Experiments with a high visibility lithium atom interferometer

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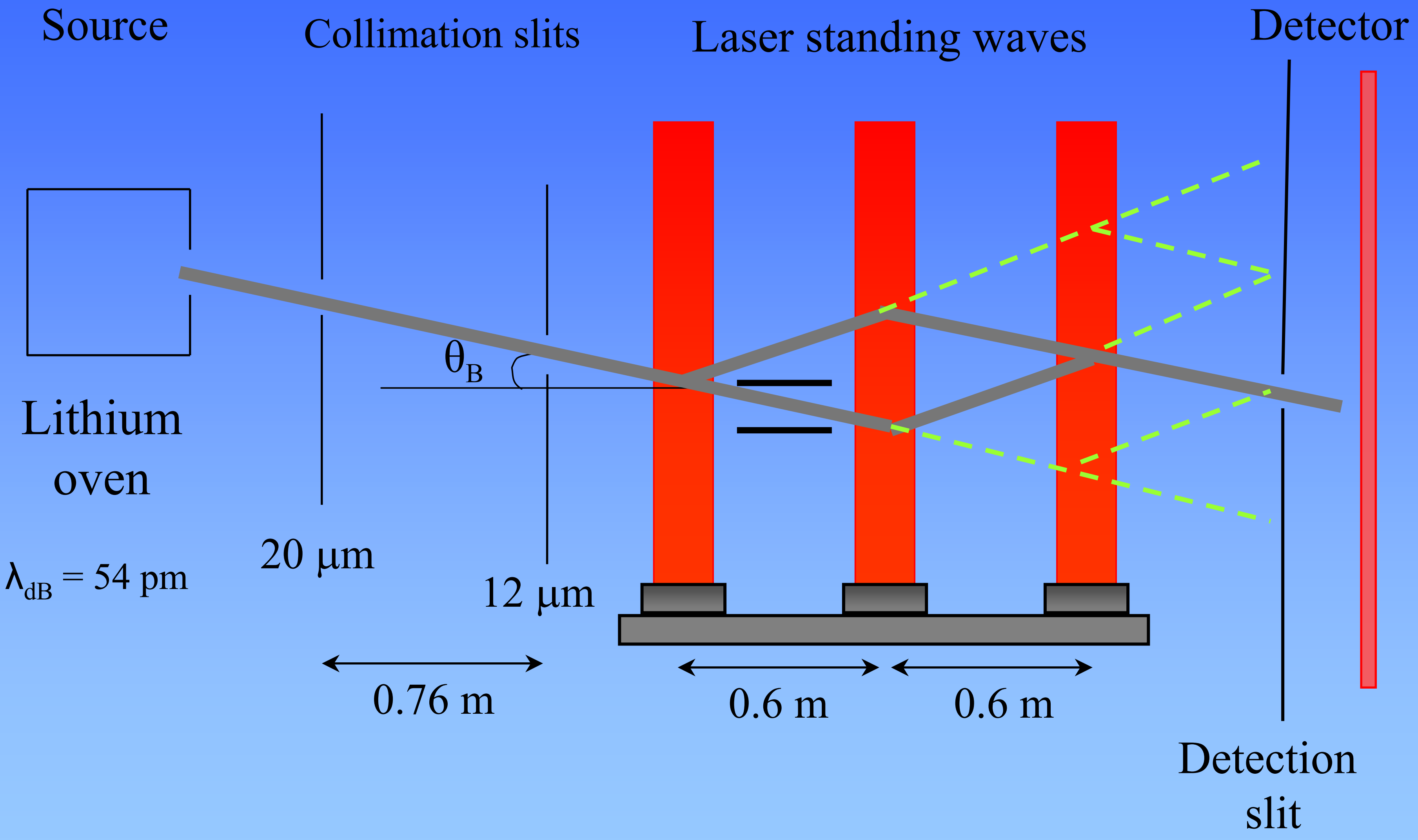
Plan

I. Our atom interferometer

II. Experiments with a magnetic field gradient

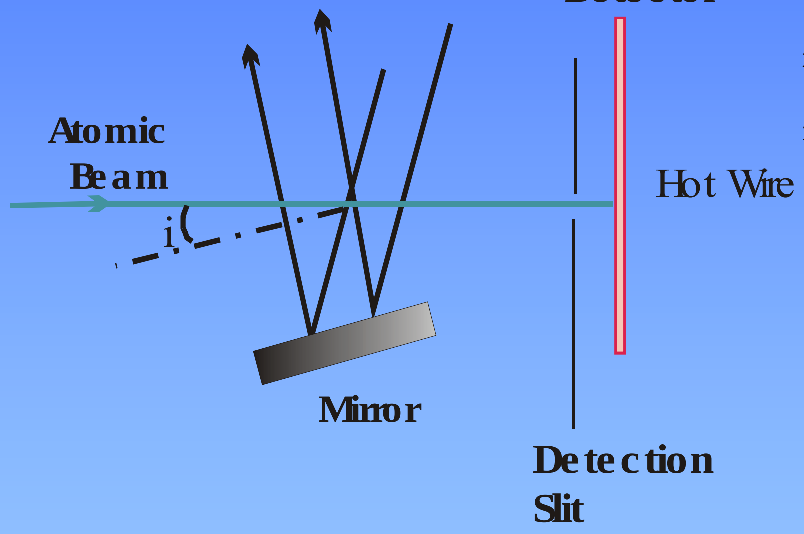
III. Lithium atom polarizability measurement

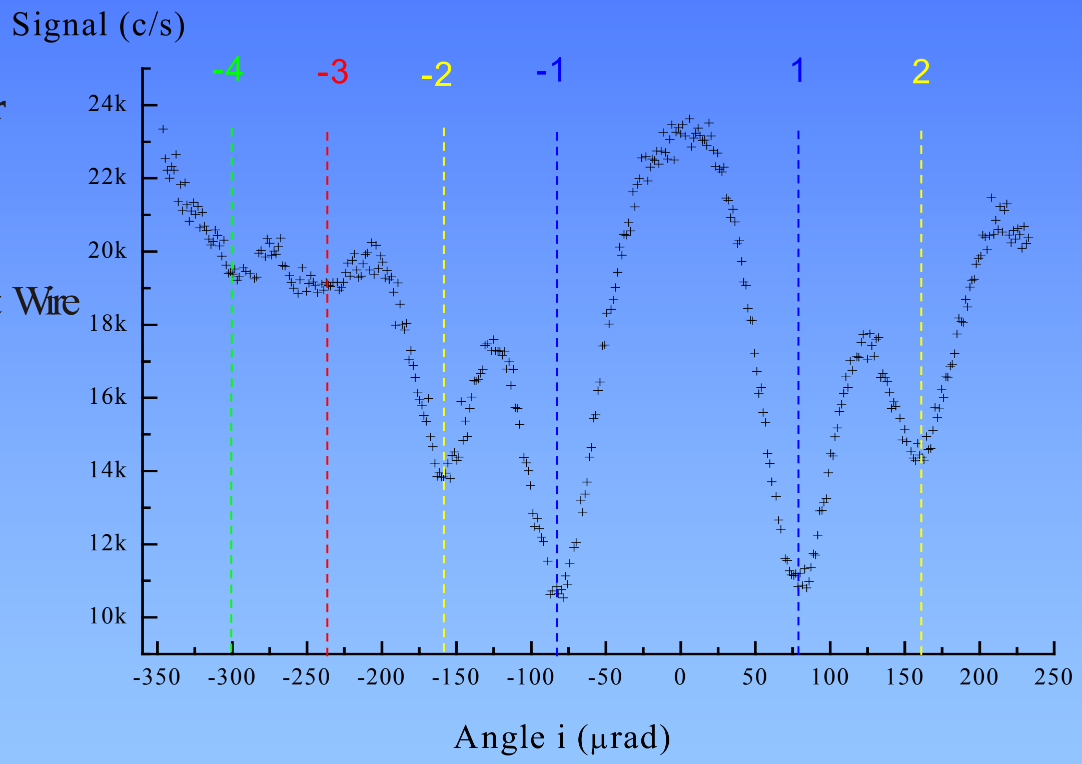
Experimental set-up



Diffraction of the lithium atomic wave

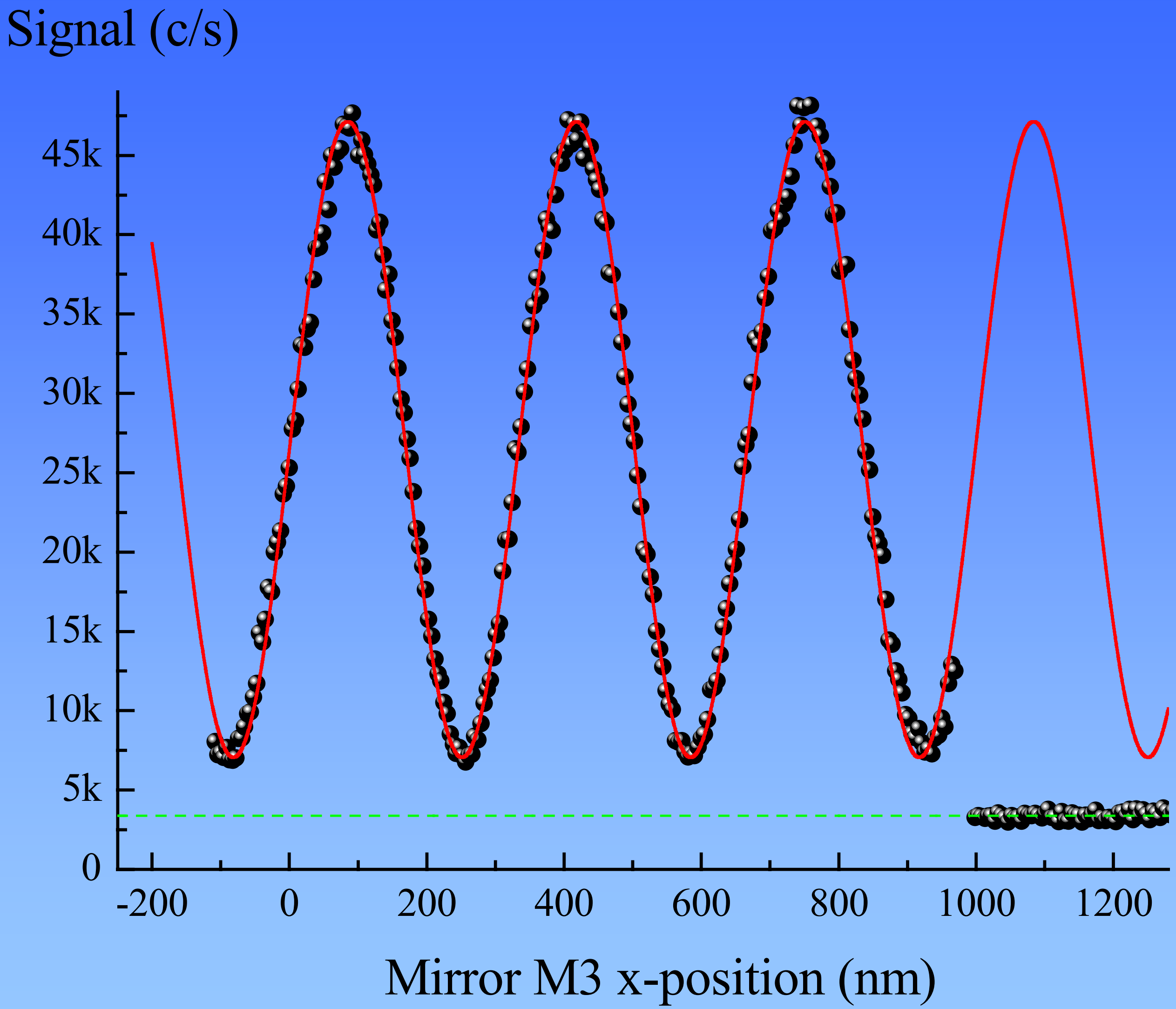
As a function of the orientation of the mirror used for the laser standing wave, the Bragg condition is fulfilled for various orders p, here from p = -2 to p = +4





Laser standing waves : $\delta_L/(2\pi) = 1.2$ GHz, $w_0 = 3.1$ mm, $P_L = 240$ mW

Lithium atom interference fringes



p = 1

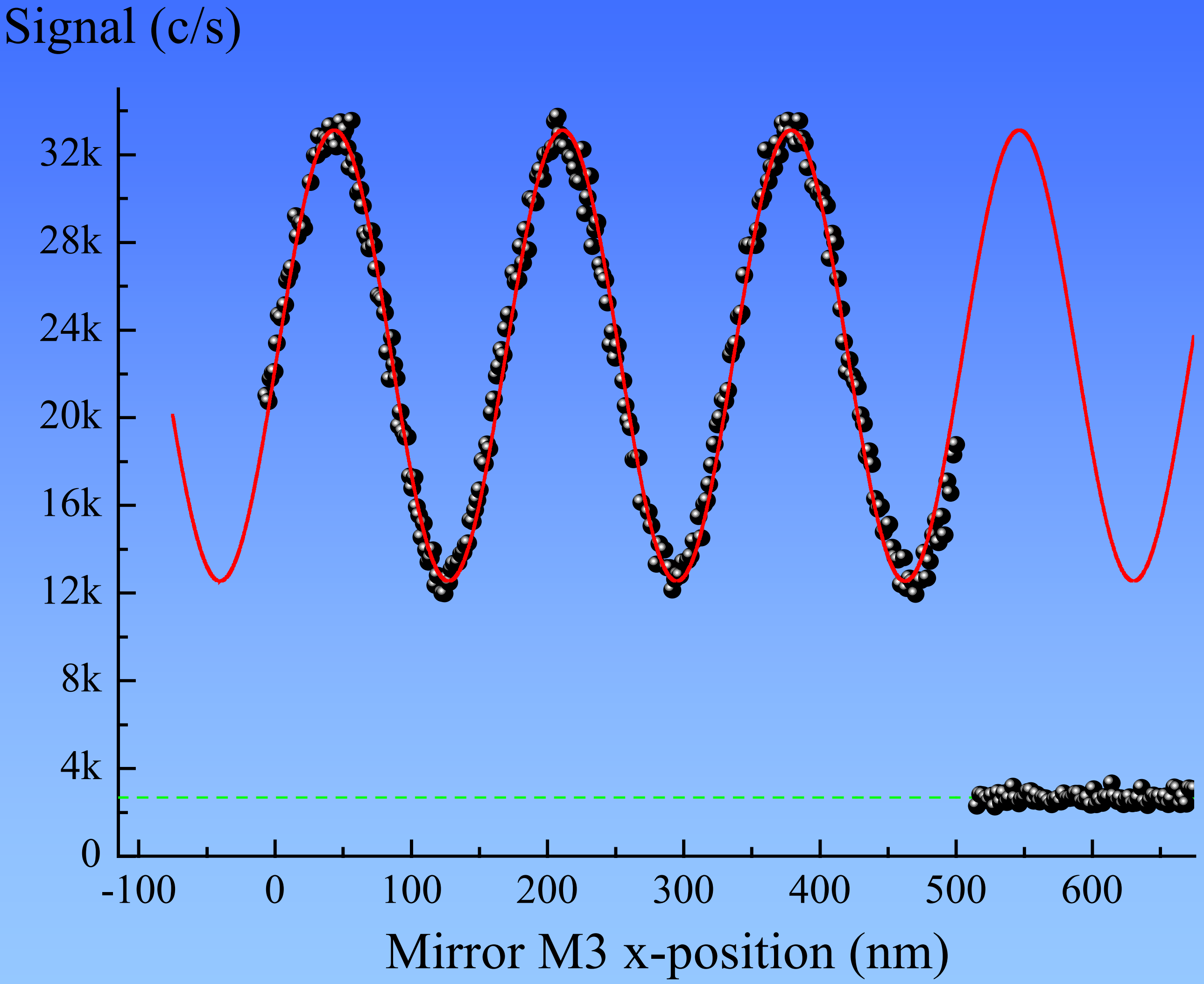
Fringe visibility V
= 84.5 ± 1%

Output Flux
I_0 = 23700 c/s

Phase sensitivity
25 mrad / $\sqrt{\mathbf{Hz}}$

Laser standing waves: $\delta/(2\pi)$ = 2.8 GHz, w_0 = 5.0 mm, P = 150 mW

Atom fringes using Bragg order 2 diffraction



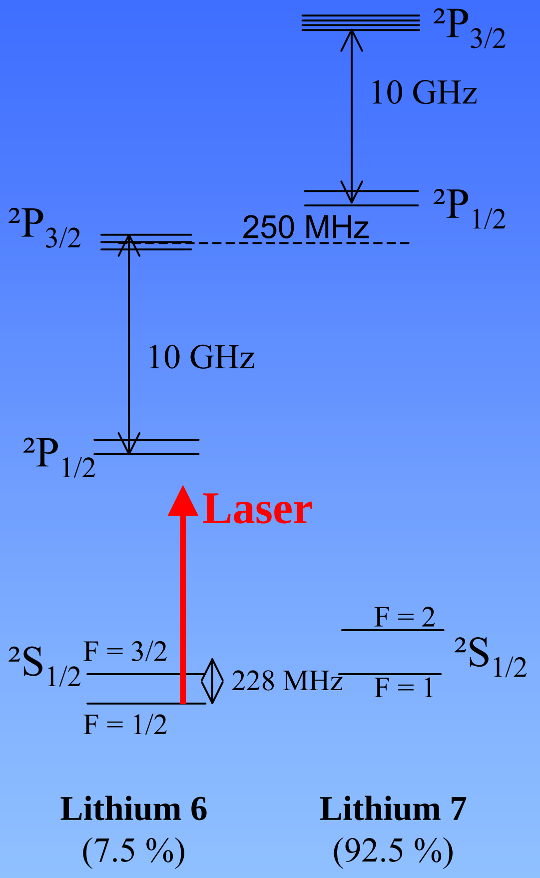
p = 2

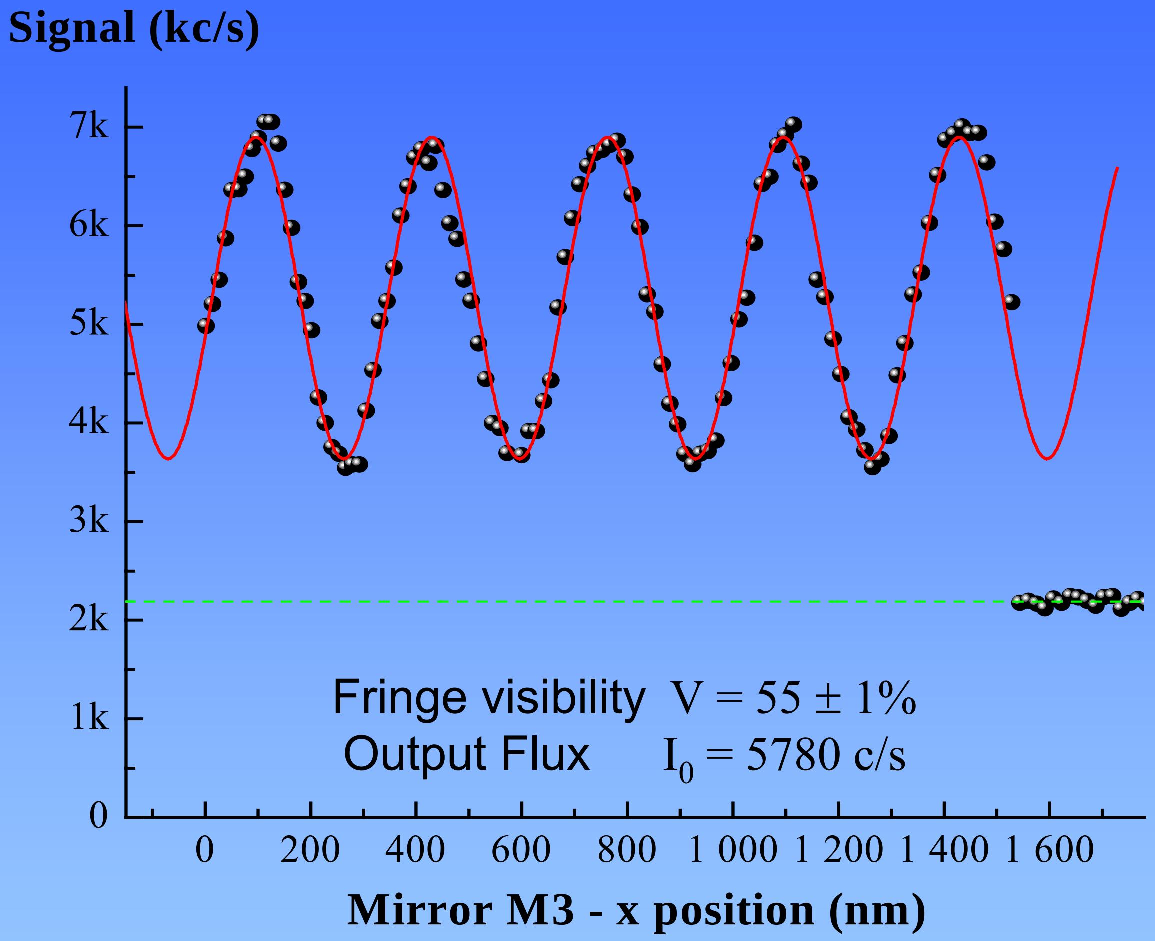
Fringe visibility
V = 54 ± 1%

Output Flux
I_0 = 20180 c/s

Laser standing waves: $\delta/(2\pi)$ = 3.1 GHz, w_0 = 1.8 mm, P = 460 mW

Isotope 6 interference fringes





Fringe visibility V = 55 ± 1%

Output Flux I_0 = 5780 c/s

A. Miffre et al., Eur. Phys. J. D., accepted for publication, available at
http://www.lanl.gov/ps/quant-ph/040182

II. Experiments with a magnetic field gradient

- The $|F, M_F\rangle$ sublevels are the eigenstates
- Adiabatic approximation

    The magnetic field B does not vanish or rotate too rapidly
- Zeeman Phase Shift

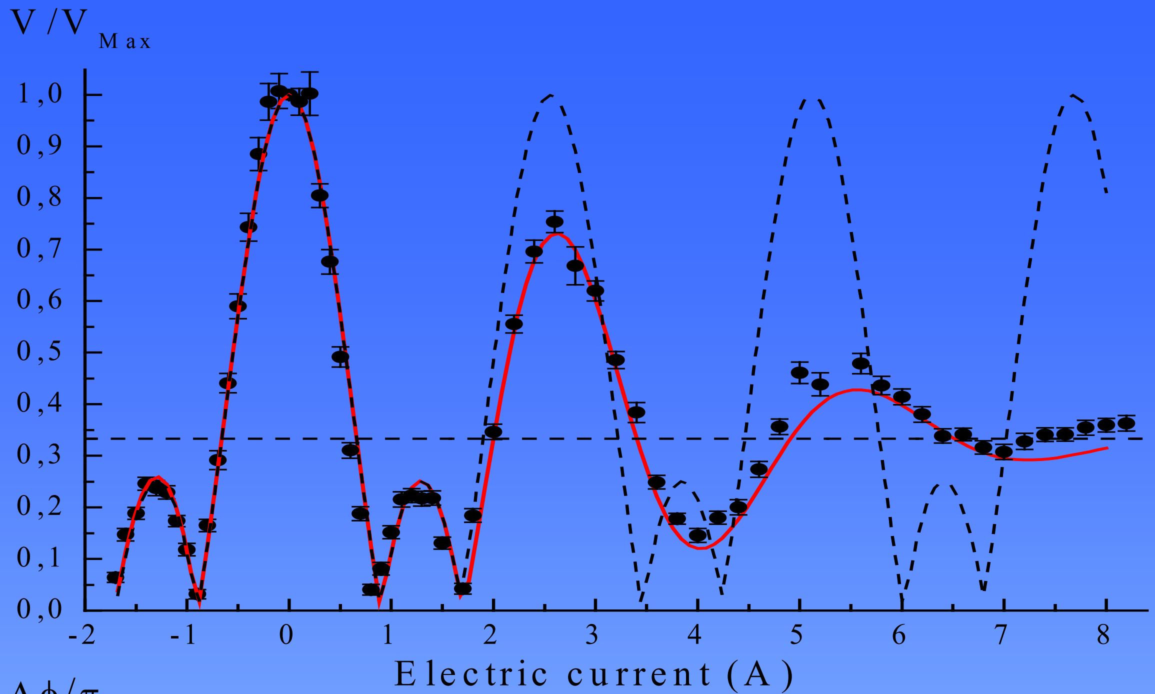
$$\Delta\phi(F, M_F) = \varphi M_F$$

$$\varphi = \frac{g_F \mu_B}{\hbar v} \int \frac{dB(s)}{dx} \Delta x(s) ds$$

- For ^{7}Li (I = 3/2), $^2S_{1/2}$, F=1 and F=2 → 8 sublevels (Landé factors $g_F = \pm 1/2$)

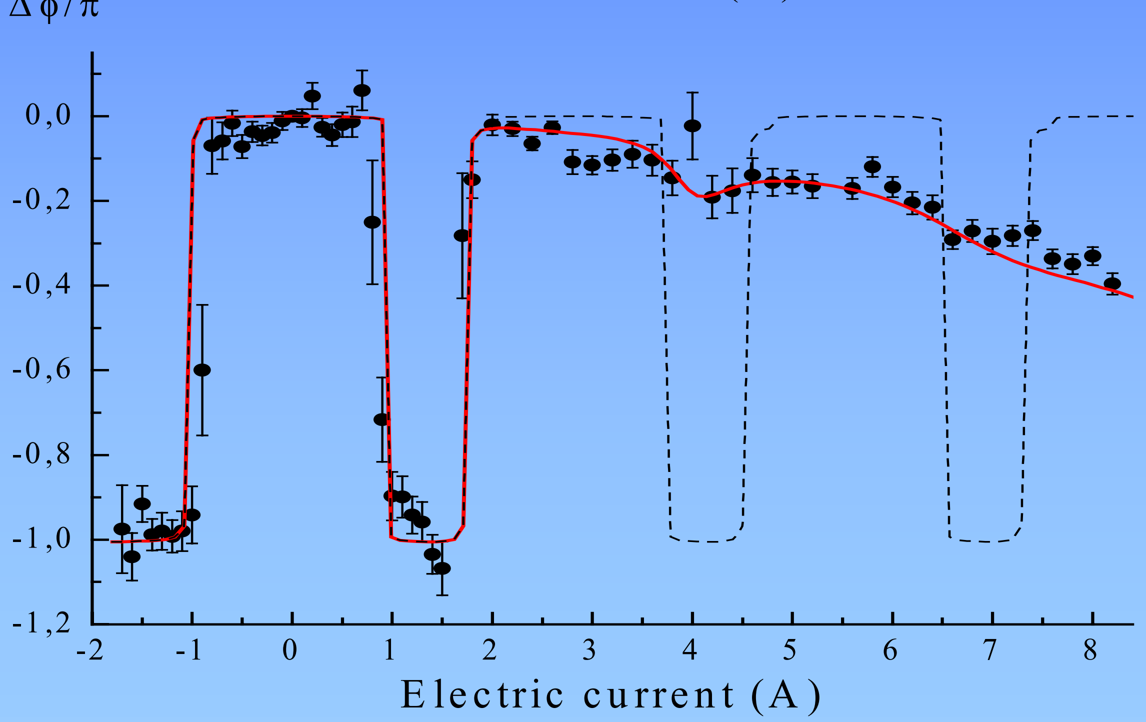
    Optical pumping in $^2S_{1/2,\, F=1}$

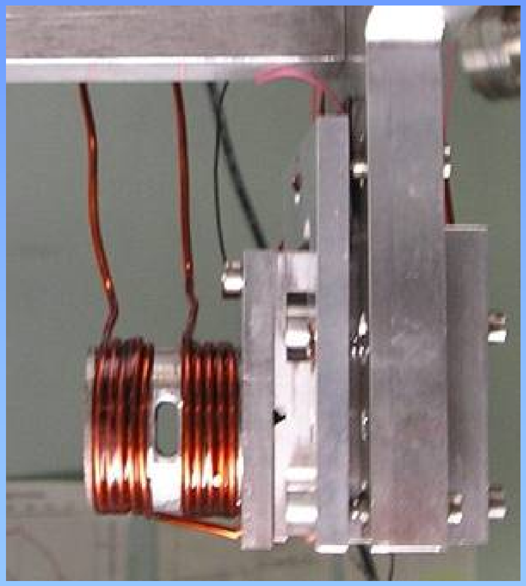
$$\frac{V}{V_{MAX}} = \frac{1 + 2\cos(\varphi)}{3}$$



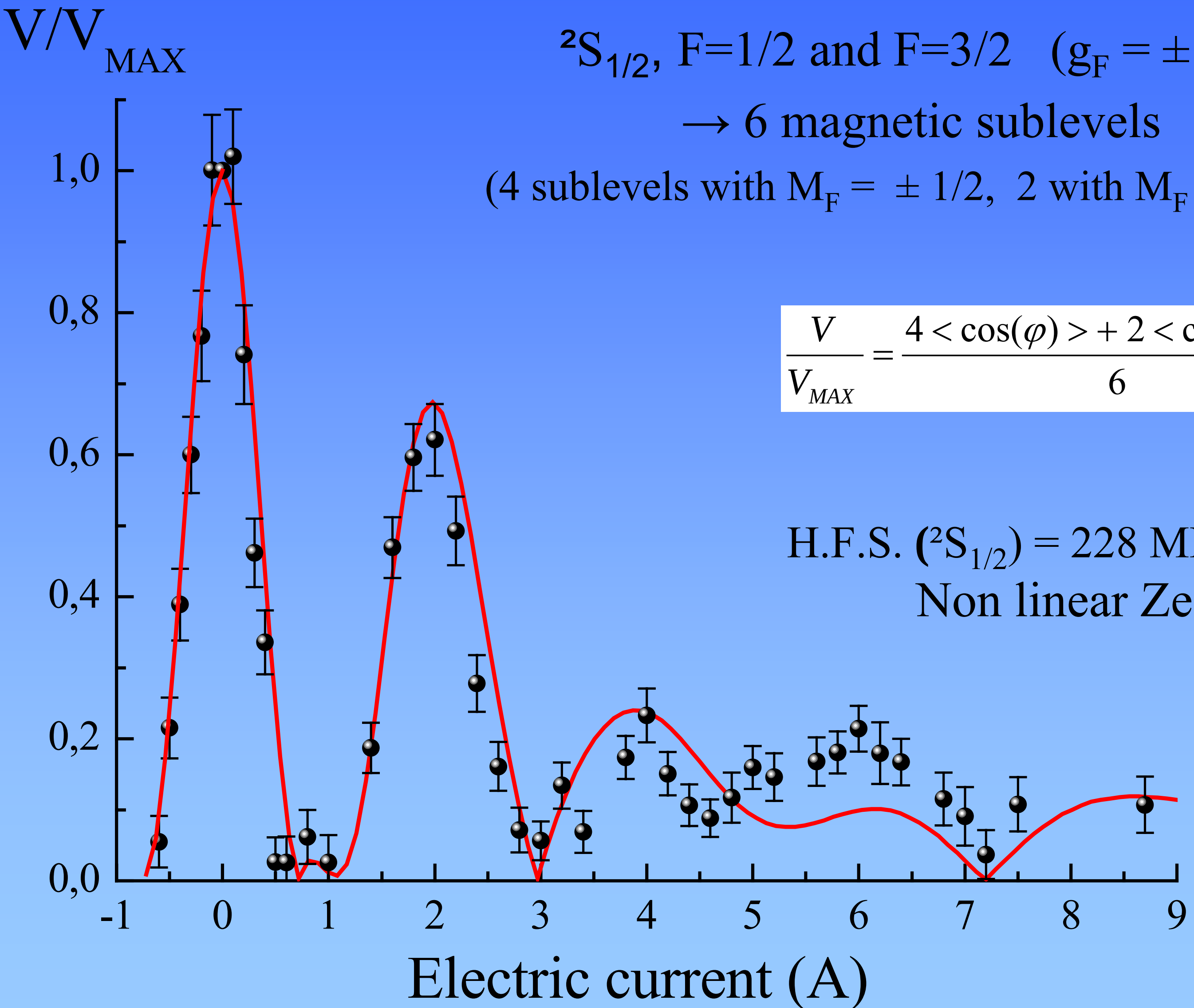
- - - - - Theoretical simulation without velocity dispersion

—— Theoretical simulation including velocity dispersion





Magnetic rephasing experiment with ^{6}Li (I = 1)



$^2S_{1/2}$, F=1/2 and F=3/2 ($g_F = \pm 1/3$)

→ 6 magnetic sublevels

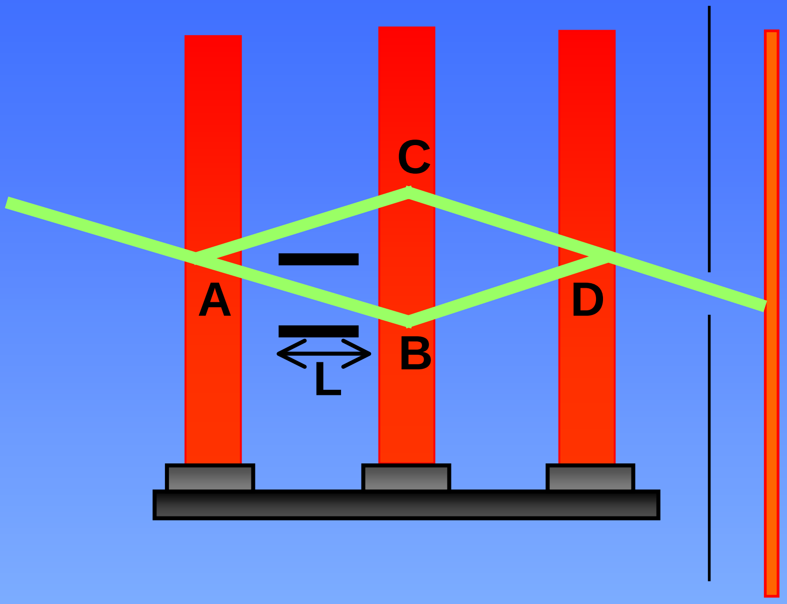
(4 sublevels with $M_F = \pm 1/2$, 2 with $M_F = \pm 3/2$)

$$\frac{V}{V_{MAX}} = \frac{4 < \cos(\varphi) > + 2 < \cos(2\varphi) >}{6}$$

H.F.S. ($^2S_{1/2}$) = 228 MHz smaller than for ^{7}Li

Non linear Zeeman effects !

III. Lithium atom polarizability measurement



$$\Delta\Phi = \int_{ABD} U(t)\,dt/\eta - \int_{ACD} U(t)\,dt/\eta$$

U = Perturbation $= -\,4\pi\varepsilon_0\alpha\,E^2/2$

D.E. Pritchard et al, Phys. Rev. A **51**, 3883
Electric polarizability of sodium atom

Stark Phase Shift $$\Delta\phi_{\mathrm{Stark}} = 4\pi\varepsilon_0\alpha\,\frac{E^2L}{2\eta u}$$

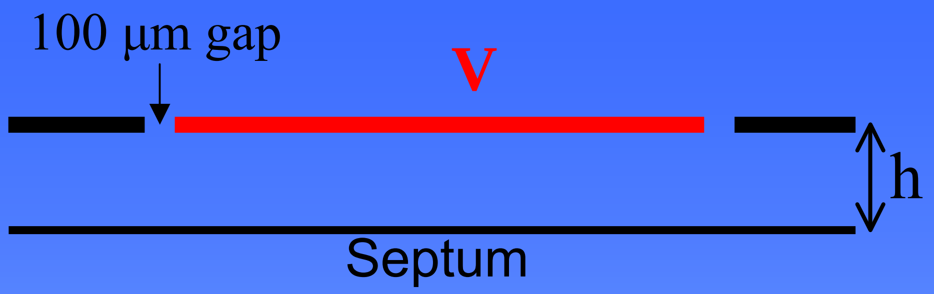
proportional to E^2/u

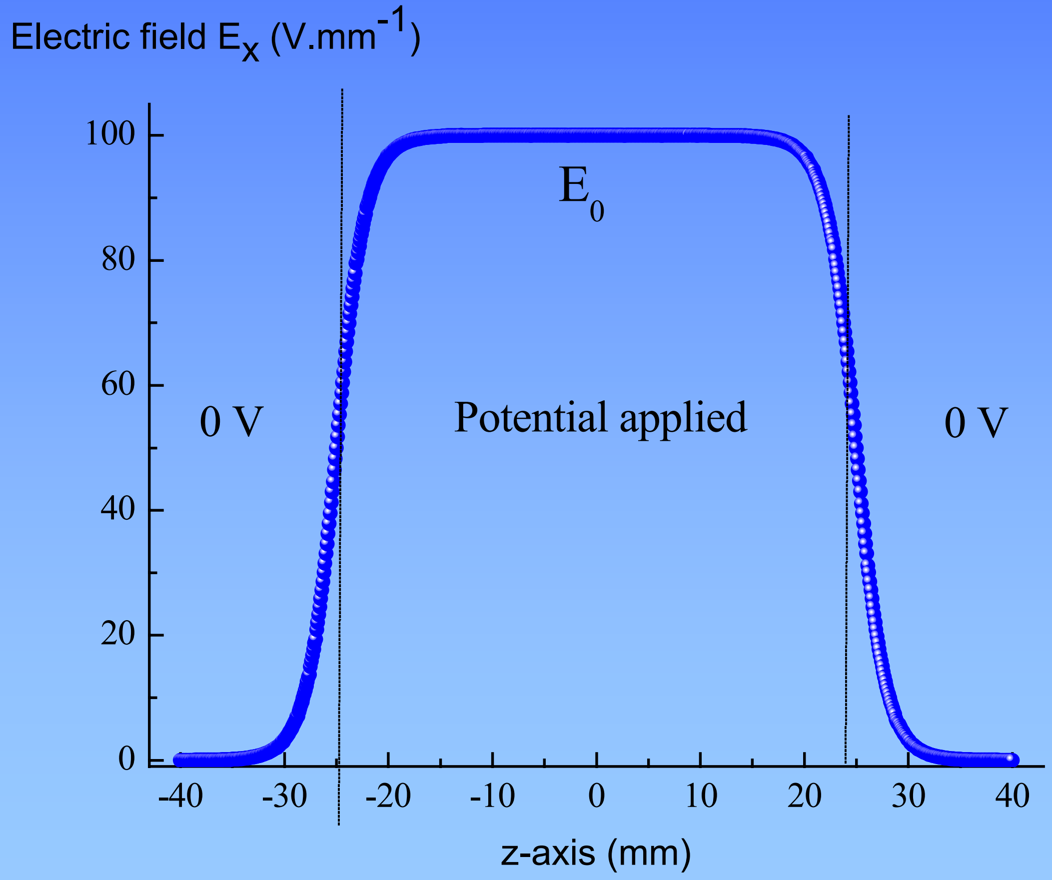
(u = mean beam velocity)

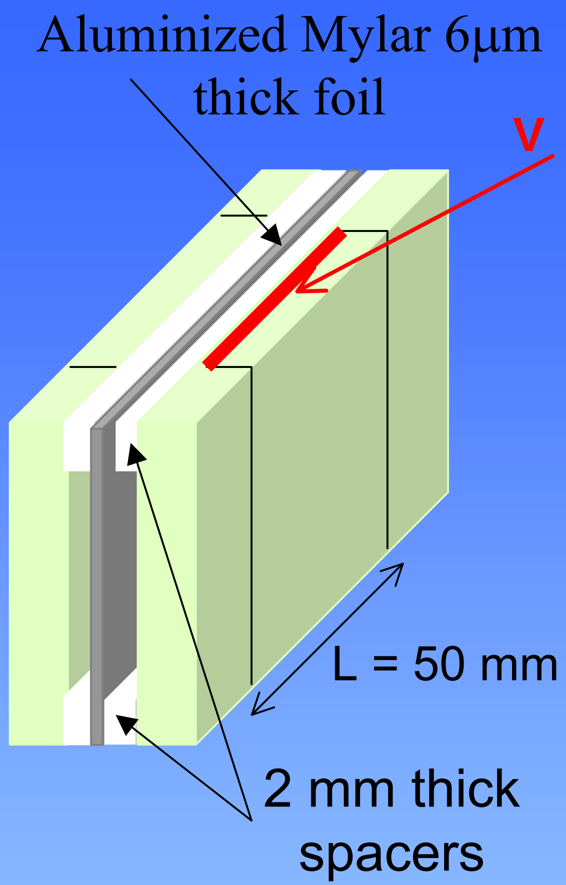
Two main difficulties :

1. Capacitor geometry, beam separation of 100 micrometers for p = 1
2. Precise knowledge of the mean beam velocity of the atomic beam

The capacitor built in Toulouse







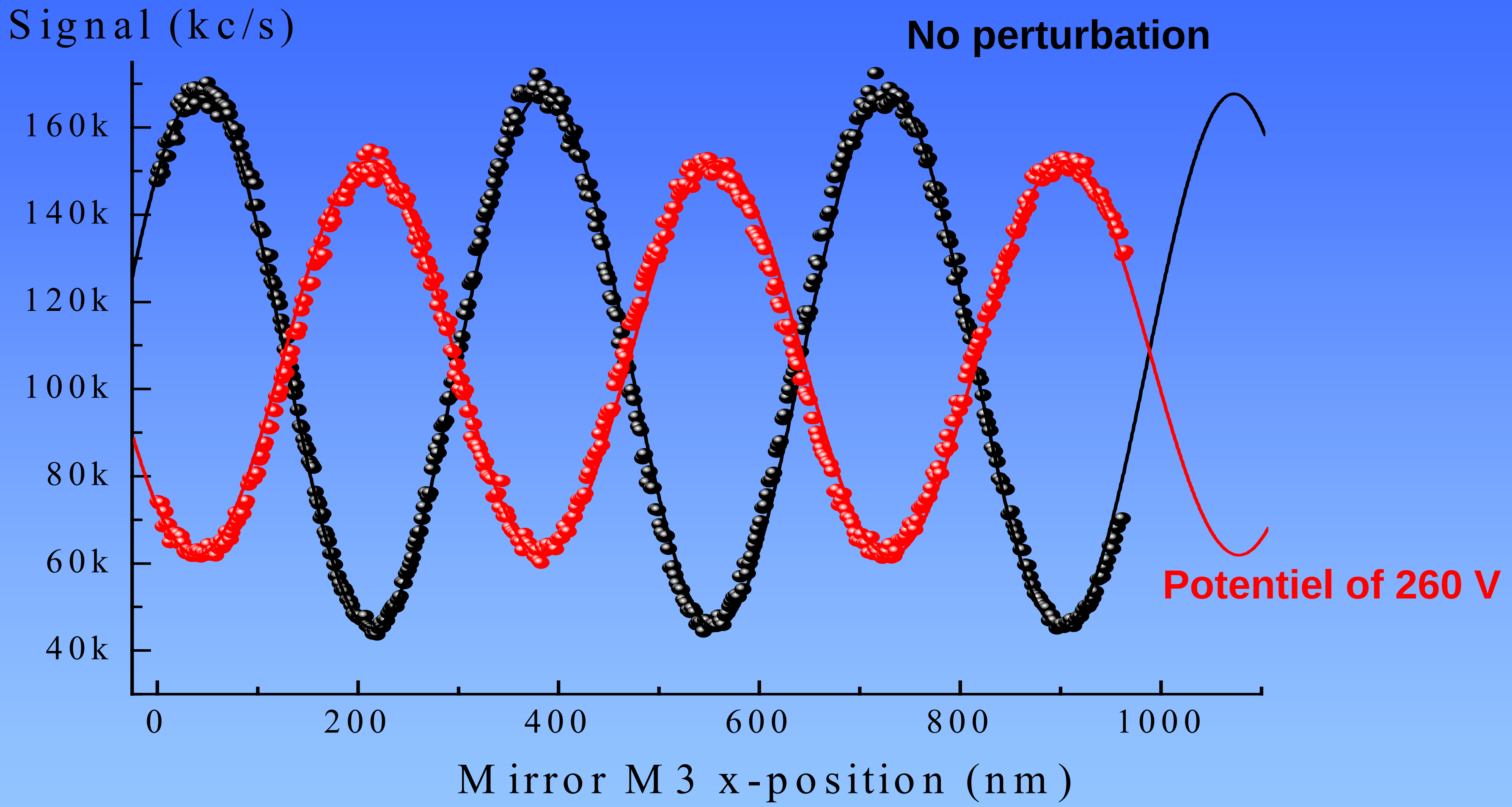
$$L_{eff} = \int E^2(z)\,dz\,/E_0^2$$

$$L_{eff} = 46{,}82 \pm 0{,}10\ mm$$

Lithium atom polarizability

Error source	Systematic errors	
Effective length	$L_{eff} = 46{,}82 \pm 0{,}10$ mm	0.21 %
Electrode spacing	$h = 2{,}027 \pm 0{,}002$ mm	2 × 0.1 %
Contact potentials		0.01 %

Observation of the phase Stark shift

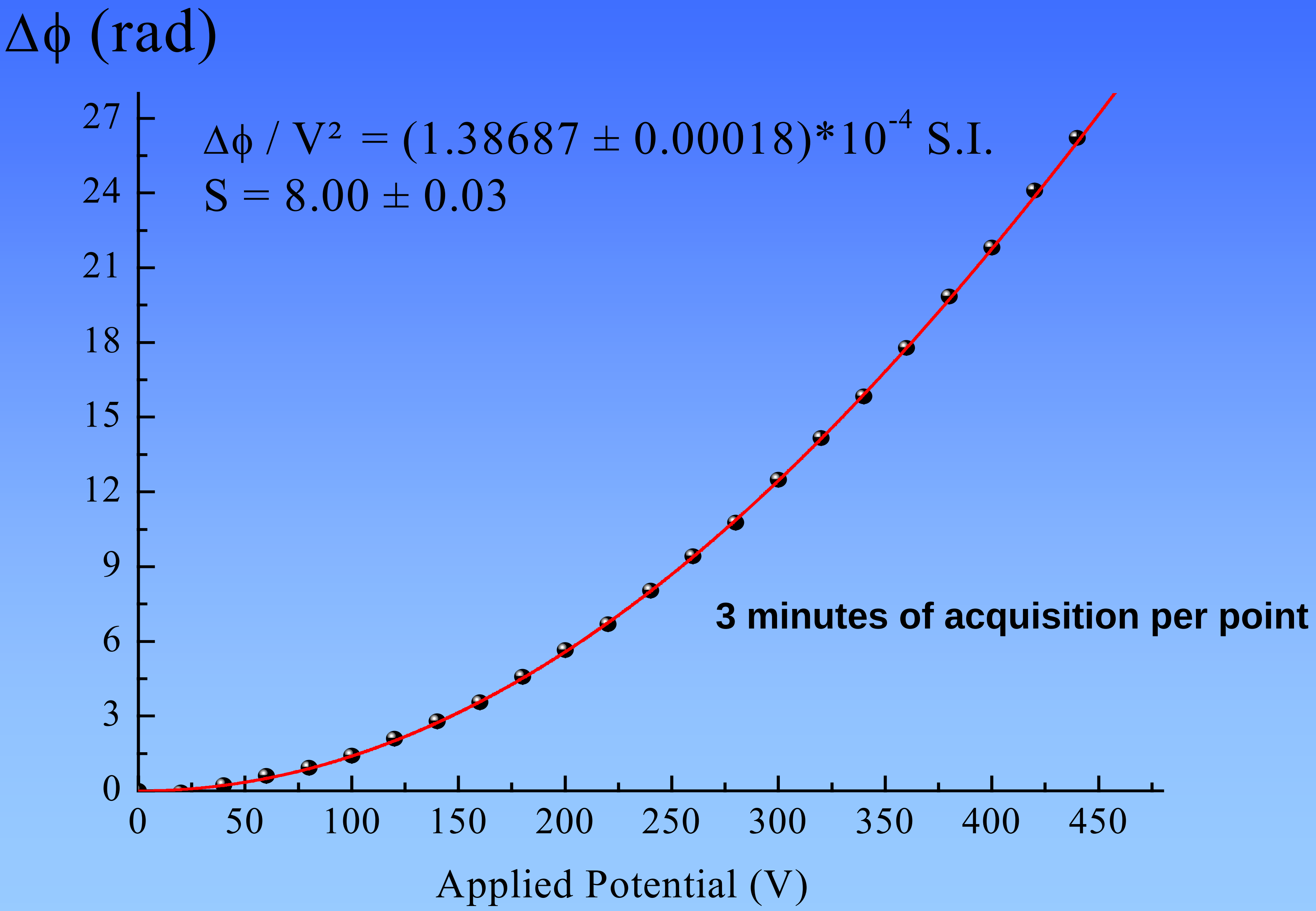


I_o = 105 000 c/s
V_0 = 60 %

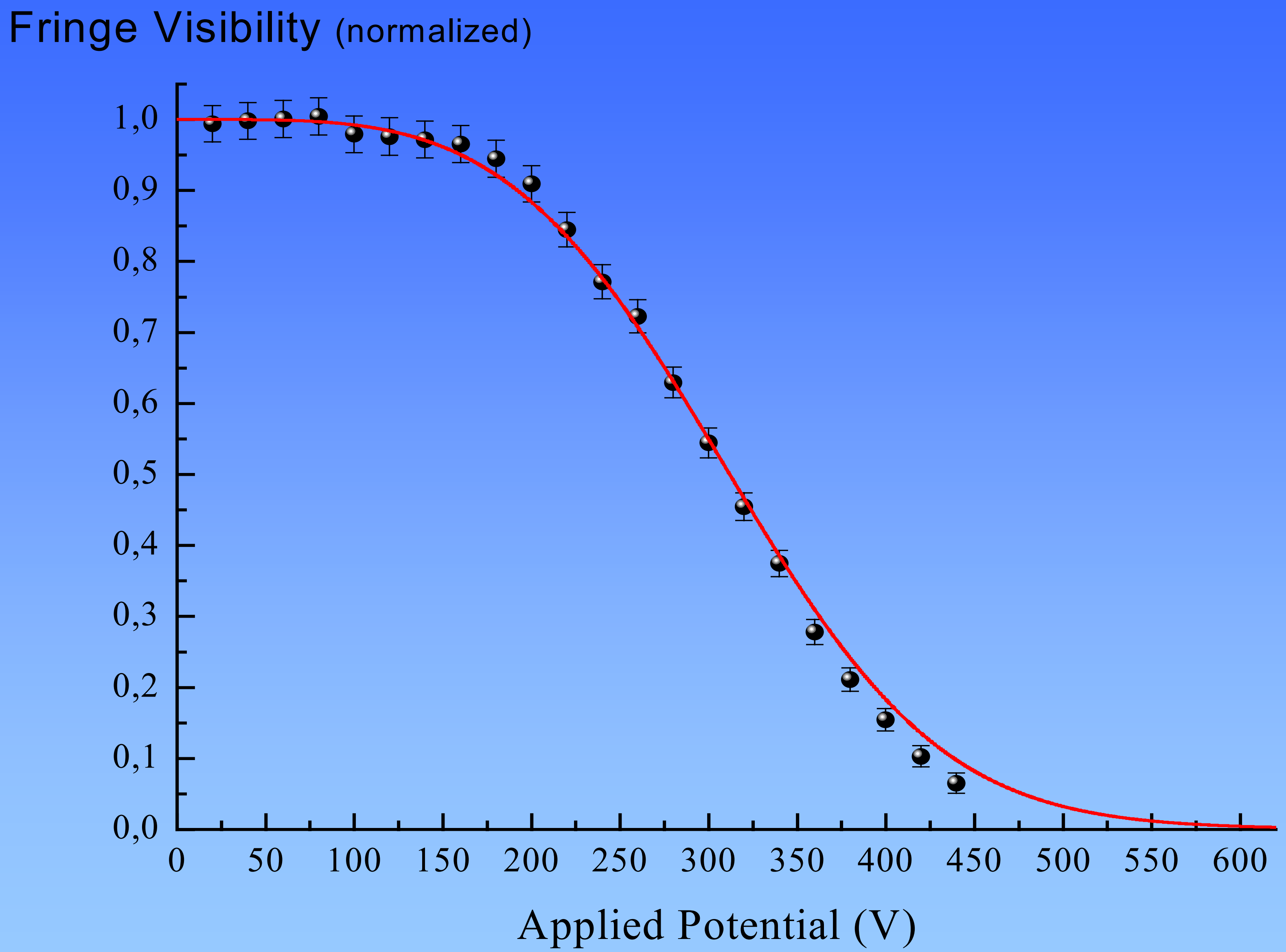
$\Delta\Phi_{Stark}$ (260 V) ~ 3π rad

Measurement of the phase shift

(Small corrections due to the velocity dispersion are included)



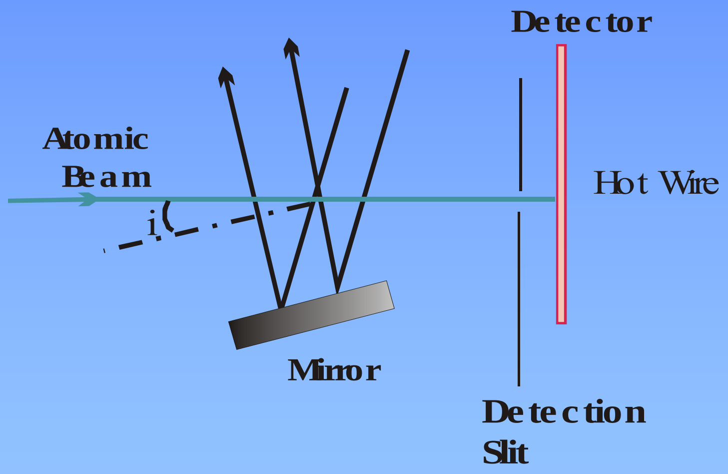
Fringe visibility as a function of the applied voltage



Mean velocity of the atomic beam

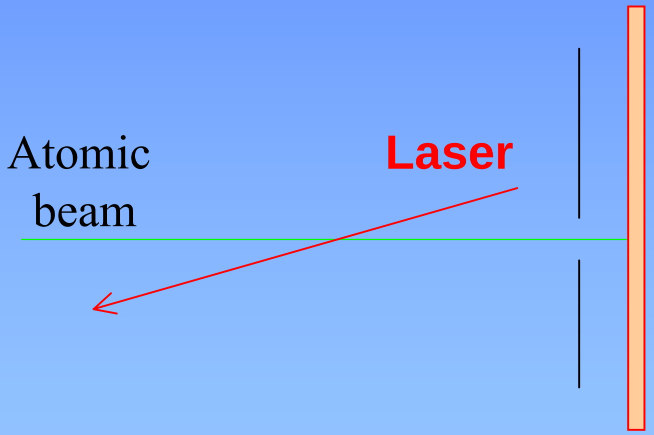
Two main methods

Bragg Diffraction



u = 1075.7 ± 5.4 m/s

Doppler effect



u = 1066.1 ± 8.1 m/s

Lithium atom polarizability

Error source	Systematic errors	Statistical errors
Effective length	0.21 %	
Electrode spacing	2 × 0.1 %	
Contact potentials	0.01 %	
Phase measurement		$\Delta\Phi / V^2 = (1.38687 \pm 0.00018) \times 10^{-4}$ SI 0.1 %, analysis in progress
Velocity measurement		$u = 1073.1 \pm 7.0$ m/s 0.65 %

$$\alpha\,(\mathrm{Li}) = 24{,}74\,(8)_{\mathrm{systematic}}(16)_{\mathrm{statistical}} \times 10^{-30}\ \mathrm{m}^3$$

Conclusions

Atom interference fringes

High visibility and high flux,
many possibilities (order 2, isotope 6)

External fields as tools

- Internal structure of the atom, nuclear spin
- Lithium atom polarizability measurement

$$\alpha\ (\mathrm{Li}) = 24{,}74\ (8)_{\mathrm{systematic}}(16)_{\mathrm{statistical}} \times 10^{-30}\ \mathrm{m}^3$$

Our measurement (~ 1 % accuracy) compares very well to the latest
done by Molof et al. in 1974 $\alpha = (24{,}3 \pm 0{,}5) \times 10^{-30}\ \mathrm{m}^3$ (precision of 2 %)
A. Molof et al., Phys.Rev. A, ***10****, (1331-1140)*

D. E Pritchard et al (1995) : Sodium atom electric polarizability

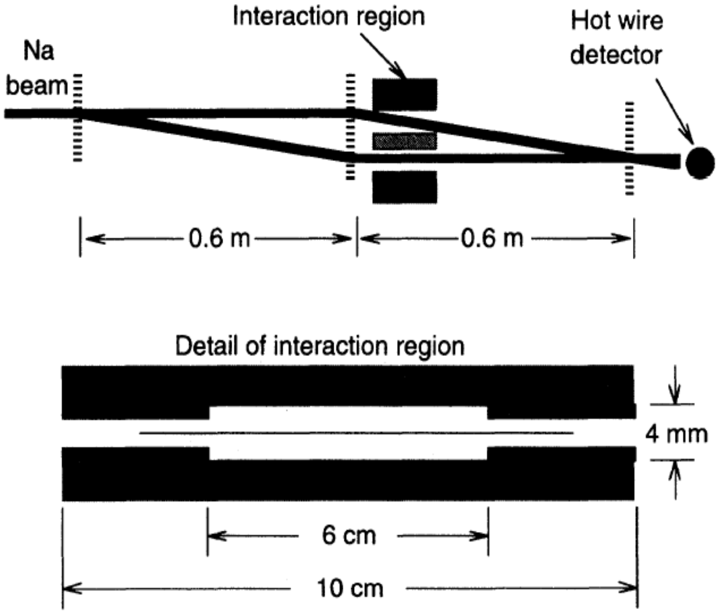


FIG. 1. Schematic of our interferometer and interaction region. Vertical dashed lines are 200-nm-period diffraction gratings. The detail of the interaction region shows the 10-μm copper foil suspended between the side plates. The guard electrodes are indicated in black at both ends.

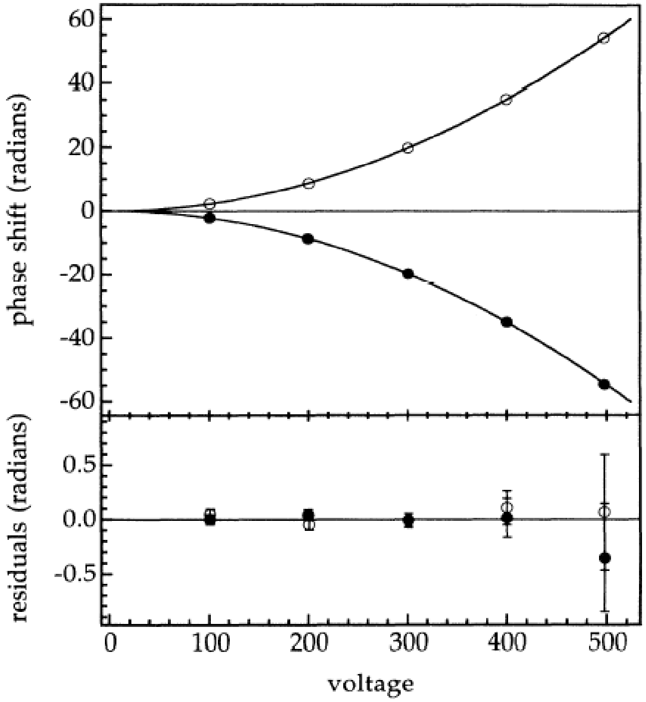


FIG. 5. Phase shift of the interference pattern as a function of voltage applied (in volts) to the left (open circles) or right (filled circles) side of the interaction region. The fit is to a quadratic and the residuals are shown in the lower graph.

$U = -4\pi\varepsilon_0\alpha E^2/2$ → $\Delta\Phi$ proportional to E^2/v

Accuracy on α : $\pm$ 0.25 % statistical $\pm$ 0.25 % systematics

Main difficulties: capacitor geometry,

precise knowledge of velocity distribution

Index of refraction of gases for atomic waves

The index n is complex and expresses the effect of collisions.
(n-1) is proportional to the gas density
Re(n-1) measures the dephasing of the wave
Im(n-1) measures the attenuation of the wave

Experiments with sodium by D. Pritchard et al.

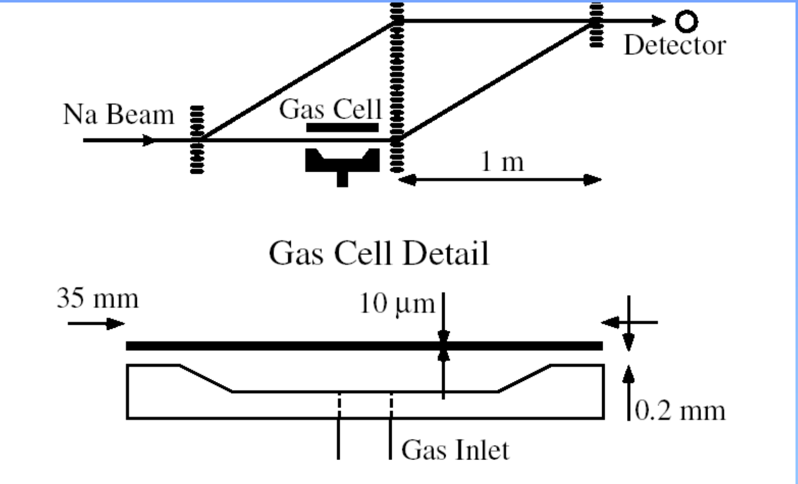


FIG. 1. Schematic of the atom interferometer and the gas cell.

$$\rho(v) = \frac{Re(n-1)}{Im(n-1)}$$