The Space Atom Interferometer project: status and prospects

F Sorrentino¹ K Bongs² P Bouyer³ L Cacciapuoti⁴ M de Angelis^{1,5} H Dittus⁶ W Ertmer⁷ J Hartwig⁷ M Hauth⁸ S Herrmann⁹ K Huang¹⁰ M Inguscio¹ E Kajari^{11,14} T Könemann⁹ C Lämmerzahl⁹ A Landragin¹² G Modugno¹ F Pereira dos Santos¹² A Peters⁸ M Prevedelli¹³ E M Rasel⁷ W P Schleich¹⁴ M Schmidt⁷ A Senger⁷ K Sengstock¹⁵ G Stern³ G M Tino¹ T Valenzuela² R Walser¹⁶ P Windpassinger¹⁵

¹ Dipartimento di Fisica e Astronomia and LENS, Università di Firenze, Polo Scientifico, via Sansone 1, I-50019 Sesto Fiorentino, Italy

² Midlands Ultracold Atom Research Centre School of Physics & Astronomy University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

³ Laboratoire Charles Fabry de LInstitut dOptique, Centre National de la Recherche Scientifique, Campus Polytechnique Rd 128, 91127 Palaiseau, France

⁴ European Space Agency, Research and Scientific Support Department, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

 5 Istituto di Fisica Applicata CNR, via Madonna del Piano 10, I-50019 Sesto Fiorentino

⁶ Institute of Space Systems, German Aerospace Center (DLR), Robert-Hooke-Strasse 7, D 28359 Bremen, Germany

 7 Institute of Quantum Optics, Leibniz Universität Hannover, Welfengarten 1, D $\,$ 30167 Hannover, Germany

⁸ Humboldt-Universität zu Berlin, Unter den Linden 6, D-10099 Berlin, Germany

 9 University of Bremen, Centre of Applied Space Technology and Microgravity (ZARM), Am Fallturm, D - 29359 Bremen, Germany

¹⁰ Institute of Optics, Physics Department, Zhejiang University, China

 11 Theoretische Physik, Universität des Saarlandes, Postfach 151150, D-66041 Saarbrücken, Germany

¹² Observatoire de Paris - SYRTE 61 avenue de l'Obseravtoire, 75014 Paris, France

¹³ Dipartimento di Fisica dell'Università di Bologna, Via Irnerio 46, I-40126, Bologna, Italy
 ¹⁴ Institut für Quantenphysik, Universität Ulm, Albert-Einstein-Allee 11, D-89081 Ulm,

Germany

¹⁵ Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, 22 167 Hamburg, Germany

¹⁶ Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstr. 4a, D-64289 Darmstadt. Germany

E-mail: sorrentino@fi.infn.it

Abstract. This paper presents the current status and future prospects of the Space Atom Interferometer project (SAI), funded by the European Space Agency. Atom interferometry provides extremely sensitive and accurate tools for the measurement of inertial forces. Operation of atom interferometers in microgravity is expected to enhance the performance of such sensors. Main goal of SAI is to demonstrate the possibility of placing atom interferometers in space. The resulting drop-tower compatible atom interferometry acceleration sensor prototype is described. Expected performance limits and potential scientific applications in a micro-gravity environment are also discussed.

1. Introduction

Matter-wave interferometry has recently led to the development of new techniques for the measurement of inertial forces, with important applications both in fundamental physics and applied research. The remarkable stability and accuracy that atom interferometers have reached for acceleration measurements can play a crucial role for science and technology. Quantum sensors based on atom interferometry had a rapid development during the last decade and different measurement schemes were demonstrated and implemented. Atom interferometry is used for precise measurements of the gravitational acceleration [1, 2, 3], Earths gravity gradient [4, 5], and rotations [6, 7]. Experiments on the validity of the equivalence principle [8] and on the measurement of the gravitational constant G [9, 10, 11] have been performed, while tests of general relativity [12] and of Newton's $1/r^2$ law [13, 14] as well as the detection of gravitational waves [15, 16] have been proposed. Accelerometers based on atom interferometry have been developed for many practical applications including metrology, geodesy, geophysics, engineering prospecting and inertial navigation [5, 17, 18]. Ongoing studies show that the space environment will allow us to take full advantage of the potential sensitivity of atom interferometers [19, 20].

Space Atom Interferometer (SAI) is a project of the European Space Agengy (ESA contract n. 20578/07/NL/VJ, AO-2004-064/082), with the main goal to demonstrate the possibility of applying such technology to future space missions.

In analogy to optical interferometers, atomic matter-waves can be split and recombined giving rise to an interference signal. Different schemes have been used for splitting, reflecting and recombining atomic matter waves. In the SAI project, the Raman interferometer is chosen as the basic configuration [1]. This approach was proven to be the most succesful so far in atom interferometry, at least for classical atom sources with respect to applications in precision experiments. Raman transitions change the internal hyperfine state and at the same time the external momentum state of the atom by 2 photon recoils. A sequence of three atom-light interaction processes with time separation T can be applied to coherently split, redirect and recombine the atomic de Broglie wave. After the first beam splitter two atomic de Broglie waves emerge. Their relative momenta differ by the photon recoil transferred to the atom. Choosing the duration of the atom-light interaction properly one may (as in the first and the third zone) equally split the incident waves (so called $\pi/2$ pulse), or (as in the second zone) deflect entirely the incident waves (π pulse). The two exit ports of the interferometer could be addressed and detected separately by means of spectroscopic techniques, like the excitation by laser and detection of the fluorescence.

The sensitivity of such atomic sensors depends on the free evolution time during which the matter wave accumulates phase along the interferometer trajectories. The output phase of a Raman pulse matter-wave accelerometer is

$$\phi = kaT^2 \tag{1}$$

where k is the wavevector associated to the Raman transitions $(1.6 \times 10^7 \text{ m}^{-1} \text{ in Rb})$, a is the acceleration and T is the time interval between Raman pulses [2]. The phase resolution $\Delta \phi$ depends on the signal-to-noise ratio (SNR) at detection; for high enough number of atoms, detection is limited by quantum projection noise (QPN) and the phase resolution per shot is $\delta \phi \approx 1/\sqrt{N}$, thus the acceleration resolution per shot is

$$\delta a = \frac{1}{\sqrt{NkT^2}}.$$
(2)

Laser cooling is required to reach lower temperatures for a maximum extension of the free evolution time T as well as a high efficiency to achieve large numbers, N, of cold atoms. In absence of gravity the duration of the interaction is limited by the drift time of the atoms through the experimental apparatus due to thermal diffusion, which could be in principle tens of seconds for the lowest atomic temperatures (nK) presently reached. On Earth, gravity is the major problem for cold atom optics: the free fall of about 5 m in one second restricts the measurement time well below 1 s. Sensitivities of $\sim 10^{-8} \text{ g}/\sqrt{\text{Hz}}$ to acceleration and of $\sim 0.5 \text{ nrad s}^{-1}/\sqrt{\text{Hz}}$ to rotations have been demonstrated, which are already at the level of the best optical interferometry sensors. A huge sensitivity improvement is expected in microgravity, where T can be increased by more than one order of magnitude.

2. The SAI project

The main goal of the SAI project is to demonstrate the technology readiness of atom interferometry inertial sensors for space applications. For this purpose, a compact prototype of a single-axis accelerometer based on ultracold ⁸⁷Rb has been realized (see section 2.1). At the same time, the project investigated new schemes, based for example on quantum degenerate gases as source for the interferometer (see section 2.2).

2.1. Transportable atom interferometry sensor prototype

The design of the SAI sensor prototype has been described in detail in [22]. The prototype is a vertical accelerometer, and allows both operation in microgravity and in ground tests. Design target was to keep the prototype as compact as possible without degradation of sensitivity as compared to existing laboratory instruments. In ground tests, a typical measurement cycle with interferometer duration $2T \sim 100 \text{ ms}$, repetition rate $\sim 5 \text{ Hz}$ and QPN-limited detection of $\sim 10^6 \text{ atoms per cycle}$ (SNR ~ 1000) would result in virtual acceleration sensitivity of 10^{-8} m/s^2 at 1 s. In microgravity experiments, a typical measurement cycle with interferometer duration $2T \sim 2 \text{ s}$, repetition rate $\sim 0.3 \text{ Hz}$ and QPN-limited detection of $\sim 10^6 \text{ atoms per cycle}$ would result in virtual acceleration sensitivity of $5 \cdot 10^{-11} \text{ m/s}^2$ at 1 s.

A modular laser system is connected through optical fibers to the sensor head consisting of an ultra-high vacuum system with attached optics and fiber connectors, surrounded by μ -metal shields to control stray magnetic fields (see fig. 1). In order to demonstrate the possibility of application in microgravity, the sensor was designed to fit into a standard capsule of the Bremen drop tower. Most of the technological solutions have already proved to be compatible with the acceleration loads of the Bremen drop tower [23]. The mechanical structure holding the vacuum system and all necessary optics is contained in a cylindrical volume with diameter ~ 60 cm and height ~ 150 cm. Fig. 2 shows the SAI sensor assembly.

The same vacuum chamber is used for both trapping and cooling the atoms and to detect them at the end of the interferometric sequence. This scheme is mandatory to demonstrate possible future operation in microgravity, where the relative velocity and the rotation between the atoms and the chamber will be ideally null. On the other hand, the possibility of launching the atomic sample is important for ground testing of the instrument. The implementation of a 2D magneto-optical trap (MOT) [21] as source of cold atoms for a standard 3D-MOT ensures ultra-high vacuum conditions in the loading and interferometer regions, important for operating the sensor with coherent atomic sources such as a Bose-Einstein Condensate (BEC) and for testing its performance at long interrogation times.

A short vertical tube above the main chamber allows to tune the interaction time and to operate the sensor as a gravity gradiometer for characterization and performance measurements. Since the interferometer sequence has to happen close or within the main chamber, magnetic shielding of the tube would not be sufficient. A double layer of μ -metal shield encloses the whole vacuum system. The mechanical structure, including magnetic shield, is qualified for drop tower experiments. The mounting of μ -metal layers is rigid enough to withstand 50 g accelerations. In order to find the optimal shape for the magnetic shield, we implemented a numerical model based on a commercial software (ANSYS). According to our calculations, the magnetic field would be



Figure 1. Scheme of the SAI sensor; the main vacuum chamber is employed for 3D-MOT, interferometer sequence and detection; it is separated from the 2D-MOT chamber by a differential pumping tube: background vacuum pressure is of the order of 10^{-9} torr in the main chamber and $10^{-6} \div 10^{-7}$ torr in the 2D-MOT chamber.



Figure 2. A picture of the SAI sensor assembly; the rack on the left contains the electronics, power supplies and laser modules; the sensor head on the right contains the vacuum system with attached optics enclosed in the double-layer magnetic shield; the mechanical structure of the sensor head is the central cut of a standard drop tower capsule.



Figure 3. A picture of the 2D-MOT system and main vacuum chamber separated by a dual μ -metal layer.

uniform in time and in space within 30 nT along the atom interferometry region during a free fall in the drop tower. The same analysis has been used to find a configuration of coils to produce a uniform bias field in the region where the atom interferometry sequence takes place. The overall mass of the magnetic shield will be about 85 kg.

The 2D-MOT for the Space Atom Interferometer (see fig. 3) is a mixture of the design implemented in the CASI experiment [35] for cold-atom Sagnac interferometer and the ATLAS experiment [36] for an all optical produced Bose-Einstein condensate.

The main vacuum chamber is shown in fig. 3. It has 24 view-ports giving access for cooling laser beams, 2D-MOT atomic flux, laser beams for optical BEC, and detection optics.

The vacuum system is contained in the central part of the drop-tower capsule, between two horizontal platforms that are connected by four vertical stringers. All kind of implemented components are rigidly mounted on the capsule platforms to withstand decelerations up to 50 g during the impact of the drop capsule at the end of the free fall.

The laser system for cooling and detecting Rb atoms, and to generate the laser beams for Raman transitions, is split into six compact modules as shown in fig. 4. In the master module, a laser is stabilised on the Rb FM spectroscopy signal (see fig. 5) and sent to a second module, where it is amplified. This light is used as a reference for an offset-lock in the repumper module and in the Raman laser system; in addition, it is also forwarded to the 2D-MOT and 3D-MOT laser modules. The two MOT modules shift the master frequency to the cooling frequency and amplify it, in addition allowing a control of the laser detuning from resonance and of laser power. Finally, they distribute the cooling and repumping light onto several outputs. Each module was designed and optimised for compactness and robustness. The mounts had already been developed and tested under drop-tower conditions in the framework of the QUANTUS project [23].

The Raman laser optical setup contains two Extended Cavity Lasers (ECLs). The Raman master laser is overlapped on a photodiode with the reference laser. The resulting beat note signal is locked on a 100 MHz reference provided by an auxiliary output of the frequency synthesis



Figure 4. Left: scheme of the modular laser system; right: laser modules mounted on a 19'' rack.

chain described below. The second ECL (slave) is overlapped with the master laser and their beat note is phase locked to the low phase noise signal at 6.8 GHz (hyperfine splitting of ⁸⁷Rb) provided by the frequency synthesis chain. Since the phase difference between Raman master and slave lasers is imprinted directly on the atoms, phase noise performance of both the frequency reference and the optical phase locked loop are of key importance for the sensor performance. The phase noise spectral density for the optical phase-locked loop (OPLL) stays below a level of -120 dBrad²/Hz (1 μ rad/ \sqrt{Hz}) between 100 Hz and 60 kHz (see fig. 5). To our knowledge, the measured OPLL phase noise is among the lowest levels ever reached with diode lasers [25]. If the OPLL phase noise were the main contributing factor to overall accelerometer sensitivity, a single-shot sensitivity $\delta a/a$ of 2×10^{-10} would be achieved.

A microwave frequency source is used to generate the reference for the OPLL of the Raman lasers. The measured phase noise of the 6.8 GHz signal is shown in fig. 5. The contribution of the microwave source onto the phase noise of the interferometer is reduced down to about 1 mrad/shot for 2T = 100 ms, using commercial ultra low noise quartz oscillators. When extrapolating the performances of an atom interferometer to larger interrogation times $(2T \leq 1 \text{ s})$, the phase noise at low frequency will be the dominant contribution. Assuming a phase noise scaling as $1/f^2$ for frequencies below 10 Hz, the expected sensitivity per shot of the interferometer scales linearly with T. We calculate an interferometer phase noise of 9 mrad/shot for T = 1 s. As for the microwave frequency synthesis, the contribution of the quartz can be reduced to less than 1 mrad/shot by a careful design, independent of T.

The SAI system employs a versatile source of signals able to control the different phases of a cold atom experiment. It is based upon a series of parallel modules, generating parallel signals with only one clock. The output of all modules is generated in a Field Programmable Gate Array (FPGA). The control system is integrated in a stand-alone 19" rack (see fig. 2).

Baseline design of the SAI sensor includes integration of a coherent atomic source. Using a BEC will enable a much longer interaction time when operating the atom interferometer in microgravity. All-optical BEC has been implemented in a separate experiment using a fiber laser at 1565 nm [26], and the SAI system has been designed to be compatible with the production of a coherent source using such technique. The additional subsystems for the optical BEC consist of a commercial 1565 nm high-power, continuous-wave (CW) fiber laser and of two telescopes, which are attached to the main chamber and produce a pair of focused beams crossing at the position of the MOT. We also studied the possibility to obtain a BEC with an hybrid trap, i.e. by employing a single-beam optical trap in combination with a magnetic quadrupole to increase the axial confinement. Run-away evaporation is obtained by lowering the power of the optical trap at constant magnetic gradient [37].





Figure 5. Left: saturated spectroscopy signal from the master laser module on 1 MHz bandwidth; the main line corresponds to the $F = 2 \rightarrow F' = 3$ component of the D2 transition; linewidth is 30 MHz; SNR=1 MHz; right: phase noise spectral density of the reference frequency chain and of the OPLL (from [22]).

2.2. Theoretical studies and alternative schemes

2.2.1. Sensor modeling We studied the different sources of noise and systematic shifts that may limit the sensitivity and the accuracy of the atomic sensors. Such effects may be split into two categories, depending on whether their impact is related to the external degrees of freedom of the atoms.

Effects which do not depend on the external degrees of freedom are the time fluctuations of the phase difference between the Raman lasers, of their intensity, of the magnetic field, of acceleration and rotation. The study is based on the use of the sensitivity function first developed for atomic clocks and that has been modified for atomic interferometers [27]. The calculated sensitivity function in time and frequency domain was experimentally validated on the SYRTE atom gravimeter, showing excellent agreement with measured data [28, 27, 29]. This method has been used to determine the limit due to residual phase noise in the phase locked loop of the Raman lasers. Such calculations have also been important in the design of the reference frequency chain. The results show that a sensitivity of 1 mrad per shot in the interferometer phase is achievable. We applied the same method to study the sensitivity to the frequency fluctuations of the master Raman laser. Calculating the impact of this effect with the sensitivity function yields a limit due to the frequency noise of the Raman laser to 2.4 mrad per shot for an optical path difference of 93 cm between the counterpropagating Raman beams [28]: such result, which is again in good agreement with experimental data, shows the need of a master Raman laser with a narrow linewidth or a small distance between the center of mass of the atomic cloud and the retro-reflecting Raman mirror. The sensitivity function method was also employed to show that the effect of fluctuations of the power of the Raman lasers and time fluctuation of the magnetic field is negligible [29]. The same method can be used to estimate noise sources from vibration and rotation noise [27]. The vibration noise is clearly the limit of the sensitivity on ground and can be overcome by using the signal from a mass accelerometer [28]. Moreover, the use of the auxiliary accelerometer enables us to go beyond the linear range (with acceleration phase smaller than 1 rad), thereby providing the possibility to work in a noisy environment, such as for instance on a platform in a low Earth orbit without a drag free system.

Effects depending on the external degrees of freedom of the atoms, cannot be treated in this formalism. Four effects have been identified: wave front curvature of the Raman lasers, light shift gradients (if not perfectly cancelled), magnetic field gradients and cold atom collisions.

The effect of magnetic field gradients can be reduced by more than two orders of magnitude by exchanging the internal state at the input of the interferometer. By averaging the measurements using the two internal states successively at the input of the interferometer the effect can be reduced to below 10^{-9} g [30]. A non-magnetic vacuum chamber and careful control of external magnetic fields are therefore important to keep this effect below the instrument accuracy. In the geometry of retro-reflected Raman beams, the influence of off-resonant Raman transitions must be taken into account in order to achieve best accuracy and stability of interferometers [31]. The two photon light shift can be drastically reduced by increasing the Doppler effect and/or using colder atoms, allowing to reduce the Rabi frequency during the Raman pulses. In contrast, this effect becomes extremely large for a set-up with intrinsic small Doppler effect, as expected for space applications, and has to be taken into account in the design of the experiment

2.2.2. Advanced schemes The interest in applying atomic quantum gases to atom interferometry resides primarily in their coherence properties, which makes them more appealing than the thermal gases used so far in state-of-the-art interferometers. First, the naturally narrow momentum distribution of degenerate quantum gases represents an advantage with respect to a thermal gas produced in a standard MOT, where an additional selection stage is necessary to produce the required sub-recoil samples Second, the coherence of a quantum gas is the natural starting point to implement quantum techniques to improve the sensitivity of the interferometer, by the use of squeezing and/or entanglement, beyond the standard quantum limit. In this respect Bose gases have a strong advantage over Fermi gases. The kinetic energy of an ideal, i.e. non interacting, Bose gas at zero temperature is indeed of the order of $h\nu$, where h is the Planck constant and ν is the mean oscillation frequency of the trapping potential used to produce and initially store the gas before feeding it to the interferometer. For a Fermi gas in 3D, this quantity grows as $h\nu N^{1/6}$ due to the Pauli exclusion principle, where N is the number of particles in the sample. On the other hand, ultracold Fermi gases of identical atoms are intrinsically ideal because of the Pauli principle, while Bose gases are typically interacting. The presence of the interaction between atoms results in a strong broadening of the momentum distribution and in detrimental phase-shift and phase-diffusion effects. A first milestone in the very promising direction of employing Bose and Fermi gases to advanced atom interferometry is assessing which of the two systems is more appropriate for various kinds of applications. In a first investigation of the potentialities of Fermi gases for atom-interferometry applications, a Bloch-oscillation interferometer was tested on a gas of ⁴⁰K atoms trapped in an optical lattice [32]. The standard Fermi gas employed had a momentum width of about 1/3 of the recoil momentum, and no evidence of phase diffusion due to the atom-atom interaction was visible. We have then studied the same kind of interferometer with a weakly interacting Bose gas of 39 K atoms by tuning the s-wave scattering length, or in other words the contact interaction, almost to zero by means of a magnetic Feshbach resonance [33]. The interaction-induced decoherence of the interferometer is reduced when reducing the scattering length from its natural value by as much as a factor of 1000. In a situation of trapped high-density samples, we have observed a reduction of the decoherence rate from about 100 Hz to below 1 Hz. This is accompanied by an effective momentum width that gets as small as approximately 1/20 of the recoil momentum. Unfortunately, this great improvement of the performances cannot be obtained for free, and the price to pay is to work in presence of a rather large magnetic field. Indeed, the Feshbach resonance of ³⁹K in the F = 1, $m_F = 1$ state, is between 350 G and 400 G, and the atoms have a magnetic moment of about $0.95 \mu_B$. At least two solutions can be envisaged to attack this problem. With a trapped interferometer, there is in principle the possibility to work at a different Feshbach resonance in the ground state, for which the magnetic field is of the order of 10 G. Conversely, for free-fall interferometers, where the interaction-induced shift and diffusion are not the main limit to the sensitivity, one could work at a third resonance around 80 G

[33], where the magnetic moment is zero at a scattering length of about 10 Bohr radii. This would strongly reduce the requirements on the magnetic field gradient, at least in a Bragg-type interferometer.

Finally, when using a high density BEC as source for matter-wave interferometry, the interaction between the atoms can lead to phase diffusion and frequency shifts that arise from an inhomogeneous atomic density distribution. A systematic incorporation of these effects in the phase evolution of the BEC requires a detailed knowledge of the total particle number and the density distribution of the atomic cloud. However, the experimental realization of BECs is often accompanied with significant uncertainties in the particle number. For this reason, we explored the effect of asymmetric beam splitters within the matter-wave interferometer aiming towards a reduction of the uncertainty in the particle number $n \pm \Delta n$ of the prepared atomic ensemble. In particular, we have assumed that a coherent matter wave source in the form of a homogeneous ⁸⁷Rb BEC is fed into the input arm of the interferometer. Given that binary collisions in the degenerate quantum gas are the source of the collision phase shift, which is proportional to the particle density, we calculated the optimal working point of the interferometer.

We assume that all the atoms are initially in the ground state and denote with p the population of the excited state after the first beam splitter pulse. A detailed analysis [34] of the $p - \pi - \bar{p}$ interferometer pulse sequence shows that the particle number in the output channel is then given by

$$n_e^{out} = n\{\xi - \gamma \cos[2Tn\delta_2(p - 1/2)]\}$$
(3)

with the mixing parameters ξ,γ defined in terms of two beam splitting parameters p and \bar{p} according to

$$\xi = p\bar{p} + (1-p)(1-\bar{p}) \text{ and } \gamma = 2\sqrt{p\bar{p}(1-p)(1-\bar{p})}$$
 (4)

and with n as initial population of the ground state. The splitting parameters p and \bar{p} are realized with Raman laser pulses of specific duration. The central difference $\delta_2 = g_{ee} - 2g_{eg} + g_{gg}$ just follows from the coupling constants g_{ee} , g_{eg} and g_{gg} which appear in the Gross-Pitaevskii equation and are directly connected to the individual scattering lengths of the two particle s-wave collisions. Moreover, we have numerically simulated the experimentally more interesting case of a BEC trapped within a harmonic potential (see fig. 6). In both cases we encounter a promising behavior of this matter-wave interferometer as a number filter. We successfully examined several situations in which the uncertainty in the particle number is found to be reduced due to binary collisions in the interferometer setup.

3. Atom interferometry sensors in microgravity: present and future

3.1. State of the art

At present, worldwide and especially in Europe, several atom interferometry inertial sensors are operating. Gravity measurements with sensitivity of $8 \cdot 10^{-8} \text{ m/s}^2$ at 1 s and accuracy better than $3 \cdot 10^{-8} \text{ m/s}^2$, gravity gradient measurements with sensitivity of $4 \cdot 10^{-8} \text{ m/s}^2$ at 1 s, and rotation rate measurements with sensitivity of $6 \cdot 10^{-10}$ rad/s at 1 s and bias stability $< 70 \,\mu \text{deg/h}$ have been already demonstrated in laboratory systems. Transportable systems are being developed with similar performance. Future advances in atom optics (large momentum transfer beam splitters, high-flux atomic sources, advanced detection schemes based for example on quantum degenerate gases) are expected to largely improve the performance of such devices. However, one major limitation to the sensitivity of light-pulse atom interferometry sensors on Earth is the short interaction time achieved, due to the free fall of atoms under gravity. An improvement of several orders of magnitude is expected in microgravity environment, since the sensitivity scales as the square of the interaction time.



Figure 6. Output particle number N_e out vs the input particle number N_g in a harmonically trapped, two-component BEC after passing through an highly asymmetric interferometer with p = 0.055 and $\bar{p} = 0.5$. The (red) solid line displays the full numerical solution of the GP equation, while the (blue) dashed line represents the local density approximation of the homogeneous result. The gray shaded area illustrates the compression of number fluctuations. The (green) dotted line marked with squares is the trivial response of a $0 - \pi - 0$ interferometer (from [34]).

3.1.1. Technological developments for compact atom interferometers. Current research in the field of atom interferometry inertial sensing is proceeding along two main directions: on one side, to improve the instruments accuracy by pushing the sensitivity limits of laboratory systems with advanced atom optics techniques; at the same time, several groups are working to reduce the size, weight and power consumption without degradation of performances, in order to make transportable atomic sensors for both terrestrial and space applications. The developments in the field of commercial optics have produced impressive improvements in size, mass, stability and reliability of lasers and other optoelectronic components. Today, a complete laser system for a rubidium atom interferometer can nearly be assembled with off-the-shelf commercial components of compact size and high reliability. The industrial basis for further developing these commercial laser systems into engineering models is thus well established. Compact and trasportable atom interferometry absolute gravimeters have been developed for geophysical and metrological applications. The group of Kasevich at Stanford has developed a transportable instrument for a full determination of the gravity gradient tensor for inertial navigation [41]. At JPL in Pasadena, a compact gravity gradiometer has been realized with interesting new solutions for compactness and robustness of the apparatus [42]. The SYRTE gravimeter in Paris, intended to provide an absolute measurement of g in the context of a Watt balance experiment, is a compact laboratory apparatus designed to be transportable for comparison campaigns [43]. The atom gravimeter in Berlin, developed within the FINAQS collaboration, is a transportable apparatus for geophysical applications [44]. A second generation of compact atomic sensors is expected to yield a drastic reduction in size by replacing the current technology of free-air optoelectronics with either integrated micro-optics or fiber-based sources. Along this line, the EC STREP program iSense was started in 2010 with the main goal to develop terrestrial small-scale atomic quantum sensors.

3.1.2. Current activities for atom interferometers in microgravity. Many technology developments are presently on-going, both at ESA and at National Space Agencies, to bring atom

interferometry instruments to maturity for space applications. Within the European project Space-BEC: Quantum Gases in Microgravity, intensive activities are carried on under national funding. The parabolic flight experiments presently ongoing in the ICE project (Interferometry with Coherent Sources for Applications in Space) of the French space agency CNES, and the drop tower tests conducted by the German space agency DLR in the QUANTUS project, have demonstrated the robustness of miniaturised ultra-cold atom technology. Indeed, atom interference fringes have been detected by ICE in the noisy environment of the Zero-G parabolic flight; at the same time, the QUANTUS set-up is able to routinely produce Bose-Einstein Condensates (BEC) during the about 100 m of free fall in the Bremen drop tower and survives decelerations as high as 50 g. It is expected that the use of ultra-cold gases as sources for atom interferometry, combining the progress made with SAI, ICE and QUANTUS, will provide European scientists with unique sensor capabilities for investigations in fundamental physics.

3.2. Evolution of the SAI project

QUANTUS and ICE have been the first experiments demonstrating atom interferometry and BEC in microgravity; the space environment will allow to fully exploit the potentials of quantum sensors by overcoming the limitations of parabolic flights (large acceleration noise) and drop towers (low repetition rate). Evolution of SAI towards a space mission, either on the International Space Station (ISS) or on a dedicated satellite, would have the main goal to demonstrate the operation of a space atom interferometer with interaction time ~ 1 s and acceleration sensitivity $10^{-10} \div 10^{-11} \text{ m/s}^2$ at 1 s. The experiment would implement a dual-species differential measurement using either the ⁸⁷Rb-⁸⁵Rb, or the K-Rb pair, and would demonstrate differential acceleration measurement to better than 10^{-14} m/s^2 .

Continuation of the SAI activity between 2011 and 2014 would have the primary goal to develop and test an advanced breadboard prototype, and to develop and test engineering models of the components. In a future evolution of this project, the ground-based prototype could be operated in the Bremen drop-tower laboratories for first tests under microgravity conditions, and/or in underground, seismically quiet laboratories for ground tests and comparison with other acceleration sensors. The SAI ground-based prototype will be important for the definition of the space instrument design and for studying the ultimate limits of an atom interferometer for acceleration measurements.

3.2.1. Scientific objectives: tests of fundamentel physics A first outcome of the space mission would be a test of the Equivalence Principle at the 10^{-15} level, thus improving the current experimental limits by two orders of magnitude [38, 39]. In this case the measurement will be implemented on two different atomic clouds (e.g. ⁸⁷Rb and ⁸⁵Rb) on the same spatial trajectory. A Quantum test of the Weak Equivalence Principle (Q-WEP) on the ISS can be considered as the natural joined evolution of SAI and Space BEC. A WEP test is one of the priorities identified in the ESA Roadmap for Fundamental Physics in Space. Following the results of the study on "Atom Interferometry Test of The Weak Equivalence Principle in Space", recently approved by ESA in the frame of the General Study Programme (GSP) and to be started in the second quarter of 2011, Q-WEP will eventually be proposed for a phase A study to be conducted in the frame of the ELIPS programme.

Additionally, the experiment would be able to provide demonstrative tests of fundamental physics in microgravity [40]:

• test of quantum gravity effects: measurement of coherence time in atom interferometers with a BEC might probe models suggesting fundamental decoherence mechanisms arising from Planck scale physics; observation of wave-packet spreading with a BEC in microgravity would represent a test of scenarios with fluctuating space-time; precision measurements of

the photon recoil might be used to perform tests of modified energy-momentum relations, which may arise as a possible consequence of a quantum gravity theory;

- test of quantum mechanical effects: a search for possible additional phase shift terms in the atom interferometer response would test non-linearities in the Schrödinger equation, i.e. violations of the superposition principle;
- test of the neutrality of matter: by applying electrical potentials to the atoms in either arm of the interferometer would allow to set upper limits to the neutron charge and to test the equality of the proton and electron charge.

3.2.2. Scientific objectives: other applications On the other hand, operation with two clouds having a spatial separation of ~ 1 m can provide a measurement of the local gravity gradient with a sensitivity of $0.1 \text{ E}/\sqrt{\text{Hz}}$. Such result would demonstrate the possible use of atom interferometry based inertial quantum sensors for the exploration of the gravitational field and the mapping of gravity gradients of celestial bodies. The target SAI sensitivity would be better than the expected GOCE performance below 10 mHz by one order of magnitude. Moreover, the differential acceleration measurement at ~ $10^{-11} \text{ m s}^{-2}/\sqrt{\text{Hz}}$ on spatially separated atomic clouds could represent a first demonstrative experiment for the possible detection of low frequency gravitational waves.

4. Conclusions

The SAI sensor, a compact and transportable prototype of atom interferometry accelerometer, was buildt to demonstrate the possibility to apply such technology in future space missions. The Space Atom Interferometer project will provide a valuable insight into the potential of atom interferometry for space applications.

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