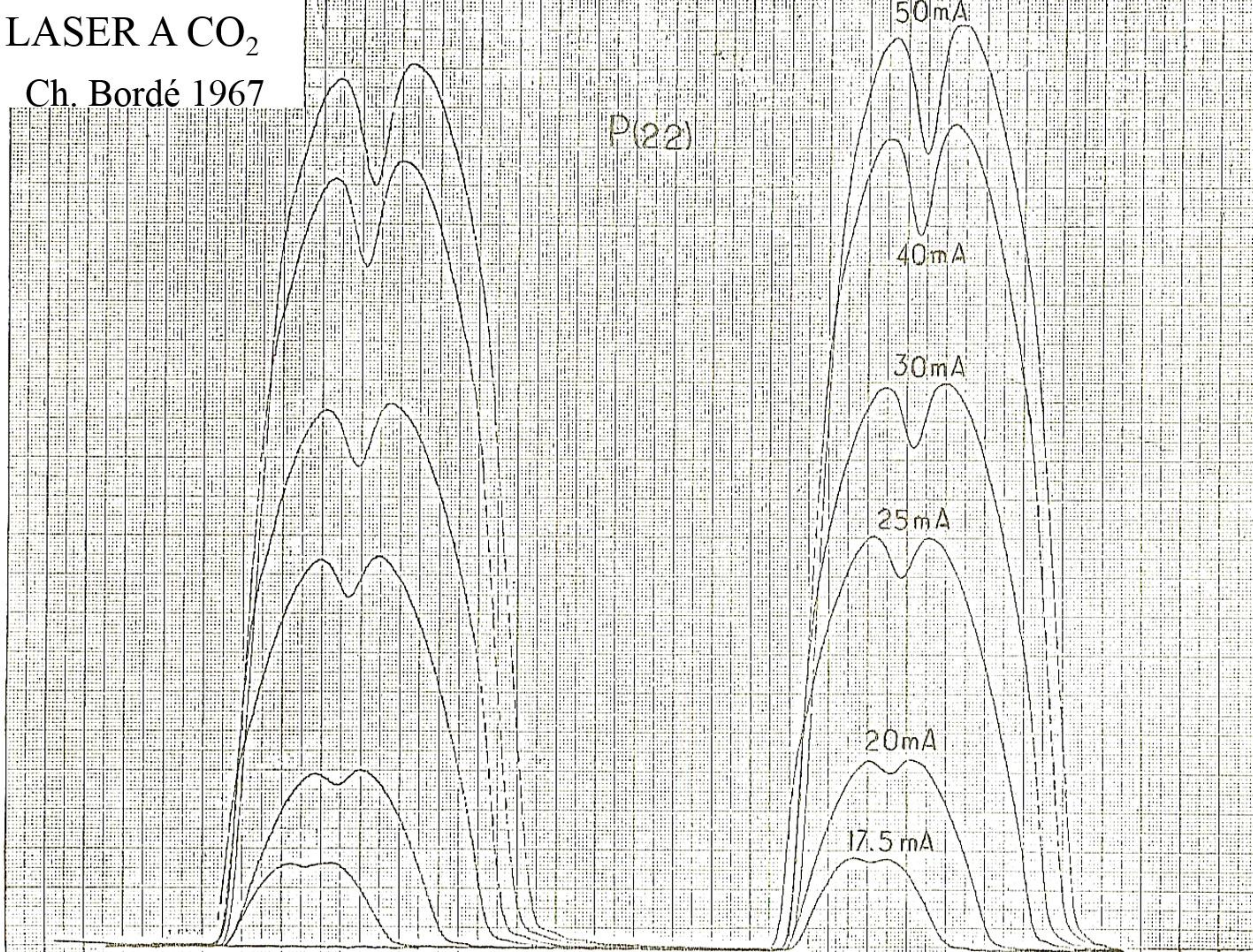


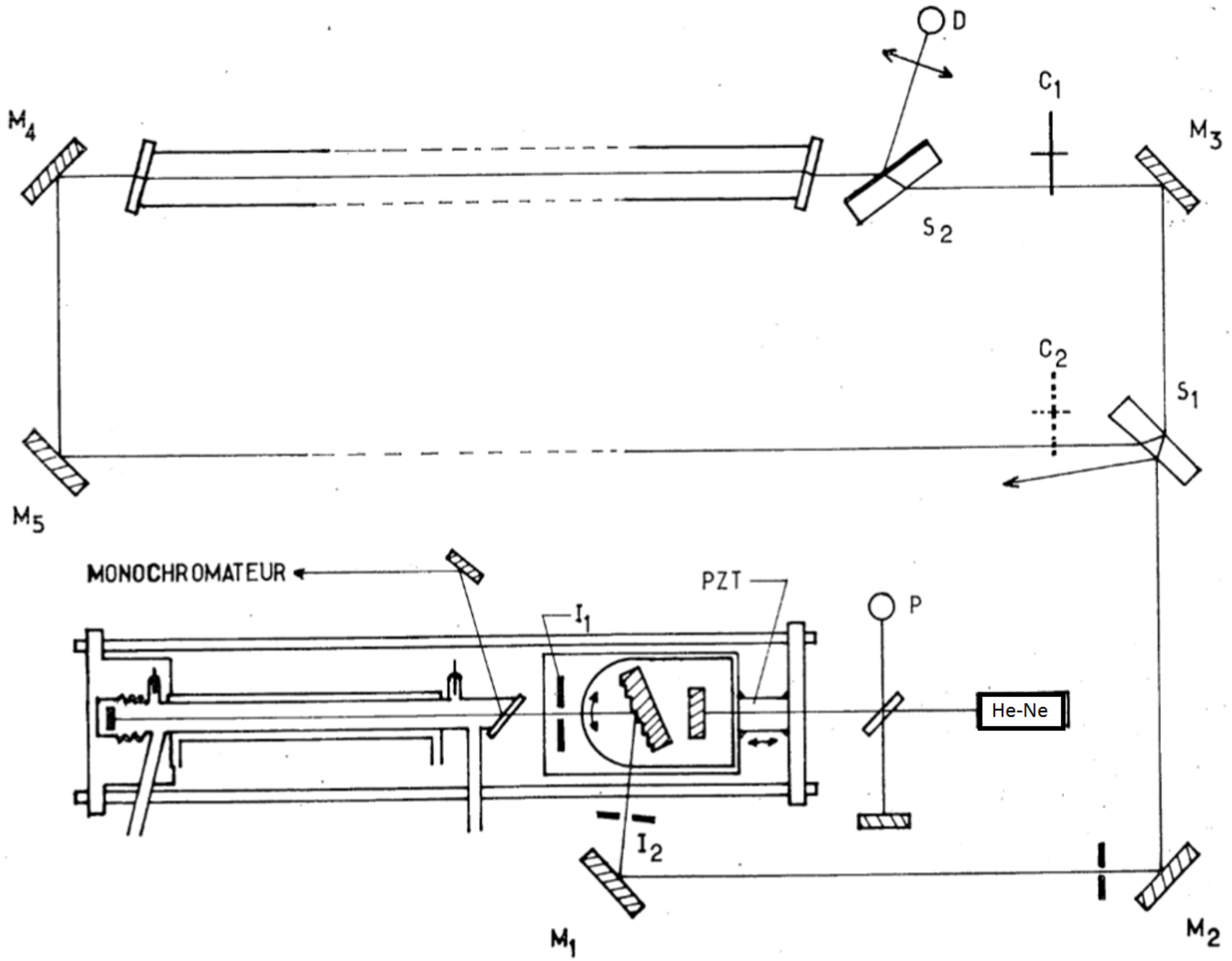


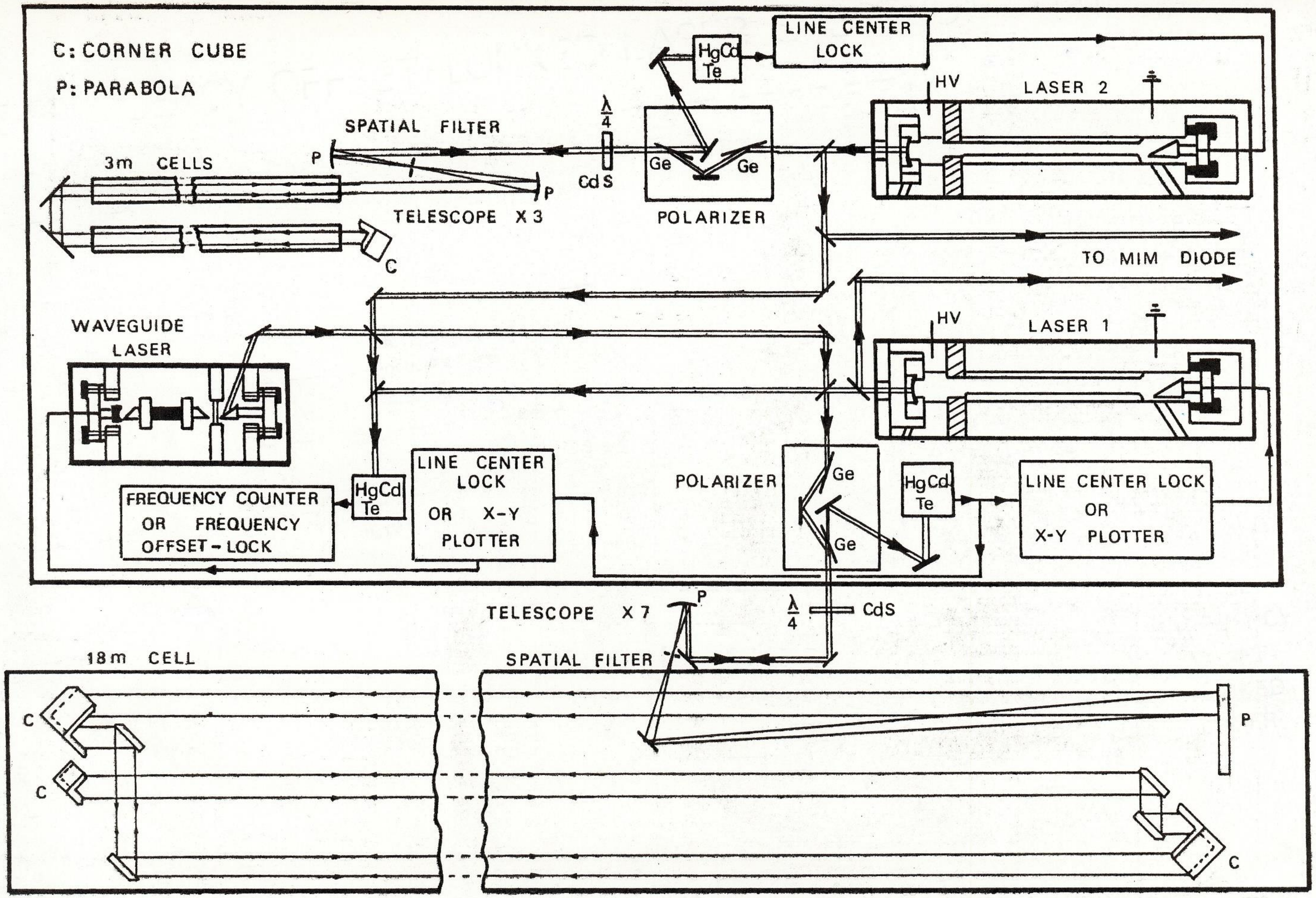


LASER A CO_2

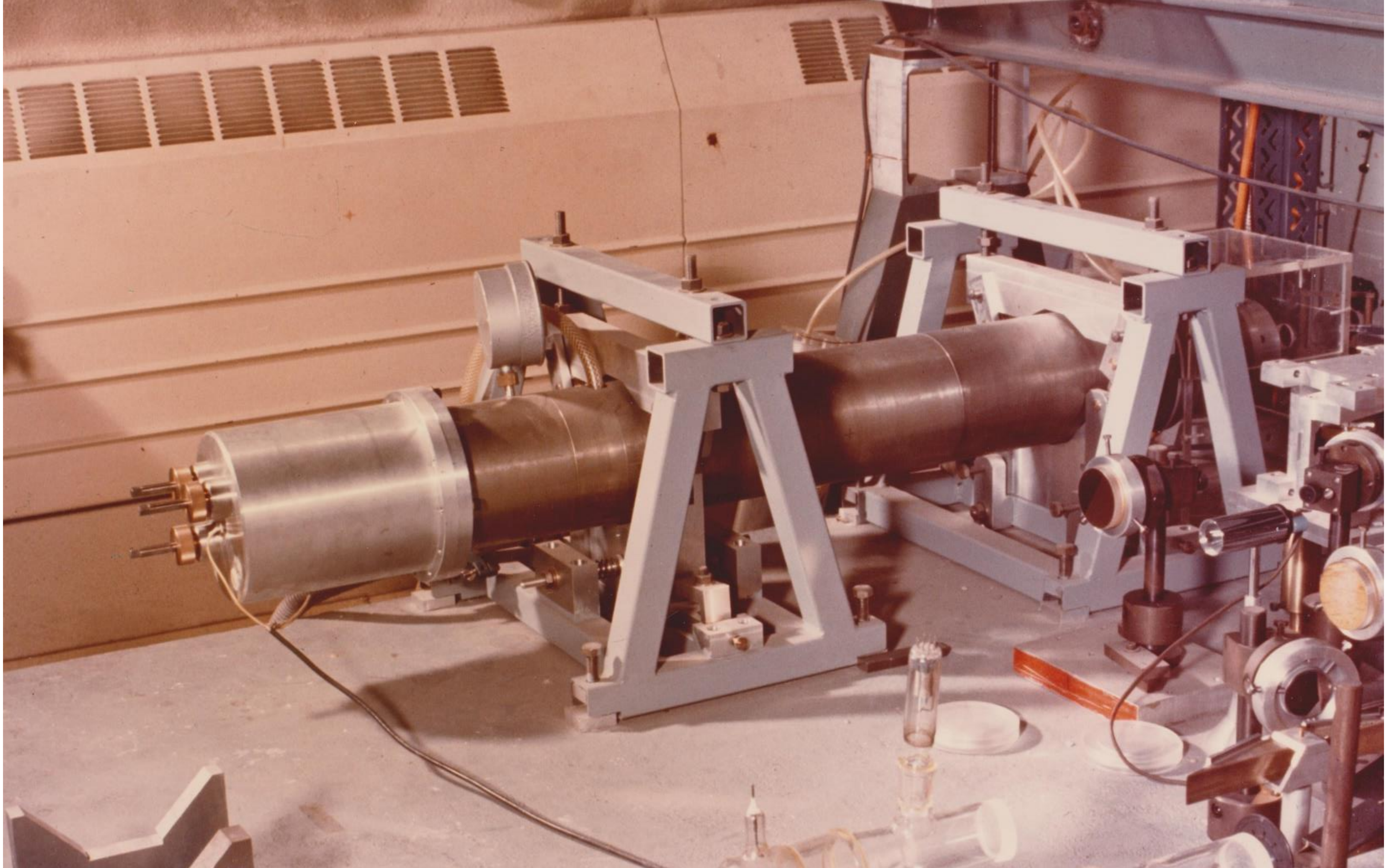
Ch. Bordé 1967

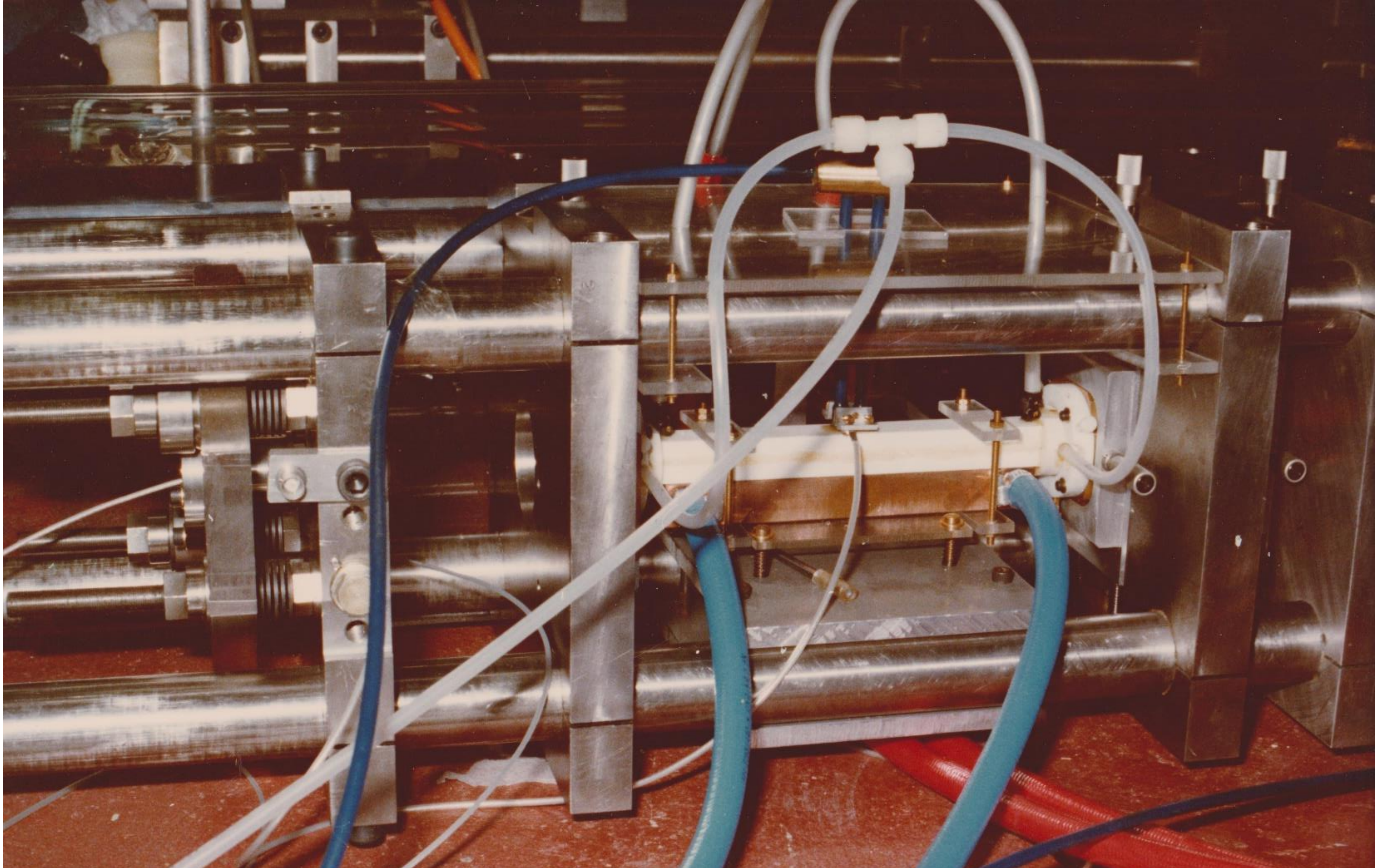


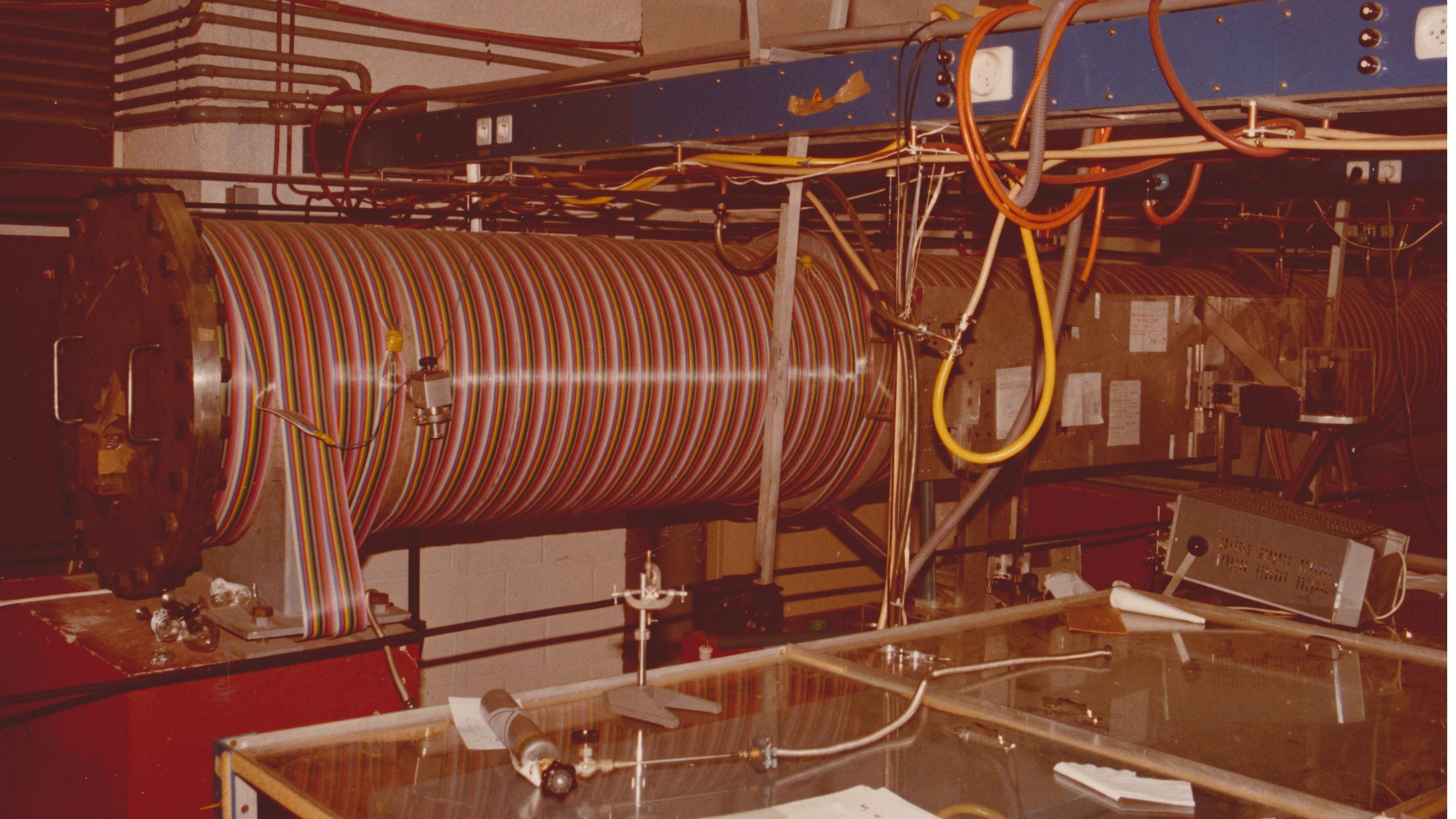

D
C1
M4
M3
S2
C2
S1
M5
MONOCHROMATEUR
PZT
I1
P
He-Ne
I2
M1
M2

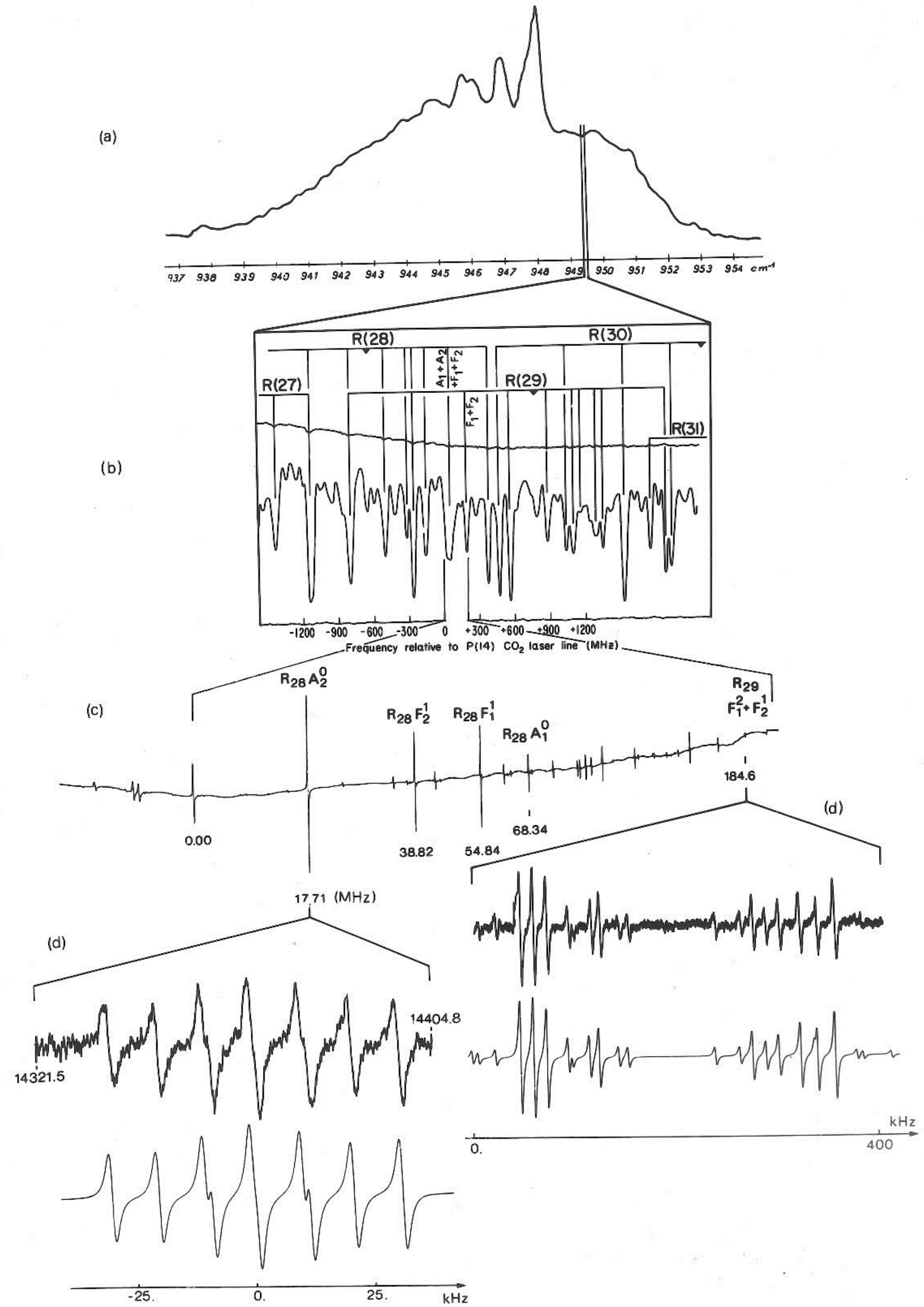


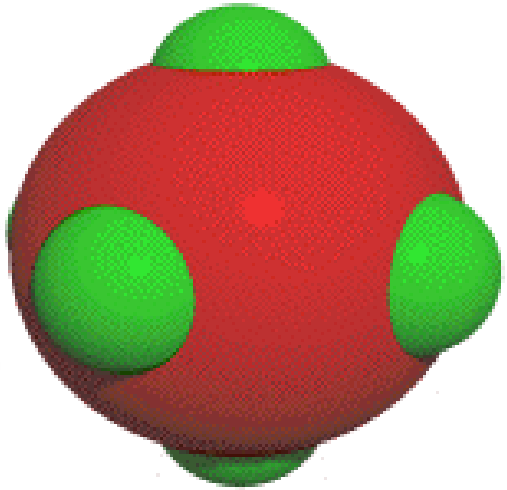
C: CORNER CUBE
P: PARABOLA
HgCd Te
LINE CENTER LOCK
HV
LASER 2
SPATIAL FILTER
λ/4
3m CELLS
P
Ge
Ge
CdS
P
TELESCOPE X3
POLARIZER
C
TO MIM DIODE
HV
LASER 1
WAVEGUIDE LASER
LINE CENTER LOCK OR X-Y PLOTTER
POLARIZER
Ge
HgCd Te
LINE CENTER LOCK OR X-Y PLOTTER
HgCd Te
FREQUENCY COUNTER OR FREQUENCY OFFSET-LOCK
Ge
TELESCOPE X7
P
λ/4
CdS
18m CELL
SPATIAL FILTER
C
P
C
C



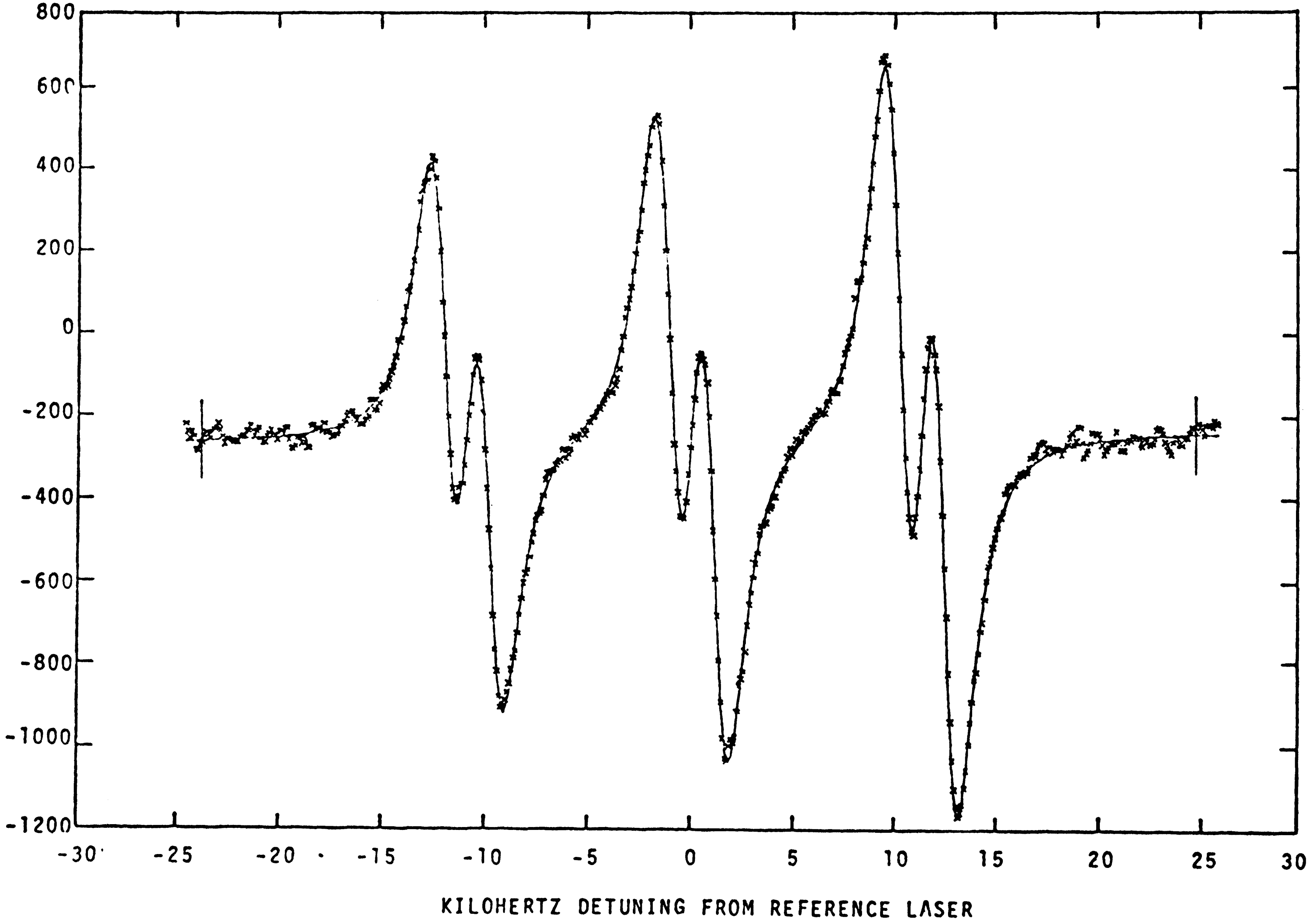




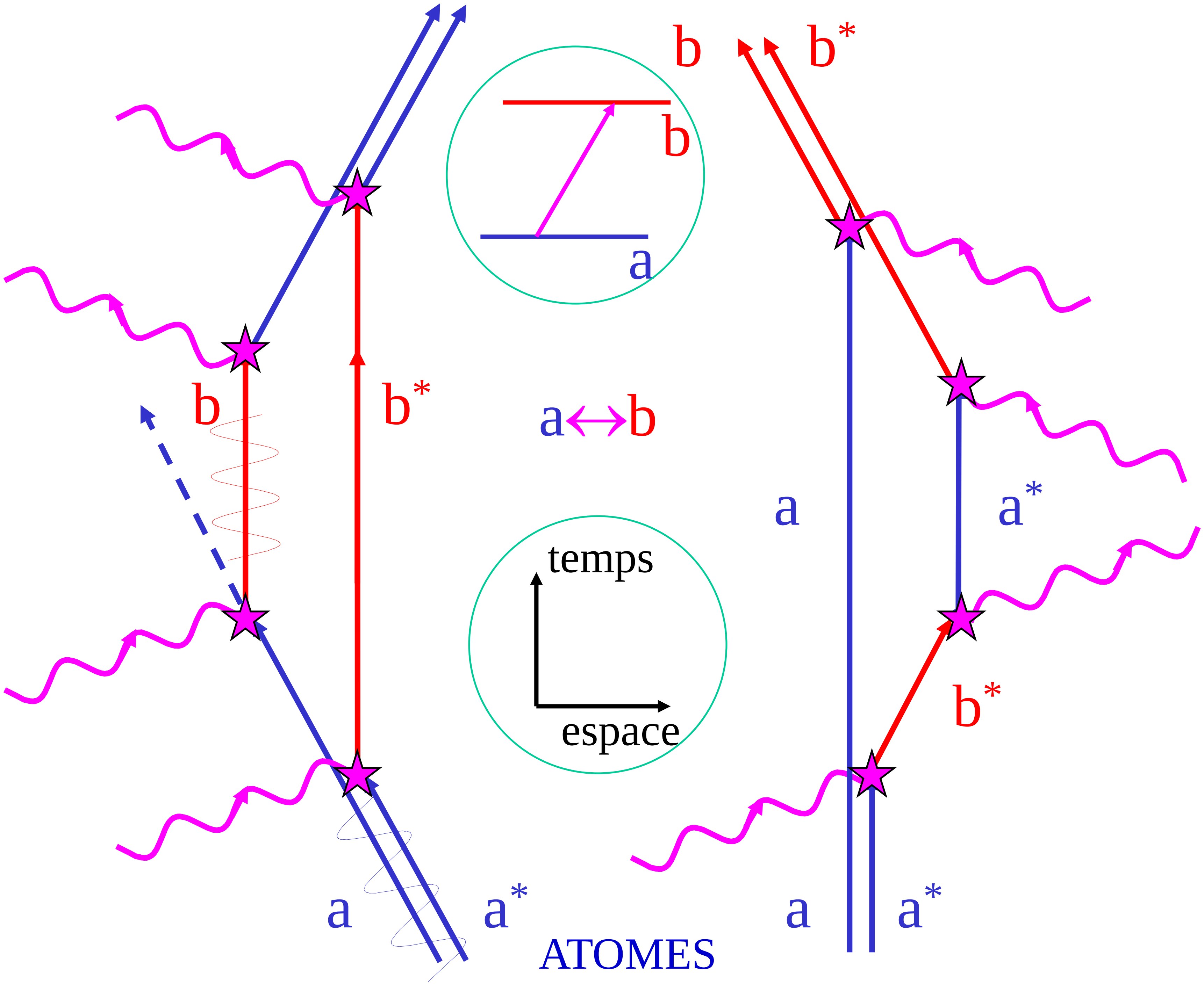

(a)
937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 cm-1
(b)
R(27)
R(28)
R(29)
R(30)
R(31)
A1+A2+F1+F2
F1+F2
-1200 -900 -600 -300 0 +300 +600 +900 +1200
Frequency relative to P(14) CO2 laser line (MHz)
(c)
R28 A20
R28 F21
R28 F11
R28 A10
R29 F12+F21
0.00
17.71 (MHz)
38.82
54.84
68.34
184.6
(d)
14321.5
14404.8
-25. 0. 25. kHz
(d)
0. 400 kHz



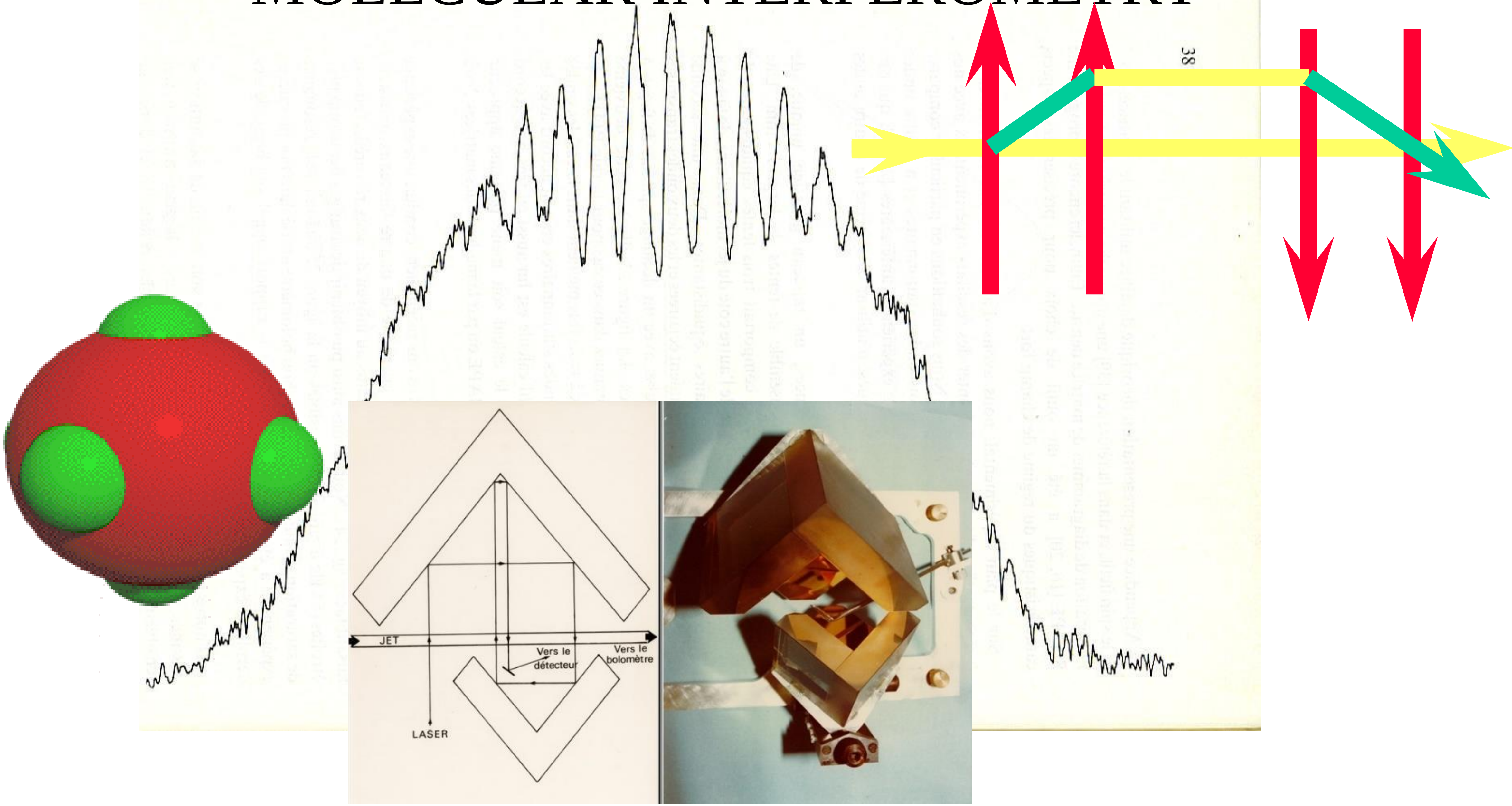
Composantes hyperfines magnétiques de la raie du méthane à 3.39 µm dédoublées par l'effet de recul: $h\nu^2 / Mc^2 = 2.16$ kHz



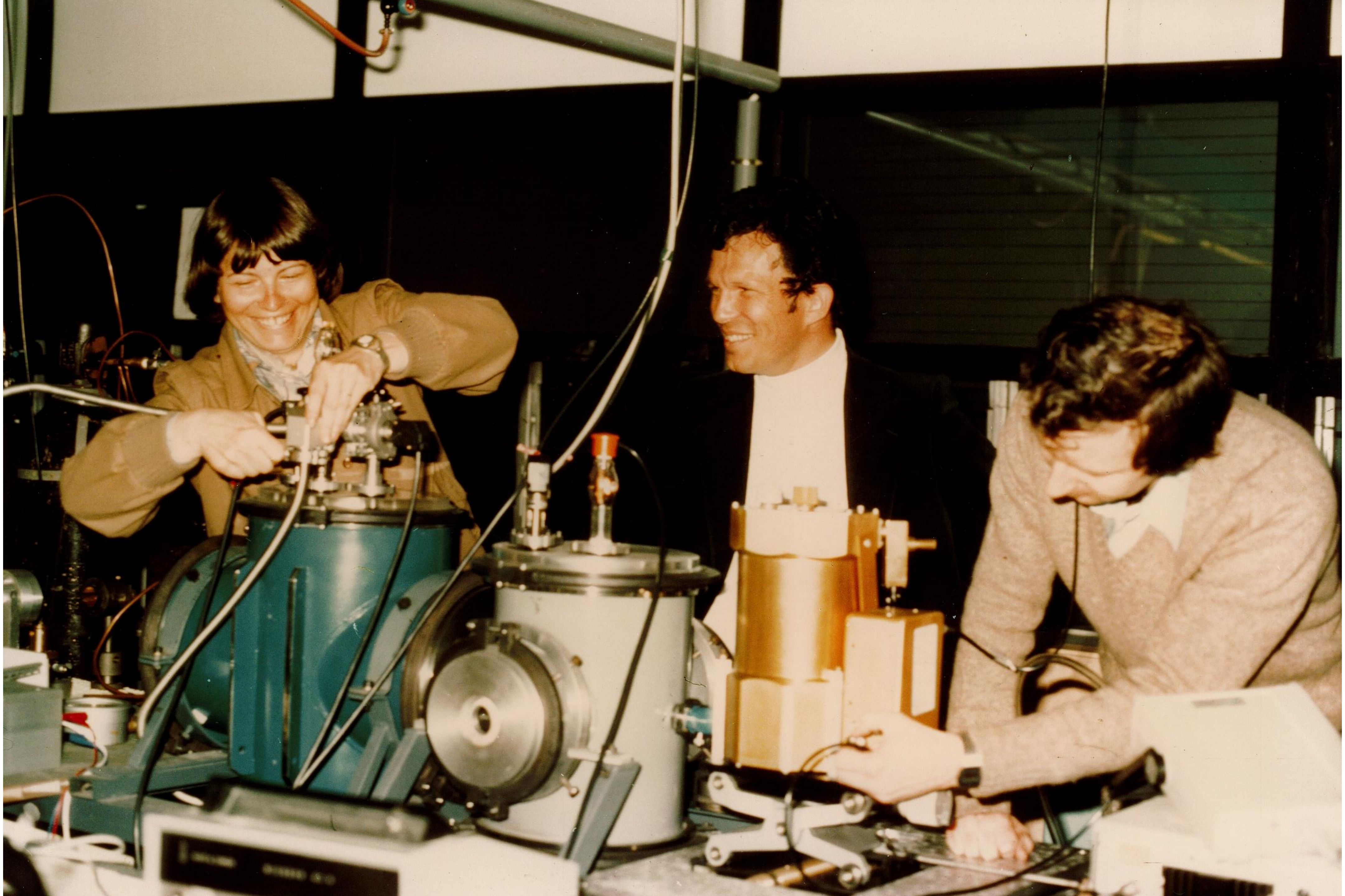
Hall, Bordé and Uehara, PRL 1976.

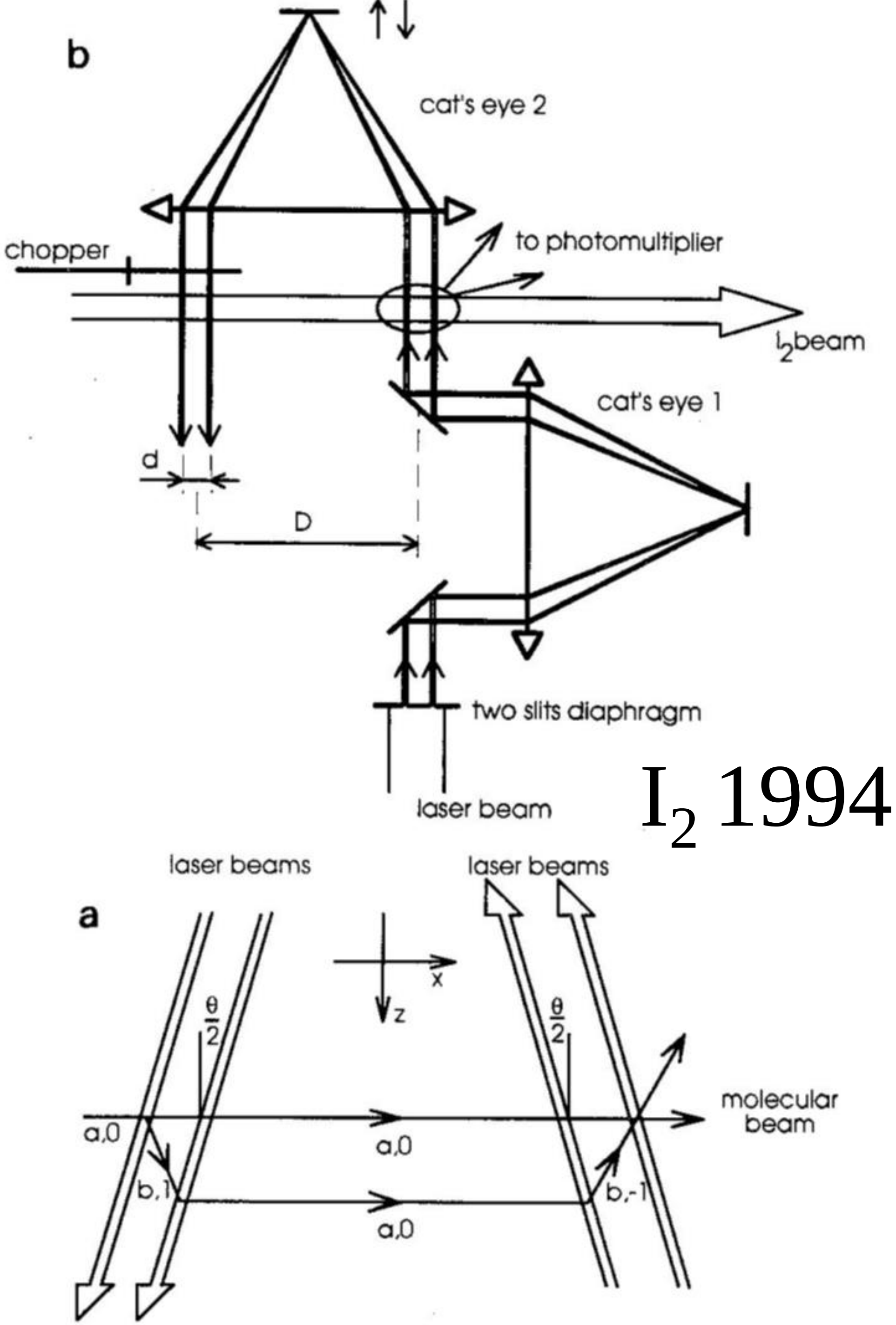

b
b*
b
a
b
b*
a↔b
a
a*
temps
espace
b*
a
a*
a
a*
ATOMES

MOLECULAR INTERFEROMETRY



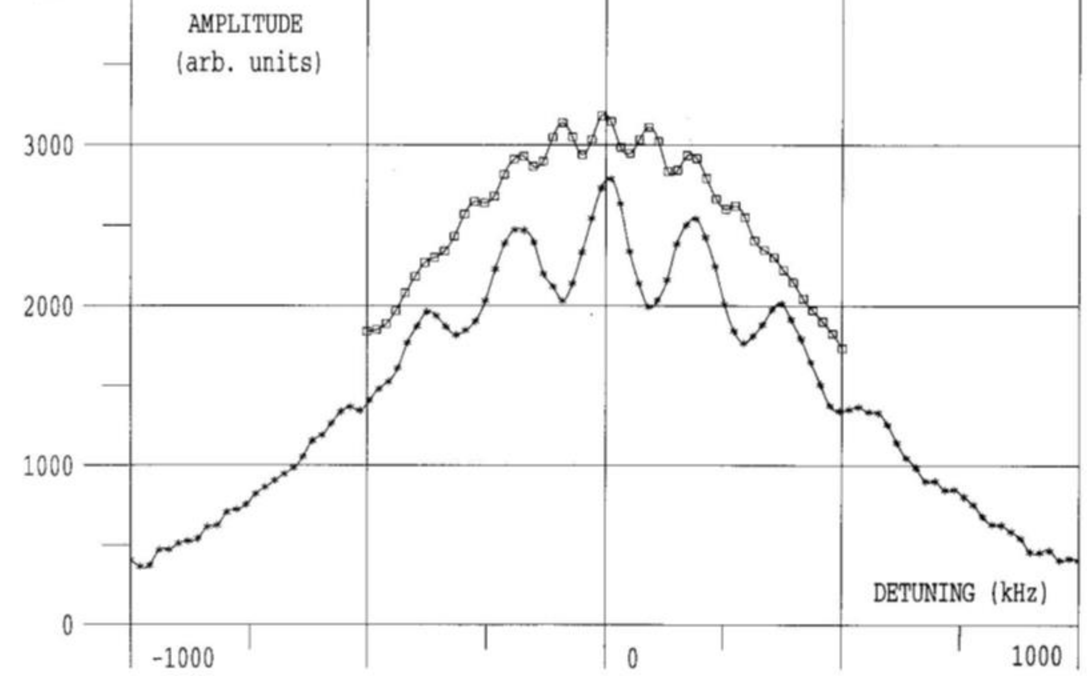
SF$_6$ 1981



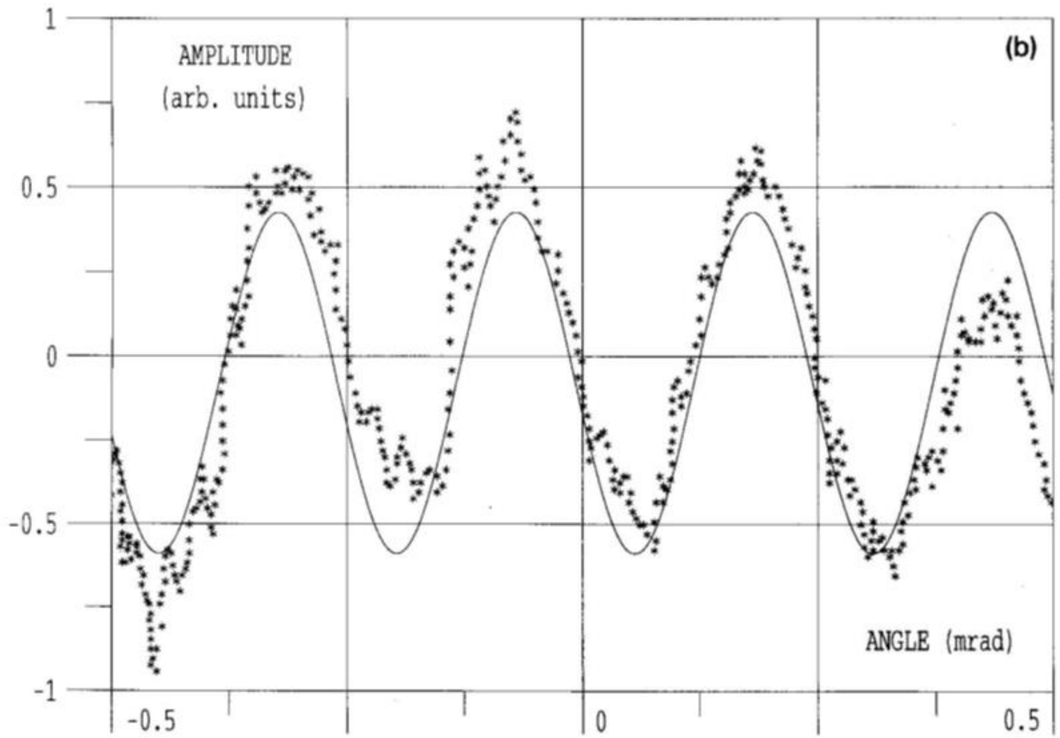


b
cat's eye 2
to photomultiplier
chopper
I_2beam
cat's eye 1
d
D
two slits diaphragm
laser beam
laser beams
laser beams
a
x
z
θ/2
θ/2
a,0
b,1
a,0
a,0
b,-1
molecular beam

I_2 1994



AMPLITUDE
(arb. units)
3000
2000
1000
0
DETUNING (kHz)
-1000
0
1000



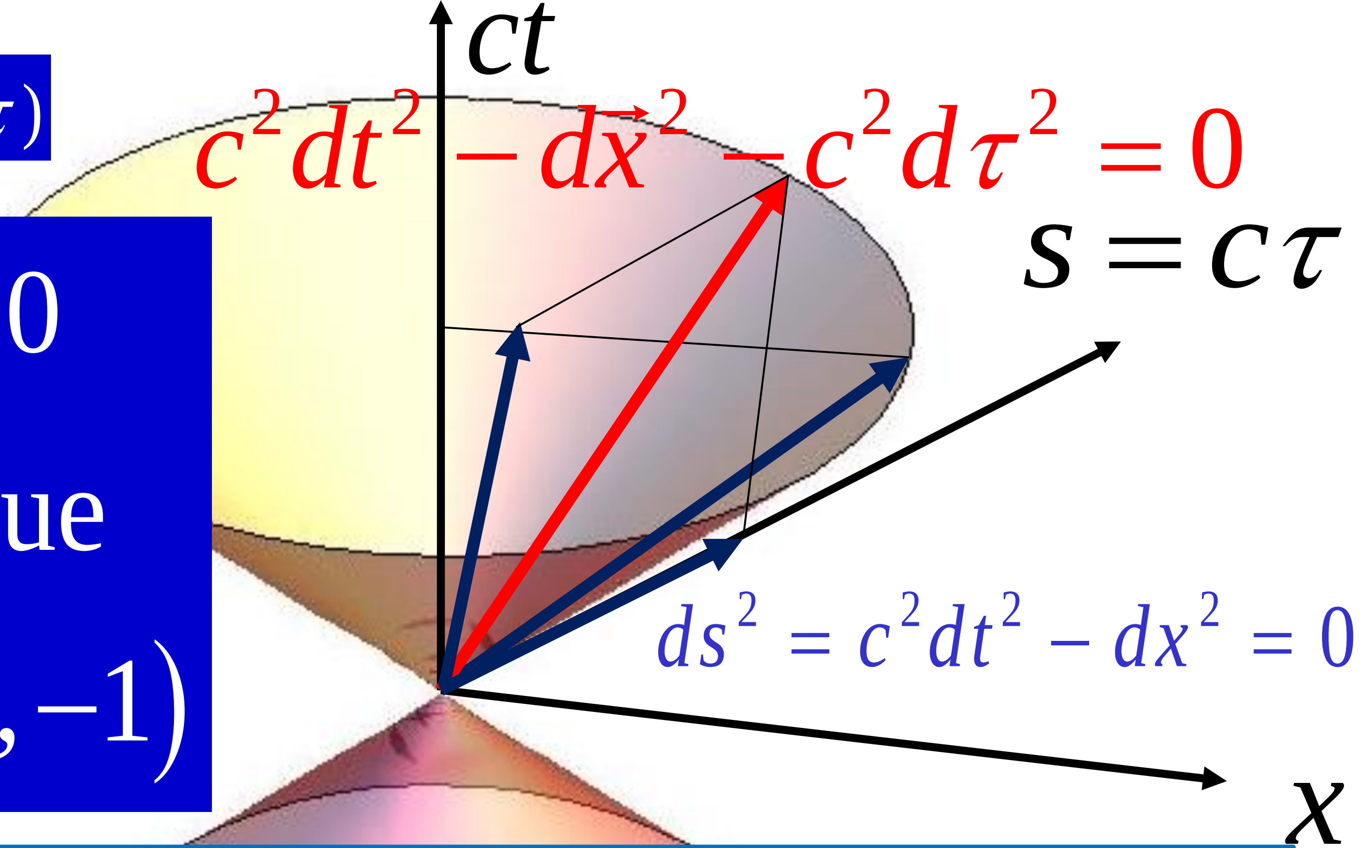
1
AMPLITUDE
(arb. units)
(b)
0.5
0
-0.5
-1
ANGLE (mrad)
-0.5
0
0.5

$x^{\hat{\mu}} = (ct, x, y, z, c\tau)$

$$G_{\hat{\mu}\hat{\nu}} dx^{\hat{\mu}} dx^{\hat{\nu}} = 0$$

tenseur métrique

$$G_{\hat{\mu}\hat{\nu}} = (1, -1, -1, -1, -1)$$



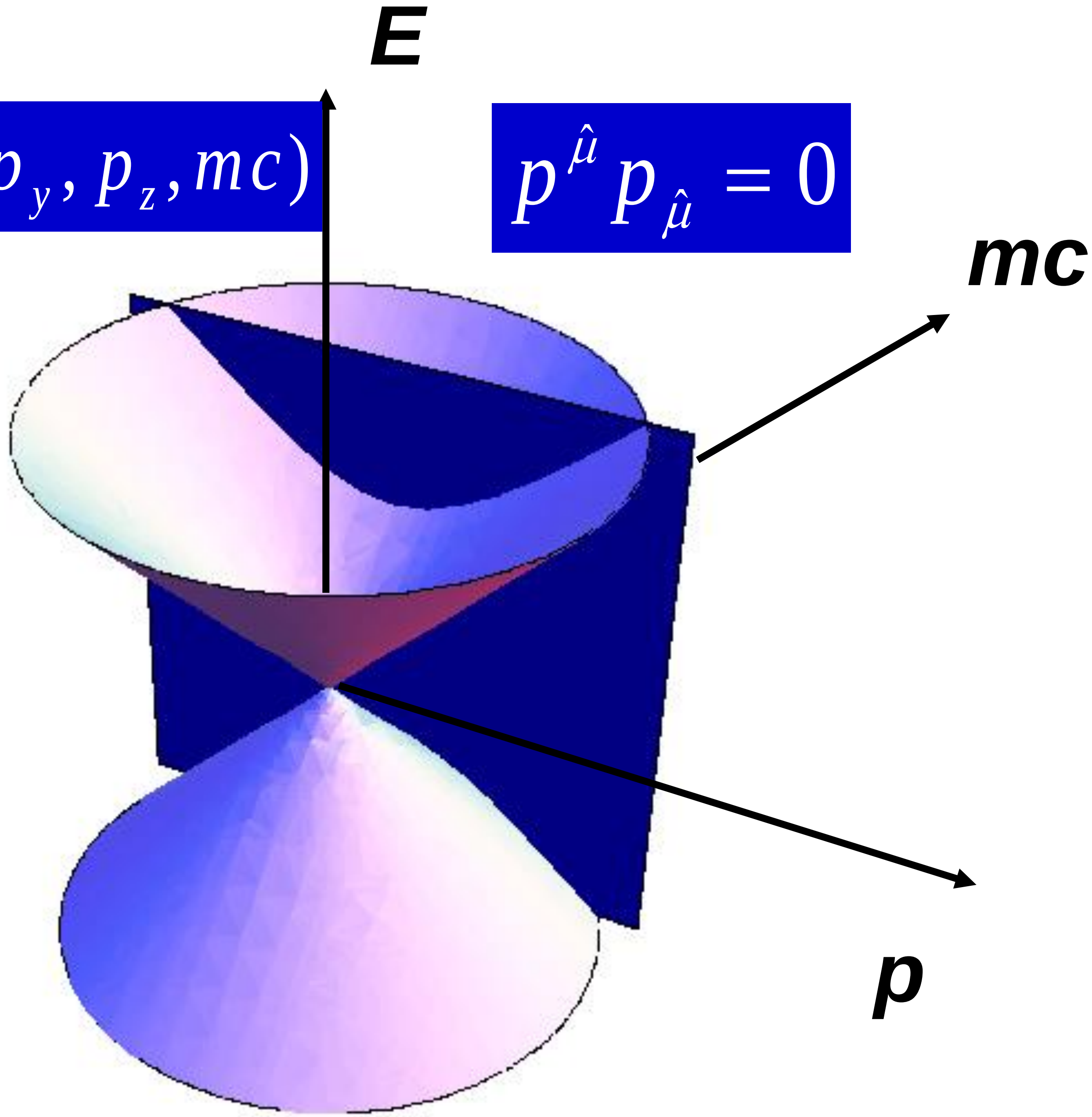
$$G^{\hat{\mu}\hat{\nu}} = \begin{pmatrix} g^{\mu\nu} & G^{\mu 4} = -\kappa A^{\mu} \\ G^{4\nu} = -\kappa A^{\nu} & G^{44} = -1 + \kappa^2 A^{\lambda} A_{\lambda} \end{pmatrix}$$

$\kappa = e/mc$ rapport gyromagnétique

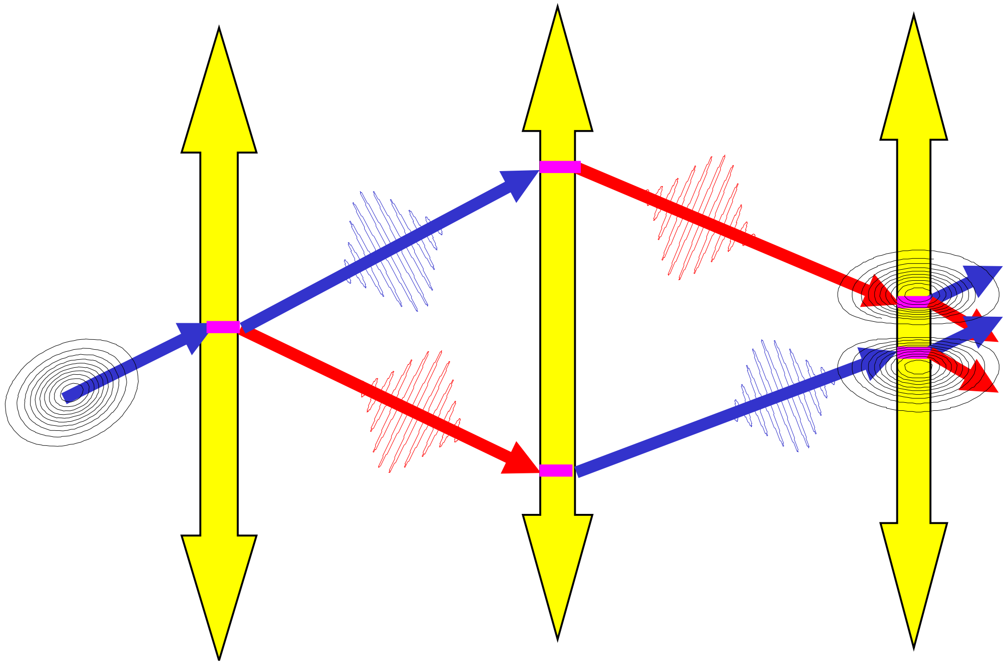
$$p^{\hat{\mu}} = (E/c, p_x, p_y, p_z, mc)$$

$$\hat{\mu} = 0,1,2,3,4$$

$$p^{\hat{\mu}} p_{\hat{\mu}} = 0$$



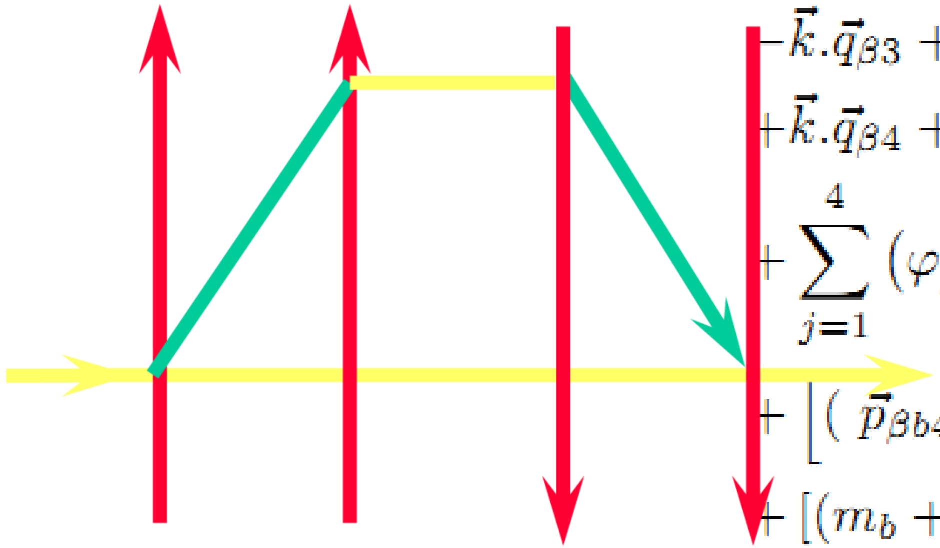
GENERAL FORMULA FOR THE PHASE SHIFT OF AN ATOM/PHOTON INTERFEROMETER



$$\delta\phi((q_{\beta,D}+q_{\alpha,D})/2) = \sum_{j=1}^{N}\left(\tilde{k}_{\beta j}q_{\beta j}-\tilde{k}_{\alpha j}q_{\alpha j}\right)-(\omega_{\beta j}-\omega_{\alpha j})\,t_j+(\varphi_{\beta j}-\varphi_{\alpha j})$$
$$+\left[(\tilde{p}_{\beta,D}+\tilde{p}_{\alpha,D})\,(q_{\alpha,D}-q_{\beta,D})/2\right]/\hbar \qquad (88)$$

$$
\begin{aligned}
\delta\phi\left(\left(q_{\beta,D}+q_{\alpha,D}\right)/2\right) \;=\; & \sum_{j=1}^{N}\left(\tilde{k}_{\beta j}q_{\beta j}-\tilde{k}_{\alpha j}q_{\alpha j}\right)-\left(\omega_{\beta j}-\omega_{\alpha j}\right)t_j+\left(\varphi_{\beta j}-\varphi_{\alpha j}\right) \\
& +\left[\left(\tilde{p}_{\beta,D}+\tilde{p}_{\alpha,D}\right)\left(q_{\alpha,D}-q_{\beta,D}\right)/2\right]/\hbar \qquad (88)
\end{aligned}
$$

Formula (88) gives for the mid-point 5D phase:



$$
\begin{aligned}
\delta\phi\left(\left(\widehat{q}_{\beta 4}+\widehat{q}_{\alpha 4}\right)/2\right) \;=\; & \vec{k}.\vec{q}_1+(m_b-m_a)c^2\tau_1/\hbar-\omega t_1 \\
& -\vec{k}.\vec{q}_{\beta 2}+(-m_b+m_a)c^2\tau_{\beta 2}/\hbar+\omega t_2 \\
& -\vec{k}.\vec{q}_{\beta 3}+(m_b-m_a)c^2\tau_{\beta 3}/\hbar-\omega t_3 \\
& +\vec{k}.\vec{q}_{\beta 4}+(-m_b+m_a)c^2\tau_{\beta 4}/\hbar+\omega t_4 \\
& +\sum_{j=1}^{4}\left(\varphi_{\beta j}-\varphi_{\alpha j}\right) \\
& +\left[\left(\vec{p}_{\beta b4}+\vec{p}_{\alpha a4}+\hbar\vec{k}\right).\left(\vec{q}_{\alpha 4}-\vec{q}_{\beta 4}\right)/2\right]/\hbar \\
& +\left[\left(m_b+m_a+m_a-m_b\right)\left(\tau_{\alpha 4}-\tau_{\beta 4}\right)/2\right]c^2/\hbar \quad (92)
\end{aligned}
$$

$$
\delta\varphi=\left(2\omega-(m_{b1}^{*}+m_{b2}^{*}-2m_{a}^{*})c^{2}/\hbar\right)T
$$

H 1994

NEW OPTICAL ATOMIC INTERFEROMETERS FOR PRECISE MEASUREMENTS OF RECOIL SHIFTS. APPLICATION TO ATOMIC HYDROGEN

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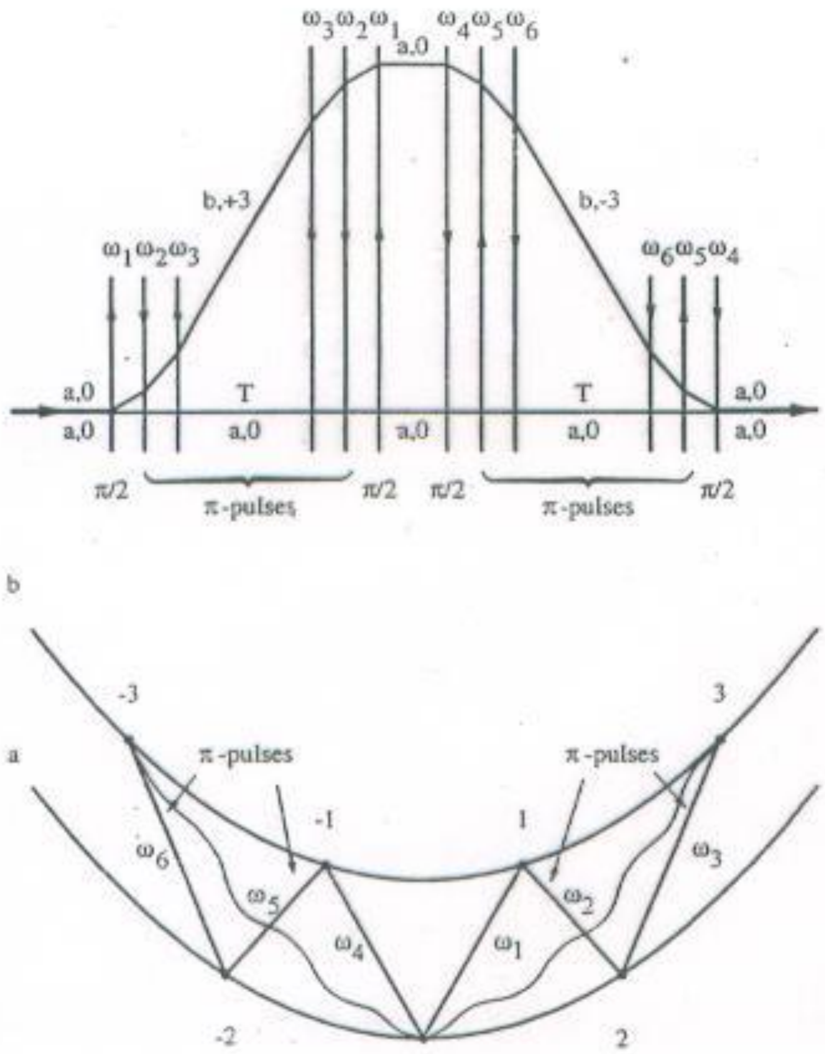
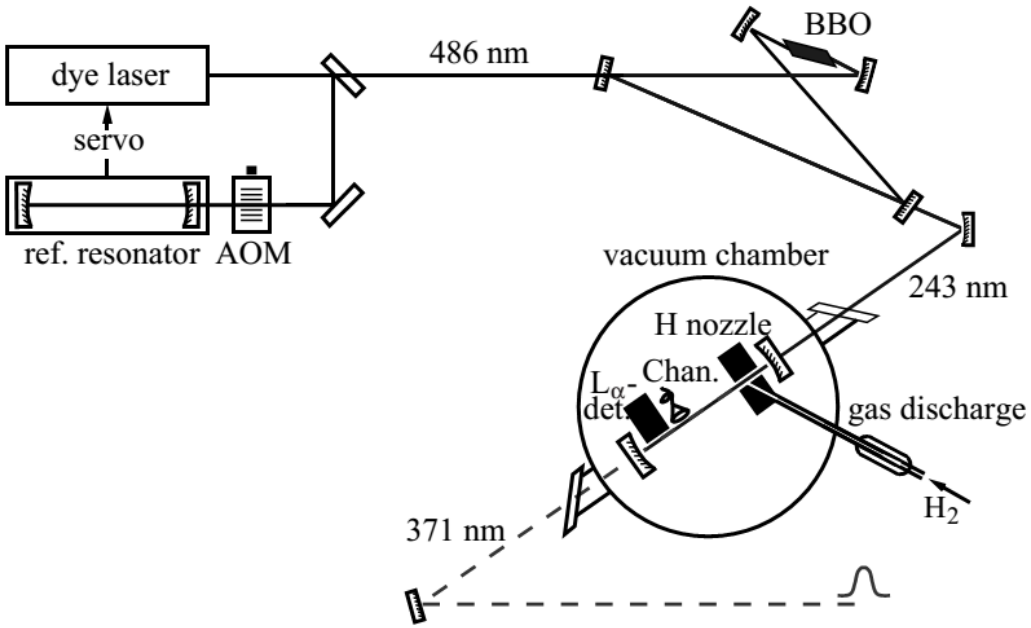


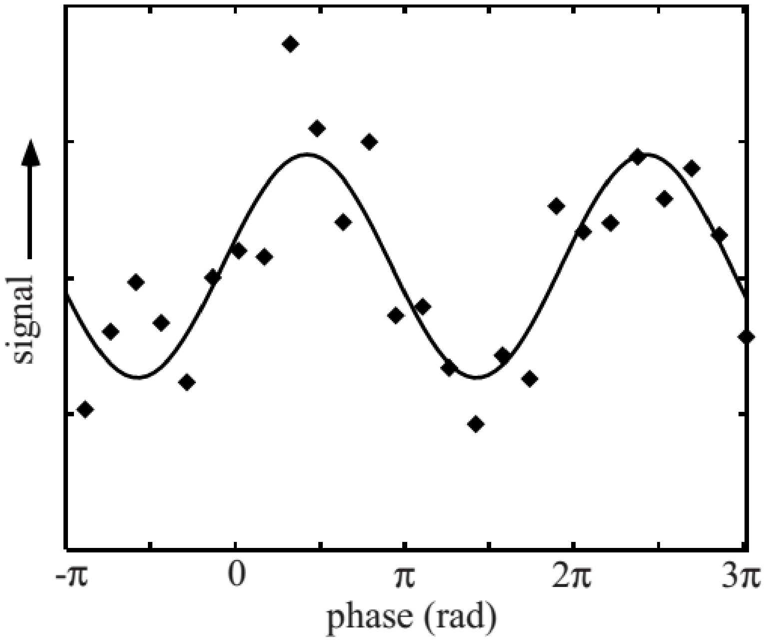
Fig. 1. Space-time and energy-momentum diagrams for an interferometer with $|m_1| = 3$ exchanged momentum quanta per interaction sequence. The two-level system interacts with effective multiphoton fields of opposite directions either perpendicular or collinear to the atomic motion. The space-time diagram displays the deflection along the optical axis versus the proper time in the "atomic frame" at the velocity $\vec{p}_0/M$. A coherent superposition of the two states $|a, 0>$ and $|b, m_1>$ is created (wiggly line) and travels freely during the time T leading to a phase shift $\varphi = (\omega_1 - \omega_2 + \omega_3 + \omega_4 - \omega_5 + \omega_6 - 2\omega_0 - 18\delta)T$. A second interferometer with opposite recoil shift is obtained by exchanging the roles of states a and b.

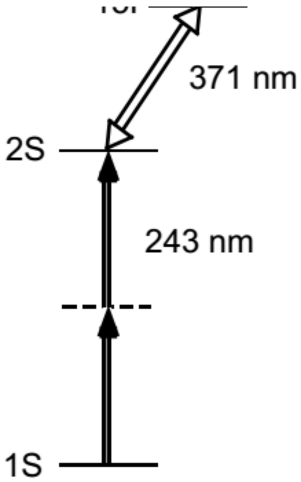
Hydrogen atom interferometer with short light pulses

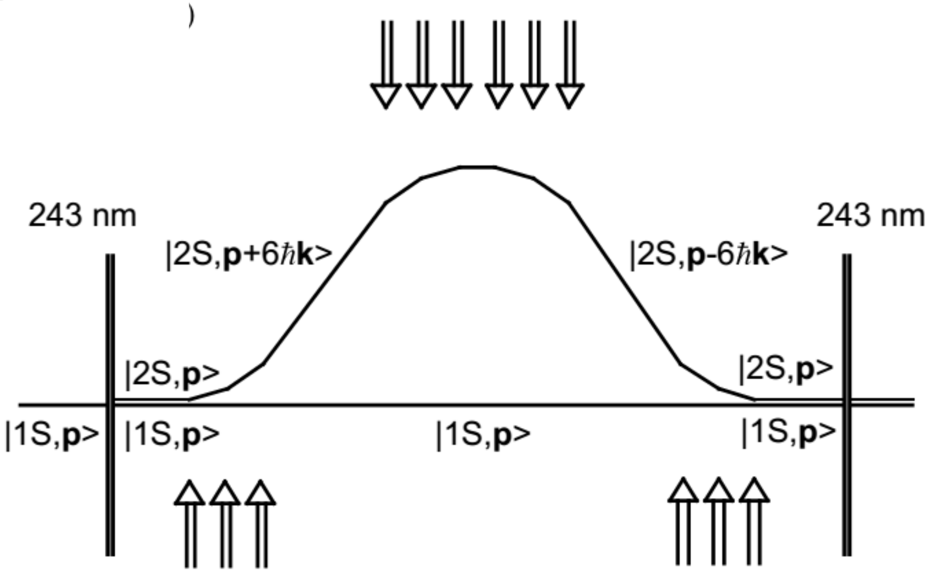
T. Heupel[1], M. Mei[1], M. Niering[1], B. Gross[1], M. Weitz[1], T. W. Hänsch[1] and Ch. J. Bordé[2]



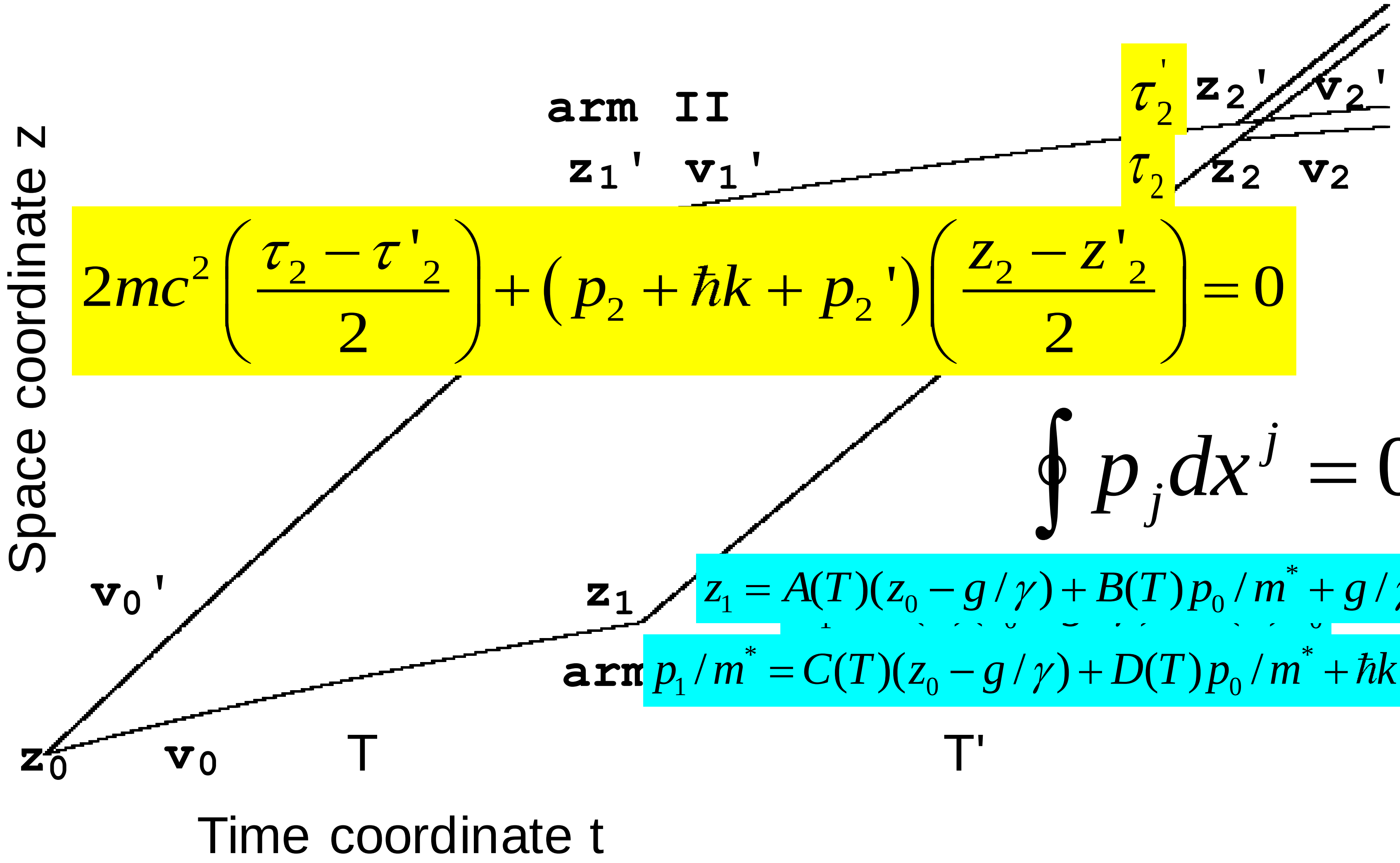
H 2002







Atomic Gravimeter



$$2mc^2\left(\frac{\tau_2-\tau'_2}{2}\right)+\left(p_2+\hbar k+p_2'\right)\left(\frac{z_2-z'_2}{2}\right)=0$$

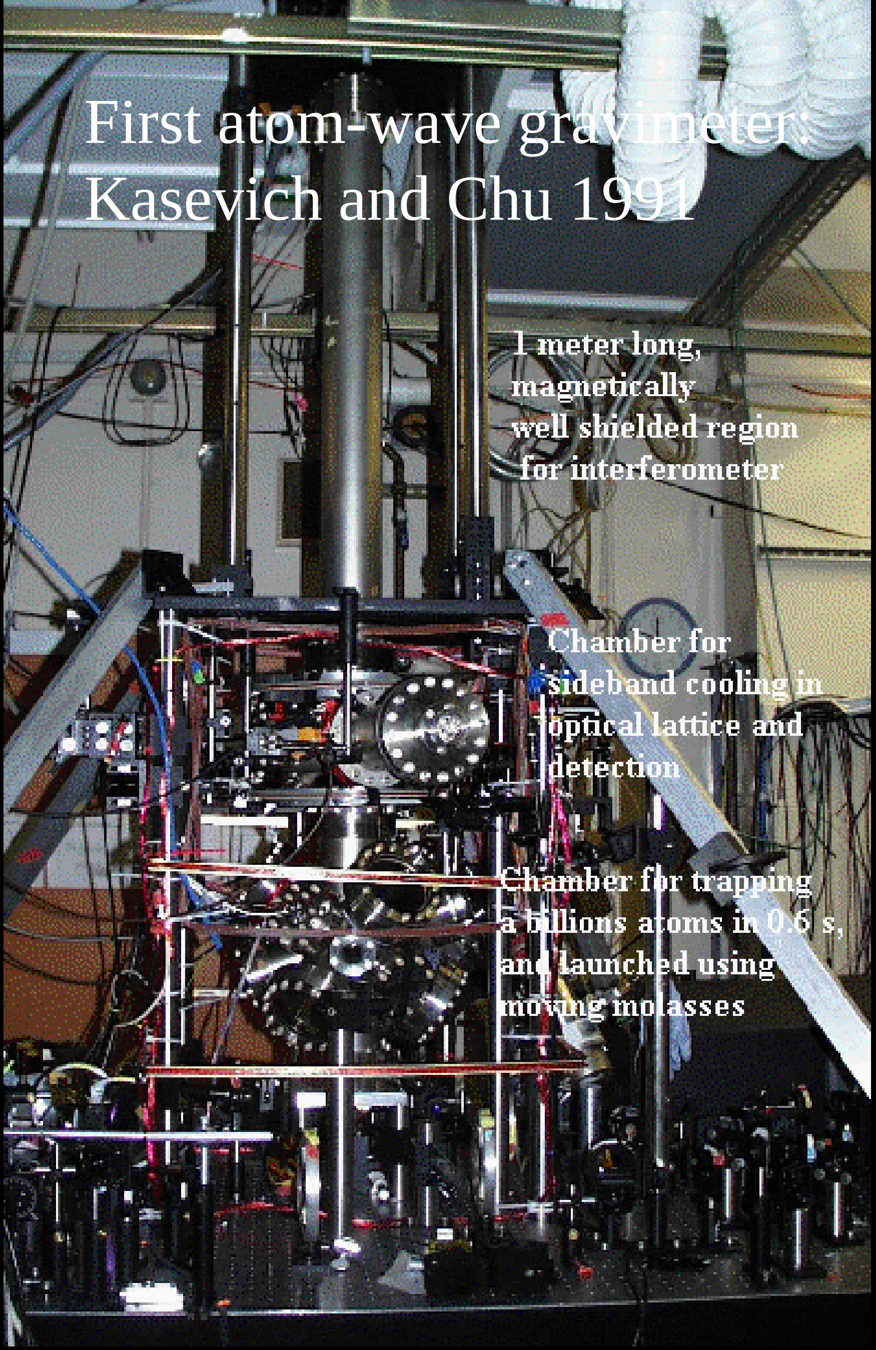
$$\oint p_j dx^j = 0$$

$$z_1 = A(T)(z_0-g/\gamma)+B(T)p_0/m^*+g/\gamma$$

$$p_1/m^* = C(T)(z_0-g/\gamma)+D(T)p_0/m^*+\hbar k/m^*$$

$$\delta\varphi = -kz_0+2k(z_1+z'_1)/2-k(z_2+z'_2)/2$$

Exact phase shift for the atom gravimeter



$$\delta\varphi = -kz_0 + 2k(z_1 + z'_1)/2 - k(z_2 + z'_2)/2$$

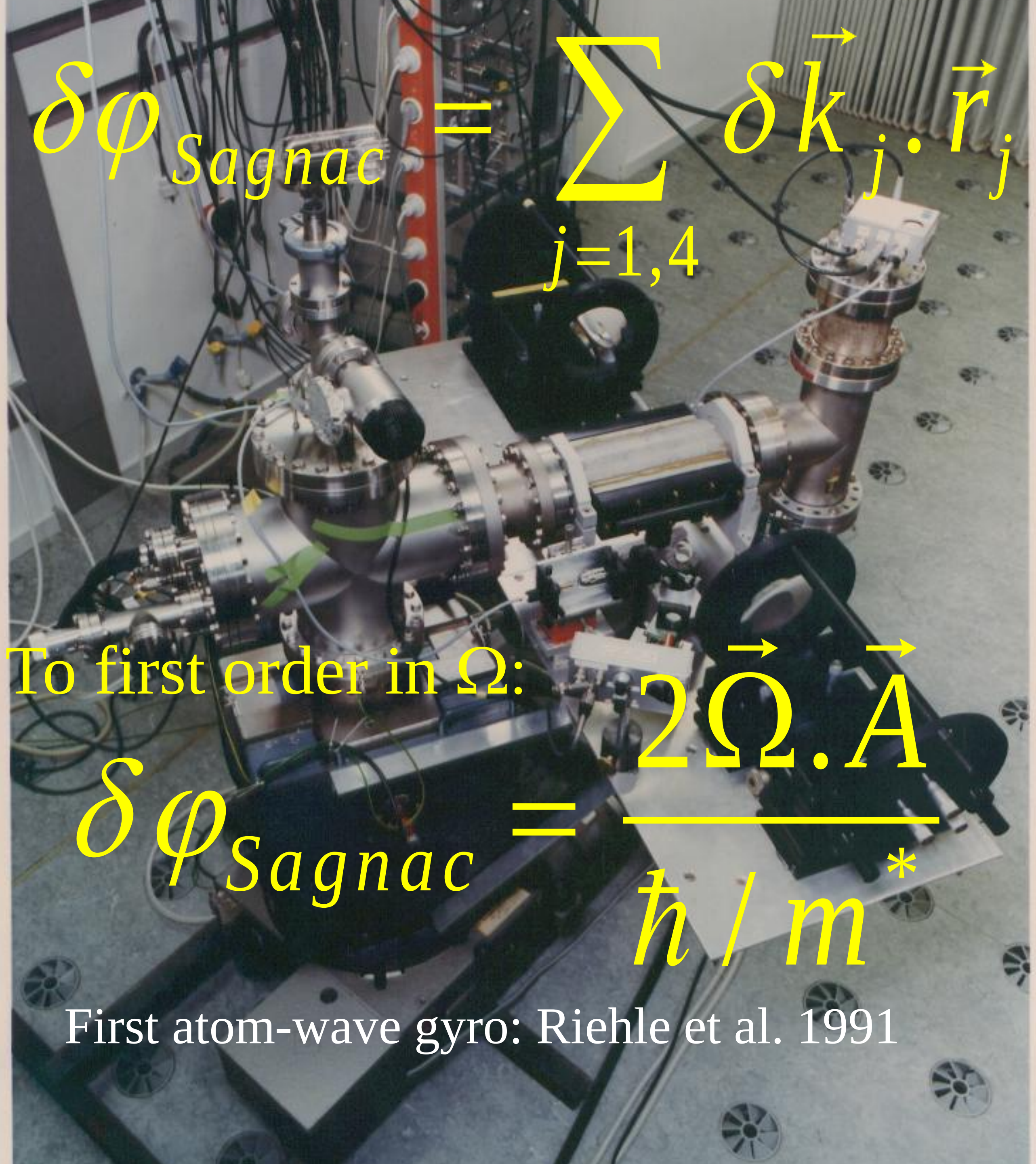
$$= \frac{k}{\sqrt{\gamma}}\left\{\left[\sinh\left(\sqrt{\gamma}\,(T+T')\right) - 2\sinh\left(\sqrt{\gamma}T\right)\right]\left(\mathrm{v}_0 + \frac{\hbar k}{2m^*}\right)\right.$$

$$\left. + \sqrt{\gamma}\left[1 + \cosh\left(\sqrt{\gamma}\,(T+T')\right) - 2\cosh\left(\sqrt{\gamma}T\right)\right]\left(z_0 - \frac{g}{\gamma}\right)\right\}$$

which can be written to first-order in γ, with T=T’:

$$\delta\varphi = kgT^2 + k\gamma T^2\left[\frac{7}{12}gT^2 - \left(\mathrm{v}_0 + \frac{\hbar k}{2m^*}\right)T - z_0\right]$$

Ch. J. B., Theoretical tools for atom optics and interferometry, C.R. Acad. Sci. Paris, 2, Série IV, p. 509-530, 2001


$$\delta\varphi_{Sagnac} = \sum_{j=1,4} \delta\vec{k}_j . \vec{r}_j$$
To first order in Ω:
$$\delta\varphi_{Sagnac} = \frac{2\vec{\Omega}.\vec{A}}{\hbar / m^*}$$
First atom-wave gyro: Riehle et al. 1991

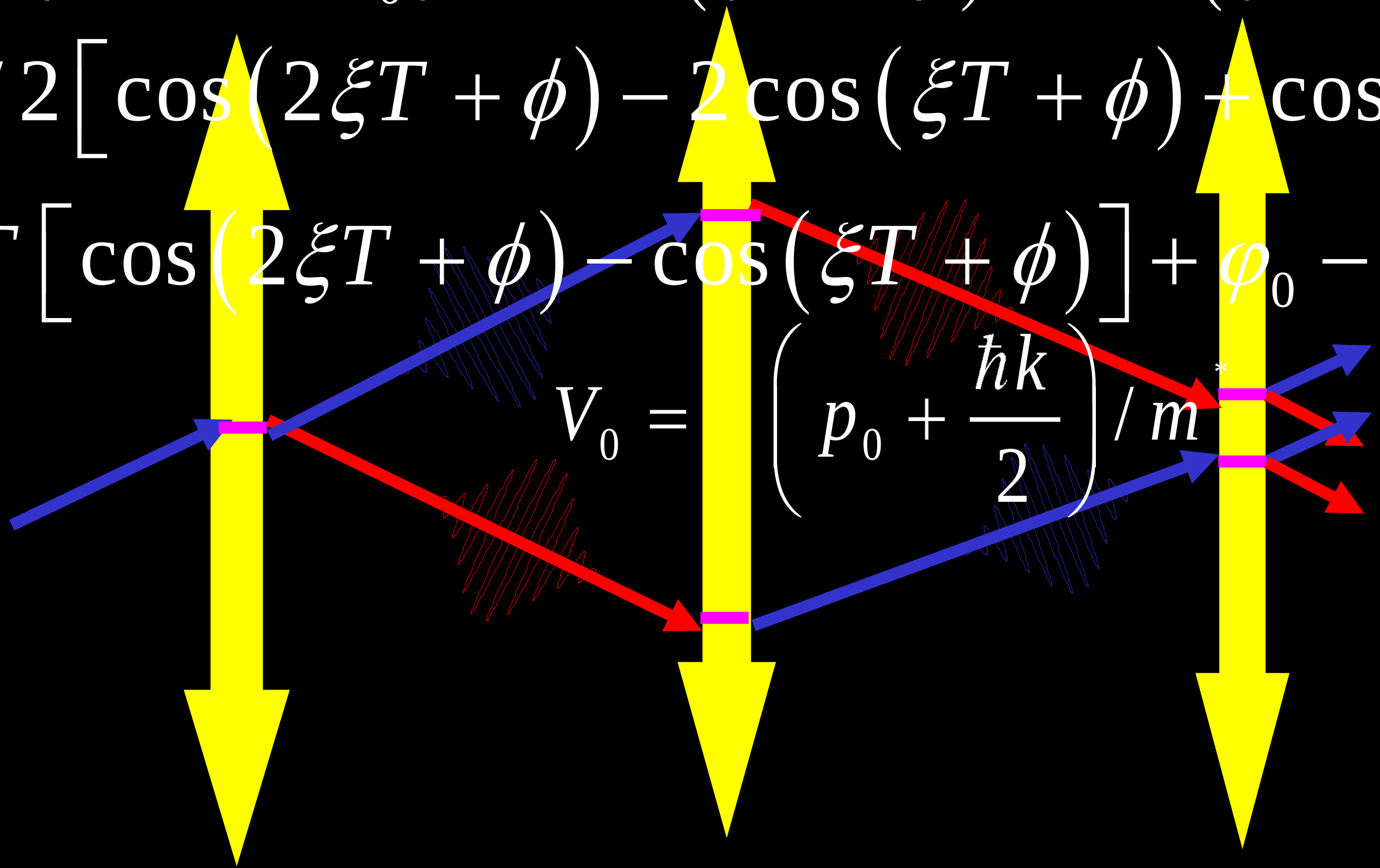
Atomic phase shift induced by a gravitational wave

$$\delta\varphi = -khV_0\xi T^2 \sin(\xi T + \phi)\,\mathrm{sinc}^2(\xi T/2)$$

$$-khq_0/2\left[\cos(2\xi T + \phi) - 2\cos(\xi T + \phi) + \cos\phi\right]$$

$$-khV_0T\left[\cos(2\xi T + \phi) - \cos(\xi T + \phi)\right] + \varphi_0 - 2\varphi_1 + \varphi_2$$

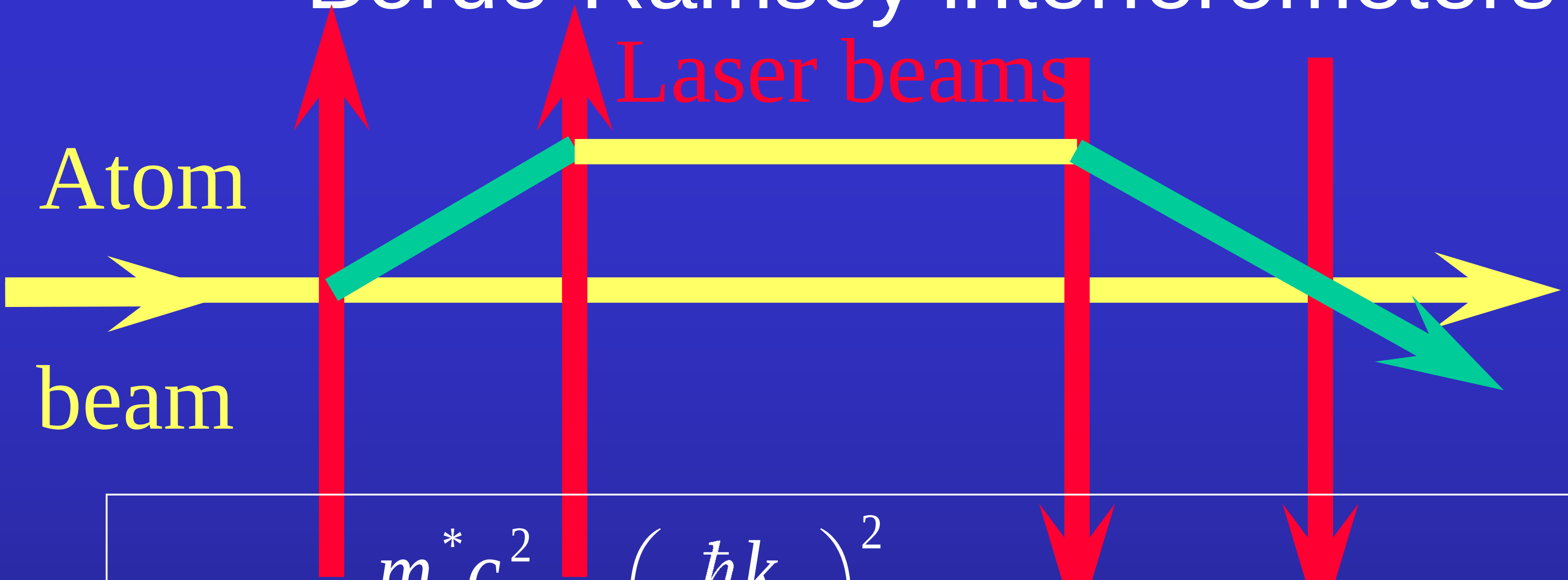
$$V_0 = \left(p_0 + \frac{\hbar k}{2}\right)/m^*$$



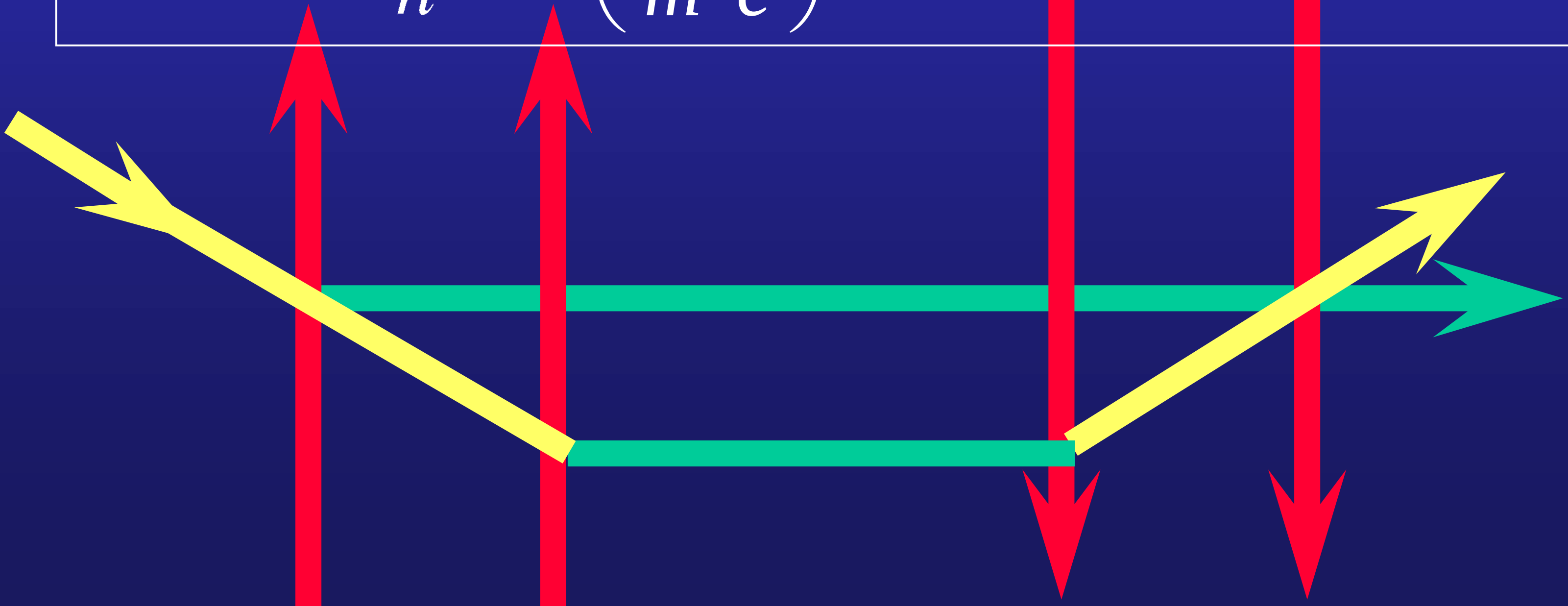
Ch.J. Bordé, Gen. Rel. Grav. 36 (March 2004)

Ch.J. Bordé, J. Sharma, Ph. Tourrenc and Th. Damour, *Theoretical approaches to laser spectroscopy in the presence of gravitational fields*, J. Physique Lettres 44 (1983) L983-990

Bordé-Ramsey interferometers



$$\delta\varphi = -\frac{m^{*}c^{2}}{\hbar}T\left(\frac{\hbar k}{m^{*}c}\right)^{2} h\cos\left(\xi T+\phi\right)\mathrm{sinc}\left(\xi T\right)$$



Merci ! Thank you !