Gravity gradiometer using large momentum transfer beam splitters

Mehdi Langlois, Sébastien Merlet, Franck Pereira Dos Santos

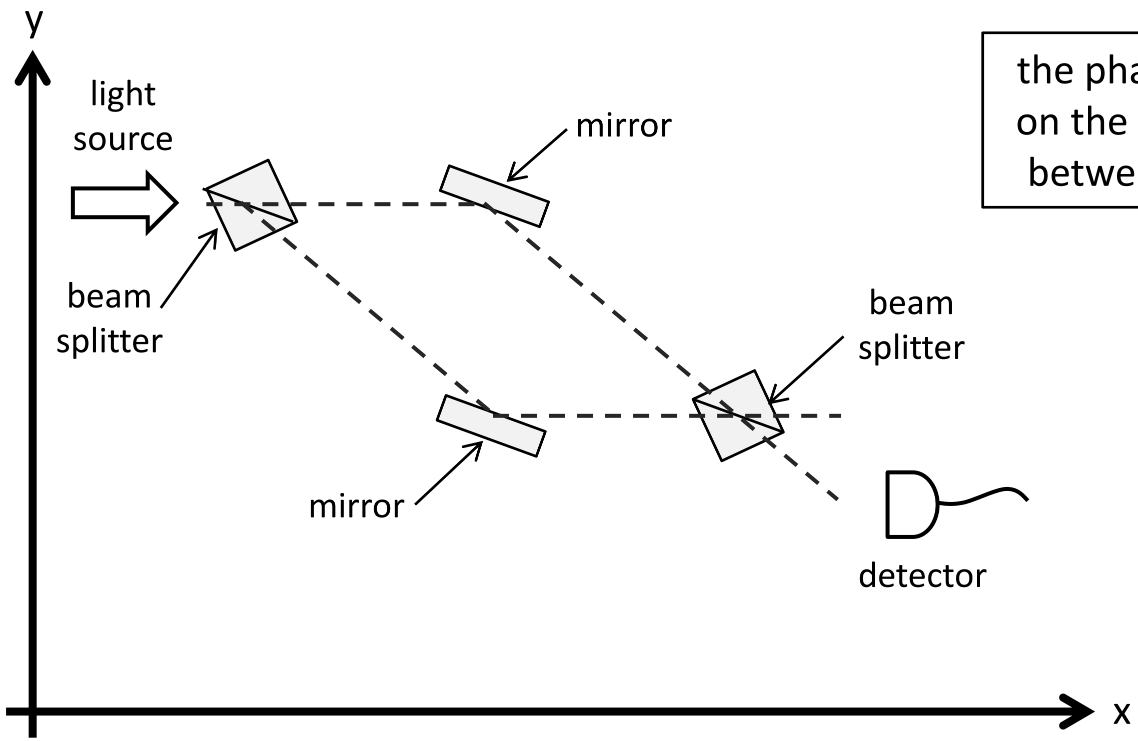
Content

- atom interferometry
- improvement techniques
- differential measurement

Atom interferometry

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

Mach-Zehnder interferometer

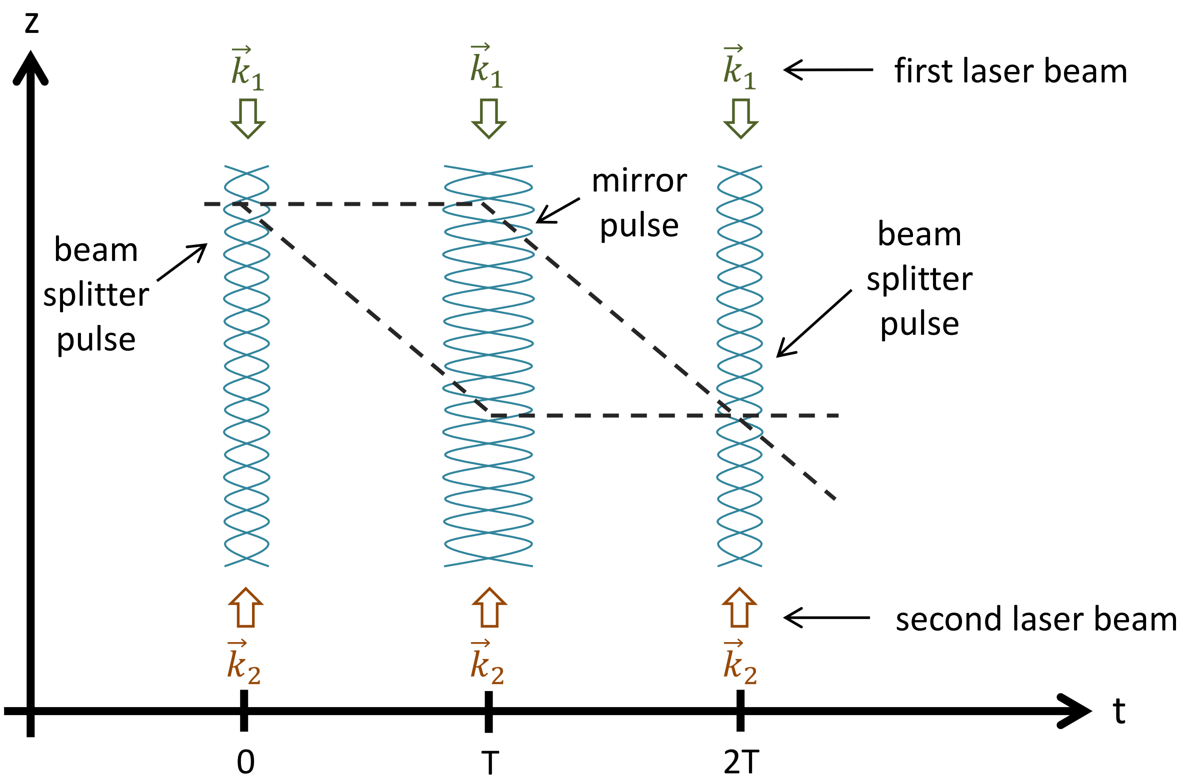


the phase shift depends
on the length difference
between the two arms

the beam is split in two arms
reflected on mirrors
and recombined at the end

Mach-Zehnder atom interferometer

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

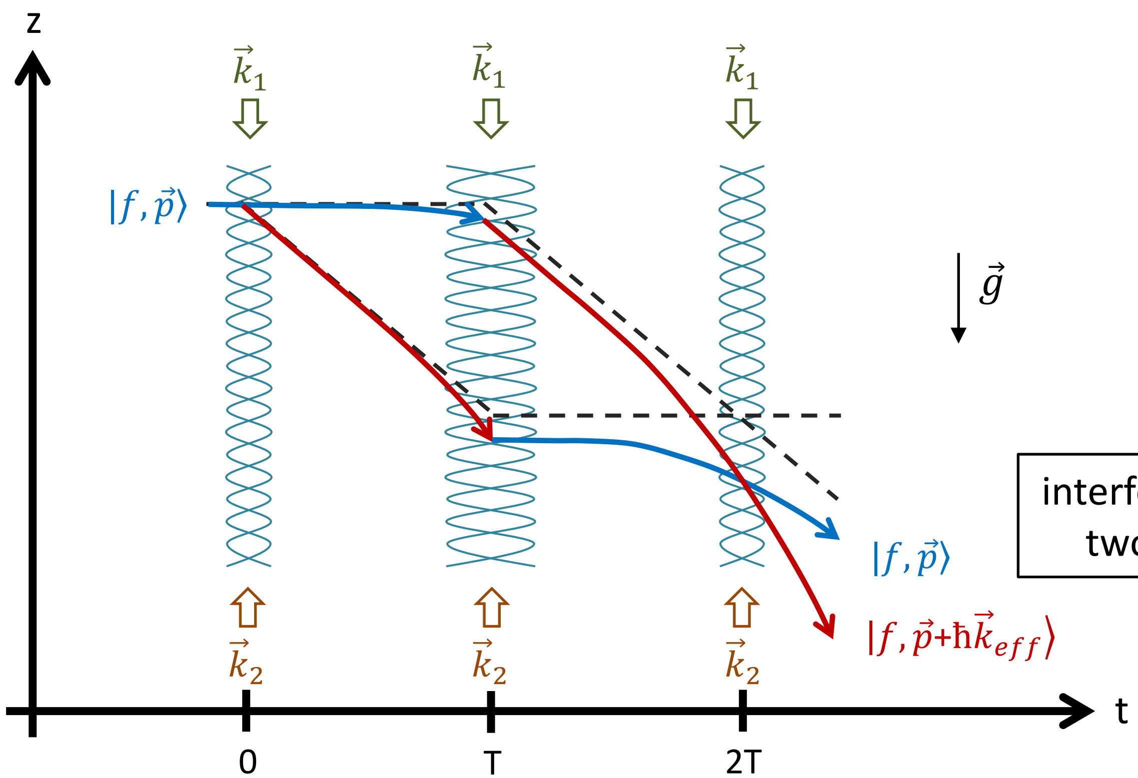


two contra-propagating laser beams

transfer a momentum $\hbar\vec{k}_{eff}$ to the atoms operate as mirror or beam-splitter

Vertical acceleration configuration

atomic trajectory deflect by the gravity



interferometry between two external states

the two arms therefore cover a different distance

Interferometer phase shift:

$$\Delta\phi = \vec{k}_{eff} . \vec{g} . T^2$$

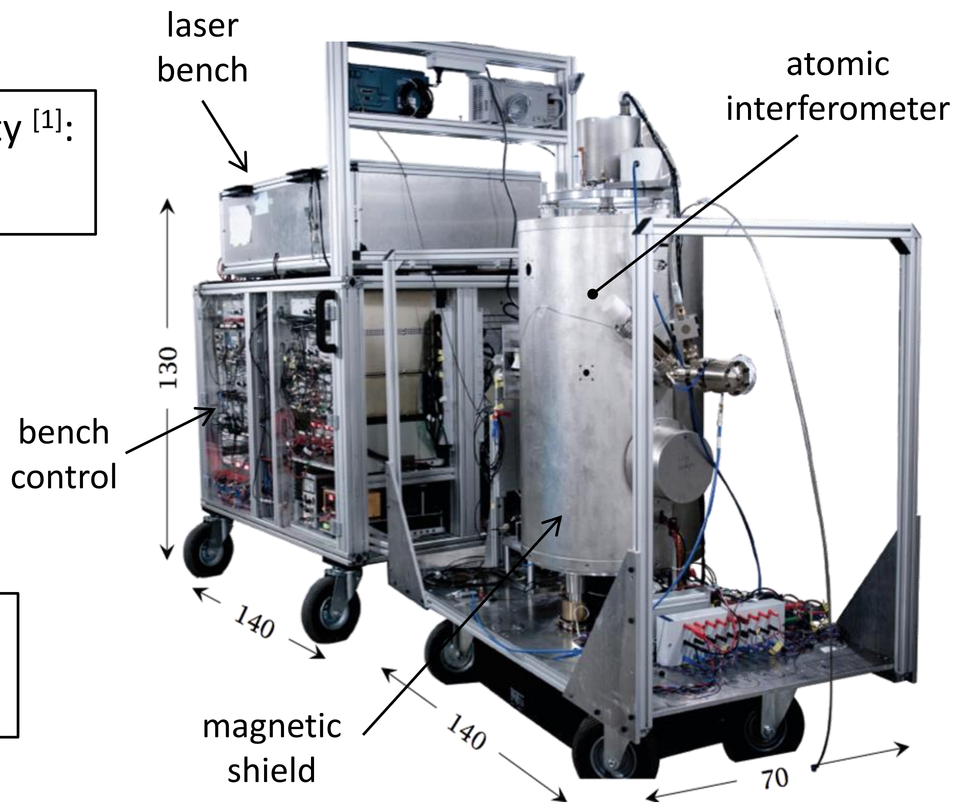
Cold atom gravimeter

Acceleration sensitivity [1]:

5.10^{-8} m.s$^{-2}/\sqrt{\mathrm{Hz}}$

Optical gravimeter:

$1{,}5.10^{-7}$ m.s$^{-2}/\sqrt{\mathrm{Hz}}$



Reached stability [1]:

2.10^{-9} m.s^{-2} at 1500 s

perceives the gravity change induced by a mass of 50 kg located less than 2 m

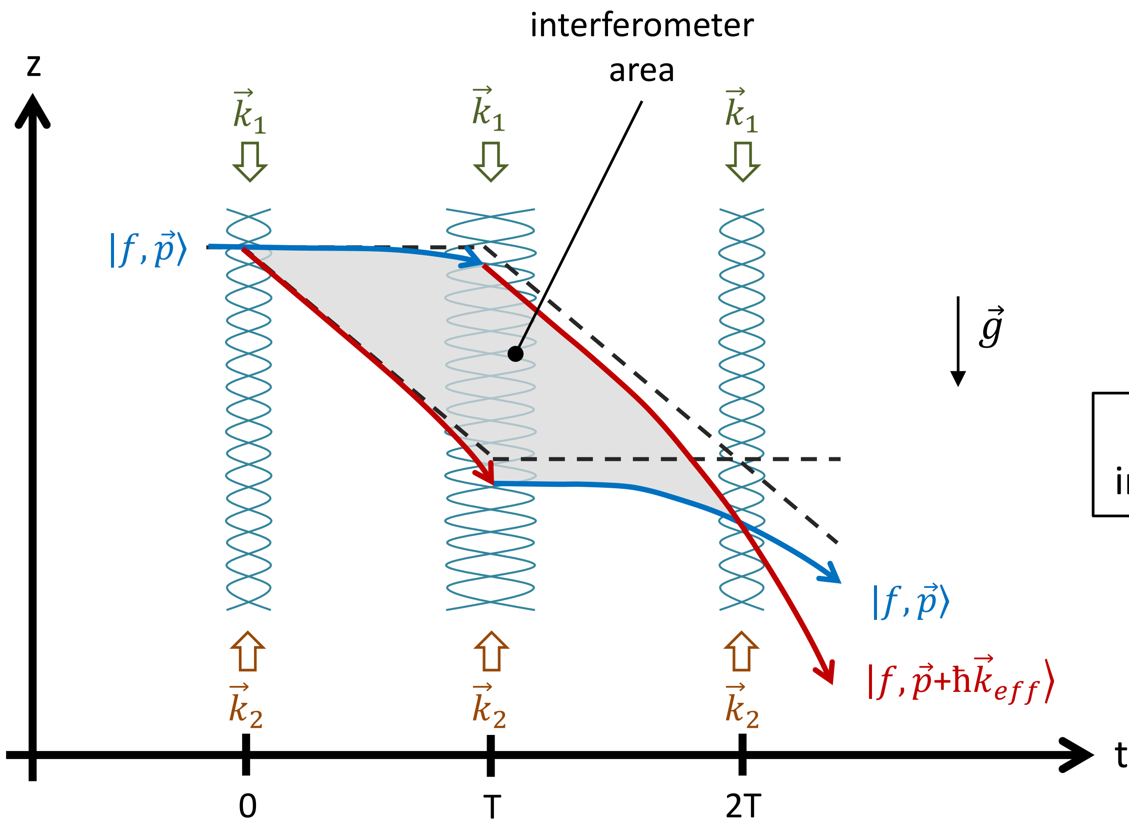
Mobile cold atom gravimeter *(LNE-SYRTE, Trappes)*

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

Improvement techniques

Precision of the atom interferometer

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



increasing the interrogation time

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

High precision atom interferometer

Duration: 2,3 s

Separation: 1,4 cm

Differential acceleration sensitivity [2]:

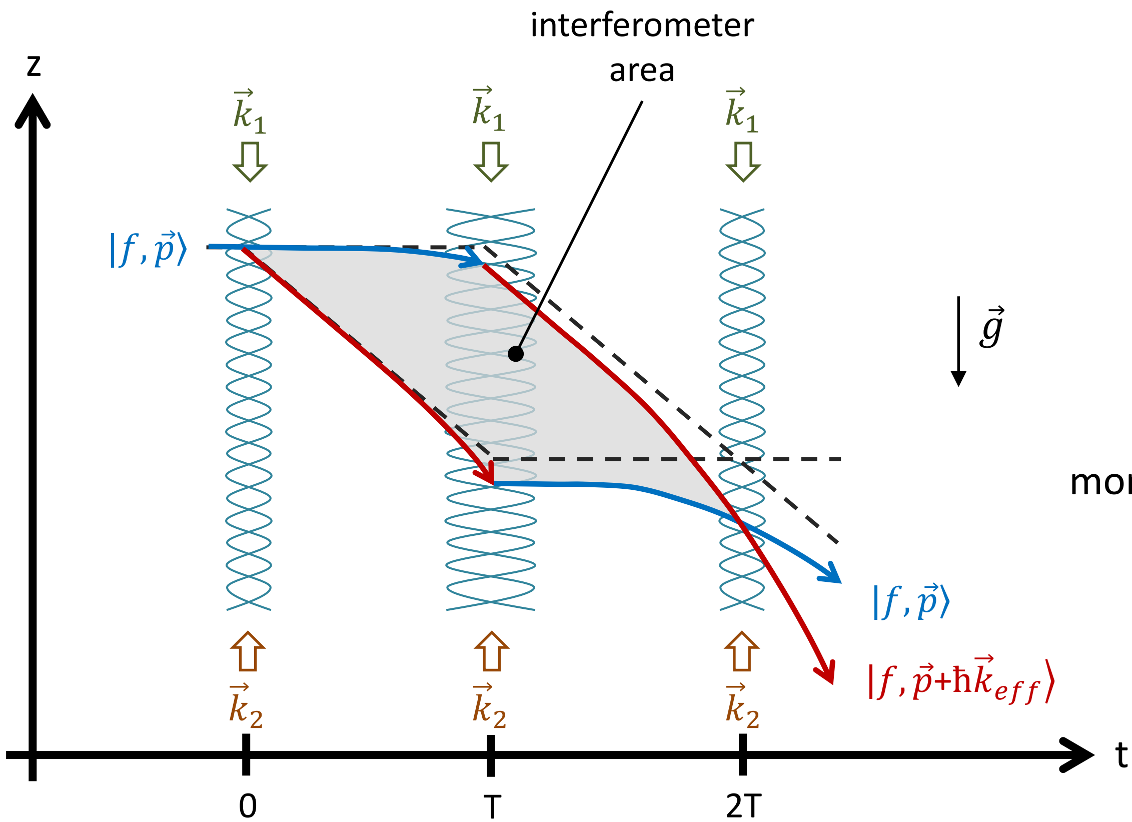
$2{,}9.10^{-10}$ m.s$^{-2}/\sqrt{\mathrm{Hz}}$

Equivalence principle test:
10 m atom drop tower *(Stanford University)*

[2] S. M. Dickerson *et al.*, Phys. Rev. Lett. **111**, 083001 (2013)

Precision of the atom interferometer

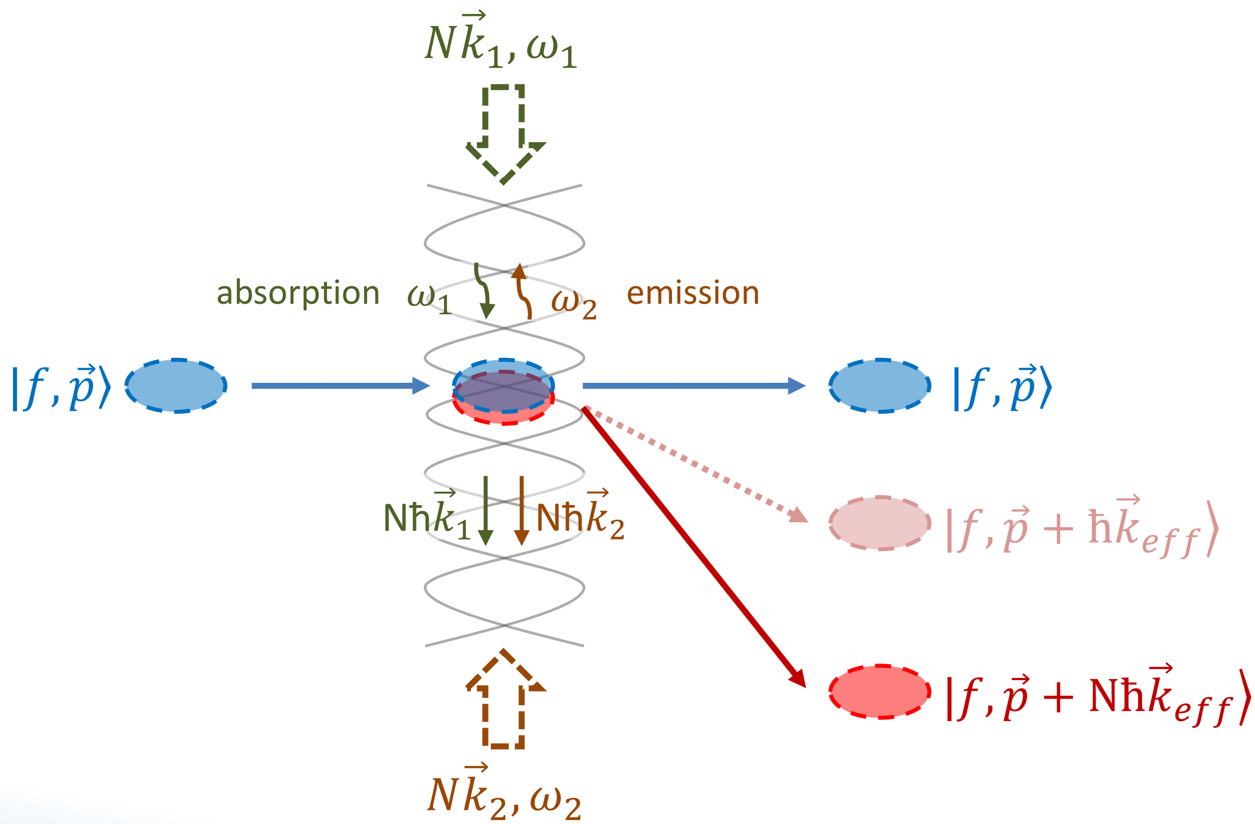
$\vec{k}_{eff} = \vec{k}_1 + \vec{k}_2$



increasing the momentum transferred

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

Large momentum transfer

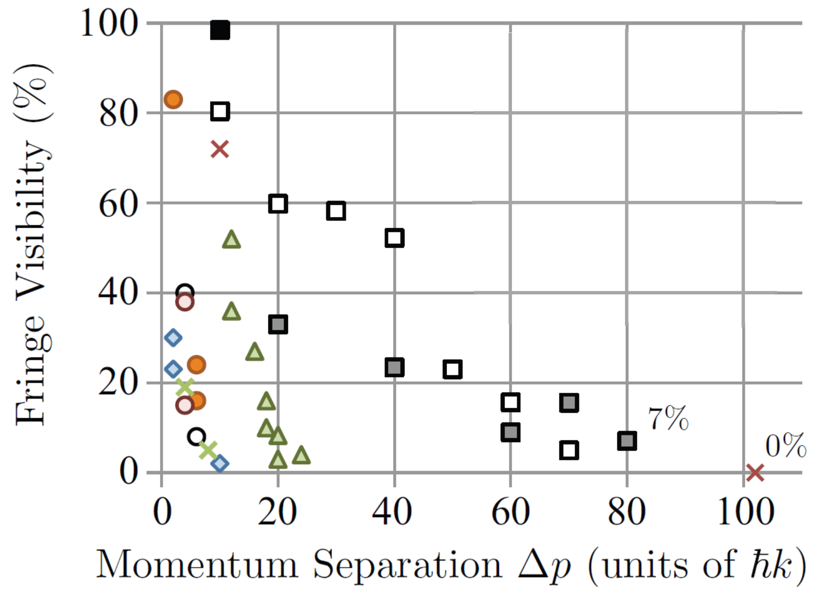


not two but several photons transferred per atom

high power laser or compact atomic cloud

Contrast

- Transition probability: $P = \frac{1}{2}(1 - C.\cos(\Delta\phi))$
- Interferometer phase shift: $\Delta\phi = \vec{k}_{eff}.\vec{g}.T^2$
- Interferometer sensitivity: $\delta P \propto C.k_{eff}.T^2.\delta g$



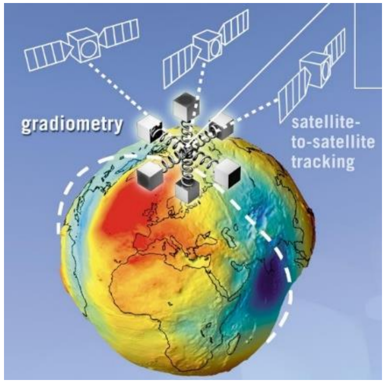
Fringe visibility for various LMT accelerometer experiments with different momentum separations [3] *(QSL, Canberra)*

[3] G. D. McDonald *et al.*, Phys. Rev. A **88**, 053620 (2013)

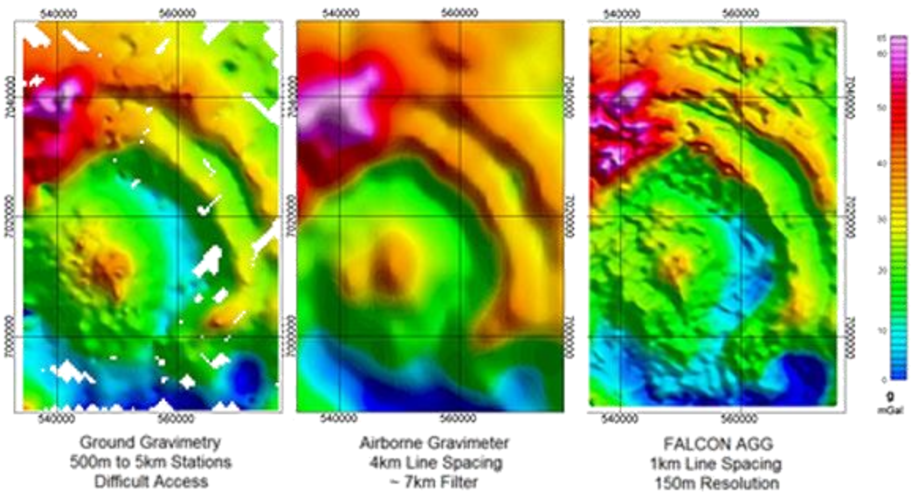
Differential measurement

Interest of gravity gradiometry

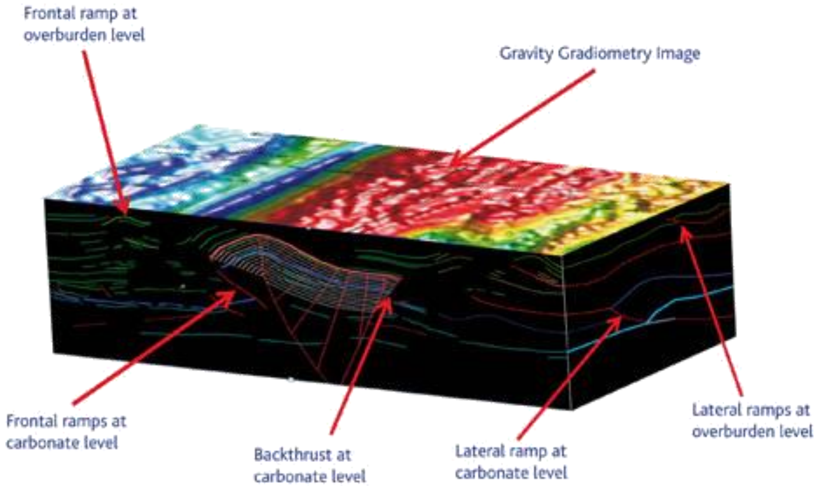
determine the geoid
with an accuracy of 1-2 cm



Components of the gravity gradient tensor with GOCE



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



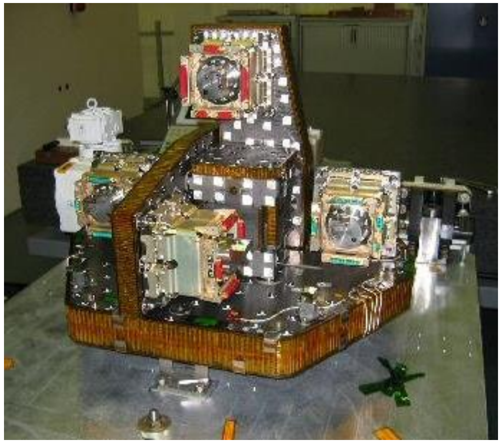
measure the subsurface density
indicate oil or gas deposits

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

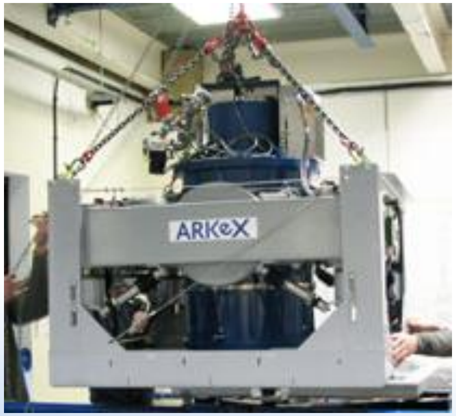
State of the art

Gravity gradiometer	*sensitivity*
Cold atom	$2{,}8.10^{-8}\ s^{-2}/\sqrt{Hz}$ [4]
Lockheed Martin	$3.10^{-9}\ s^{-2}/\sqrt{Hz}$ [5]
Superconducting (ARKeX)	$1.10^{-9}\ s^{-2}/\sqrt{Hz}$ [5]
Electrostatic (GOCE)	$4.10^{-12}\ s^{-2}/\sqrt{Hz}$ [5]

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



GOCE gradiometer is a set of electrostatic servo-controlled accelerometers



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

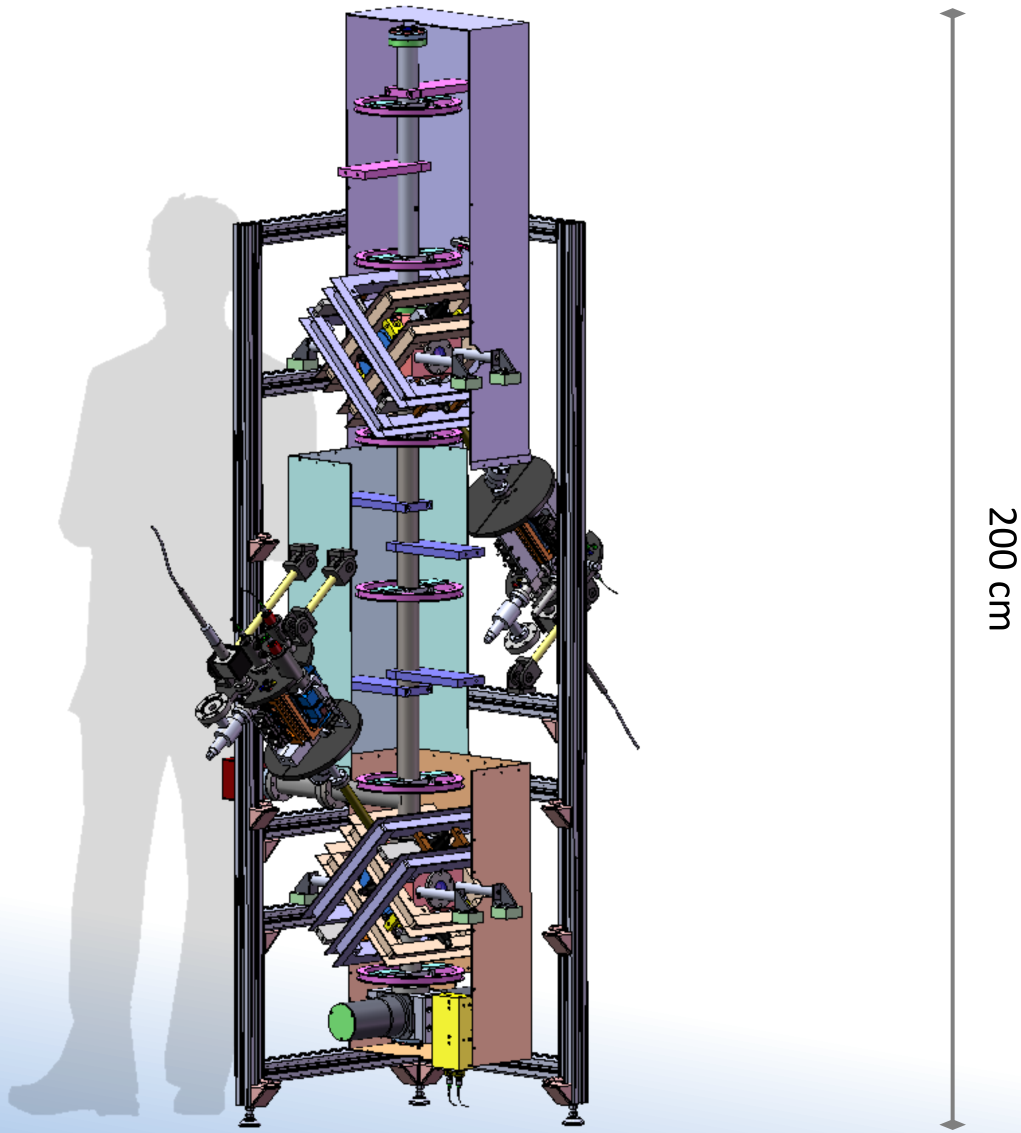
[4] J. M. McGuirk *et al.*, Phys. Rev. A **65**, 033608 (2002)
[5] D. DiFrancesco et al., Geophys. Prospect **57**, 615-623 (2009)

Vertical differential atom interferometer

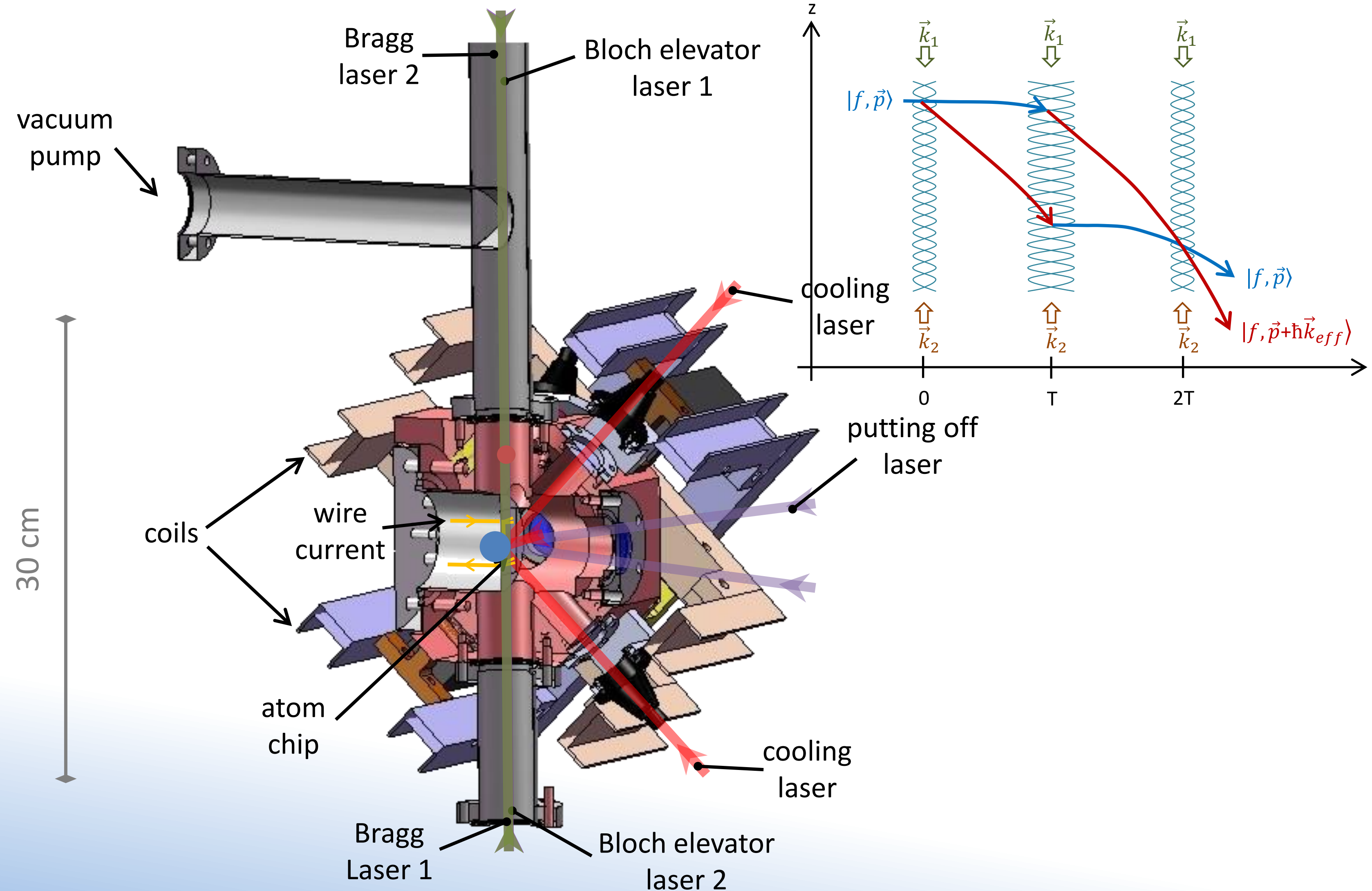
trapping on atom chip

+

high power laser source



Sequence



Bragg laser 2
Bloch elevator laser 1
vacuum pump
30 cm
coils
wire current
atom chip
cooling laser
putting off laser
cooling laser
Bragg Laser 1
Bloch elevator laser 2
z
t
0
T
2T
$\vec{k}_1$
$\vec{k}_2$
$|f,\vec{p}\rangle$
$|f,\vec{p}\rangle$
$|f,\vec{p}+\hbar\vec{k}_{eff}\rangle$

Progress

$p = 100\ \hbar k$, $2T = 500$ ms, $\Delta z = 1$ m
$T_C = 2$ s, $n = 10^5$ at, $T = 300$ nK

One cloud sensitivity	$9.10^{-11}\ m.s^{-2}/\sqrt{Hz}$
Differential sensitivity	$1{,}3.10^{-11}\ s^{-2}/\sqrt{Hz}$

-	Cooling laser:	ready
-	Detection	setting up
-	2D MOT	setting up
-	Interferometry laser:	setting up
-	Science chamber:	ordered
-	Tube:	ordered
-	Magnetic shield:	designed
-	Atom chip:	designed
-	Powerful laser:	setting up by Muquans

Thank you !