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QIBEC
Quantum Interferometry with Bose-Einstein Condensates
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D3.1
Experimental test of beam splitter techniques

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Summary

Deliverable 3.1 consists in the theoretical development and experimental testing of optimized beam splitter techniques. As envisaged in the proposal, several results have been delivered by the partners.

UULM produced optimized splitting and interferometry sequences with a fidelity of 99%, and incorporated its powerful Chopped Random Basis optimization into of UHEI's Multi Configurational Time-Dependent Hartree which allows for a more realistic description of beam splitters and interferometers. TU-WIEN focused on interferometry for trapped rather than "free-falling" atoms in view of the more rapid progress attainable in the former. Experimental splitting and recombination sequences were demonstrated and subsequently combined, to give a full Mach-Zehnder sequence, therefore covering part of Deliverable 3.2. The results obtained at TU-WIEN are the subject of an article submitted to Nature Communications [BER13].

The experimental team at CNR completed a new apparatus for the optimized production of Bose Einstein condensates of 39K with large atom number at high repetition rates [LAN12], and developed the apparatus for creating an array of double-well potentials where the position of the barrier can be finely controlled. The significant effort devoted to abating the environmental noise in the latter caused a delay in the testing of the splitting sequences. This also affected the progress towards the ``linear beam-splitter" to be realized by varying the scattering length of 39K and implementing the TU-WIEN splitting protocols.

The experimental team at UNIBAS performed experimental and theoretical work which improved on the fidelity of their internal-state beam-splitter. In particular, the "spill" into the unused hyperfine state was minimized, and Rabi rotations have been achieved with high fidelity.

Detailed descriptions of the results of the partner nodes.

UULM

The goal within this deliverable is the collaborative work between the UULM and the UHEI partners to merge the corresponding efficient methods for optimal control (CRAB) and for calculation of the dynamics of large bosonic systems beyond mean-field approach (MCTDHB). This objective has been achieved recently and the new merged algorithm CRAB+MCTDHB was employed for optimization of the transport of a bosonic ensemble including also beyond mean-field dynamics (2-3 orbitals beyond the condensate-state). Currently the UULM partner is working in close contact to the experimental UHEI partner for optimizing with the merged CRAB+MCTDHB processes useful for creation of optimal beam-splitter sequences and multi-particle entanglement.

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TU-WIEN

We focused on two beam splitting techniques:

1. The splitting of a single condensate that creates two coherent condensates, possibly with reduced number fluctuations, as shown in **Error! Reference source not found.**.

2. The recombination of two Bose-Einstein condensates, which turns the relative phase information into a population difference.

The effect of the first beam splitter is shown in Figure 1. The state prepared is strongly number squeezed, and close to Heisenberg limited, with a Heisenberg uncertainty product of only $\Delta n\ \Delta\Phi = 2.3$ ($\Delta n\ \Delta\Phi = 1$ corresponds to the limit allowed by quantum mechanics).

Secondly, we demonstrated in Ref. [BER13], that coherent Bose-Einstein condensates can be recombined efficiently in a double well potential.
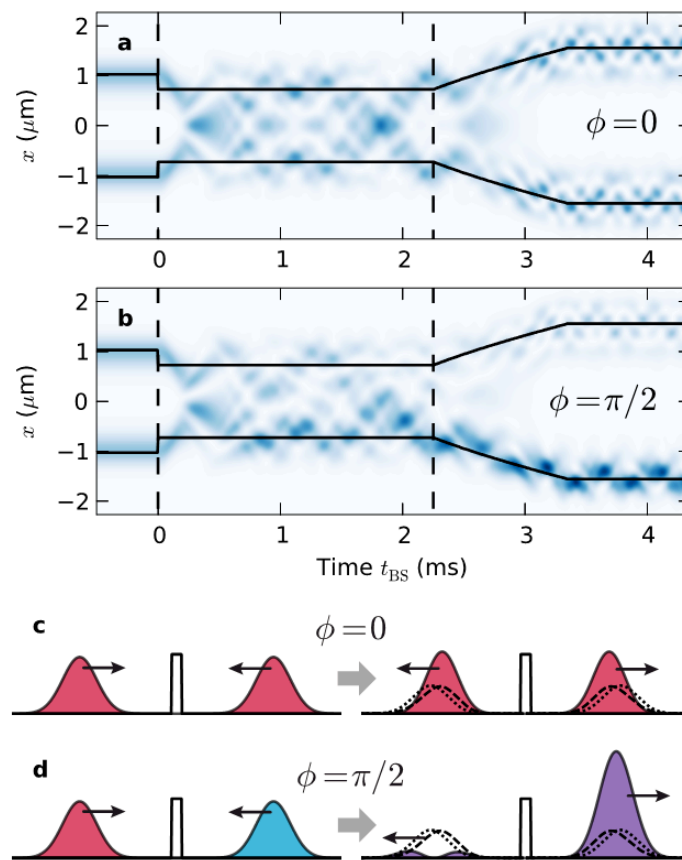

Figure 1 Principle of the BEC recombiner. a,b, Numerical simulation of the evolution of the transverse in situ density when the double-well spacing is abruptly decreased (0 < tBS < 2.25 ms) and increased again (tBS > 2.25 ms) for two different initial relative phases: $\Phi = 0$ (a), and $\Phi = \pi/2$ (b). Black lines: positions of the two potential minima. c,d, This phase sensitive recombination can be understood as the propagation and interference of two wave packets launched onto a semi-reflective tunnel barrier. The final wave packets (filled curves with outgoing arrows) are the result of the constructive or destructive interference between the reflected (dashed lines) and transmitted (dotted lines) components arising from the incoming wave packets.

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CNR

Realizing an optimized spatial beam splitter for a condensate is a challenging tasks.

The first obstacle is represented by the naturally strong inter-particle interaction between the atoms. To overcome this limitation we have implemented ^{39}K atoms where broad Feshbach resonances allow to finely tune the scattering length to zero. During the first part of the QIBEC project we have completed a new apparatus for the optimized production of Bose Einstein condensates of ^{39}K with large atom number (up to 10^6) at high repetition rates [LAN12]. The preparation time of less than 15 seconds is a factor of four shorter than previously demonstrated techniques that use sympathetic cooling with cold Rubidium atoms.
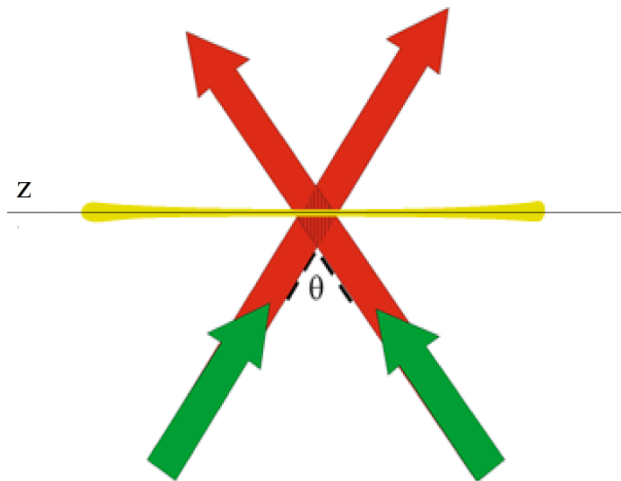

Figure 2 The two couple of beams, red and green, at 1064 nm and 532 nm, crossing at θ = 6° creates an array of double well trapping potentials along the z direction. An additional laser propagating along z provide radial trapping confinement.

The next difficulty is to realize a double well trapping potential where position and height of the central barrier can be finely controlled at will. The beam splitter for a trapped condensate can actually be performed reducing for a short time the height of the barrier to allow the tunneling of the atoms from one well to the other with a one half probability. In addition a fine-tuning of the barrier position is required to reach the condition where the trapping potential energy of the two wells is equal. Finally large shifts of the barrier position are also needed to load the atoms in only one well as a starting condition for testing the 50%-50% operation of the beam splitter. All these requirements can be accomplished using the optical dipole trap we have developed during the first part of the project, composed of a single beam responsible for the radial confinement and two lattices forming the double well longitudinal trapping potential. The first lattice is made with a 200 mW Mephisto Laser (ML) at λ_1=1064 nm injecting a 10 W Nufern amplifier. The output beam is coupled to a high power photonic crystal fiber and then split in two parts that, after two paths with a length difference DL are crossed at the atom position with an angle θ ~ 6°. This results in a primary lattice with a large periodicity of $\lambda_1/2$ Sin[θ/2] ~ 10mm. A Mephisto MOPA (MM) with 36 W at 1064 nm is then used to inject a frequency doubling stage that delivers 3 Watt at 532 nm. These green laser light is also coupled to the high power photonic crystal fiber producing an secondary lattice at the atom position with 5 mm spacing. The two lattices create an array of double well potentials where the barrier position can be shifted controlling the frequency difference between the two lasers (see Figure 3). This can be

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accomplished monitoring the beat-note of the ML and the MM and locking their relative phase. The easy shift of the relative frequency with high resolution (1 kHz) and over a broad range (300 MHz) fulfill the requirement of the fine control of the barrier position over a broad range.
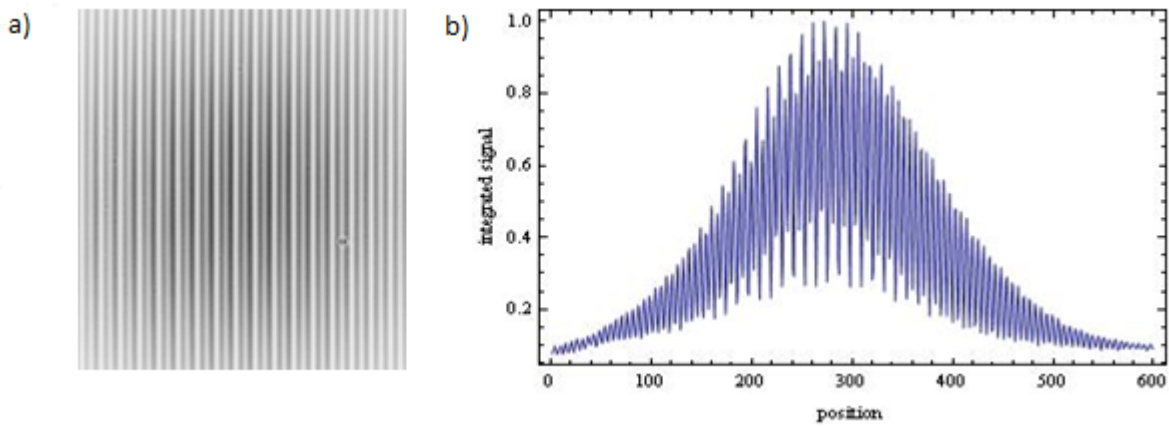

Figure 3 a) Primary and secondary lattice imaged on a CCD camera. To make them visible we have intentionally reduced the angle θ to increase the lattice sites spacing. b) Plot of the intensity along a line orthogonal to the interference pattern direction.

In order to test the stability of the double well trapping potential we have shone the interference pattern through a slit whose width was smaller than the lattice spacing in order to convert trap position fluctuations on the slit in intensity fluctuations of the light after the slit. Using a low noise photodiode, as we can see from Figure 4, we have measured several resonances.
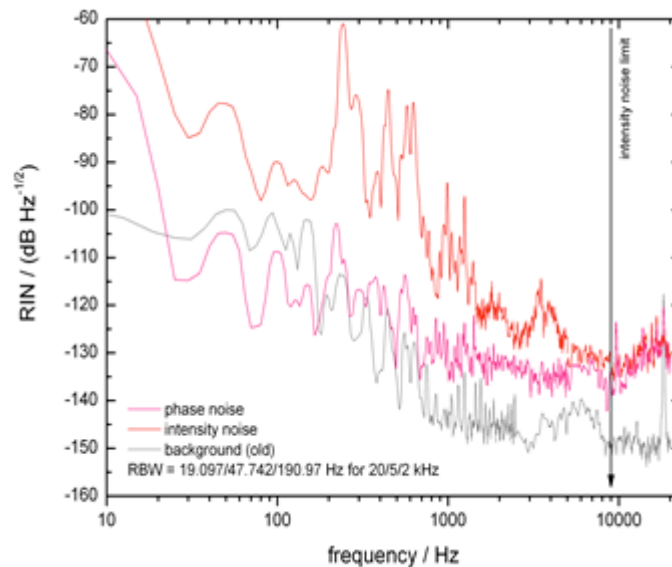

Figure 4 Mechanical instability of the array of double wells measured monitoring the trapping light through a narrow slit (red line). Intensity noise of the laser light incident on the slit (pink). Dark noise of the photodiode (grey).

Investigating the origin of the noise, we have identified the vibrations of the optics holders as the main source of instabilities. Such vibrations are deleterious for several reasons. Excitations of the condensate are caused by noise frequencies around 1kHz and few hundreds Hz because they match the trapping

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frequencies along the lattice and orthogonal to it respectively. In addition, from the noise weight function plotted in Figure 5, used to estimate the contribution of different frequency components to the rms phase noise at the interferometer output, it results clear that also frequencies as low as 1 Hz contribute significantly. In order to suppress the noise over this rather broad spectrum we have assembled all the optics for the lattices and for the radial trapping beam on two heavy steel blocks placed on legs made of viscoelastic material (Sorbothane) (see Figure 6). In this way we have realized passive isolation systems with a cut off frequency as low as 15 Hz. In addition, in order to suppress the direct coupling of acoustic waves to the optics holder we have placed the blocks in steel vacuum tight boxes. Using a floating optical table we have been able to further suppress low frequency noise down to 1 Hz. In Figure 7 we report the noise measurements performed with an accelerometer fixed at a mirror position with and without the two passive isolation systems.
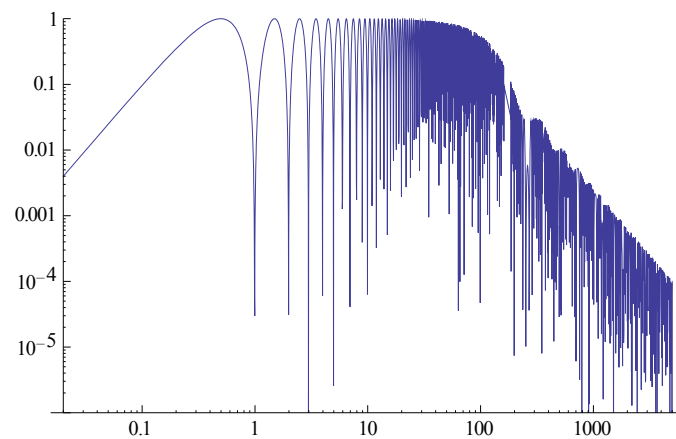

Figure 5 Noise weight function for an interferometric sequence 1 s long and with 5 ms beam splitting times. Interferometer where $\Delta E(\tau) = ma(t)L$ is the noisy energy difference between the two wells, $a(t)$ is the lattice acceleration, m is the mass of the atoms and L is the wells separation.
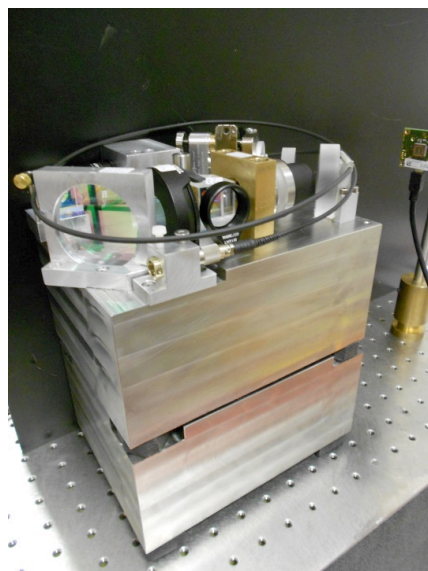

Figure 6 Radial beam optics monted entirely on two AISI316L steel blocks, 20 Kg each, placed on Sorbothane dampers. The whole structure is placed in a vacuum tight chamber.

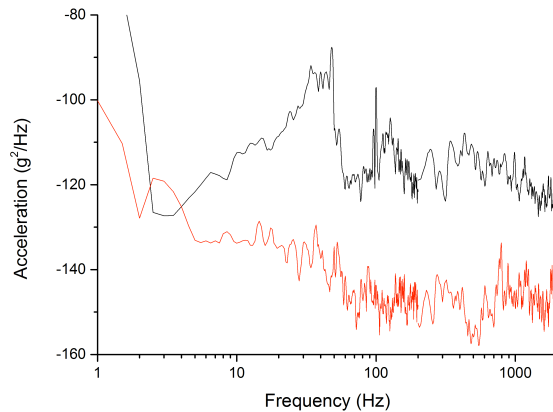D3.1 – Experimental test of beam splitter techniques

Figure 7 Spectrum of the vibrations measured with an accelerometer on a mirror holder placed on the optical table (black lines) and on the

The achieved noise suppression up to 40 dB should allow us in theory to perform beam slitter operations with a 99.9% fidelity and interferometric sequences one second long with residual rms noise smaller than 10 mrad. It will be interesting to see if low thermal drift will affect the proper 50%-50% operation of the beam splitter. From our simulations stabilities of the laser intensities, wells separation and beam splitting times at the level of 1% are needed to warrant the above fidelity.

The long work of optimization has caused a delay on the implementation of the double well trapping potential on the atoms. We are currently finalizing the assembly of the lattice optics and we expect to start the alignment of the stabilized radial beam and lattices on the atoms within the next month.

UNIBAS

Our goal was to improve the fidelity of our internal-state beam splitter. This beam splitter is a special case of a Rabi rotation in our effective two-level system of the states $|F=1,m_F=-1\rangle$ and $|F=2,m_F=+1\rangle$ of Rubidium-87. We use a microwave/radio-frequency double-resonance to coherently drive the transition between these two states.

Our state-preparation and -analysis experiments with two-component BECs of Rb-87 atoms in two hyperfine states are crucially dependent on accurate state manipulation tools. As our two chosen hyperfine states are part of the eight hyperfine ground states of Rb-87, these state manipulation tools must avoid "spilling" our atoms into any of the six unused hyperfine states. We have found in our experiments that the two-photon double-resonance drive we use to coherently transfer the atomic populations between hyperfine states are sensitive to the precise parameters we use: driving the atoms too fast between hyperfine states, or using an intermediate-state detuning that is too small, can lead to significant populations of unwanted hyperfine states, in particular the $|F=2,m_F=0\rangle$ intermediate state; and as such a parasitic population transfer is naturally stochastic, it leads to much worse atom-number fluctuations in our experiment and therefore to a major source of noise in our population measurements. Further, any noise in the microwave and radio-frequency signals used for this manipulation leads to significant parasitic "spill" transfers.

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Using numerical simulations we have determined a much better operational regime where such spilling losses can be neglected: in particular we have (i) slowed down our two-photon Rabi rotations by a factor 4 to about 500 Hz, and (ii) increased the detuning from the intermediate level to 500 kHz. Combined with (iii) a closed-loop amplitude stabilization of the microwave source and (iv) a milli-Kelvin temperature stabilization of the rf amplifier we have achieved Rabi rotations with a fidelity of 99.5 (10)% (see Figure 8), and our rotation angles now have a relative precision of 4×10^{-4} as measured with $77\pi/2$ rotations on N=1400 Bose-condensed atoms. This fidelity represents a significant advance over our previous experimental capabilities, and has opened the way to very accurate state preparation and analysis experiments currently under way.

We have attempted to use composite pulses in order to reduce our sensitivity to amplitude and phase noise in the microwave and rf pulse sources used for Rabi rotations. Such noises can be due to inhomogeneities in the driving fields due to near-field effects on the atom chip, as well as to mean-field inhomogeneities of the atomic transitions within the BEC itself. Unfortunately we observed that composite pulses lead to much worse "spilling" into the other six hyperfine ground states, and we were forced to abandon this track as our improvements in the quality of simple Rabi pulses made the errors induced by composite pulses untenable. For the same reason we have not pursued optimal-control pulses for Rabi rotations. At present we are not sure we understand the source of this poor performance of composite pulses; we may pick this topic up again whenever further improvements to our coherent rotations become necessary.
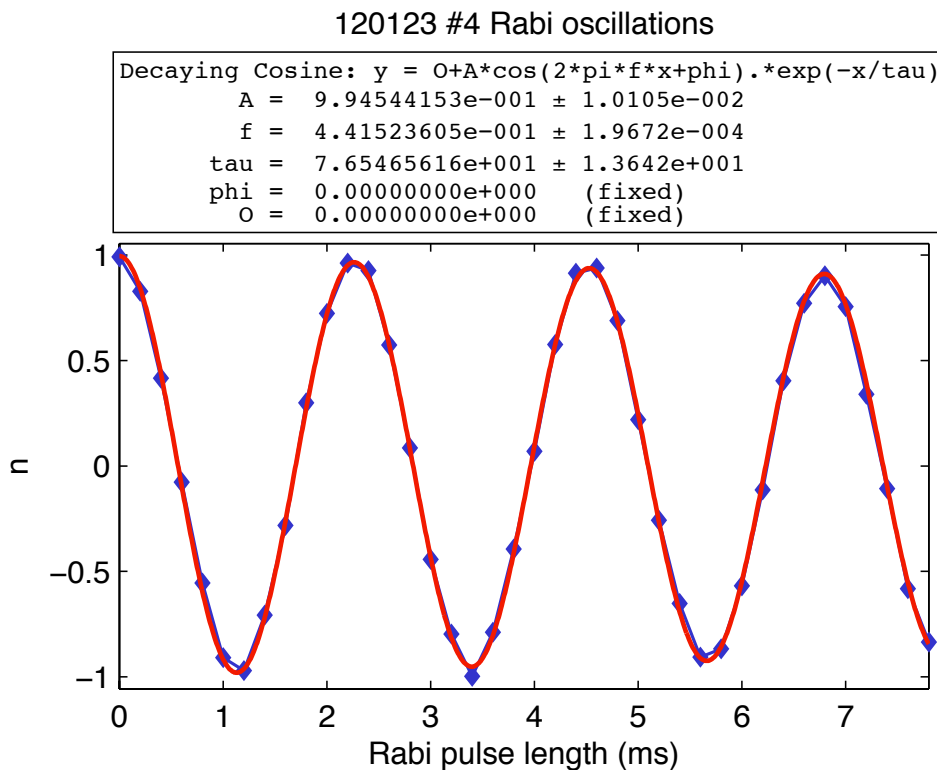

Figure 8 Coherent Rabi rotations of a two-component BEC initially prepared in a pure state. The microwave/radio-frequency two-photon drive of these transitions between the |F=1,mF=-1> and |F=2,mF=+1> states of Rubidium-87 are close to resonance with the |F=2,mF=0> state.

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