An ultra-cold atomic source in microgravity for atom interferometry

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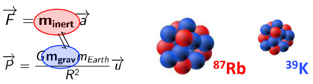
1. Abstract

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

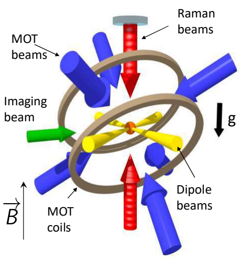
Universality of Free Fall (UFF)

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



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

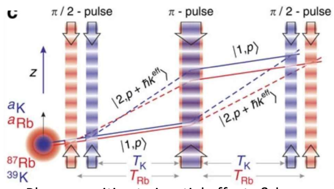
Experimental setup



- 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 [3]
- Dipole trap for evaporative cooling

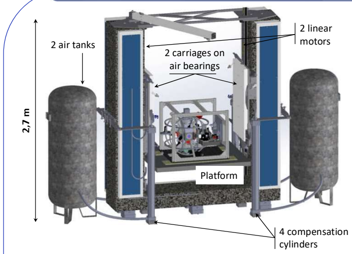
Experiment on the 0g plane

A dual-species atom interferometer



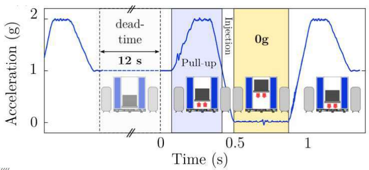
- Phase sensitive to inertial effects & laser : $\Delta\phi = (\mathbf{k_{eff}}.\mathbf{a})T^2 + \Delta\varphi_{laser}$
- On ground : η = **1.6.10^{-6}**
- Systematic effects (studied in [4]): $\delta\eta$ = **5.10^{-8}**

3. Interferometry with cold atoms on the zero-g simulator

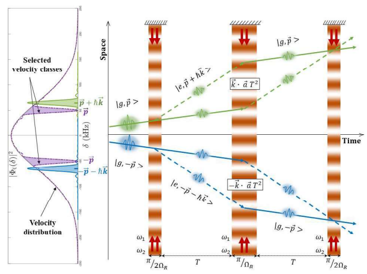


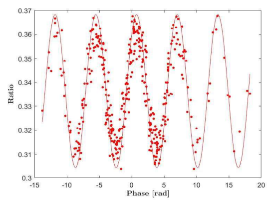
Performances

- 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**



Interferometry with cold atoms in 0g





Fringes in a Mach Zehnder time interferometer with 2T=20 ms interrogation (FRAC method).

- Cold Atoms : Magneto-Optical Trap (MOT) + Grey Molasses **7µK**
- Double Single Diffraction scheme
- Sensitivity : $5{,}6\ 10^{-8}$ per shot

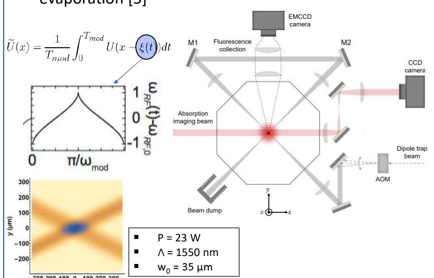
4. Ultra-cold sources onboard the Zero-G plane

Motivation

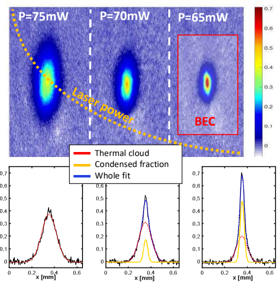
- Increase the contrast (more atoms addressed)
- Increase the interrogation time (atoms must stay in Raman beams effective area)

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]



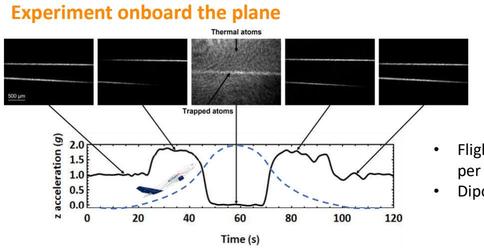
BEC production



- Critical temperature : **150 nK**
- Phase Space Density (PSD) : **0.93**

- Gray molasses on the D2 line during DT loading
- Adiabatic compression by lowering the modulation
- Evaporation in 3 s

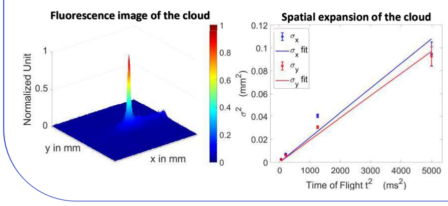
Experiment onboard the plane



Novespace Zero G plane

- Flight campaign : 3 days, 31 parabolas per day, **22 s** of microgravity
- Dipole trap aligned for 0g phase

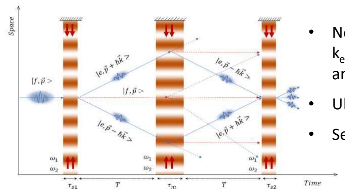
Bose-Einstein condensation in microgravity



- Evaporation ramps adapted to microgravity : no gravity sag
- Estimated temperature (using time of flight method : **100 nK**

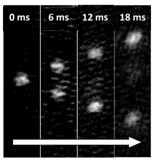
5. Interferometry with UC atoms

The double diffraction regime in 0g



- No Doppler effect in 0g → ± k_{eff} degenerate and centered around recoil frequency
- Ultra-cold atoms needed
- Sensitivity doubled

TOF



Diffracted cloud in 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

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