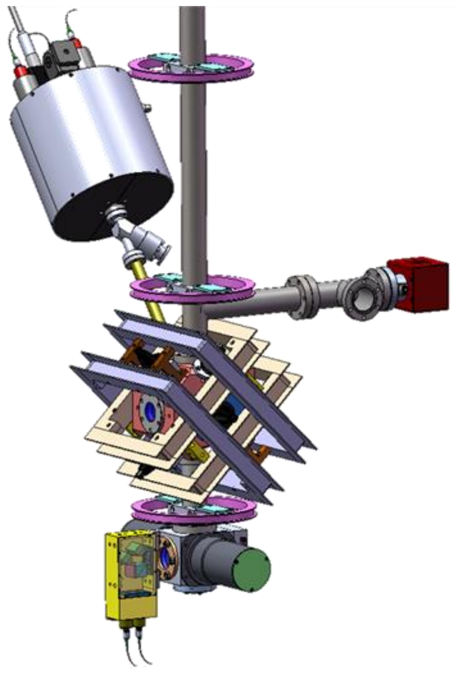
SYRTE - IACI

AtoM Interferometry dual Gravi-GradiOmeter AMIGGO

from capability demonstrations in laboratory to space missions

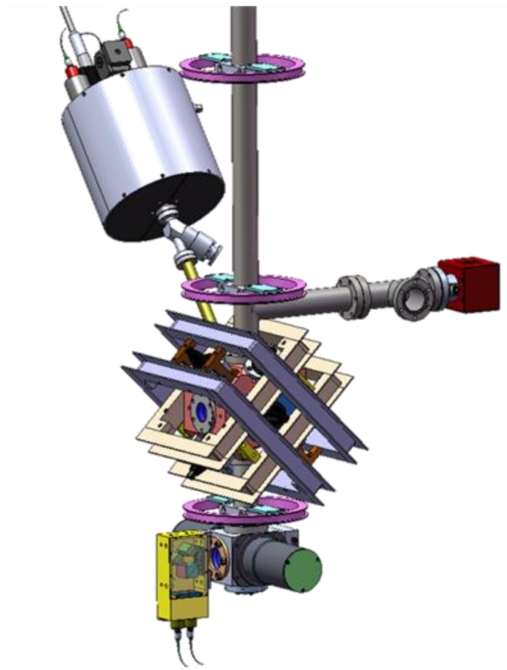
A. Trimeche, R. Caldani, M. Langlois, S. Merlet, C. Garrido Alzar and F. Pereira Dos Santos

Outline



- Interest of Gravity Gradiometer
- State of the Art
- Atomic Interferometer
- Technical Improvements
- Advancements
- Next Steps

Outline



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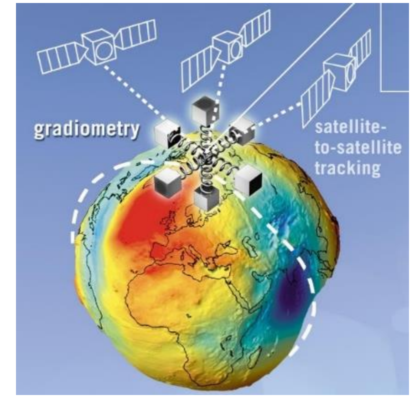
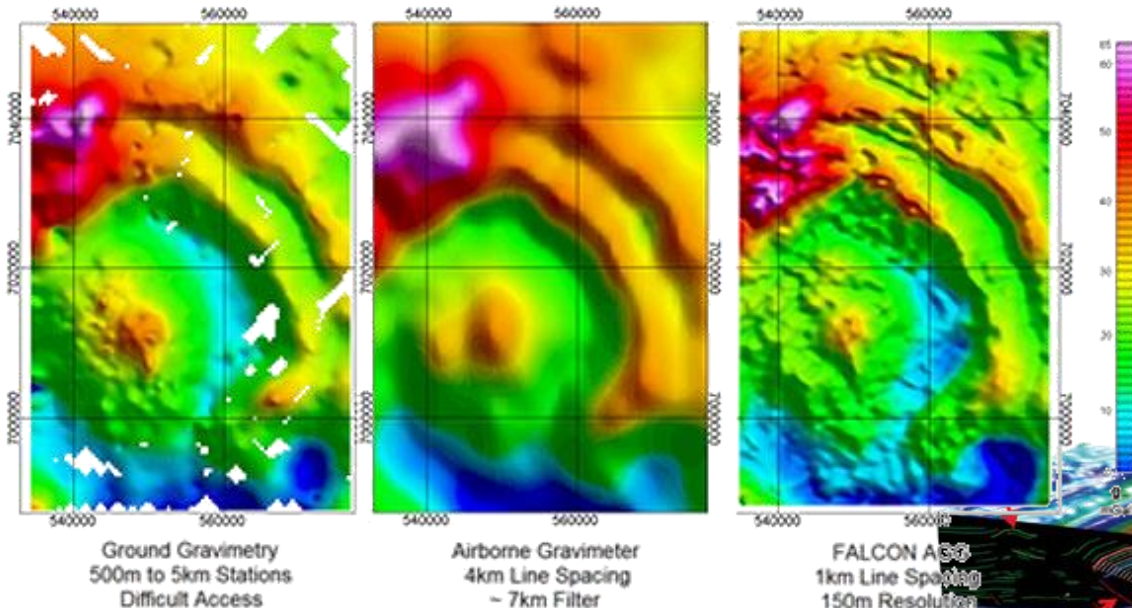
Interest of gravity gradiometer

Determine the geoid with an accuracy of 1-2 cm.

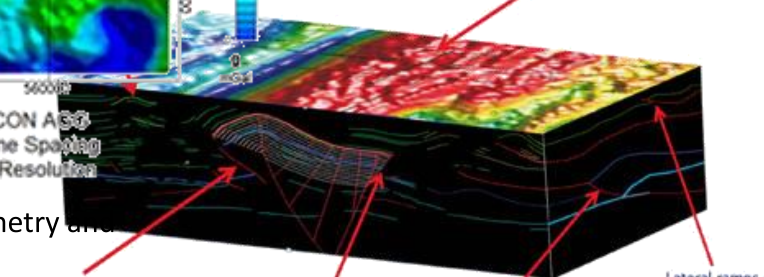


Components of the gravity gradient tensor with GOCE



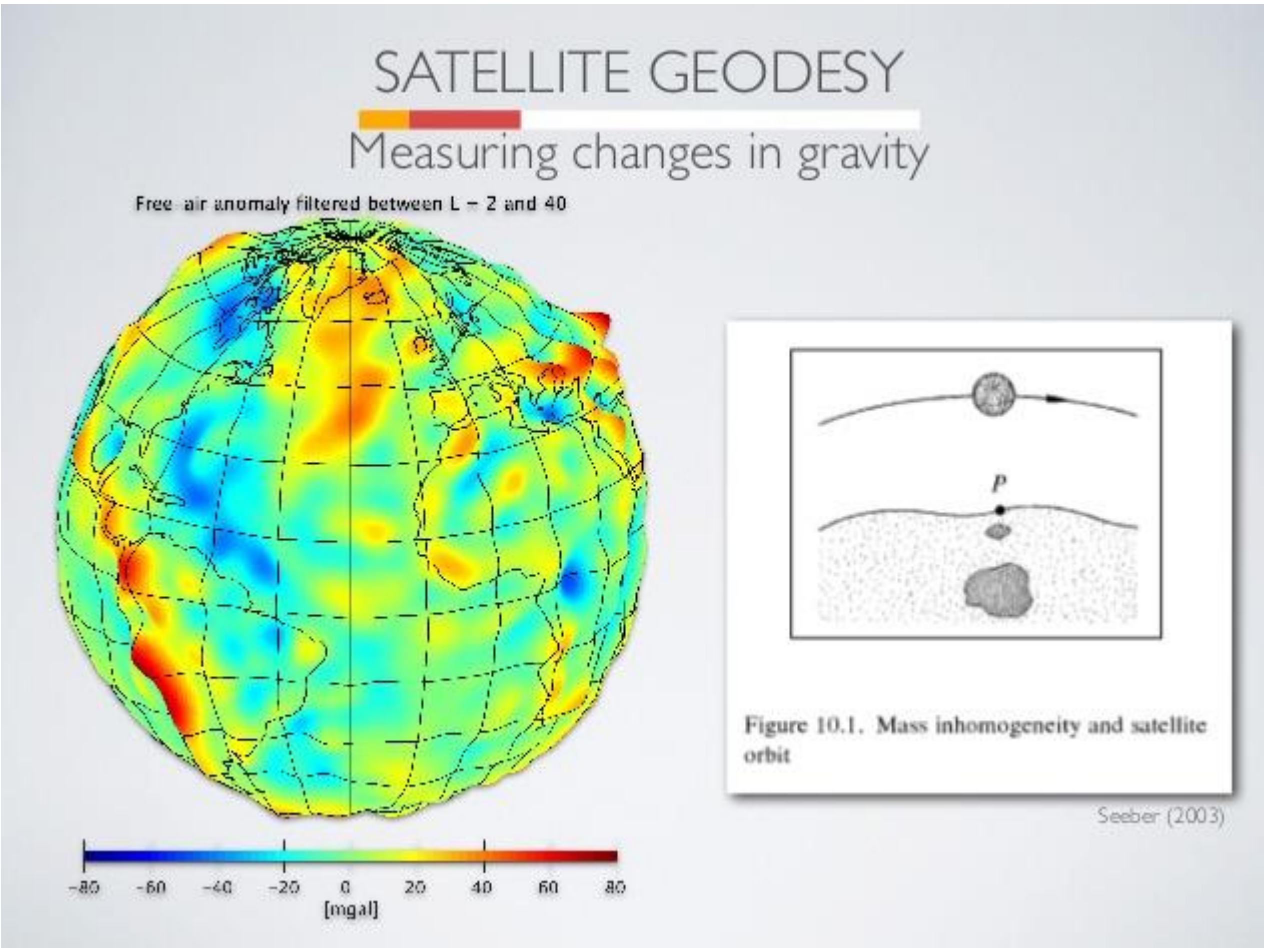
Difference between ground gravimetry, airborne gravimetry and airborne gravity gradiometry by Falcon

Measure the subsurface density indicate oil or gas deposits.



A 3D cube image linking the 2D modelled lines with a gravity gradiometry image by ARKeX

Interest of gravity gradiometer



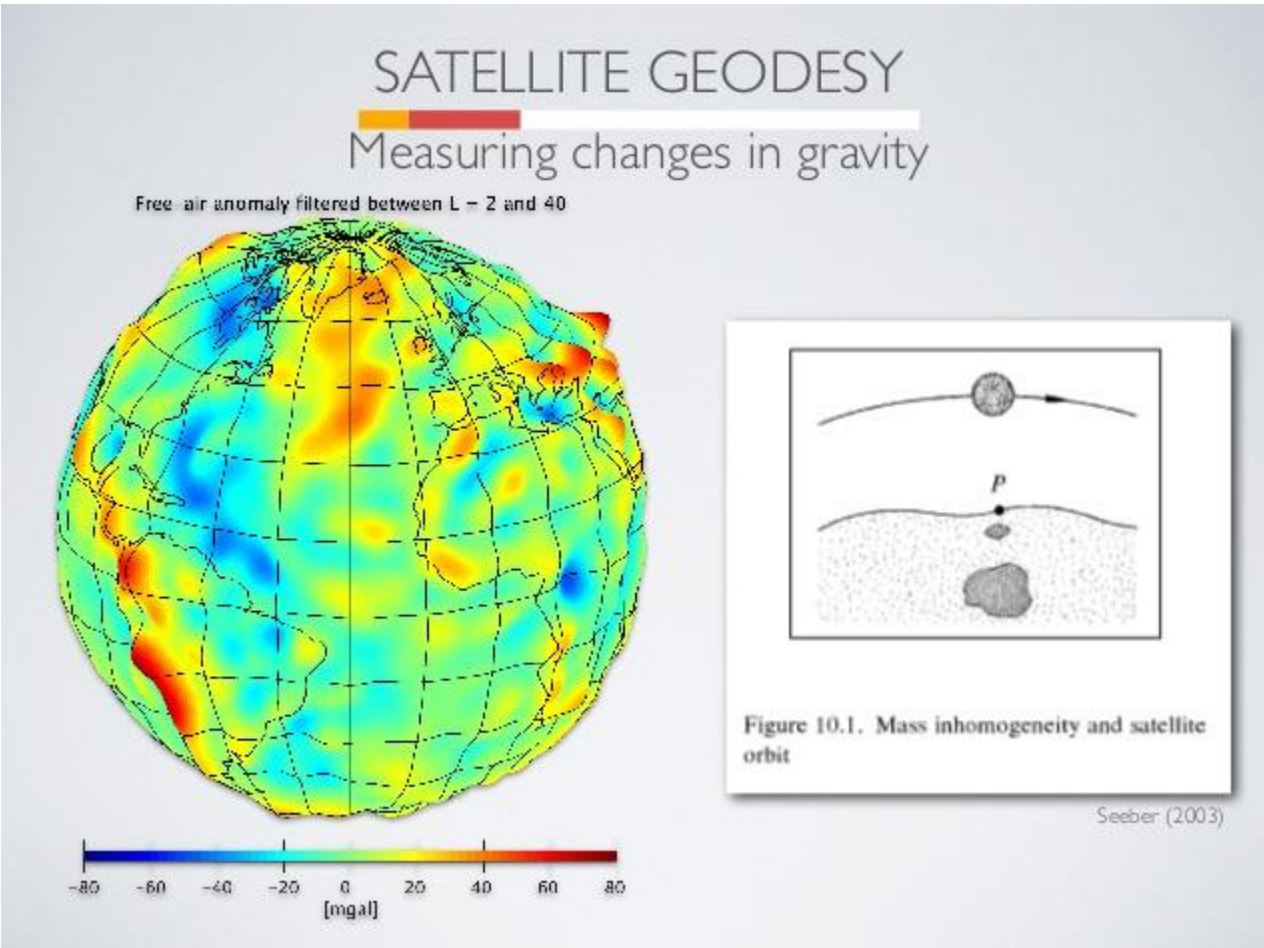
Newton's law of universal gravitation:

$$g = \frac{G \, . \, M}{d^2}$$

- g : Surface gravity (Acc)
- G : gravitational constant
- M : mass of the object
- d : distance of the object

Measurement of g ->
Determination of M | d ??
-> Lack of information

Interest of gravity gradiometer



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Measurement of g ->
Determination of M | d ??
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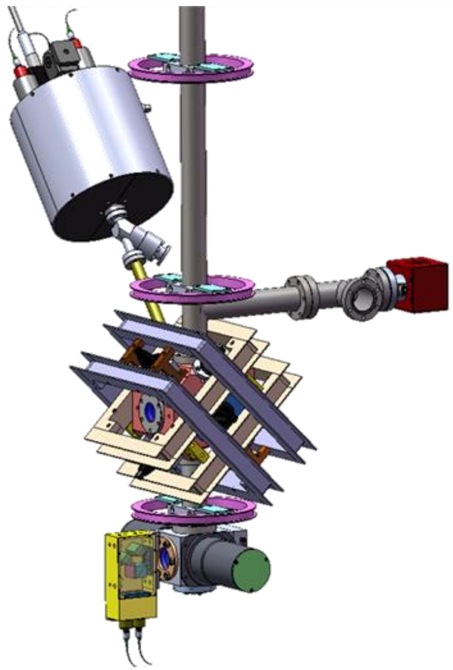
Measurement of g & δg ->
Determination of M & d !!

Outline



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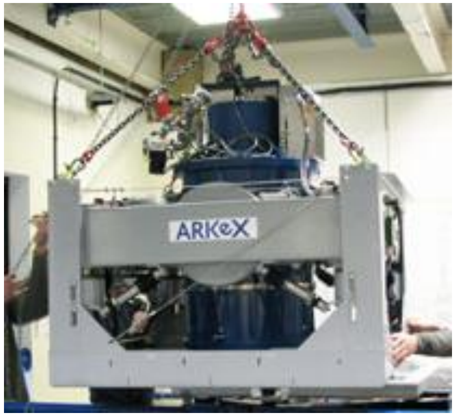
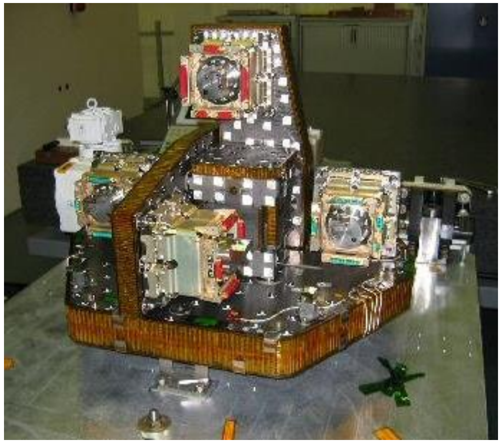
State of the art

Gravity gradiometer	*sensitivity*
Cold atom	12.10^{-9} $s^{-2}/\sqrt{Hz}$ [1]
Lockheed Martin	3.10^{-9} $s^{-2}/\sqrt{Hz}$ [2]
Superconducting (ARKeX)	1.10^{-9} $s^{-2}/\sqrt{Hz}$ [2]
Electrostatic (GOCE)	15.10^{-12} $s^{-2}/\sqrt{Hz}$ [2]

Lockheed Martin gradiometer consists of two opposing pairs of accelerometers arranged on a spinning disc



ARKeX gradiometer uses super conductivity for levitation of the proof masses and for the inherent stability



GOCE gradiometer is a set of electrostatic servo-controlled accelerometers

[1] P. Asenbaum *et al.*, Phys. Rev. Lett. 118, 183602 (2017)
[2] D. DiFrancesco *et al.*, Geophys. Prospect **57**, 615-623 (2009)

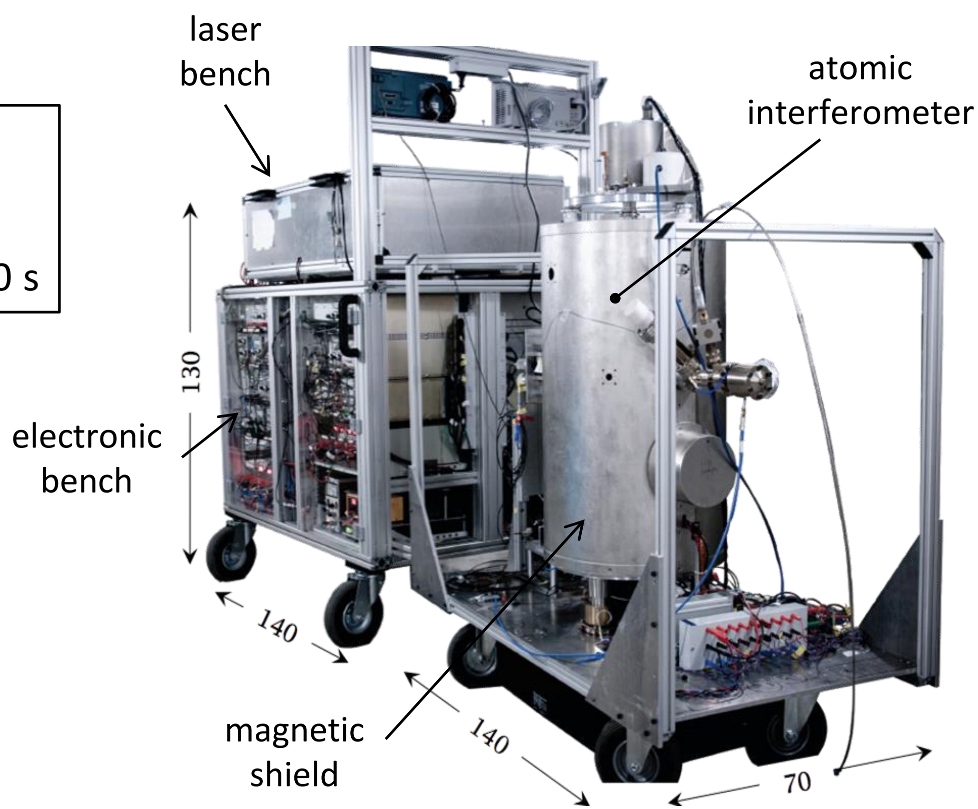
State of the art and limitation

Reached stability [1]:

5.10^{-8} m.s^{-2} @ 1s

5.10^{-10} m.s^{-2} @ 1500 s

Frequency = 3 Hz

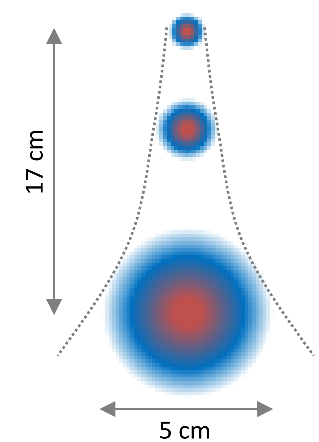


Mobile cold atom gravimeter *(LNE-SYRTE)*

Accuracy: $4,3.10^{-8}$ m.s^{-2}

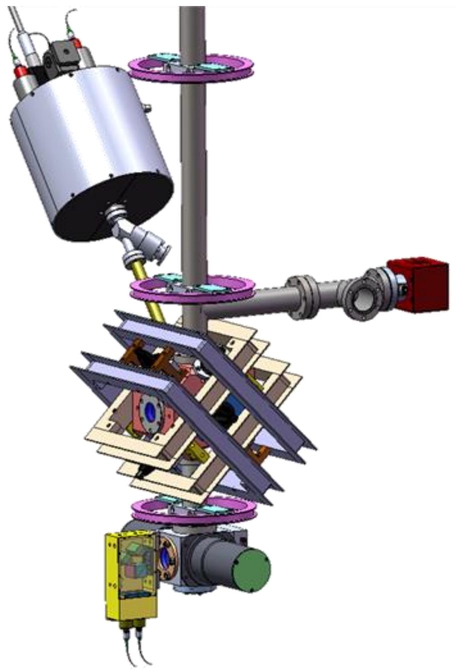
limited by the wavefront aberration: 4.10^{-8} m.s^{-2}

Temperature = 2 µK



[3] P. Gillot et al., Metrologia **51,** L15 (2014)

Outline



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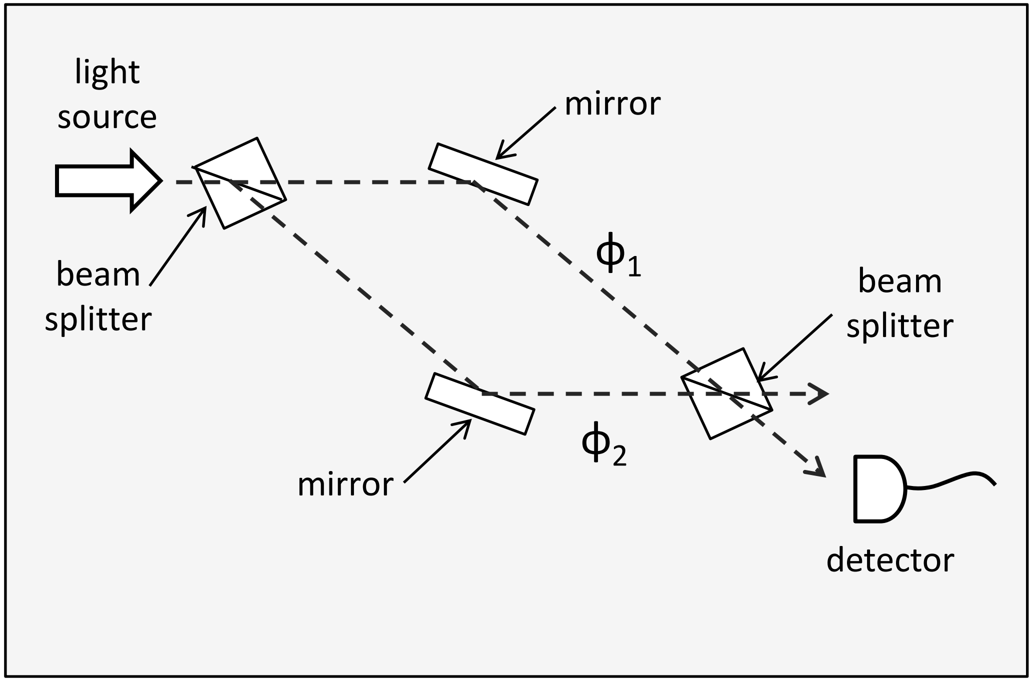
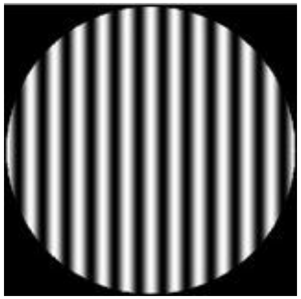
Optical Mach-Zehnder interferometer

The light beam is separated in two paths, reflected and recombined.



The phase shift depends of the length difference between the two arms.

$I_1 \propto \Delta\phi$



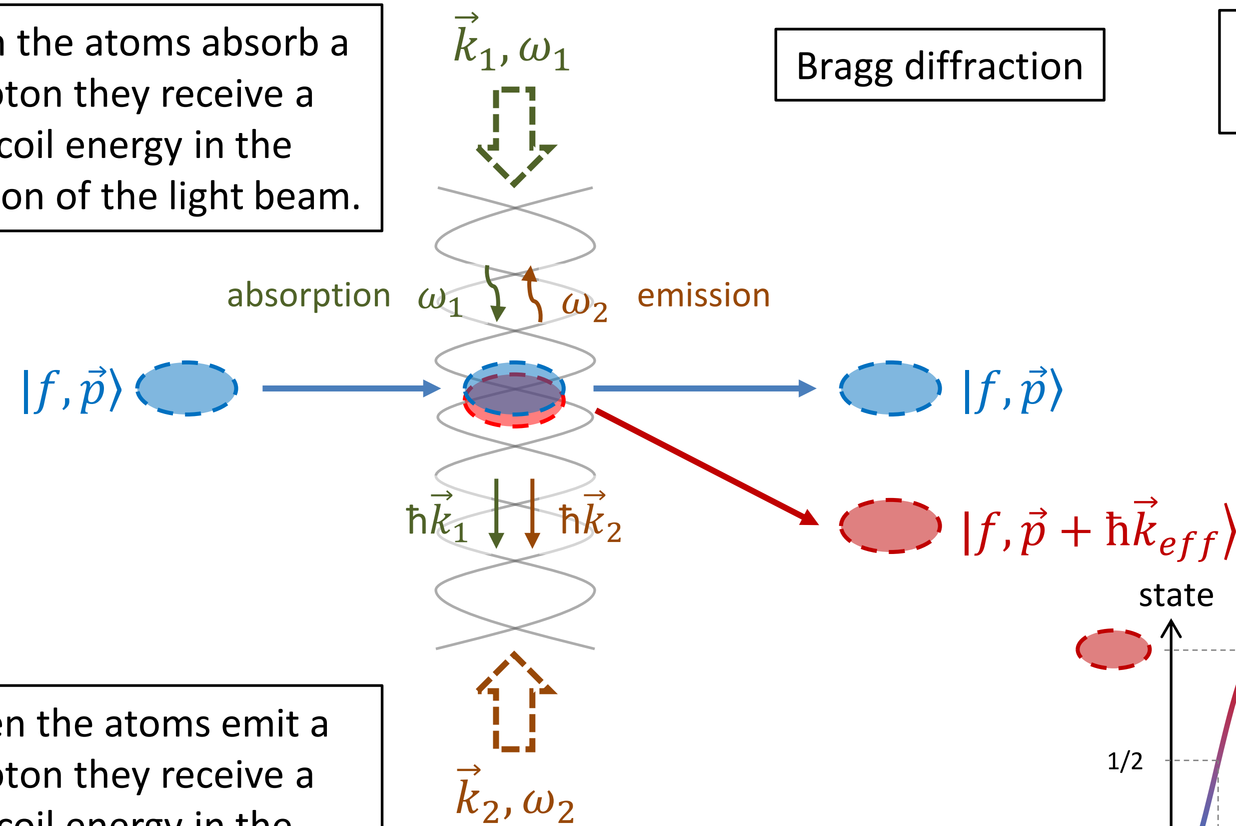
The intensity detected depend of the phase of the interferometer

Tool for atom interferometry

When the atoms absorb a photon they receive a recoil energy in the direction of the light beam.

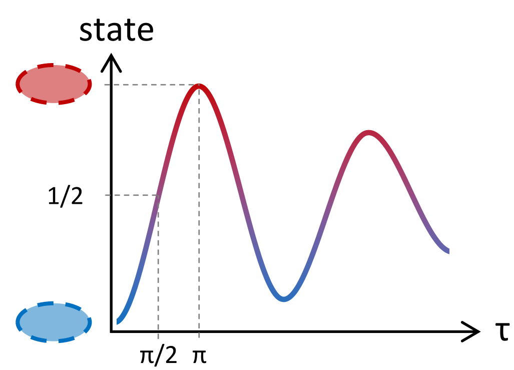
Bragg diffraction

Simultaneous two-photons transition



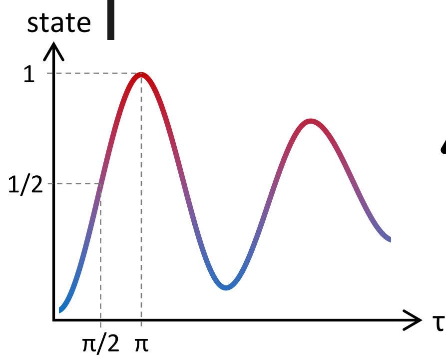
Total wave number:
$\vec{k}_{eff} = \vec{k}_1 + \vec{k}_2$

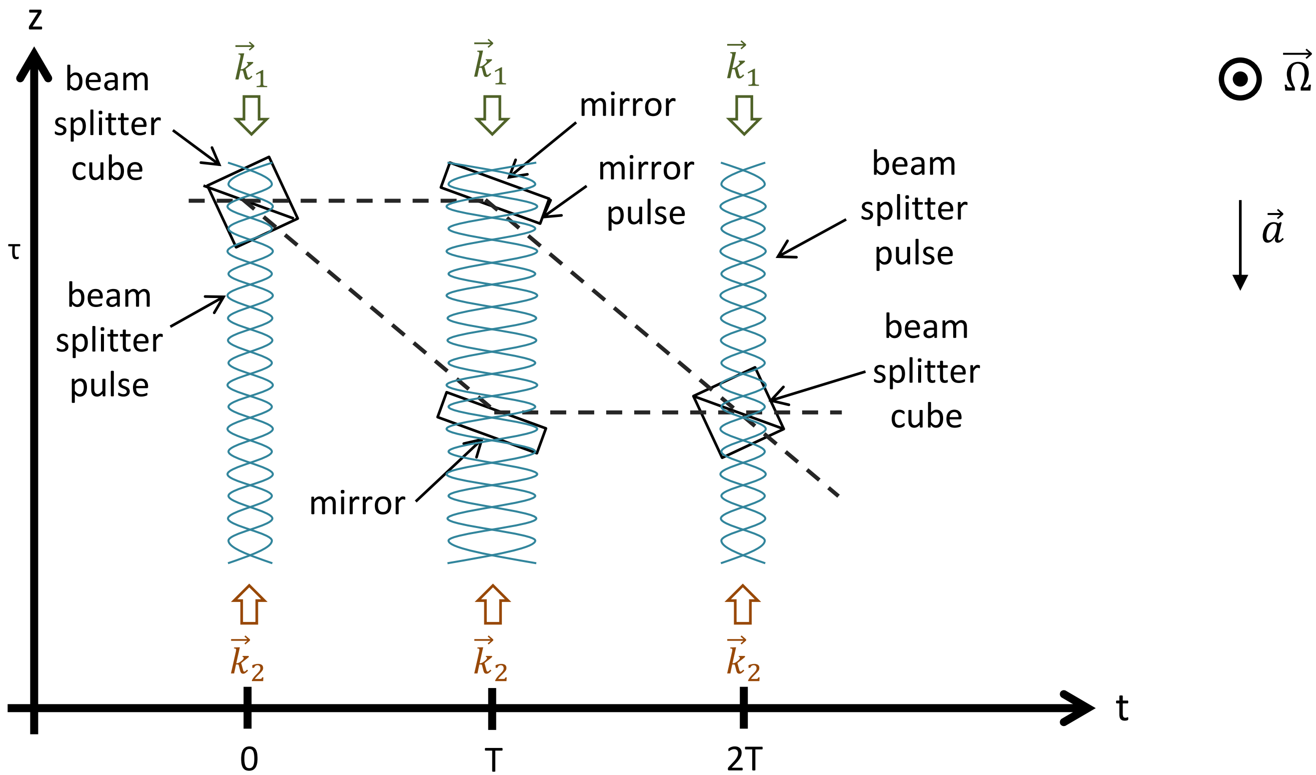
When the atoms emit a photon they receive a recoil energy in the direction of the light beam.



Rabi oscillations

Mach-Zehnder atom interferometer



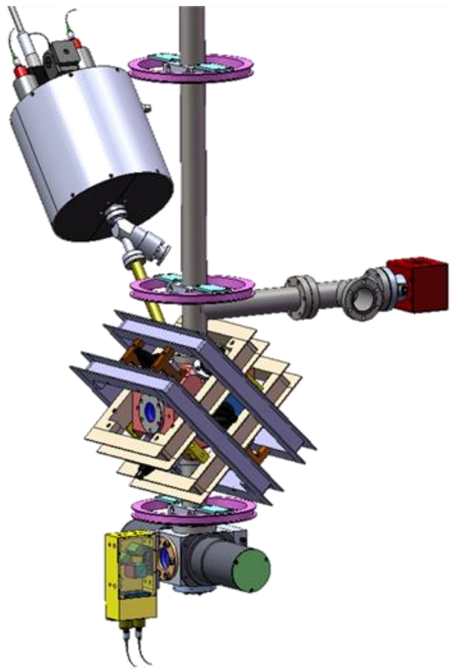


The beamsplitter cubes are replaced by pulses which half the atoms changes state.

The mirrors are replaced by pulses which all the atoms changes state.

$$\Delta\phi = \vec{k}_{eff}.\vec{a}.T^2 - 2.\vec{k}_{eff}.(\vec{\Omega} \times \vec{a}).T^3$$

Outline



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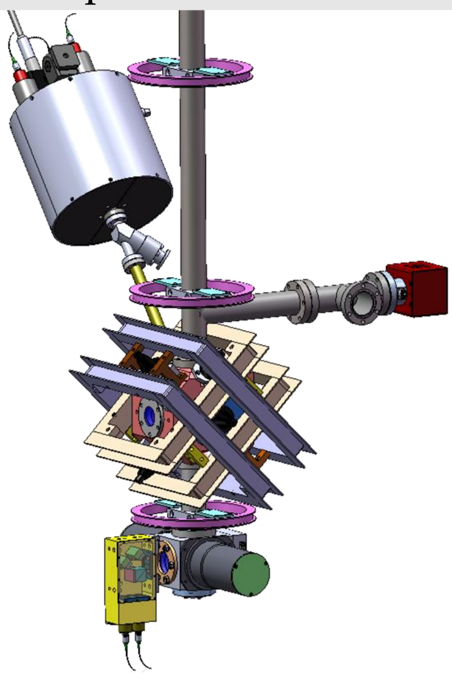
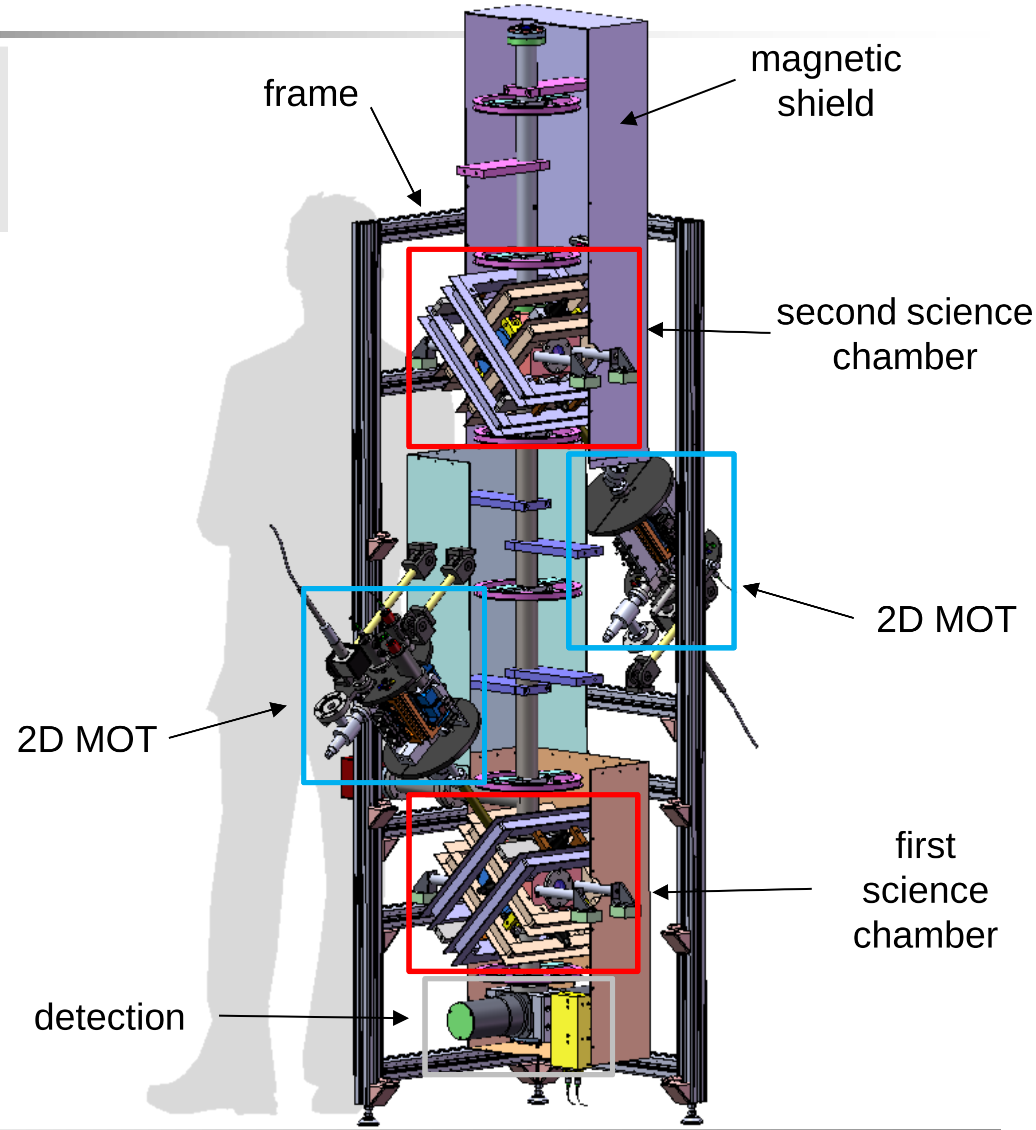
Our project : Gradiometer

- Combining :
  - → Ultra Cold Atoms,
  - → multiphotonic transitions





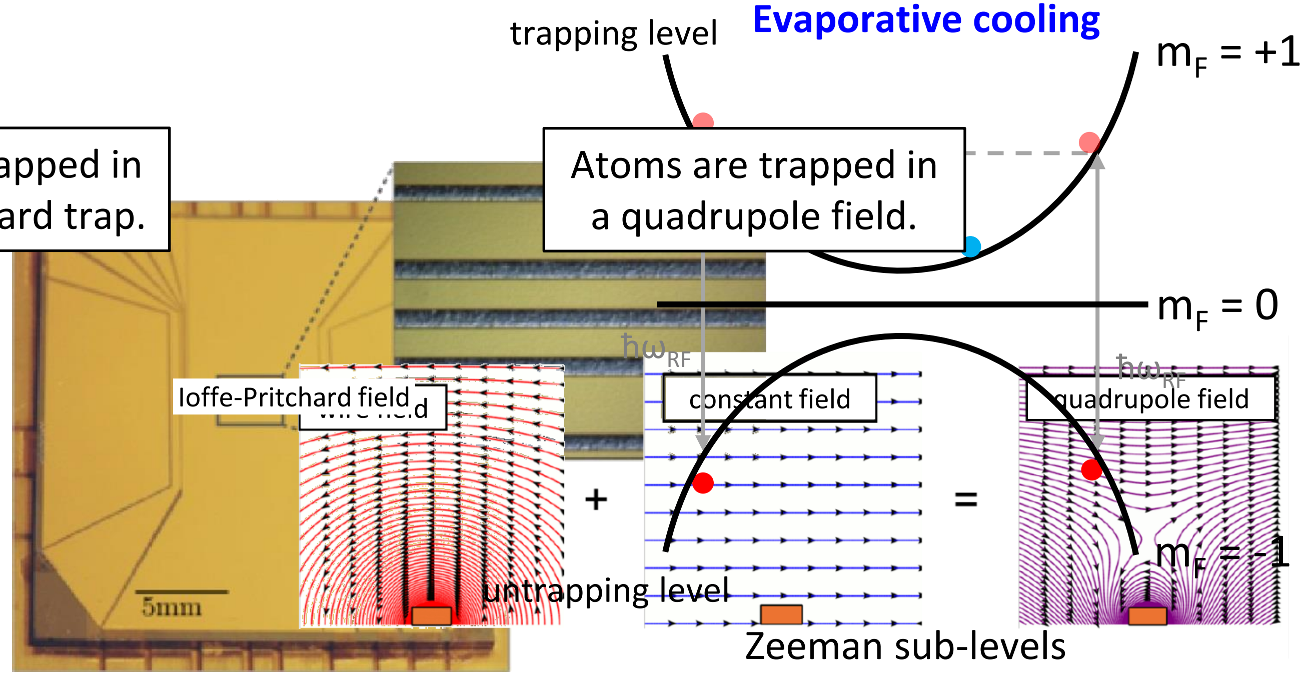
2 gravimeters interogated by the same laser.

→ The same bias

Atom chip : Ultra-cold atoms

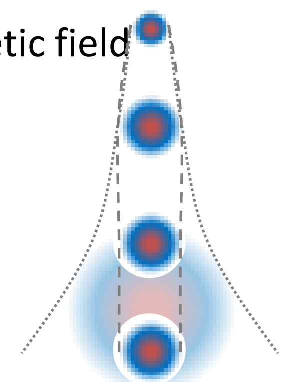
Atoms are trapped in a Ioffe-Pritchard trap.

Atoms are trapped in a quadrupole field.



Atom chip

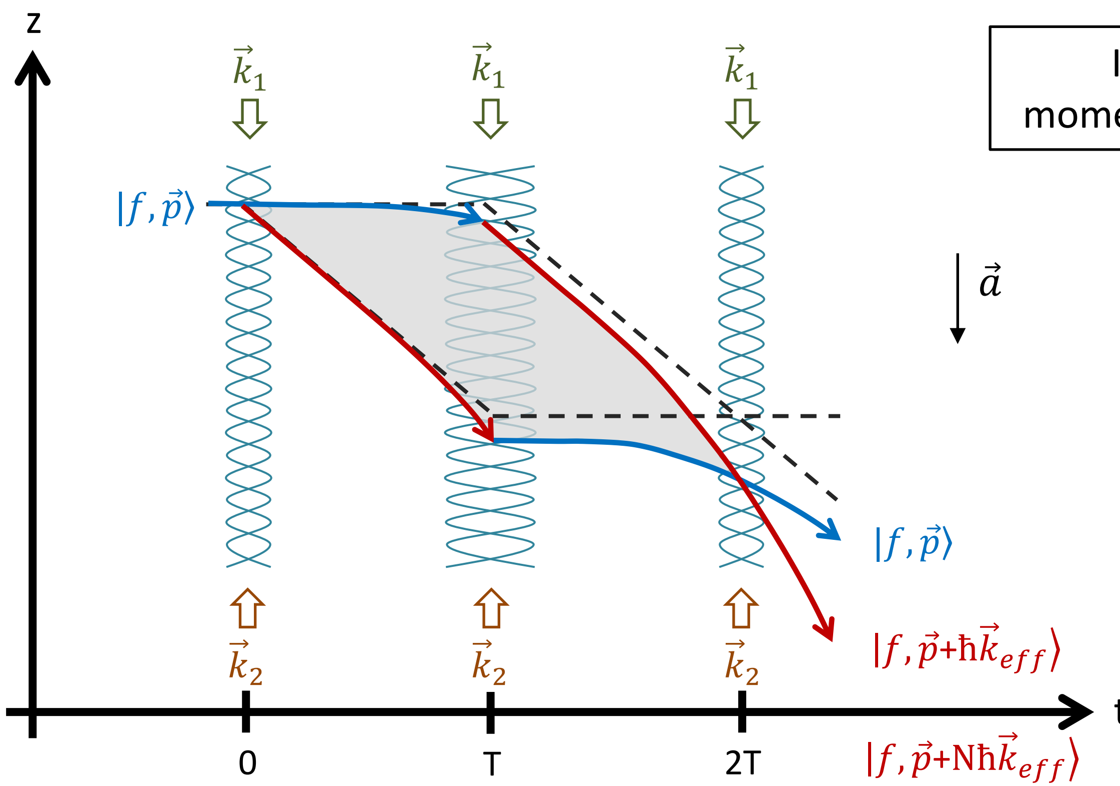
Magnetic field



50 nK

The hottest atom are transferred into an untrapping state by radio-frequency in order to keep only the ultra-cold atoms.

Increase separation of atoms



Increasing the momentum transferred.

$\vec{k}_{eff} = \vec{k}_1 + \vec{k}_2$

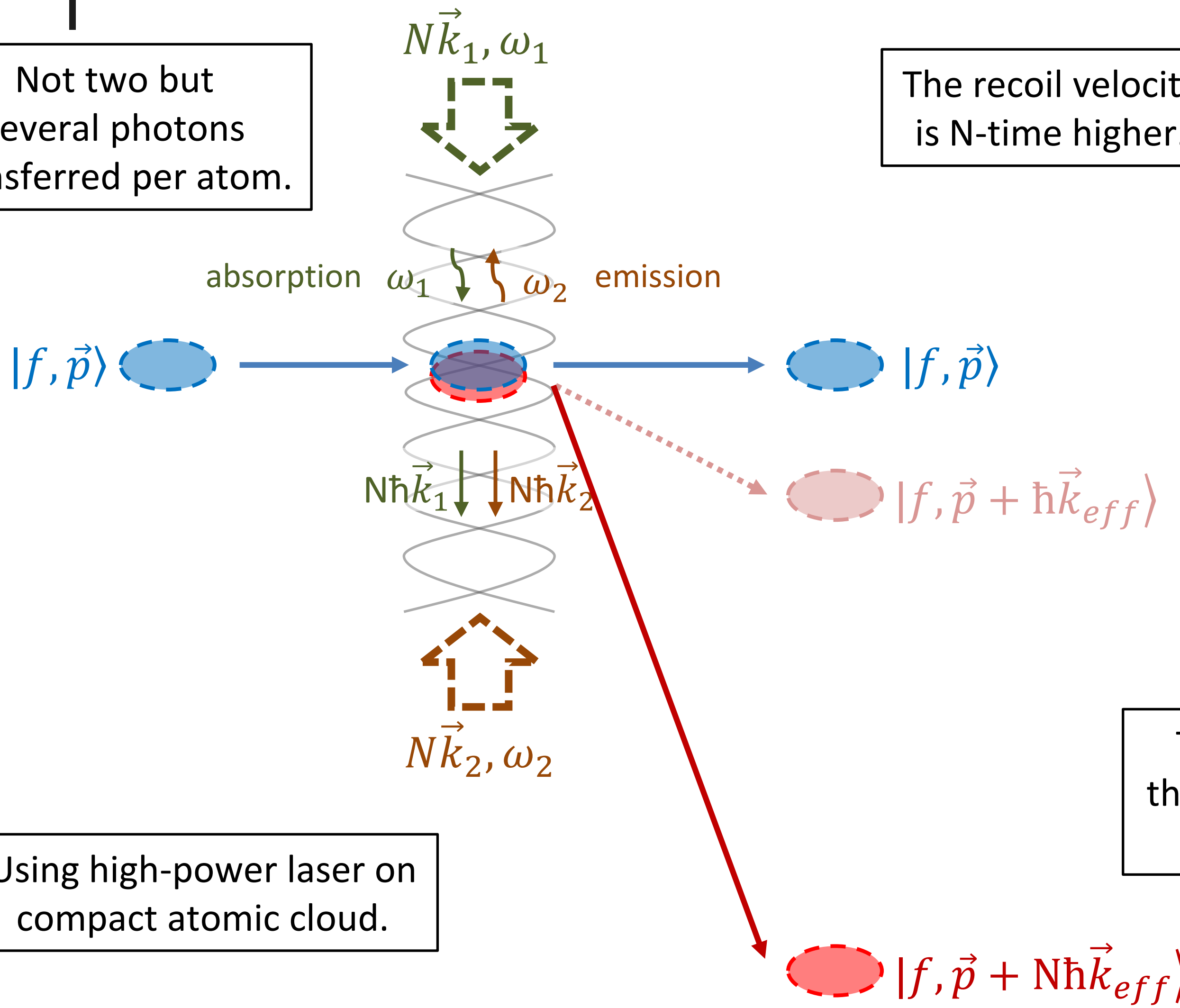
The sensitivity of the measurement depends of the interferometer area.

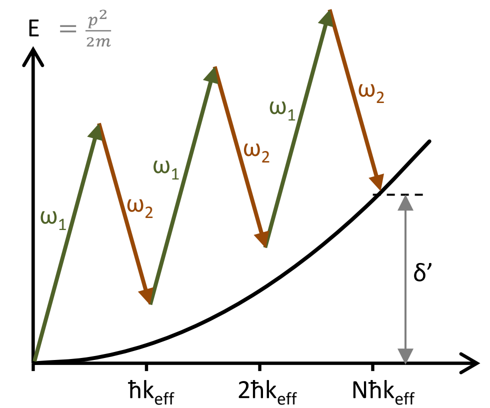
Interferometer phase shift: $\Delta\phi = N\,\vec{k}_{eff}.\vec{a}.T^2$

Large momentum transfer

Not two but several photons transferred per atom.

The recoil velocity is N-time higher.



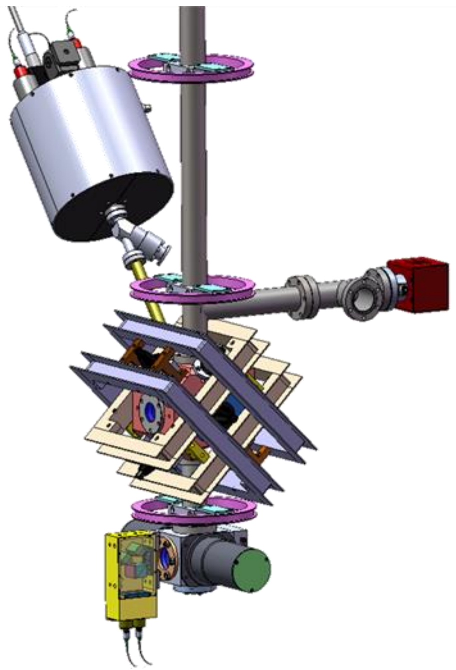


Resonant frequency

The detuning is chosen so that the atom have to absorb and emit several photon.

Using high-power laser on compact atomic cloud.

Outline



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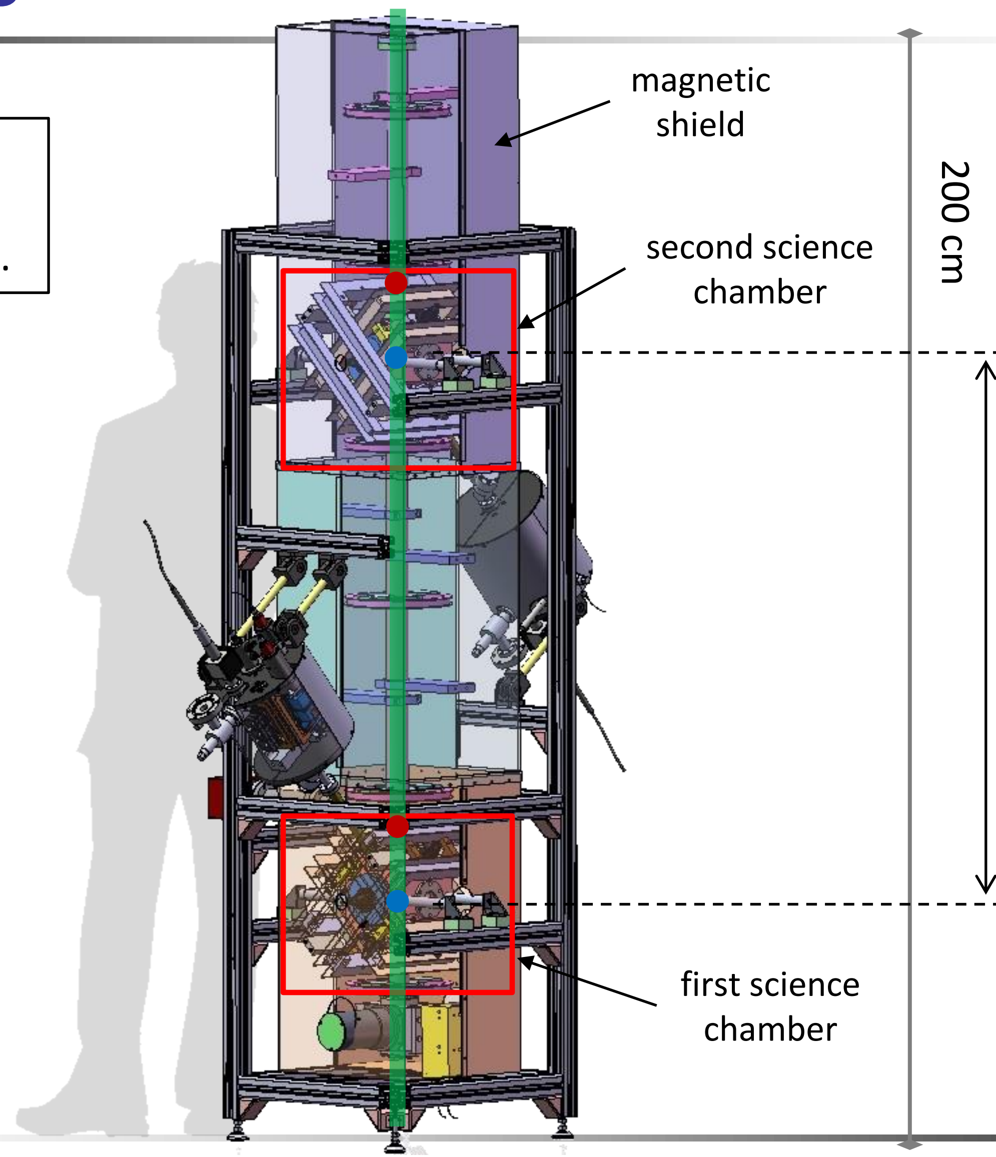
Our objective

- Two science chambers.
- Two atom chips.
- One interrogation laser.

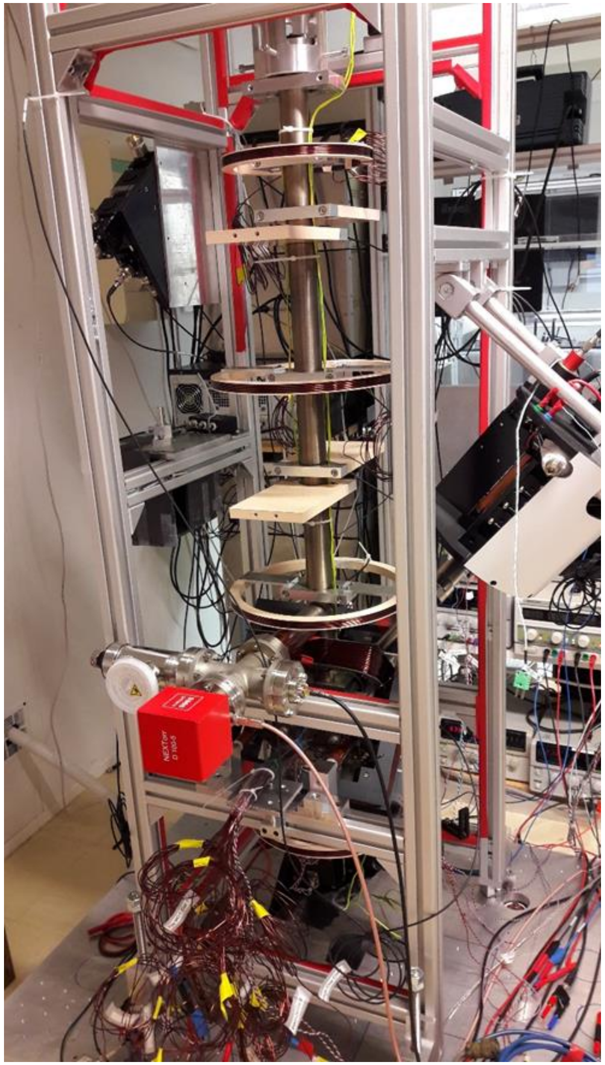
Trapping on atom chip.

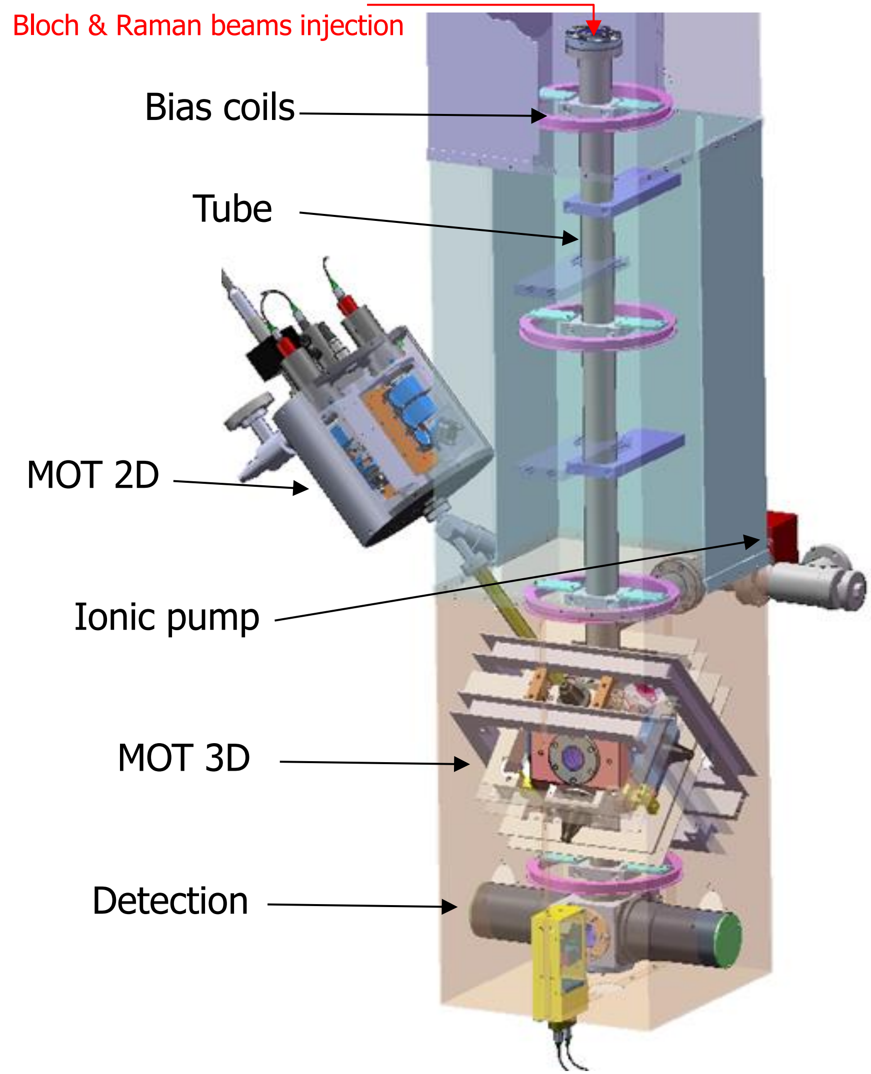
+

High power laser source.

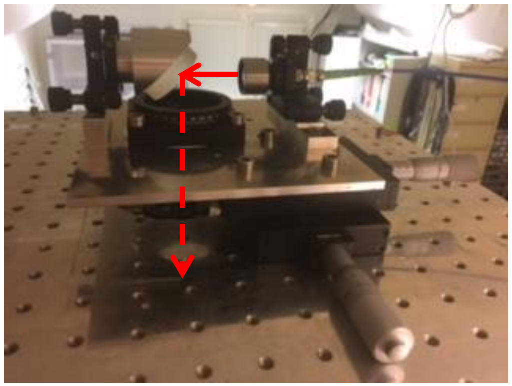


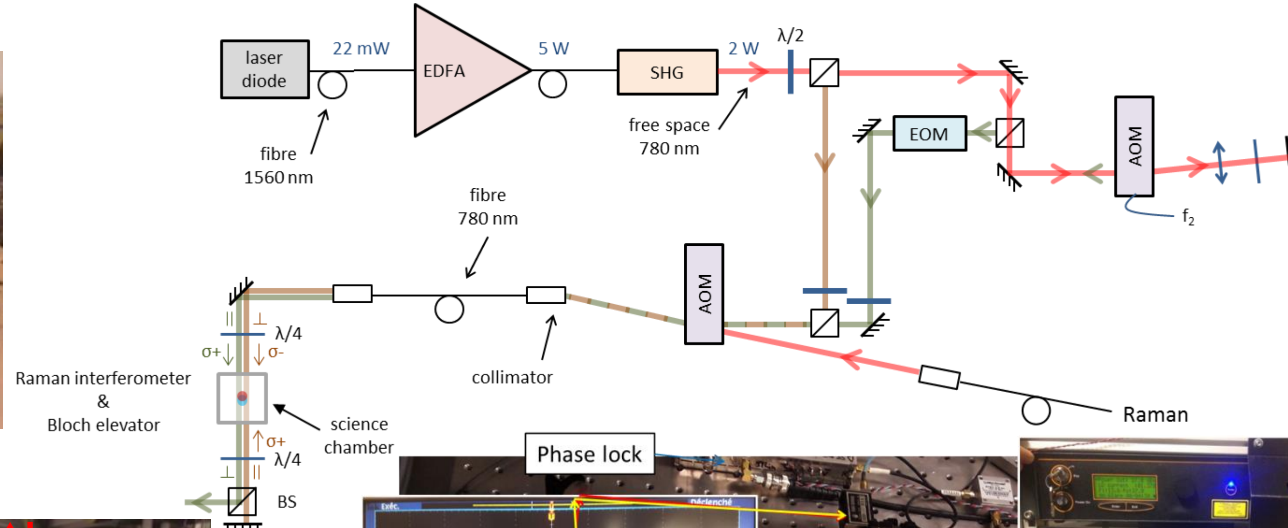
1st Source Chamber

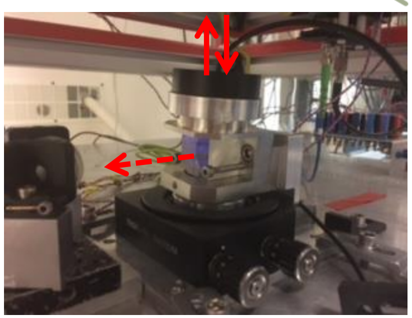


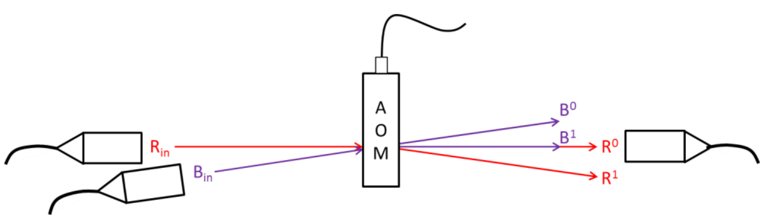


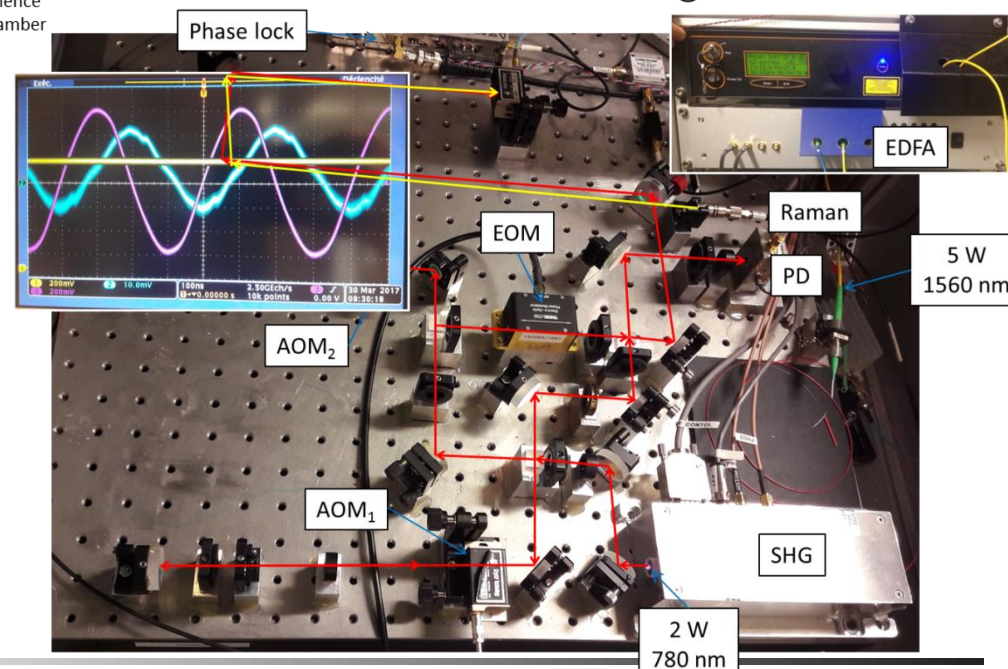
The Bloch & Raman Injection





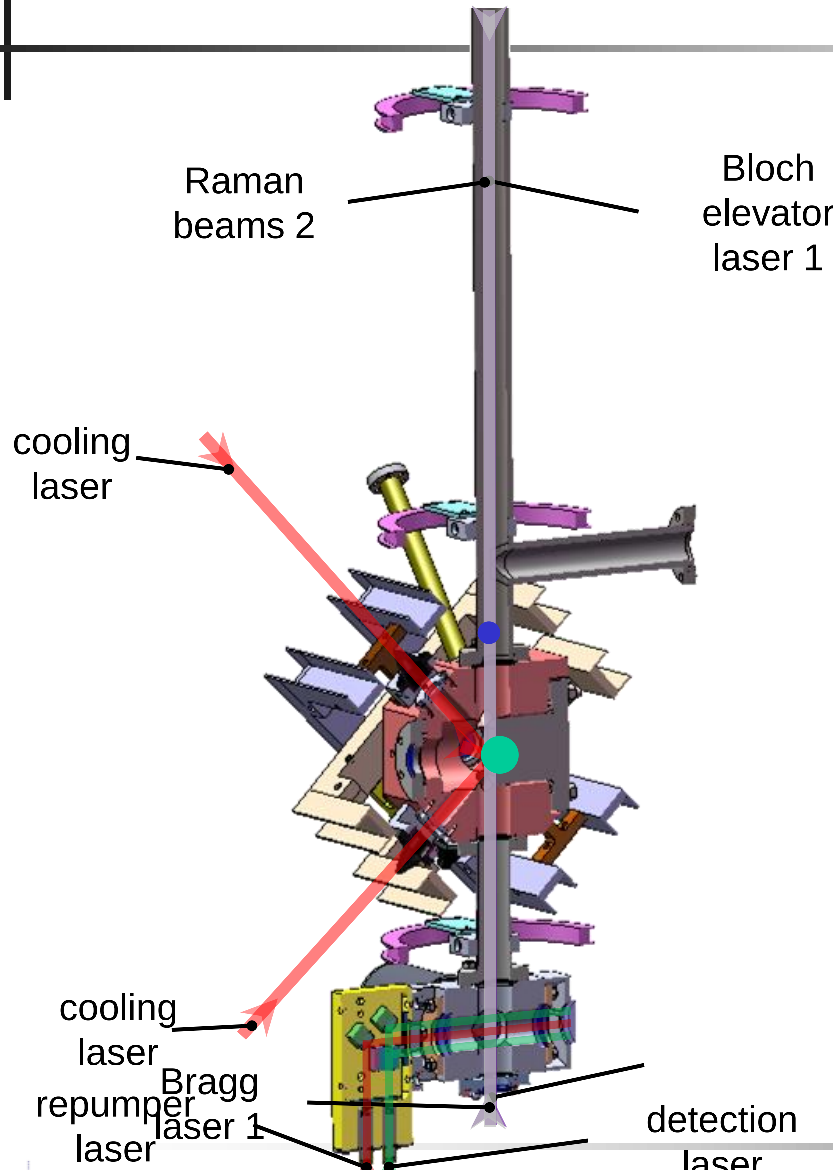


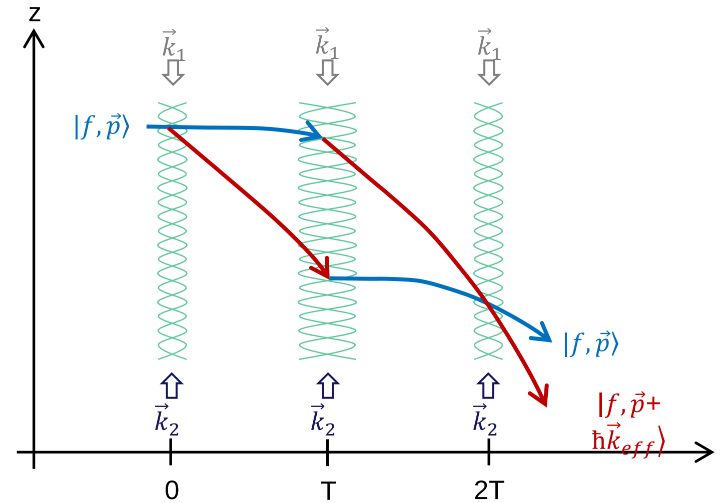


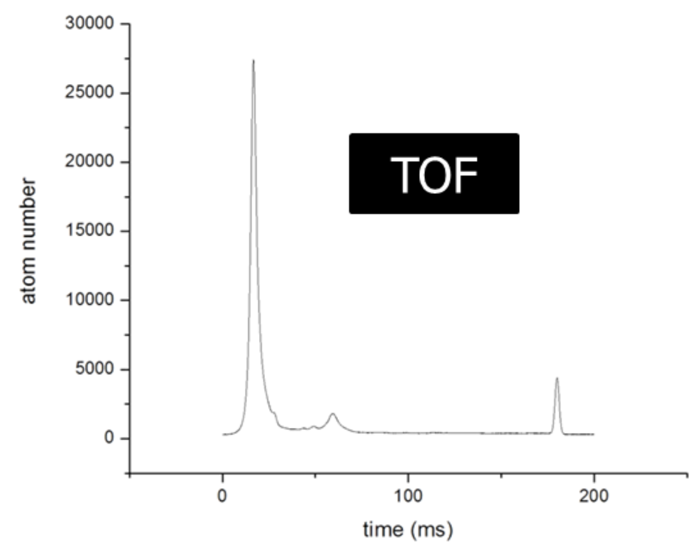


l'Observatoire de Paris SYRTE
Systèmes de Référence Temps-Espace

Test of the 1st Source Chamber



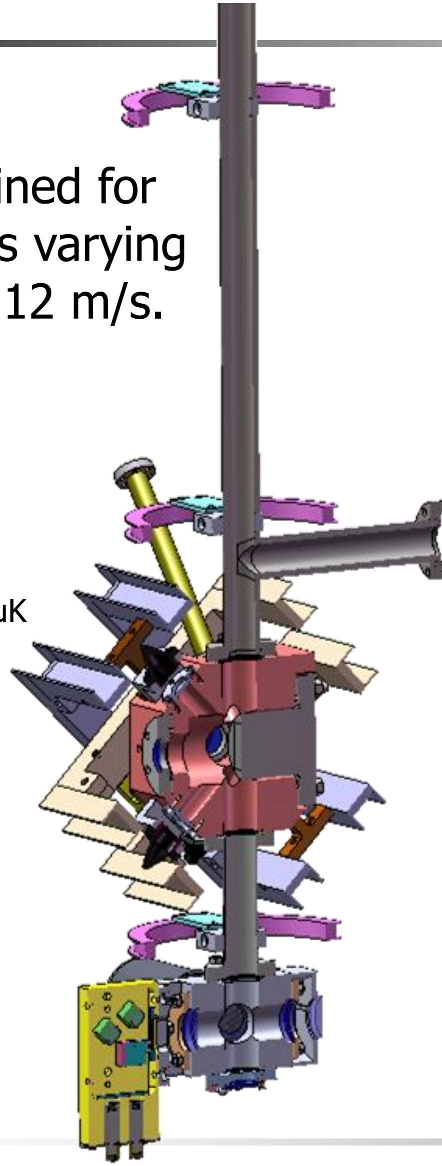


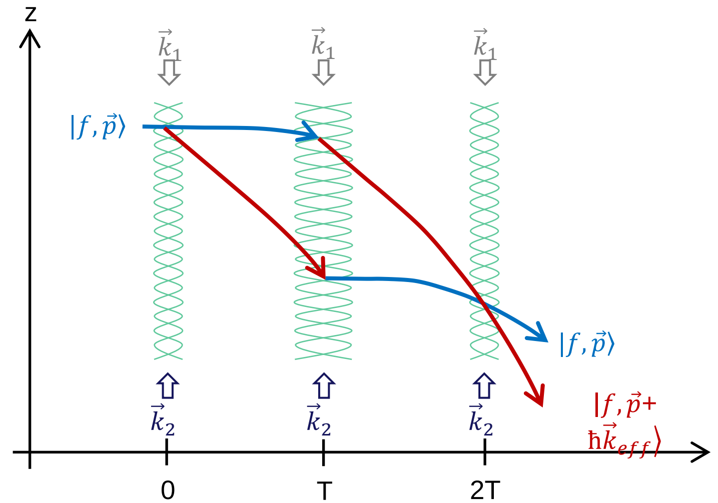


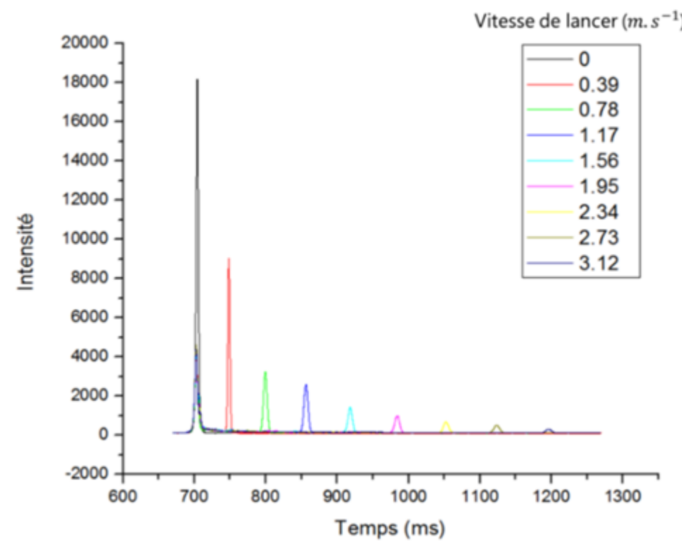
Bloch elevator

TOF signals obtained for launching velocities varying between 0 and 3.12 m/s.

- Atom : 87Rb
- Laser Bloch : 250 mW
- Atom temperature : 1,7 μK



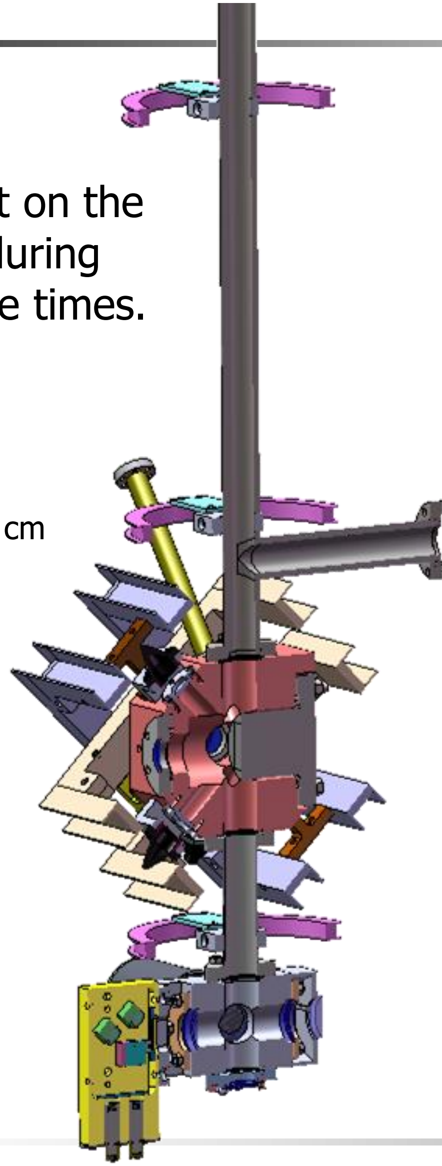


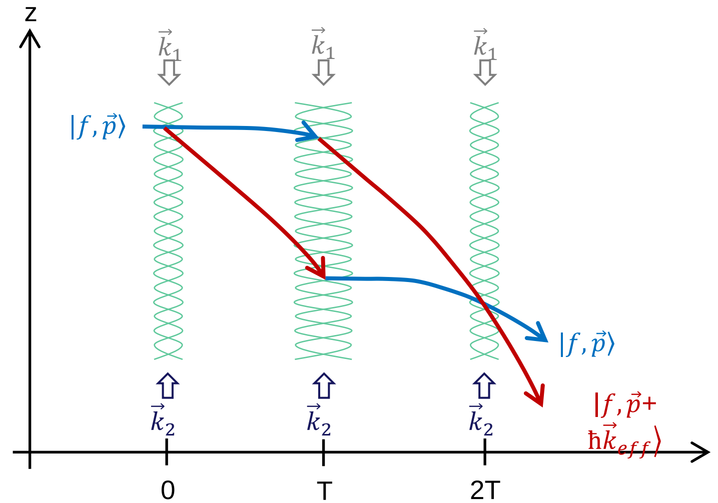


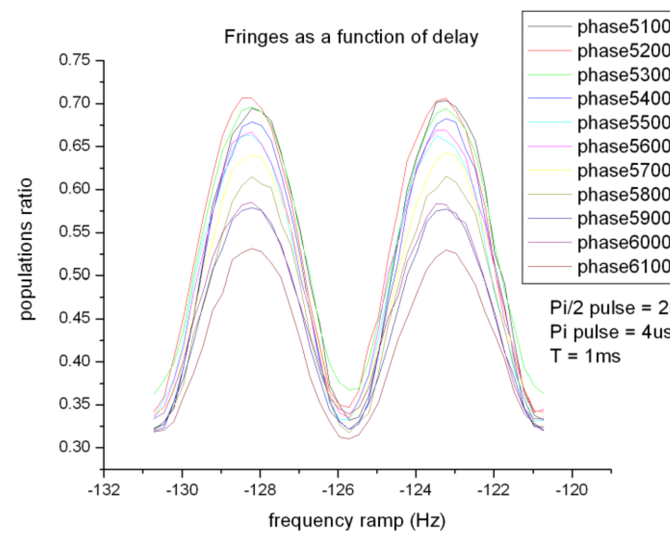
Raman interferometer

Phase measurement on the launched atoms during ascension at multiple times.

- Launch speed : 1.76 m/s
- Theoretical apogee : 16.5 cm
- Π pulse : 4 µs

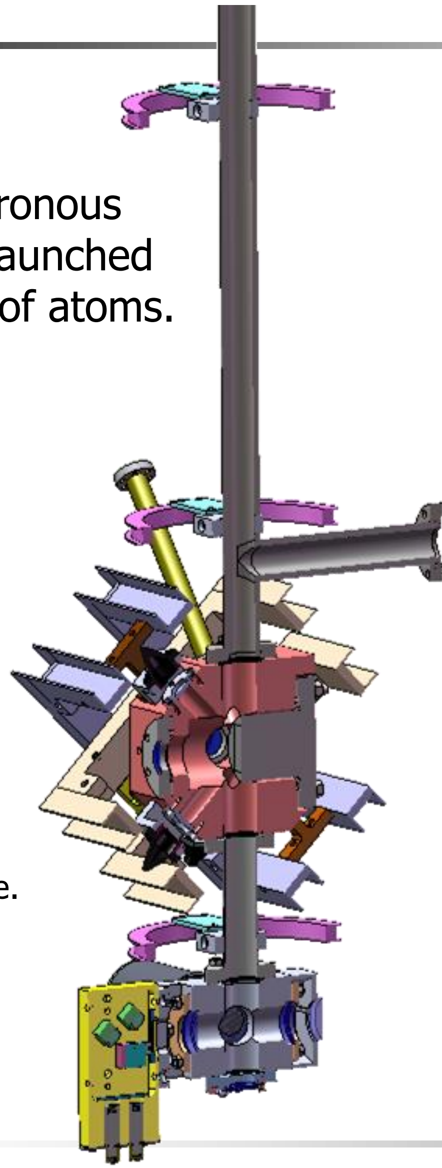


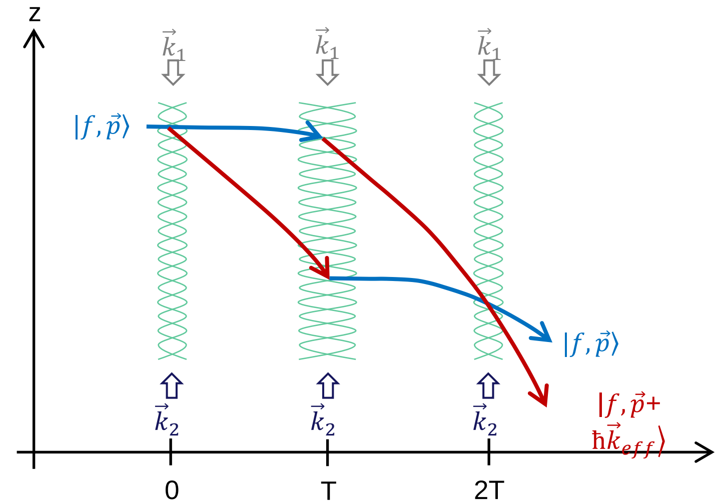




Interference with 2 clouds

Fringes of 2 synchronous interferometers : 1 launched and 1 dropped cloud of atoms.



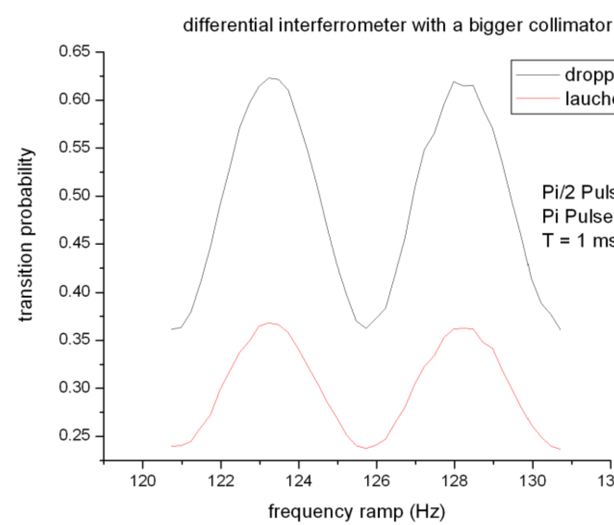


Launched cloud :

- Launch speed : 1.76 m/s
- Theo. apogee : 16.5 cm
- Π pulse : 4 µs

Dropped cloud :

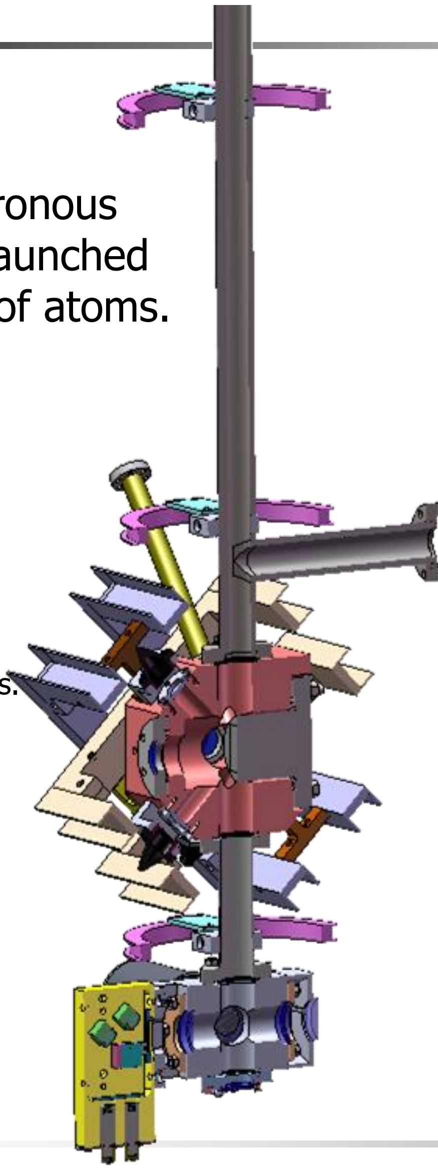
- Created during the ascending of the first cloud.
- Dropped when the first cloud reaches the apogee.

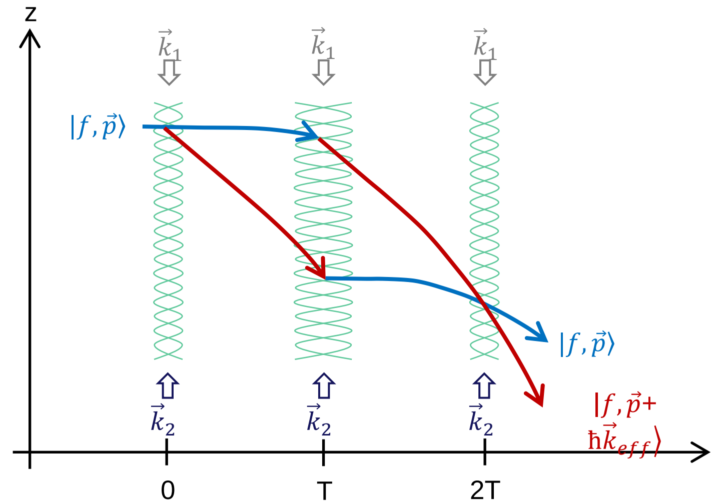


T=1 ms

Differential interferometer

Fringes of 2 synchronous interferometers : 1 launched and 1 dropped cloud of atoms.

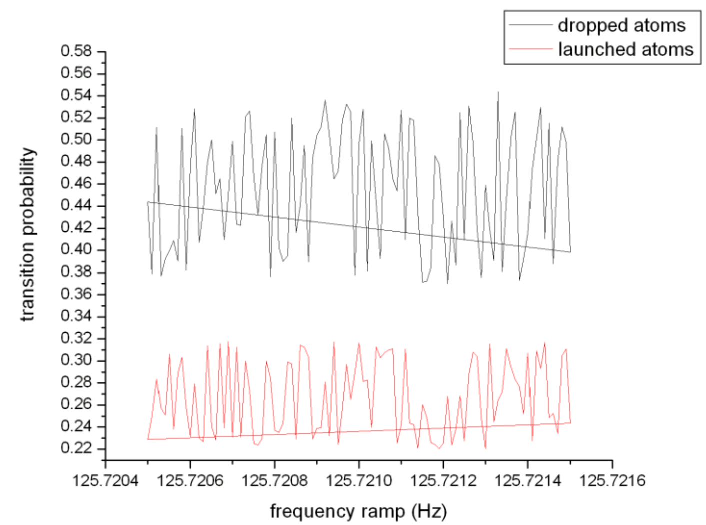




We increase the interference time.

We don't observe fringes BUT we observe some correlation between the phase fluctuations.

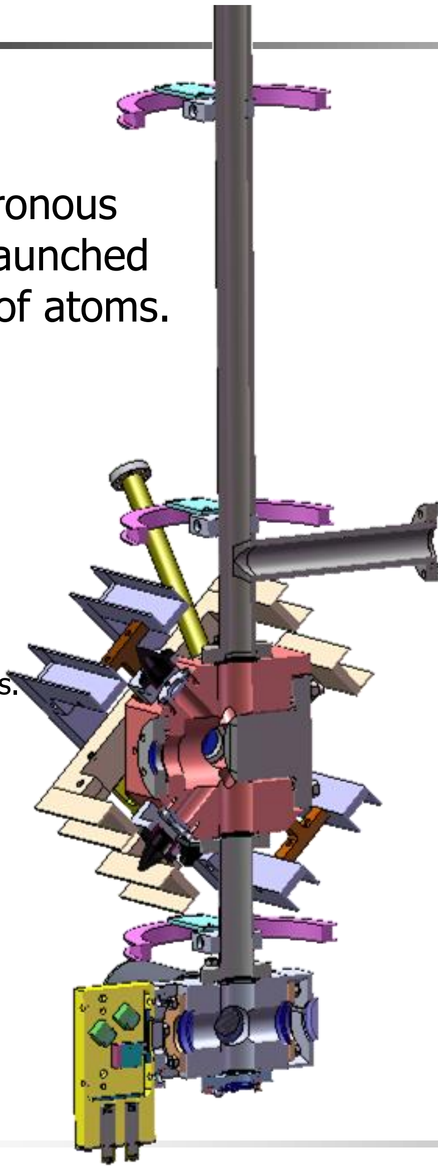
→ We make a parametric plot between those two signals !!

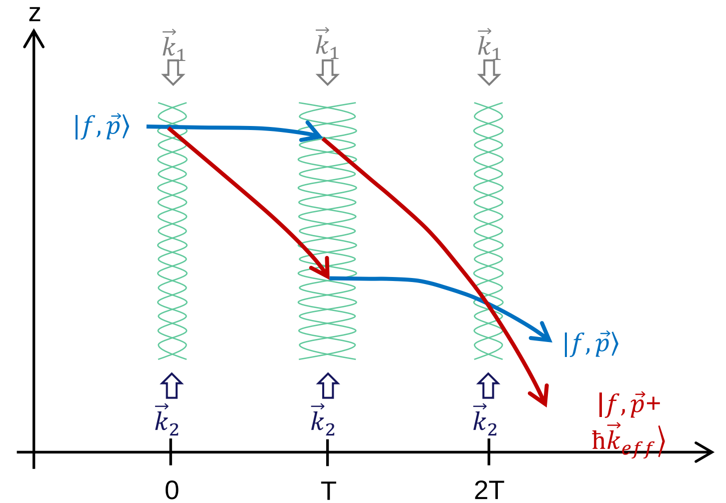


T=35 ms

Differential interferometer

Fringes of 2 synchronous interferometers : 1 launched and 1 dropped cloud of atoms.





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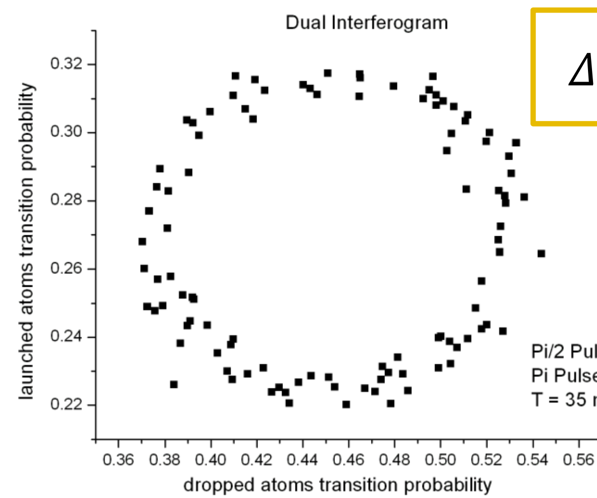
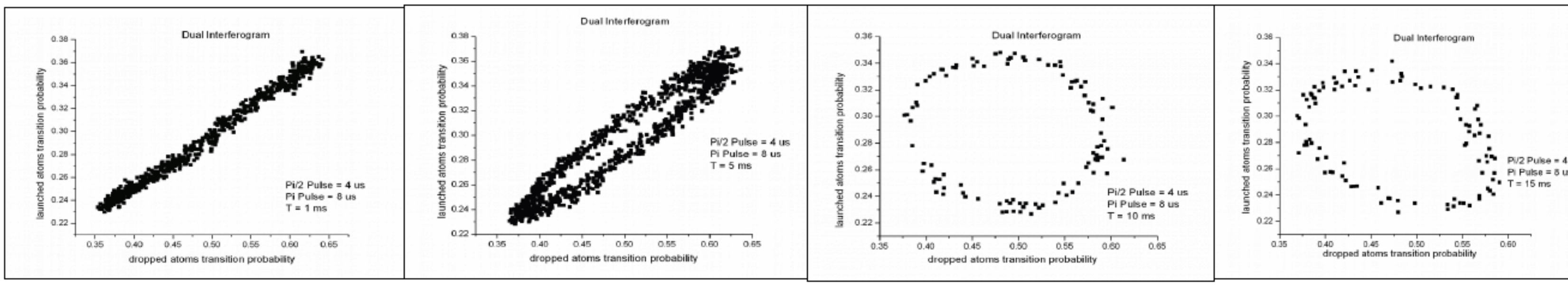


$\Delta\varphi=\pi/2$

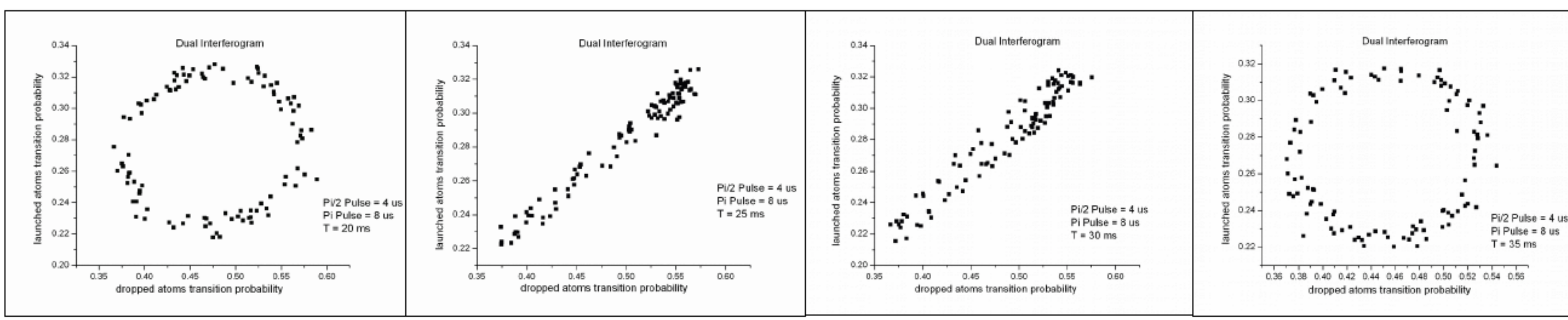
T=35 ms

Differential interferometer

The same for various interference time → The differential phase depends on T



T = 1ms 5ms 10ms 15ms



T = 20ms 25ms 30ms 35ms

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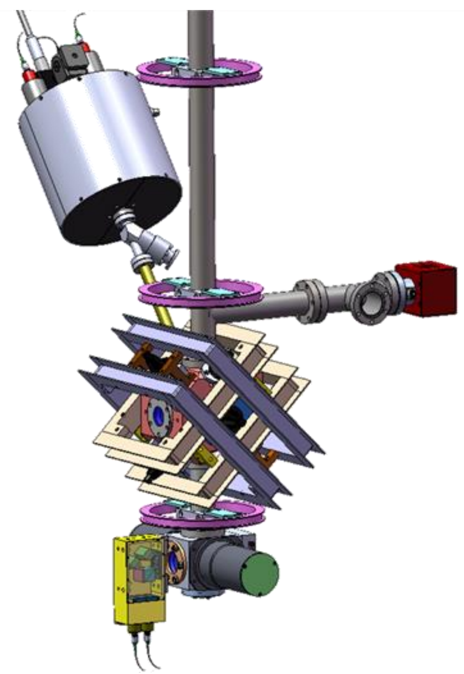

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Next Steps

- Performances ?

(in the lab)

$p = 100\ \hbar k$, $2T = 500$ ms, $\Delta z = 1$ m

$T_C = 2$ s, $n = 10^5$ at, $T = 300$ nK

One cloud sensitivity	9.10^{-11} m.s$^{-2}/\sqrt{\mathrm{Hz}}$
Differential sensitivity	**126 mE @ 1s**

- Performances ?

In Space ? No gravity so 2T can be increased, for ex 2T=5s **2 mE @ 1s**

Next:
- Improve these performances (launch higher and increase T & the contrast).
- Reject the vibration noises and measure *g* with one source.
- Mount the 2nd source chamber & making the same tests.
- Exchange the reflecting mirror by the atom chips and test them.
- Cooling down the atoms to reach a few hundreds of nano-K.
- Test the Bragg diffraction in order to increase the interferometer sensitivity.
- Measure g & δg with high precision.

THANK YOU !