Atom interferometry with ultra-cold atoms onboard a Zero G plane for space applications

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1. Abstract

The **ICE** project (Interférométrie à source Cohérente pour l'Espace) aims to be a proof of concept for a space mission using **quantum particles**, i.e., atomic clouds of potassium and rubidium in a matter-wave interferometer to **test the Weak Equivalence Principle** in microgravity [1]. The whole experiment is adapted to the **Novespace Zero G aircraft** that provides 22 s of microgravity per parabolic trajectory. In parallel with the onboard experiments, a **microgravity simulator** installed in the laboratory allows the sensor head (200 kg) to be in weightlessness for 500 ms, with a high repetition rate. To increase the interrogation time and the sensitivity of the measurement, the production of **ultra-cold sources** in microgravity with all-optical methods is studied both on the simulator [2] and onboard the Zero G plane. In microgravity with ultra-cold sources, a particular regime of atomic interferometry called **double diffraction** takes place, which we study theoretically and experimentally on the simulator. We report on the production of **Bose-Einstein Condensates** (BEC) in microgravity both on the simulator and onboard the aircraft, and on our first results of interferometry in the double diffraction regime.

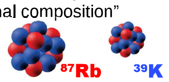
2. The ICE experiment

Universality of Free Fall (UFF)

- "The trajectory of a body in free fall with a gravitationnal field is independent of its mass or its internal composition"

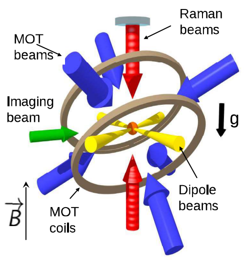
$\vec{F} = m_{inert}\vec{a}$

$\vec{P} = \frac{G m_{grav} m_{Earth}}{R^2}\vec{u}$

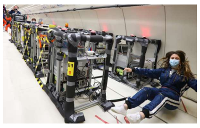


- Eotvös parameter : $\eta = 2\frac{a_{Rb} - a_K}{a_{Rb} + a_K}$
- Ultimate goal on ICE : UFF test at 10^{-11} level

Experimental setup

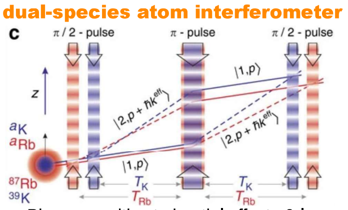


- A transportable experiment, adapted to the 0g-plane
- Telecom fiber-based laser systems at 780 nm (^{87}Rb) and 767/770 nm (^{39}K)
- Compact, 1 titanium chamber vacuum system (+ 2D MOT), 19 optical axes
- Fringe Reconstruction by Accelerometer Correlation (FRAC): Hybridization with classical sensors
- Dipole trap for evaporative cooling



Experiment on the 0g plane

A dual-species atom interferometer

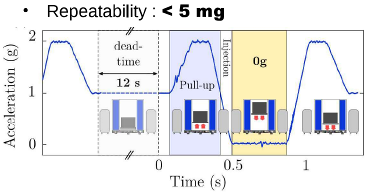


- Phase sensitive to inertial effects & laser : $\Delta\phi = (\mathbf{k}_{eff} \cdot \mathbf{a})T^2 + \Delta\varphi_{laser}$
- On ground η = **1.6.10⁻⁶**
- Systematic effects : δη = **5.10⁻⁸**

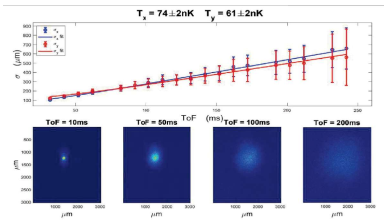
3. Ultra cold atoms on the zero-g simulator

Performances

- Up to 500 ms of microgravity
- Repetition rate : 1 parabola every 12 s
- Thousands of parabolas per day
- Maximum vibration amplitude : **100 mg**
- Repeatability : **< 5 mg**



Ultra cold atoms in μ-gravity



- Work in progress
- Evaporation ramps adapted to the
- The absence of sag in microgravity allows us to reach cooler température compare to standard gravity

4. Ultra-cold sources onboard the Zero-G plane

Motivation

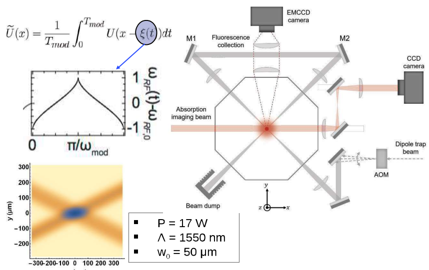
- Increase the contrast (more atoms addressed)
- Increase the interrogation time (atoms must stay in Raman beams effective area)

Novespace Zero G plane

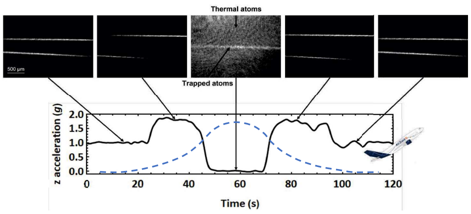
- Flight campaign : 3 days, 31 parabolas per day, **22 s** of microgravity

Setup

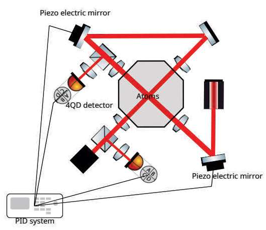
- Far-off resonance dipole trap : 1550 nm
- Time averaged potential with spatially modulated beams → add a degree of freedom to optimize the evaporation [5]



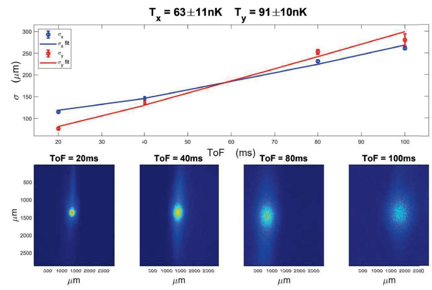
Experiment onboard the plane



- Compensation of misalignment with an active beam stabilization system

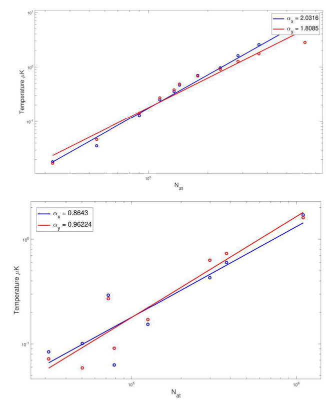


Fluorescence imaging of the cloud in 0g



- Work in progress !
- Evaporation ramps adapted to microgravity : no gravity sag
- Estimated temperature (using time of flight method): 80 **nK**
- Estimated PSD : 2.3

Efficiency of evaporation in 1g and 0g



Future work & applications

- Pathfinder mission for the development of an engineering model (CARIOQA)
- Earth observation and gradiometry (GRICE)
- Weak Equivalence Principle test from space (STE-QUEST)

References

[1] B. Barrett et al, *Dual matter-wave inertial sensors in weightlessness,* Nature Comm. **7**, 13786 (2016)
[2] G.Condon et al, *All-Optical Bose-Einstein Condensates in Microgravity,* Phys. Rev. Lett. **123**, 240402 (2019)
[3] B. Barrett et al, *Correlative methods for dual-species quantum tests of the weak equivalence principle,* New J. Phys. **17**, 085010 (2015).
[4] B. Barrett et al, *Testing the Universality of Free Fall using correlated 39K 87Rb atom interferometer,*
[5] R. Roy et al, *Rapid cooling to quantum degeneracy in dynamically shaped atom traps*, Phys. Rev. A **93**, 043403 (2016)

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