Photonique interférométrie atomique

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LNE — Le progrès, une passion à partager
CNRS
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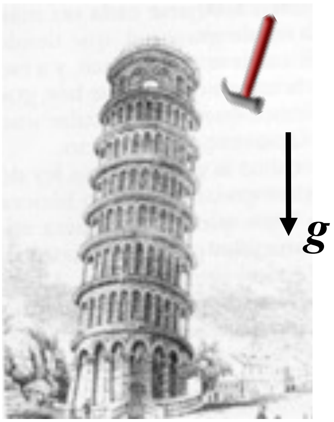
IFRAF

Atom interferometry as Inertial sensors

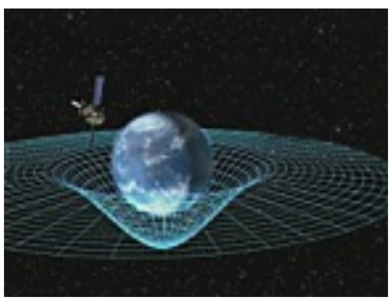
Interest from the 90th for the sensitivity

long term stability and accuracy

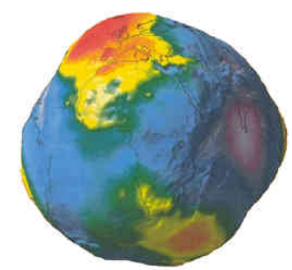


- Fundamental physics
  - measurement of α, G...
  - watt balance (gravimeter)
  - test of general relativity

Lense-Thirring effect (gyroscope), STE-QUEST, anomalous gravity…(accelerometer), gravitational waves detectors…



- Inertial navigation satellite, submarine…

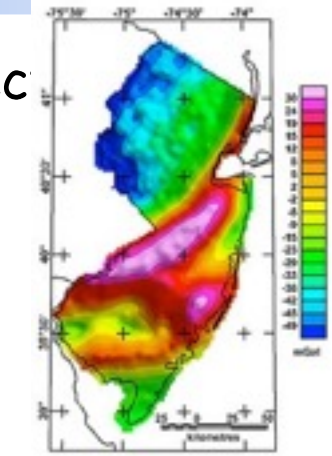


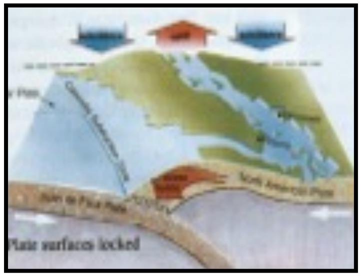
- Geophysics ground or space

Earth's rotation rate, tidal effects, gravity field mapping …

Simple examples in geophysics

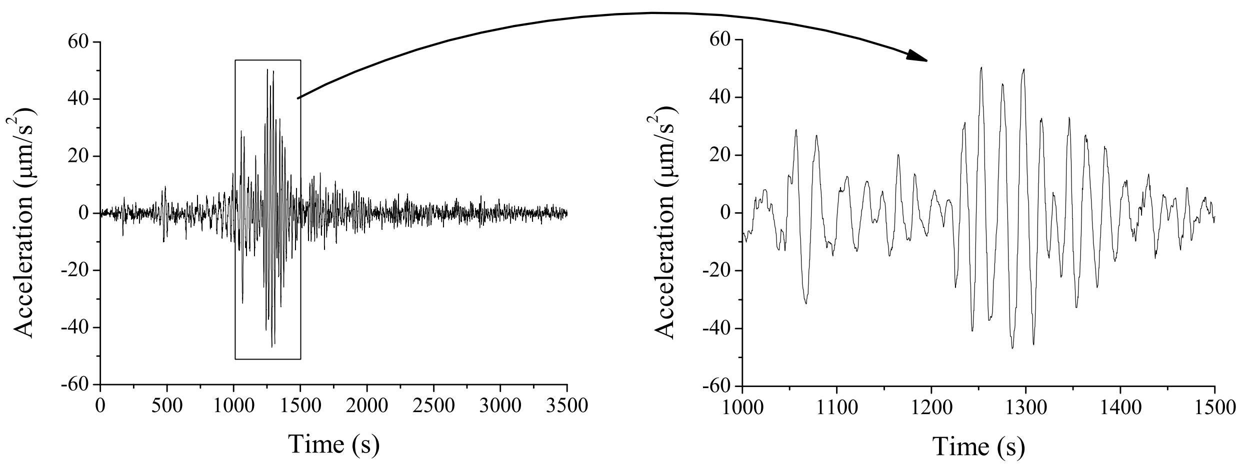
- Measurement of (Bouguer) gravity anomaly to detect modifications of mass distribution





- Deformation and constraints:
  - accumulation during seismic cycle...

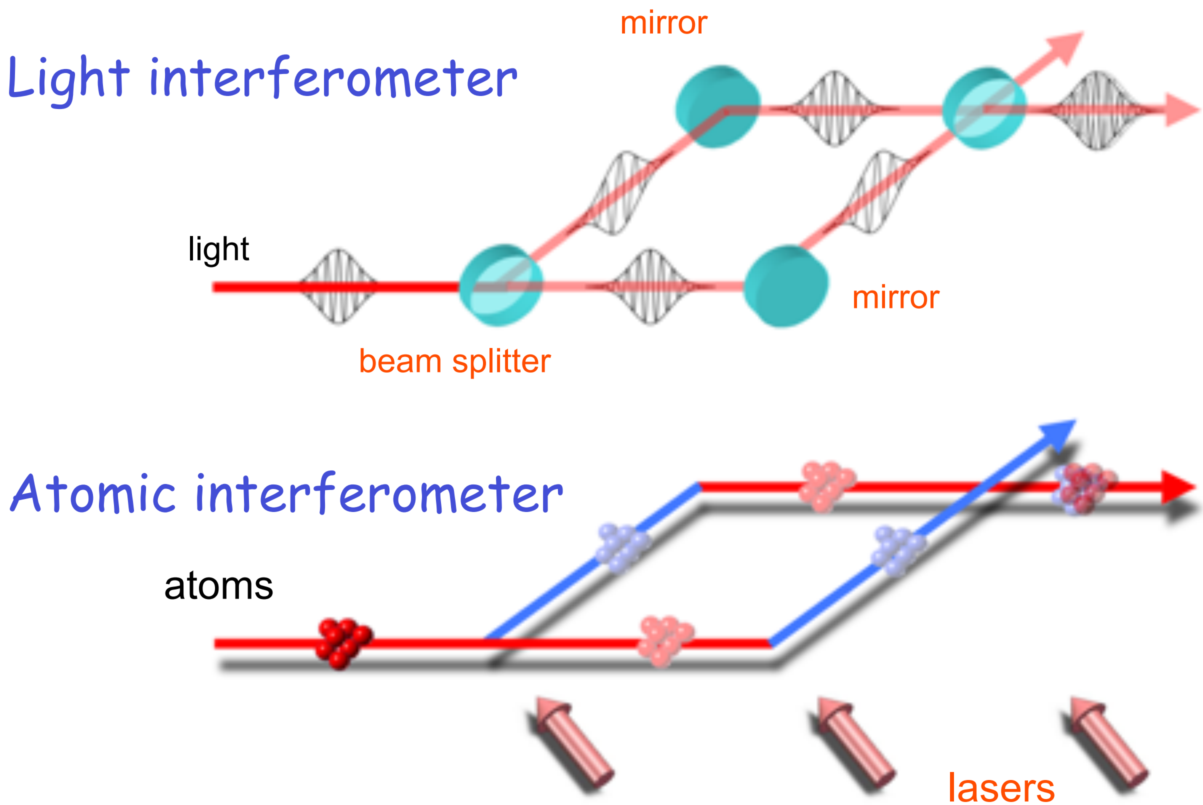
- Volcanology: 4D mapping of mass distribution evolutions (time/space variations)

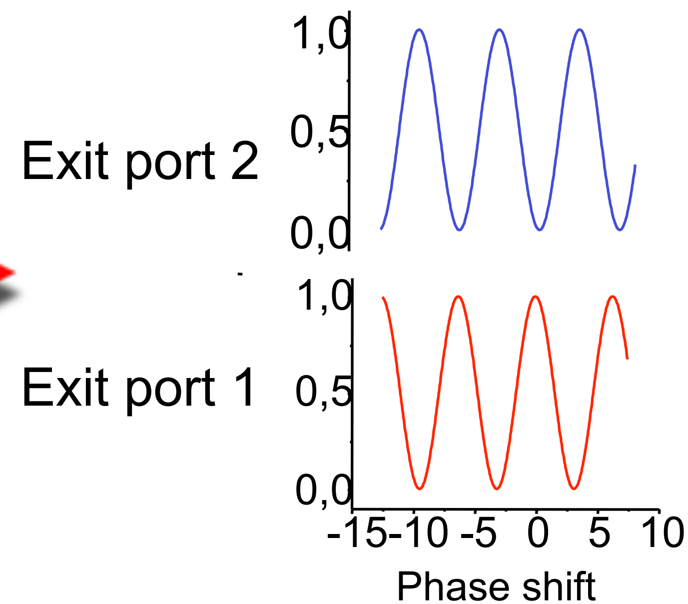


Earthquake in China 2 Mars 20^{th} 2008 (magnitude 7,7)

S. Merlet, et al., Metrologia ***46****, 87–94, (2009)*

Mach-Zehnder type interferometer



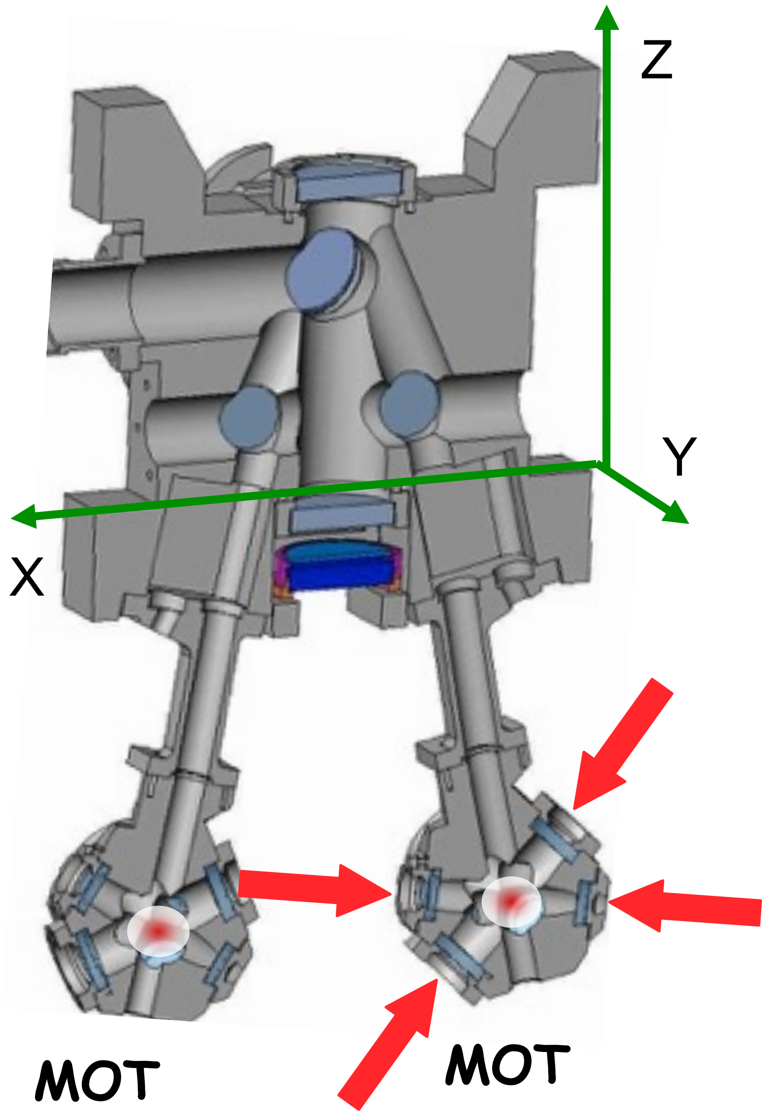


$\Delta\varphi$: difference of accumulated phase shift along the two arms : **2 waves interference**

$$\boxed{P_1 = \frac{1}{2}(1 + \cos\Delta\Phi)}$$

Most of the inertial sensors used two photon Raman transitions

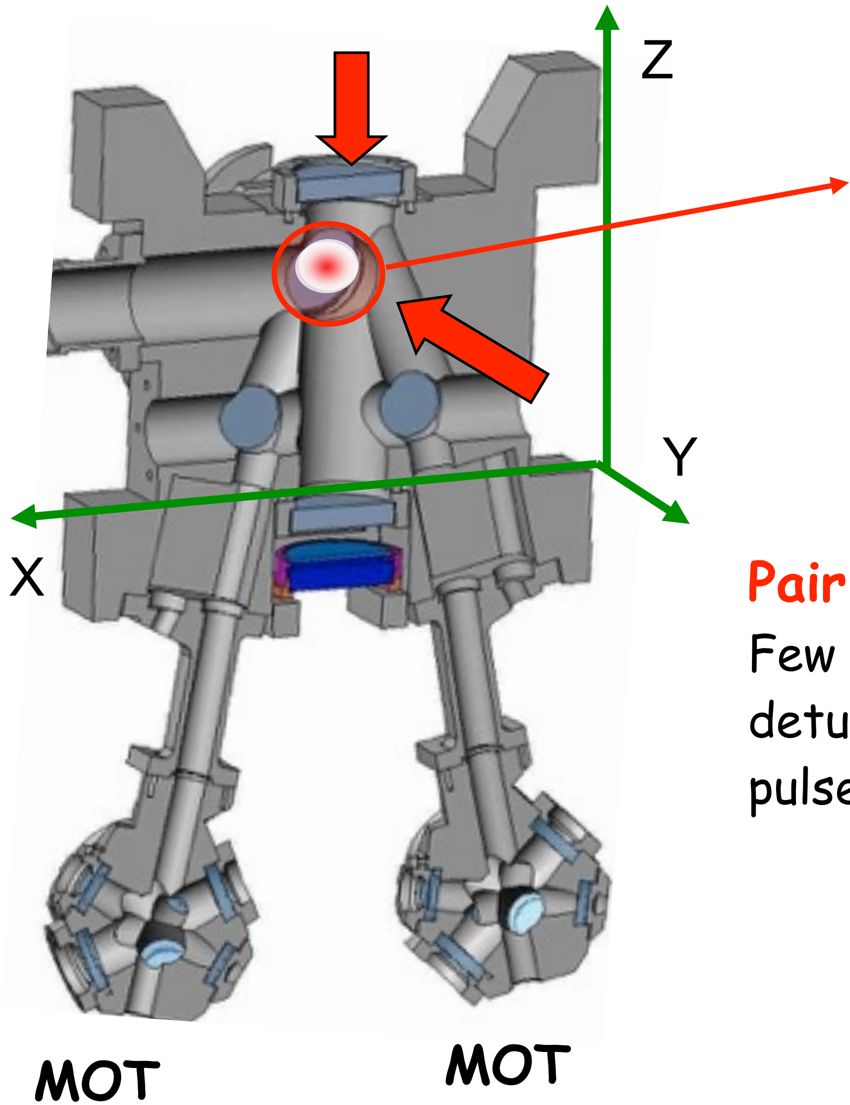
Example: Cold atom gyroscope

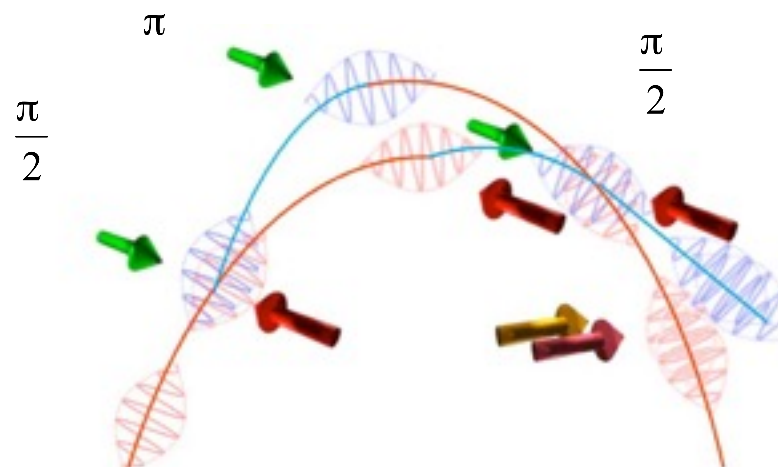


Trapping lasers: 6 beams per MOT

Cooling light (852 nm):
total power ~ 100 to 200 mw
Repumping light (852 nm + 9.2 GHz)
total power few 10 mW

Example: Cold atom gyroscope





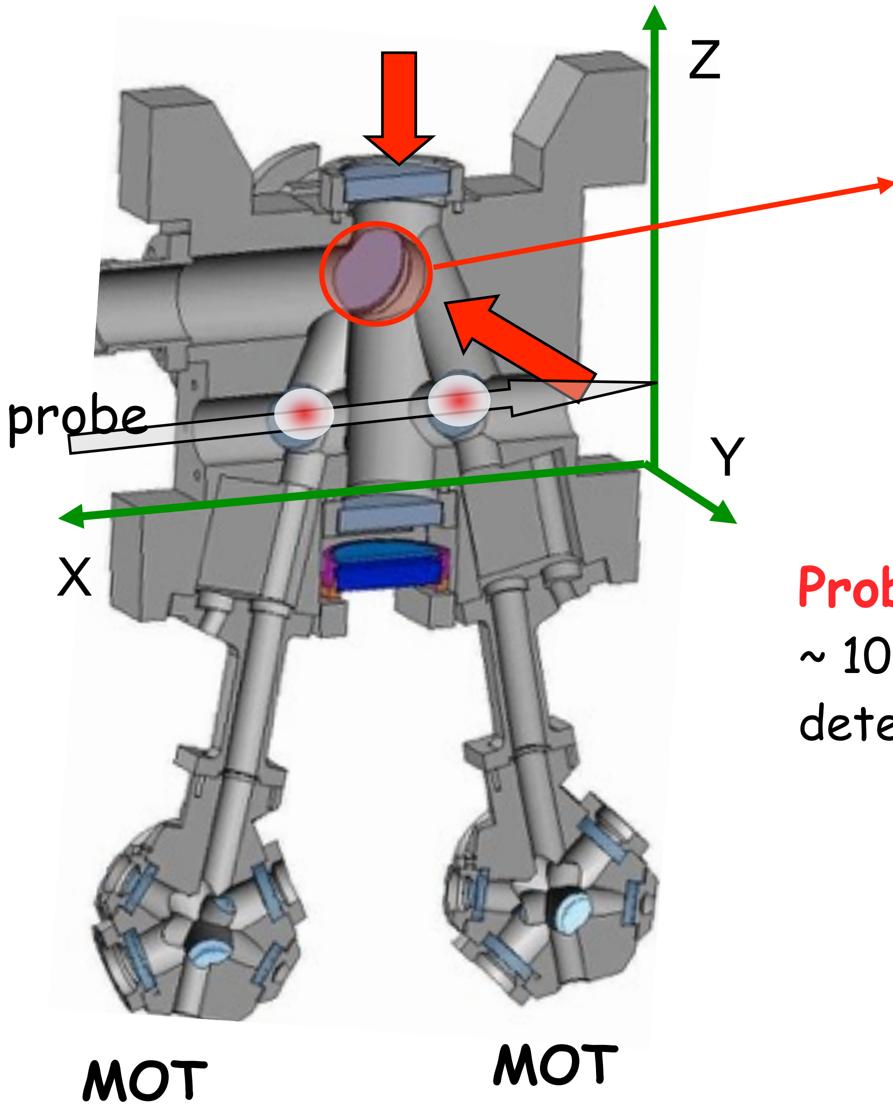
Pair of Raman Lasers

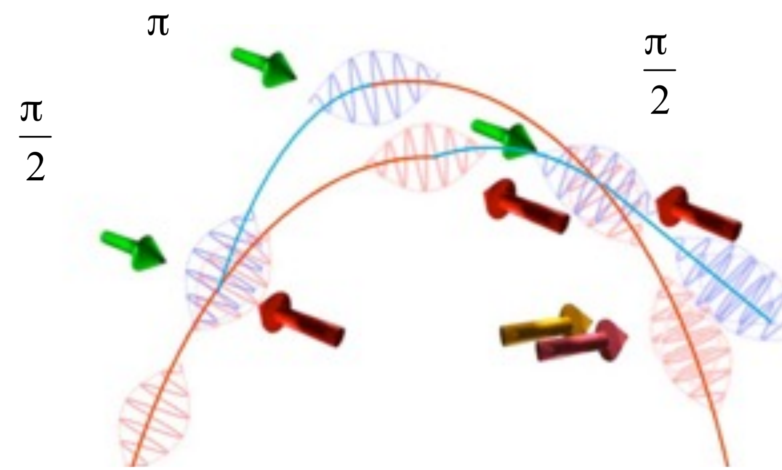
Few 100 mW per beam

detuning to trapping lasers (~500 MHz)

pulses of ~ 10 μs

Example: Cold atom gyroscope



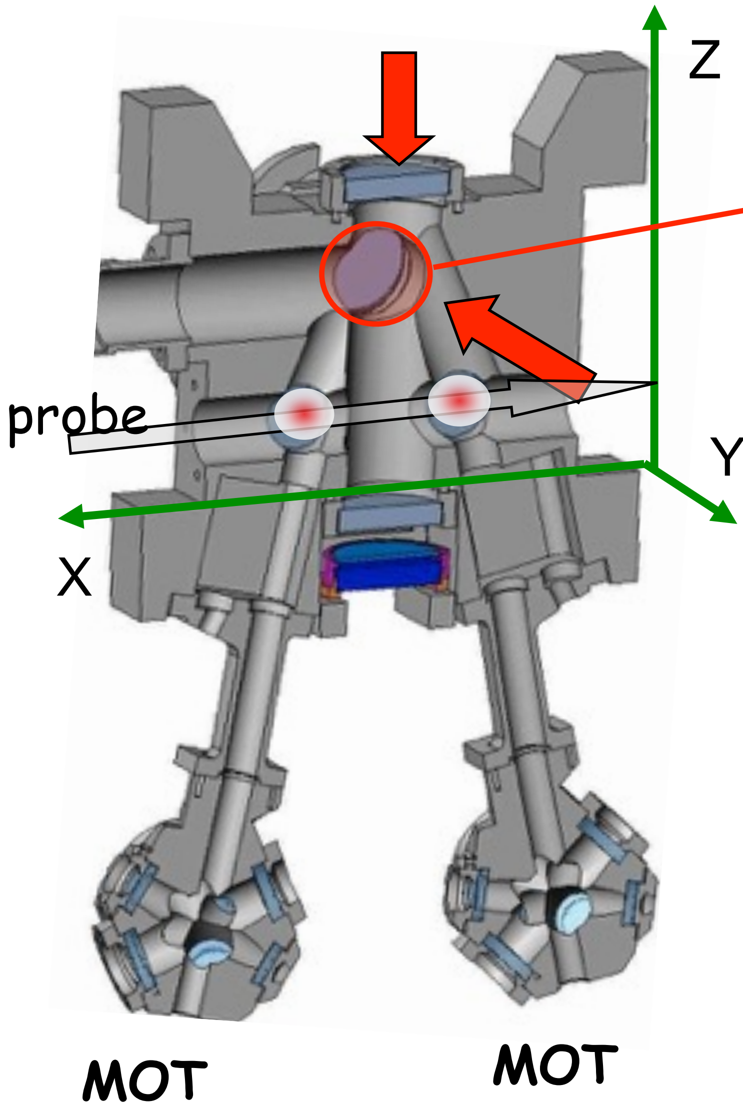


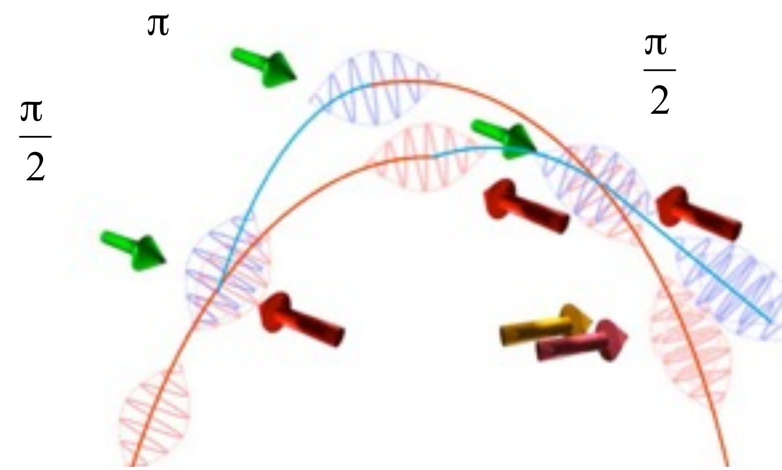
Probe beams

~ 10 mW (similar frequencies than trap beams)

detection duration ~ 20 ms

Example: Cold atom gyroscope





Sequential operation

with requirements on the lasers:

linewidth, agility, precise alignment, polarization, extinction ratio, wave front…

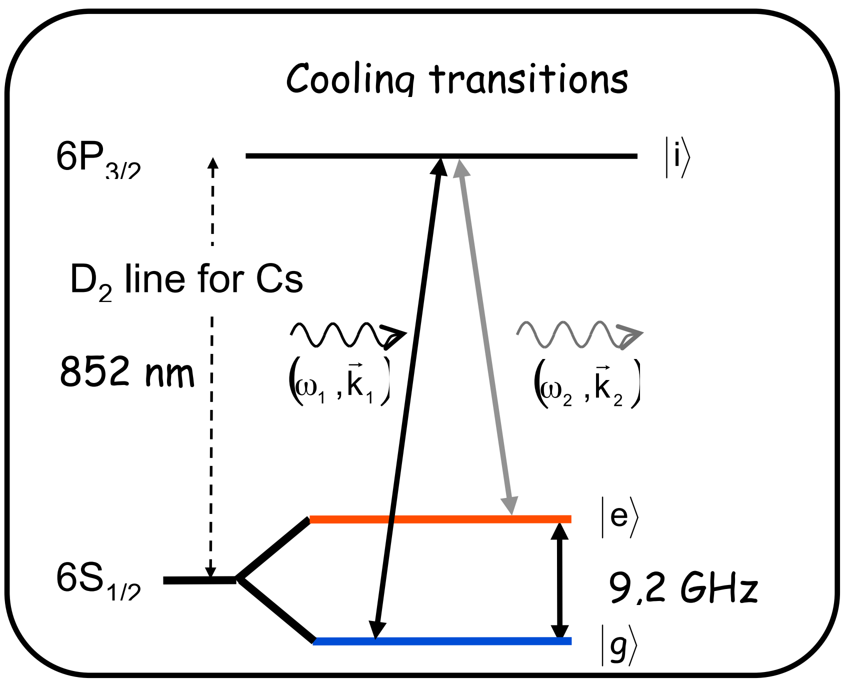
Lasers for cooling and detection

Mostly use of alcaline atoms: Cs, Rb, K…

available lasers sources (852, 780, 767 nm…): semi-conductor, telecom x2

2 different lasers (cooler and repumper): few 100 mW (to 1 W) and few 10 mW

- difference of frequency in the GHz range (~ 9 GHz for Cs)
- linewidth << Γ= 6 MHz, in practice <100 kHz (ECDL)
- frequency agility of the order of 100 MHz for different phases: trap, molasses, detection



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Lasers beams for cooling

Mostly use of alcaline atoms: Cs, Rb, K…

available lasers sources (852, 780, 767 nm…): semi-conductor, telecom x2

2 different lasers (cooler and repumper): few 100 mW (to 1 W) and few 10 mW

- difference of frequency in the GHz range (~ 9 GHz for Cs)
- linewidth < 100 kHz
- frequency agility of the order of 100 MHz for different phases: trap, molasses, detection

« **shaping of the laser beam** »

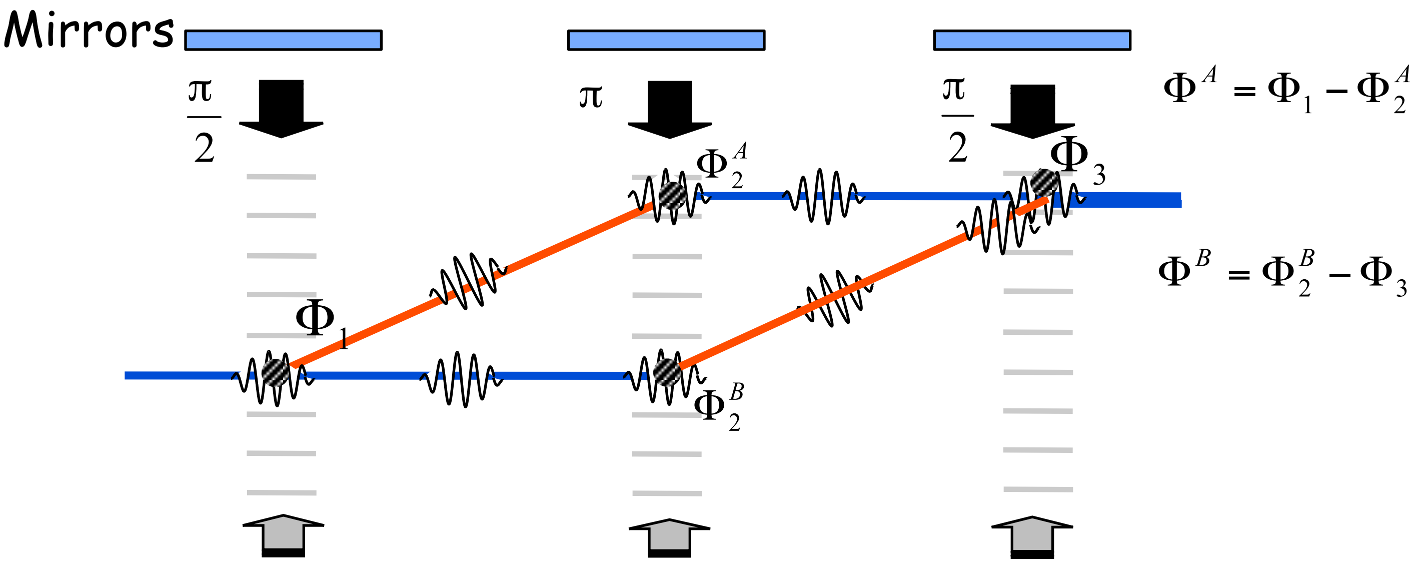
- needs for 6 beams for 3D MOT, 5 beams for 5D MOT and detection
- needs of good polarization quality PER > 20 dB for all beams
- power control: change of power during the sequence (within 100 μs)
- switch with very good extinction ration: >100 dB

In practice: fiber links from laser sources to vacuum chamber for alignment stability : launching direction

Atom interferometry with Raman transition

Laser : at center of the wave packet $\varphi_i = k.r_i + \varphi_l$

2 independent laser beams or carried together and retro-reflected
Control of the relative phase between the two lasers (mrad level)
Knowledge of the exacte frequencies : scaling factor

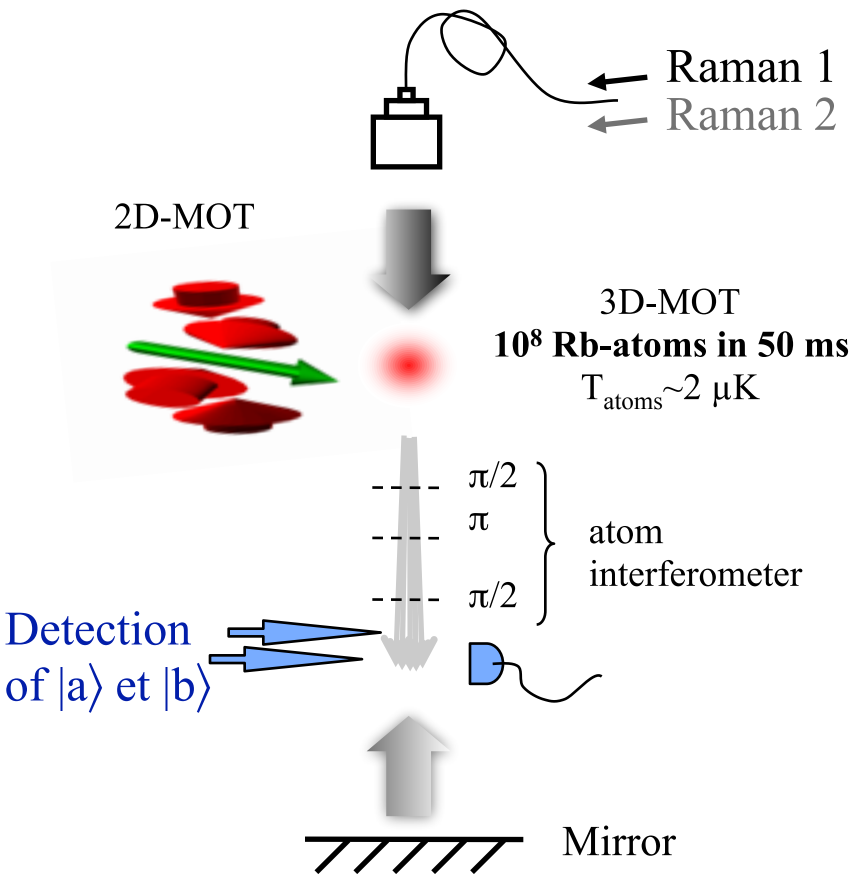


$$\Delta\Phi = \Phi^A - \Phi^B \quad \boxed{= \Phi_1 - 2\Phi_2 + \Phi_3}$$

Relative displacements of the referential frame of the center of mass of the atoms/laser

Gravimeter

SYRTE gravimeter: accuracy for watt balance and metrology in gravimetry



Interrogation time: 160 ms

Cycling frequency: 3 Hz

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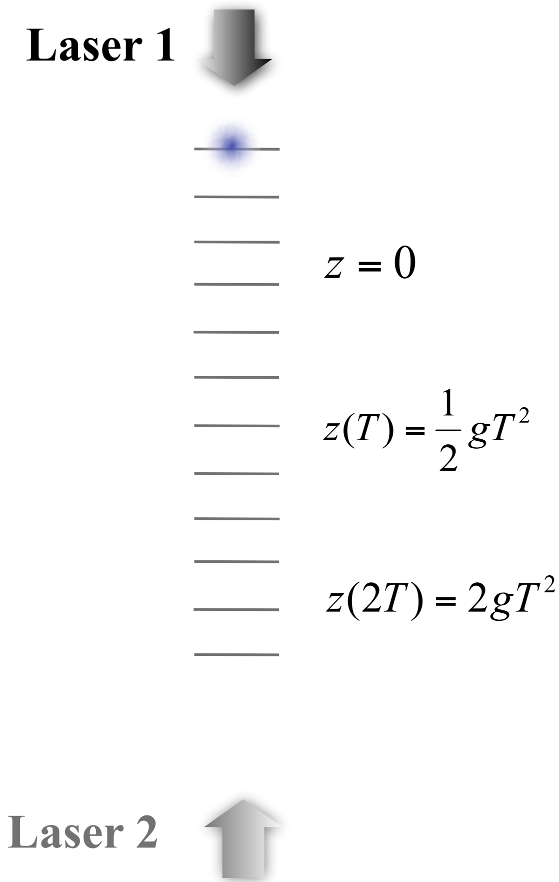
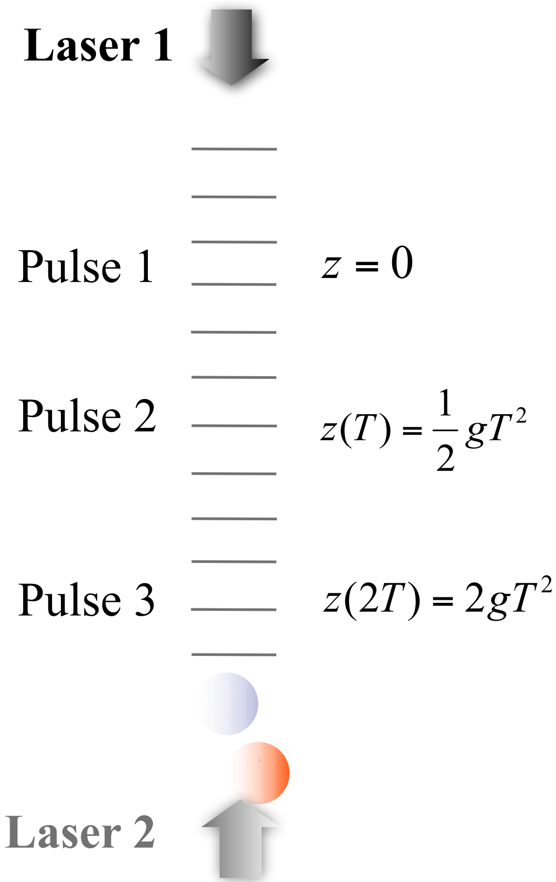
Gravimeter configuration



Vertical interferometer

$\Rightarrow$ Free fall along the equiphase planes

Gravimeter configuration



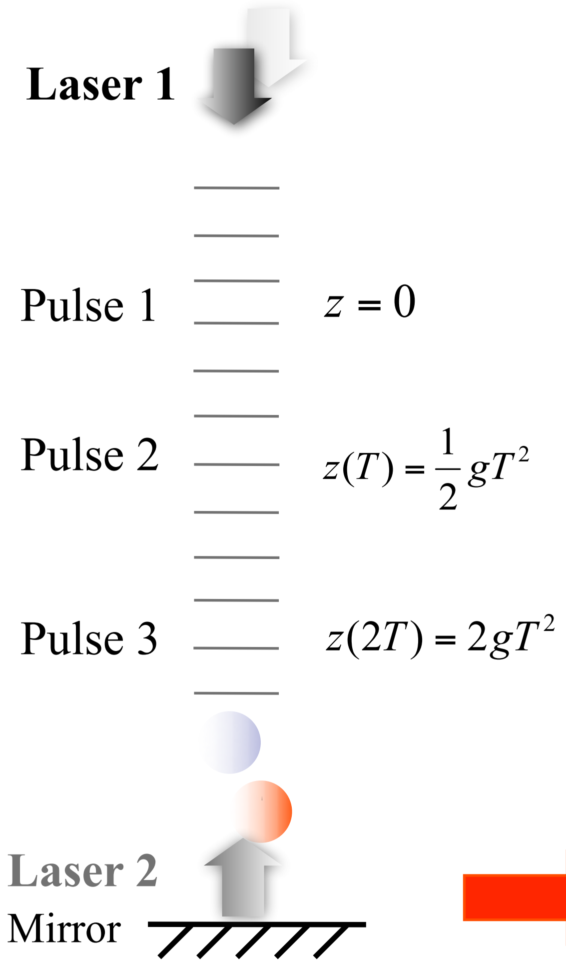
Vertical interferometer

$\Rightarrow$ Free fall along the equiphase planes

Sensitivity to gravity acceleration :

$$\Delta\Phi_{\text{int}} = -\vec{k}_{eff}\,\vec{g}\,T^2 + \delta\Phi_{noise} + \delta\Phi_{sys}$$

Gravimeter configuration



Vertical interferometer

$\Rightarrow$ Free fall along the equiphase planes

Sensitivity to gravity acceleration :

$$\Delta\Phi_{\mathrm{int}} = -\vec{k}_{eff}\,\vec{g}\,\mathrm{T}^2 + \delta\Phi_{noise} + \delta\Phi_{sys}$$

Two overlapped Raman beams retroreflected

$\Rightarrow$ **Equiphases** defined by the **mirror position**

$\alpha\ (z_1 - 2\,z_2 + z_3)$

atomic measurement = measure of the relative displacement atoms/mirror with a very precise ruler

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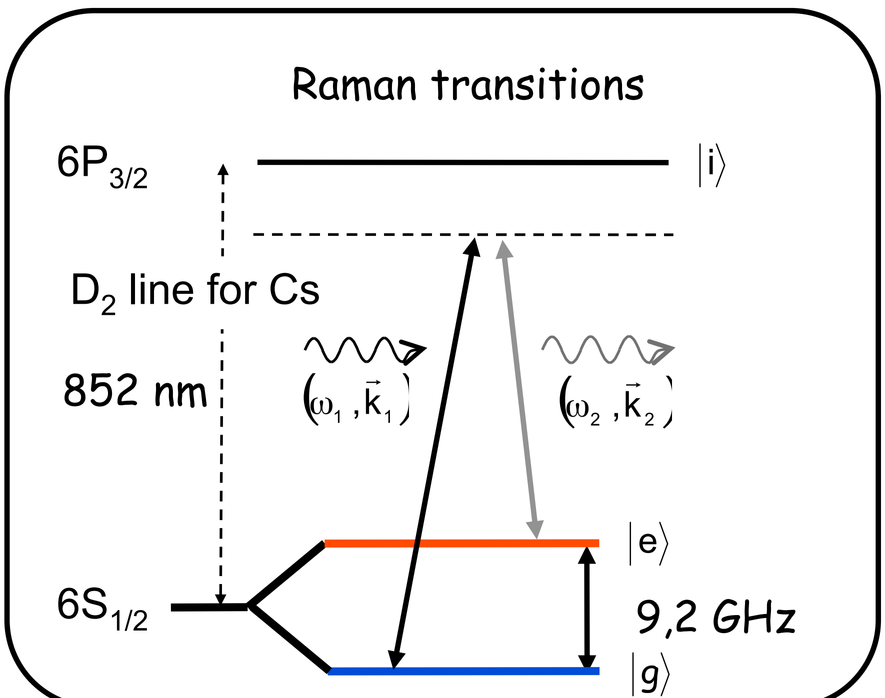
Lasers for atom interferometers: cooling

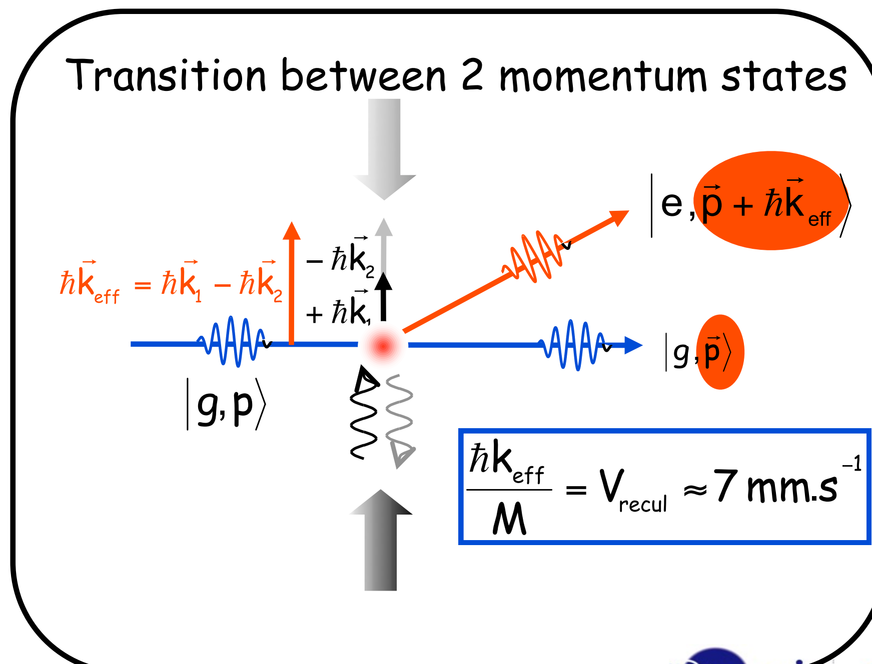
Mostly use of alcaline atoms: Cs, Rb, K…

available lasers sources (852, 780 or 767 nm): semi-conductor, telecom x2

2 different lasers with: few 100 mW each (to 1 W).

- linewidth <100 kHz (ECDL)
- frequency detuning from resonance of~ 500 MHz
- 2 lasers perfectly in phase (with 9.2 GHz difference for Cs)
- accuracy in the frequency knowledge < 300 kHz (case of a gravimeter)





Lasers for Raman transitions

Mostly use of alcaline atoms: Cs, Rb, K…

available lasers sources (852, 780 or 767 nm) : semi-conductor, telecom x2

2 different lasers with: few 100 mW each.

- linewidth <100 kHz (ECDL)
- frequency detuning from resonance of~ 500 MHz
- 2 lasers perfectly in phase (with 9.2 GHz difference): phase locked or frequency generation (EOM…)
- accuracy in the frequency knowledge < 300 kHz (frequency spectroscopy)

« **Shaping of the laser beams** »

- needs from 1 to 3 pairs of Raman laser
- needs of good polarization quality PER > 20 dB
- pulses: typical duration 10 μs (rising time <1μs)
- switch with very good extinction ration: >100 dB
- quality of the laser wave fronts

In practice: **fiber links** from laser sources to vacuum chamber for alignment stability : defines the direction of the inertial measurement

Photonic needs for AI

- **New** **laser sources ?**: ECDL (near infra-red) from Germany or US only, DFB ?, or telecom + doubling (guided component in Japan only)
- **Needs for** **fiber or integrated components** in near-infra-red range (780, 852 nm..) for polarization maintaining or polarizing fibers
- **Beam splitters** : micro-optic only ?
- **Modulation of power and fast switch**:
  - AOM: high power consumption and difficulties for thermal fluctuations
  - mechanical switch ? : velocity (<1 μs) and polarization (>20 dB of PER) and good extinction ratio (>100dB)?
- Polarization control in fiber ?

- Compliant with large **temperature variations** and **vibrations**: geophysics and inertial navigation