Laboratoire Kastler Brossel
Physique quantique et applications

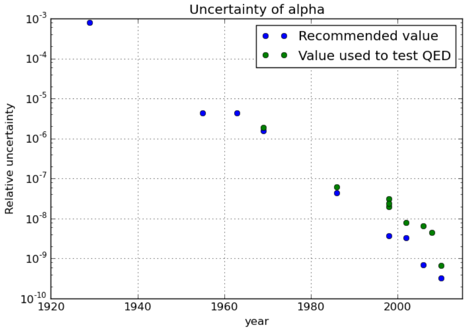
Determination of the fine structure constant with atom interferometry

Pierre Cladé

Fine structure constant :

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \quad (1)$$

- Magnetic moment of electron : $\frac{g_e}{2} = 1 + C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + \ldots$
- Measurement g_e, determination of α, test of QED



Introduction

Rydberg constant :

$$hR_\infty c = \frac{1}{2}m_e c^2\alpha^2 \Rightarrow \alpha^2 = \frac{2R_\infty}{c} \times \left(\frac{h}{m_e}\right) \qquad (2)$$

Mass ratio are well measured : $m_e \to m_{Rb}$

Experiment started in Paris in 1998 : current uncertainty 1.3 ppb (2010)

Outlook :

- The "h/m" constant
- Principle of the experiement
- Discussion on systematic effects

h/m

Conversion factor for energies

- $h\nu = mc^2$ (Compton frequency)
- $h\nu = \frac{1}{2}mc^2\alpha^2$ (Rydberg frequency)
- $h\nu = \frac{1}{2}mv_r^2$ (Recoil frequency)
- $h\nu = mg\lambda$ (Bloch frequency)

Constant of quantum mechanics

$$i\frac{\partial\psi}{\partial t} = -\frac{\hbar}{2m}\frac{\partial^2\psi}{\partial x^2} \qquad (3)$$

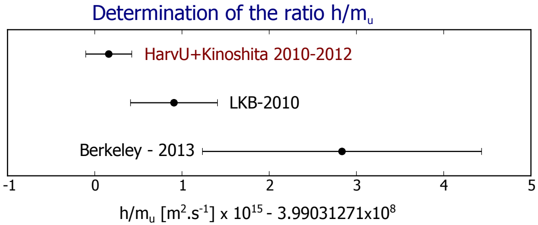
"Diffusion coefficient" of the Schrödinger equation ($m^2.s^{-1}$)

Redefinition of the S.I.

Macroscopic (M) to microscopic experiments (m and h):

- Watt balance : measurement of h/M
- Silicon sphere : measurement of M/m

The link is done with a measurement of h/m

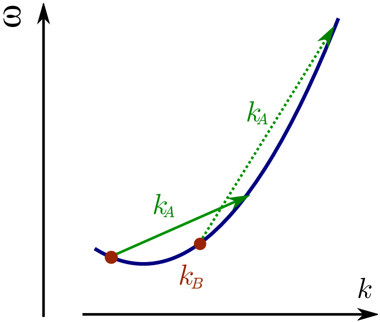


After the redefinition : link between AMU and SI.

Dispersion relation

Non relativistic equations :

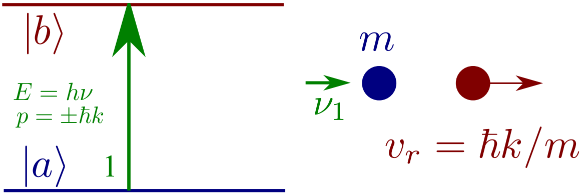
$$i\frac{\partial\psi}{\partial t} = -\frac{\hbar}{2m}\frac{\partial^2\psi}{\partial x^2} \Rightarrow \omega = \frac{\hbar}{2m}k^2 \quad (4)$$



- Second derivative
- k_A and k_B : photon recoil

- Atom recoil
- Doppler effect
- Atom interferometer

Atom light interaction



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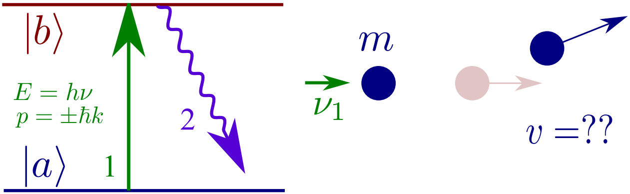
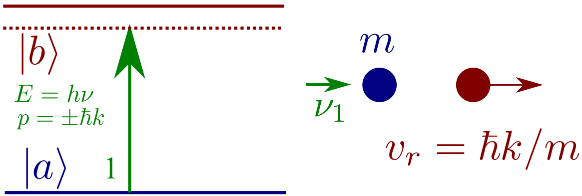
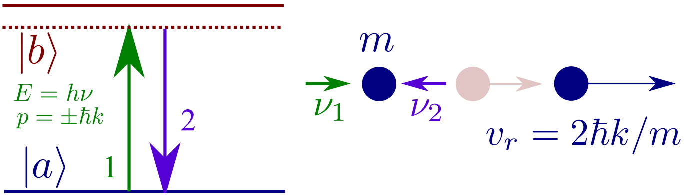


Spontaneous emission

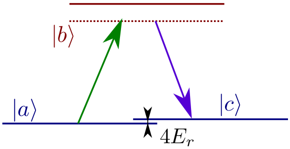
Atom light interaction



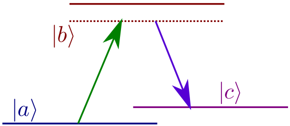
Atom light interaction



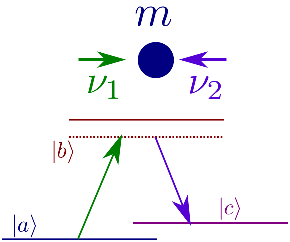
Two photon transition to supress spontaneous emission.



Same internal state



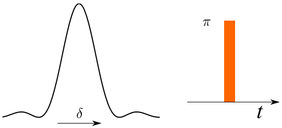
Two different internal states



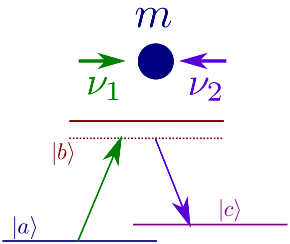
Doppler effect

$$\delta = \left(\vec{k_1} - \vec{k_2}\right) \cdot \vec{v}$$

- Selection of a subrecoil velocity distribution



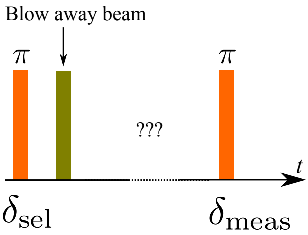
Introduction to atom interferometry



Doppler effect

$$\delta = \left(\vec{k_1} - \vec{k_2}\right) \cdot \vec{v}$$

- Selection of a subrecoil velocity distribution
- Measurement of the final velocity distribution



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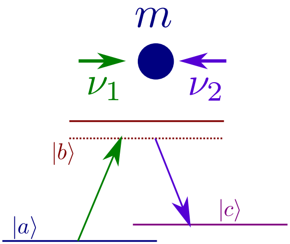

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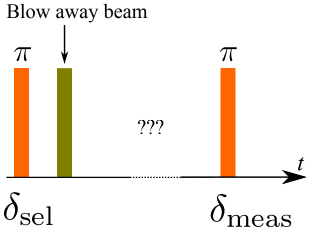
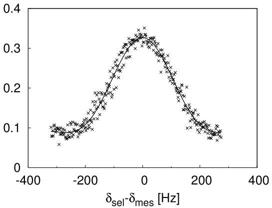
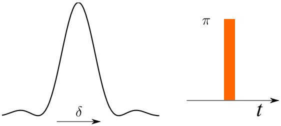
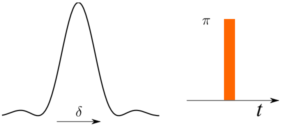




Rabi  .

Atom interferometry

Rabi



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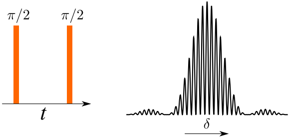
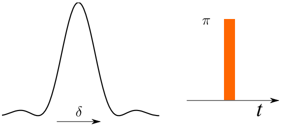
Method of Separated Oscillatory Field (Ramsey)
Replace a π pulse by two $\pi/2$ pulses.



Atom interferometry

Rabi



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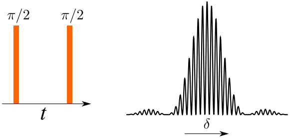
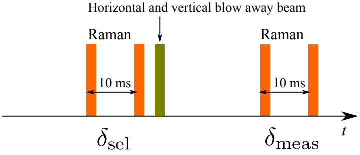
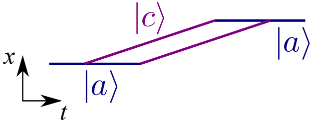
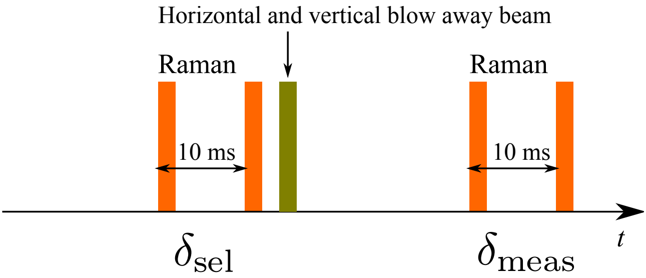






Ch.J. Bordé (1984→...)

Measuring velocities



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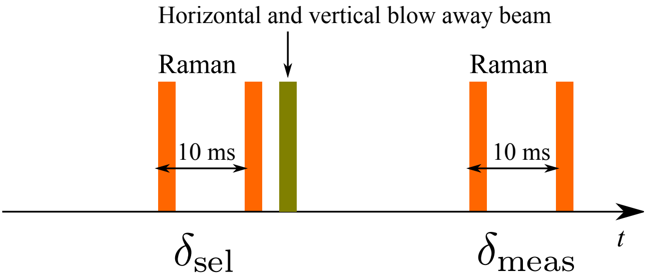
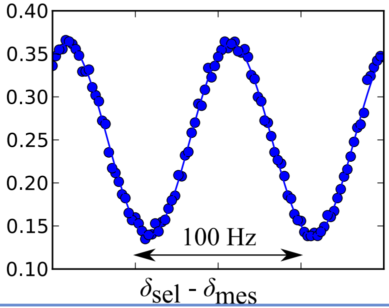
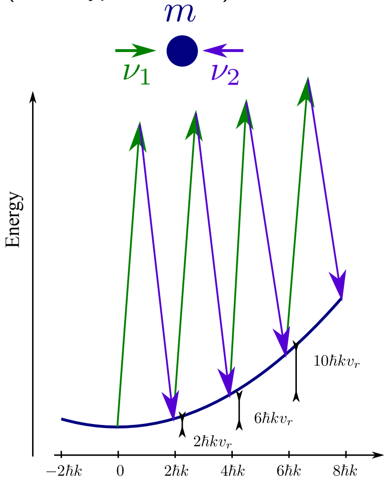




Coherent acceleration of atoms

Succession of stimulated Raman transitions (same hyperfine level)



Bloch oscillations

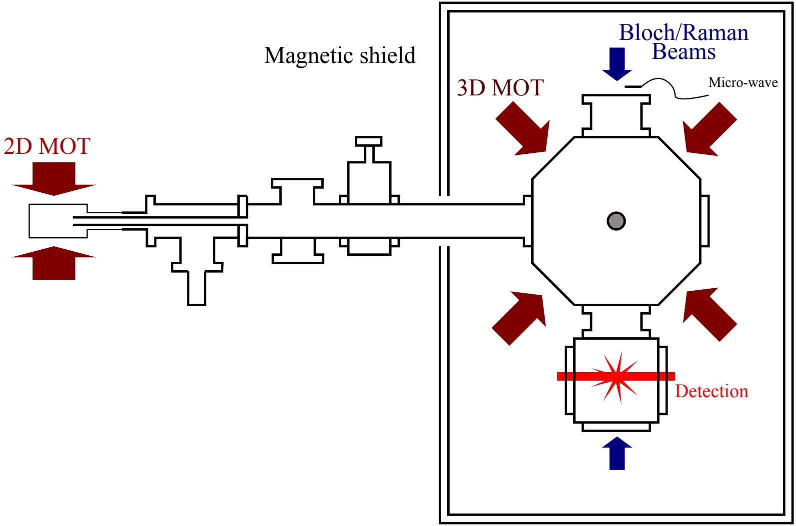
$$\delta = \nu_1 - \nu_2 \propto t$$

Adiabatic passage : acceleration of the atoms

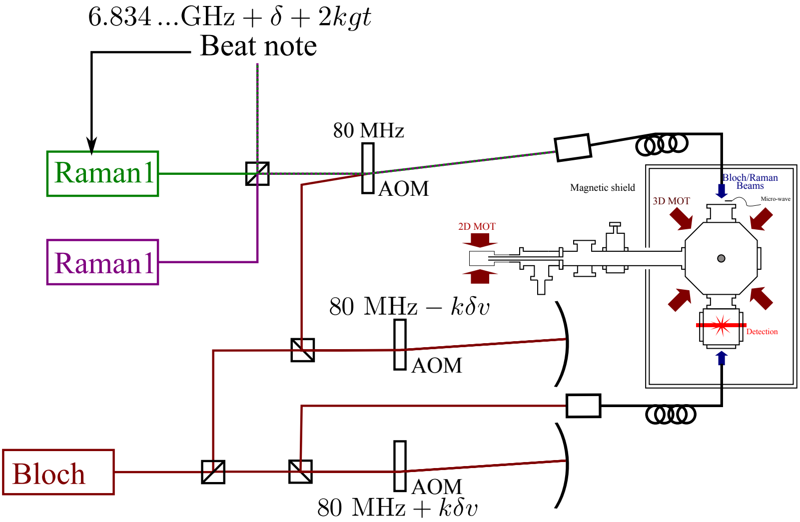
The atoms are placed in an accelerated standing wave : in its frame, they are submitted to an inertial force
→ Bloch oscillations in a periodic potential

Ben Dahan, *et al.*, PRL 76, (1996)
(group of C. Salomon, LKB, Paris)

Apparatus

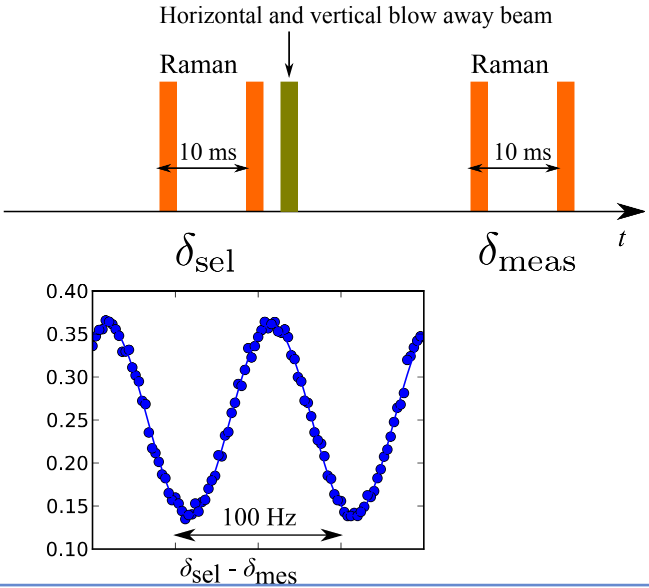

Magnetic shield
Bloch/Raman
Beams
Micro-wave
3D MOT
2D MOT
Detection

Apparatus



$6.834\ldots\text{GHz} + \delta + 2kgt$
Beat note
80 MHz
AOM
Raman1
Raman1
Magnetic shield
Bloch/Raman Beams
Micro-wave
3D MOT
2D MOT
Detection
$80\ \text{MHz} - k\delta v$
AOM
Bloch
AOM
$80\ \text{MHz} + k\delta v$

Measuring velocities



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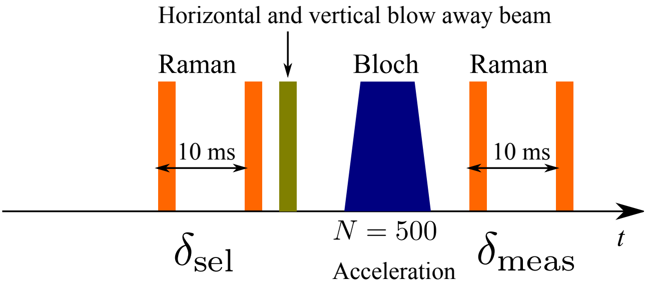

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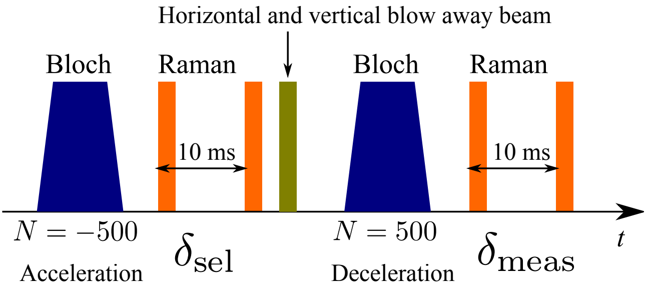

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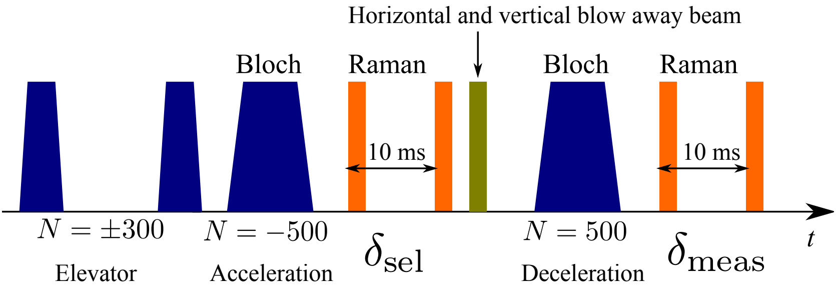
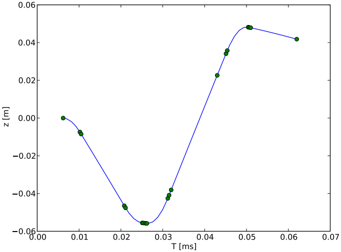
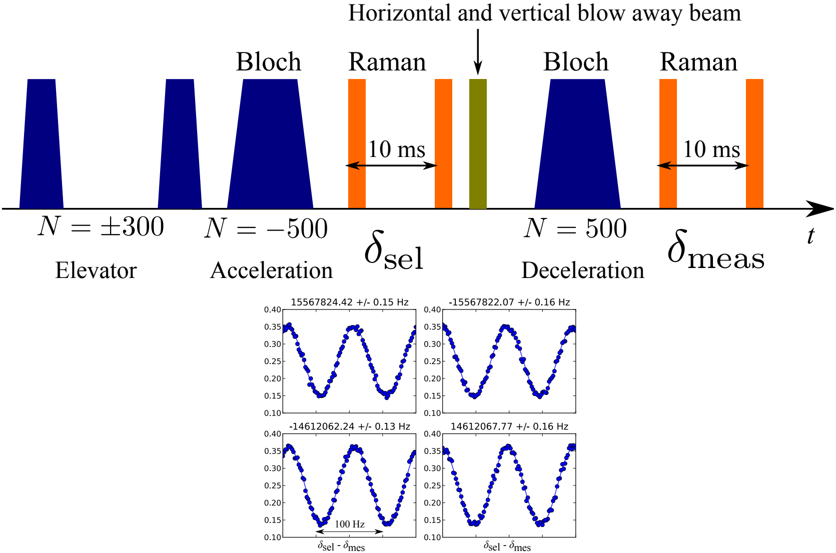
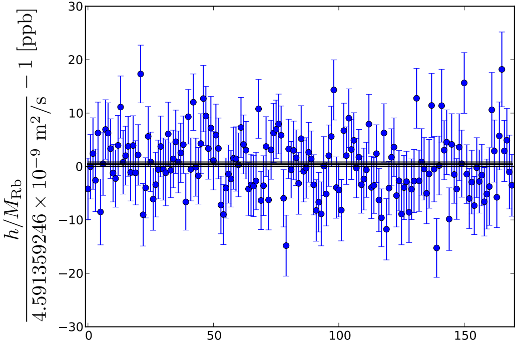




Measuring velocities



Results (2010)



170 measurements (14 hours)

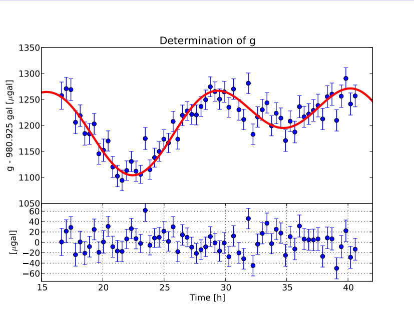
Each measurement : 6×10^{-9} (h/m) and 3×10^{-9} (α)

Relative uncertainty on h/m : 4.4×10^{-10} and 2.2×10^{-10} on α.

Results (2010)

Improvement of statistics

- Vibration isolation



- Reliability of the whole experiment (total time of 1000 h)

Relative uncertainty on h/m of 5×10^{-9} in 3 mn.

Error Budget (α)

Source	Correction	Uncertainty 10^{-10}
Laser frequencies		1.3
Beams alignment	-3.3	3.3
Wavefront curvature and Gouy phase	-25.1	3.0
2nd order Zeeman effect	4.0	3.0
Gravity gradient	-2.0	0.2
Light shift (one photon transition)		0.1
Light shift (two photon transition)		0.01
Light shift (Bloch oscillations)		0.5
Index of refraction atomic cloud and atom interactions		2.0
Global systematic effects	-26.4	5.9
Statistical uncertainty		2.0
Rydberg constant and mass ratio		2.2
Total uncertainty		6.6

Error Budget

Source	Correction	Uncertainty 10^{-10}
Laser frequencies		1.3

Wavefront curvature and Gouy phase shift

What is the momentum of a photon ?

$p = \hbar \frac{\partial \phi}{\partial z}$ where ϕ is the phase of the laser beam.
$p = \hbar k$ holds only for perfect plane-wave.
For a Gaussian beam :

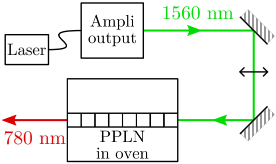
$$\frac{\partial \phi}{\partial z} = k + \frac{1}{2k}\left(\frac{4}{w^2} - \frac{4r^2}{w^4} + \frac{r^2k^2}{R^2}\right) \tag{5}$$

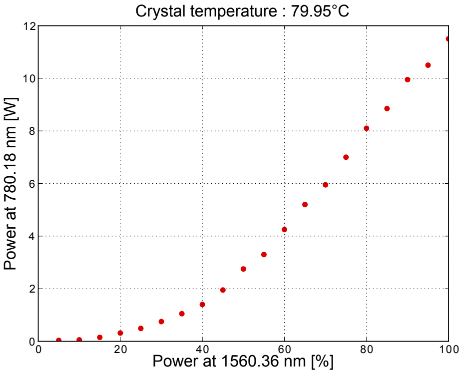
where w is the waist of the beam, R the wavefromnt curvature and r the distance from the propagation axes of the beam.

- We are now using a larger beam waist (smaller Gouy phase shift, better alignment)

SHG fibered laser system

- Laser at 1560 nm
- Amplifier : 30 W
- Freq doubling : PPLN crystal





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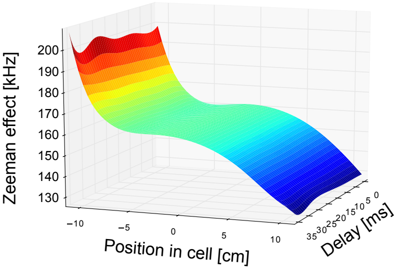
Magnetic field

- Mapping of the magnetic field
  - Spectroscopy (on $m_F = 1$) at different positions



- Calculation ($m_F = 0$) of the effect on each spectra and for h/m
  - Effect : $0.1\ \mathrm{ppb}$
  - Measurement at different bias field

Error Budget

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Current status

- Better statistics
- Improved : Gouy phase shift
- Improved : Beam aligenement
- Improved : 2nd order Zeeman effect

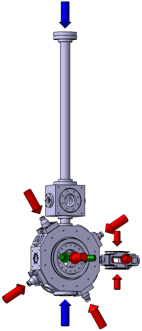
However, we have a systematic effect correlated to the intensity of the laser used for Bloch oscillations that we don't understand yet.

New project

High precision atom interferometry using large momentum transfer beamsplitter

- Evaporative cooling (technique used for BEC)
- Dipole trap

- Shot noise limited detection
- Vibration isolation
- Magnetic shield
- Optical frequency measurement
- Wavefront design



Design of a setup to reach the 2×10^{-10} accuracy
Main systematic effects :

- Atom-atom interaction
- Wavefront curvature and Gouy phase shift

Laboratoire Kastler Brossel
Physique quantique et applications

Ph.D Students

R. Battesti (2003)
P. Cladé (2005)
M. Cadoret (2008)
R. Bouchendira(2012)
M. Andia
R. Jannin
C. Courvoisier

Permanents

C. Schwob
L. Julien
P. Cladé
S. Guellati-Khélifa
F. Nez
F. Biraben

Postdoc

E. de Mirandes (2006-2007)