All-Optical Diffractive Element Approach to Compact, Simple, Rapid BEC Creation in Space

ESA Contract N.: 4000120052/17/NL/BJ

Executive Summary Report

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1 Introduction

1.1 Scope of Document

This document summarises the findings of the contract, No. 4000120052/17/NL/BJ, "All-Optical Diffractive Element Approach to Compact, Simple, Rapid BEC Creation in Space"

2 Summary of objectives

The objectives of the activity were to experimentally verify the applicability and utility of the recently developed technique of the gMOT[1] for rapid creation of a Bose-Einstein condensate (BEC). The programme of research aimed to optimise the system for minimised cycle time, maximum atom number, and minimised atomic temperature. An additional constraint for the system was to demonstrate trapping of the atomic sample and evaporative cooling through the condensate threshold in a far-off-resonance optical dipole trap (ODT) [2]. Furthermore, the system was designed with future applications in mind by maximising the optical access to the produced BEC.

The major tasks of the activity were:

- Review, propose, trade-off and selection of the components capable of meeting the performance requirements stated in the SOW.
- Module design and breadboarding of systems.
- Module testing and characterization of MOT.
- Characterisation of BEC cold atom source in terms of atom number, temperature, position and velocity at release from the trap.

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[1] "A surface-patterned chip as a strong source of ultracold atoms for quantum technologies," C. C. Nshii, *et al.* Nat. Nanotechnol. **8**, 321 (2013).

[2] *"All-Optical Formation of an Atomic Bose-Einstein Condensate"*, M. D. Barrett, *et al.*, Phys. Rev. Lett., **87**, 010404 (2001)

In addition, the SOW listed the specific work tasks as:

- A review of the design of binary gratings for applicability to BEC creation.
- Analysis of the laser and vacuum requirements.
- Assembly of the cold atom source.
- Achievement and characterisation of a 3D grating MOT.
- Loading ultracold atoms into an optical dipole trap.
- Evaporation to BEC.
- Development of roadmap for future advances.

3 Review of experiment sequence

The sequence of the experiment is:

1. **Dual 2D/3D gMOTs** – the 2D gMOT produces a beam of cold atoms that pass through the differential pumping hole to the low-pressure chamber, where the 3D gMOT is loaded. Atoms are first cooled in the 2D gMOT in a region of significant atomic pressure, enabling rapid capture but also losses, and transferred to the 3D gMOT where the background pressure is much lower, and atoms can be held for tens of seconds.
2. **3D MOT** –3D gMOT allows the full cooling and trapping of large numbers of atoms in a single volume. Once the 3D gMOT is loaded, the light and magnetic fields for the 2D MOT system are extinguished to prevent any extra losses.
3. **Compressed MOT (CMOT)** – To maximise the density of atoms loaded into the magnetic trap the atoms are compressed using an increased magnetic-field gradient and increased detuning to enhance the magneto-optical restoring forces, and reducing cloud volume at the cost of increased temperature.
4. **Optical molasses** – the optical molasses stage further cools the atoms to the 10 μK regime using sub-Doppler cooling mechanisms. This requires cancellation of background magnetic fields to the μT level and magnetic field gradients to the level of 10 μT/cm.
5. **Optical pumping** – atoms are transferred into a single state, $|F = 2, m_F = 2\rangle$, using a circularly polarised beam aligned along a bias magnetic field.
6. **Optical dipole trap** – atoms are loaded into the trapping potential generated by a focussed, high-powered (20 W) 1070-nm laser. To maximise the number of atoms the position of the beam is rastered at ~10 kHz to create a time-averaged trapping potential
7. **Evaporative cooling** – the atomic temperature is decreased, and the phase space density is increased by reducing the trap depth. The density is kept at a near constant value by reducing the range of rastering of the optical dipole trap.
8. **Detection** – the atoms are imaged using absorption techniques onto a CCD sensor. Time-of-flight detection allows extraction of the momentum distribution and temperature of the atoms.

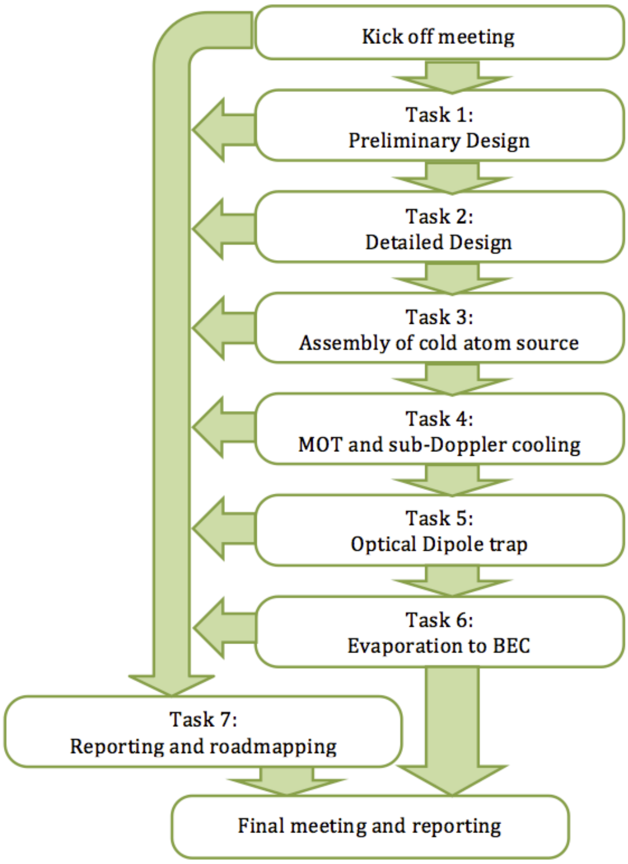

Figure 1 Review of the proposed study plan, which was followed through the project.

4 Summary of findings

The project achieved all the major and specific tasks up to the point of evaporation to BEC. The final step was not achievable in the time frame of the project due to a lower than expected atomic density being achieved after optical molasses. The measured atomic parameters within the crossed optical dipole trap were not sufficient to achieve efficient evaporative cooling.

5 Main findings

Through the project significant progress has been made towards the understanding and performance of grating magneto-optical traps, gMOTs, and towards demonstrating their utility as a reliable and robust core platform of technology for miniaturisation of ultra-cold atom devices. This result poses interesting opportunities for applications for Earth and space-borne sensing, and wider application.

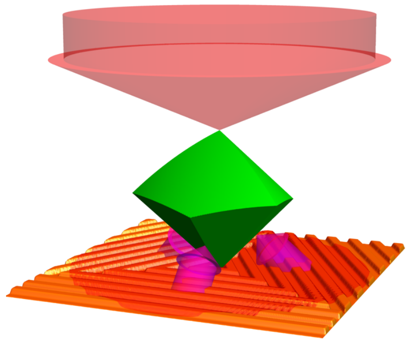

Figure 2 Schematic of the grating MOT technology: a single downward laser beam (red) hits a grating (gold) and creates diffracted beams (cyan). Atoms are trapped at µK temperatures in the laser overlap zone (green).

5.1 Laser system

All light for the laser-cooling stages is operated from a single laser, constructed by the project partner Muquans. The highly agile system is formed from a seed laser at 1560 nm, which is amplified in an EDFA and frequency-doubled in a non-linear crystal to reach the desired wavelength of 780 nm. The total power available for laser cooling is approximately 200 mW, which is limited by the requirements of optical elements, such as acousto-optical modulators and optical fibres, that have less than perfect efficiency. The results indicated below clearly show the utility of the Muquans approach for laser cooling in the gMOT configuration.

5.2 2D gMOT

In this work we have demonstrated the single-beam operation of a high flux beam source of ultracold atoms using an etched grating of 75×24 mm^2 in size. The loading rate from the 2D+ gMOT into a secondary trapping stage gMOT was measured to be $>10^8$ atoms/second, which is a sufficient flux for the subsequent stages of the experiment.

Parameter	Value
2D-grating period	1200 nm
2D-grating duty cycle etched:unetched	55:45
2D-grating coating	100 nm Au
2D-grating size	75 mm x 24 mm

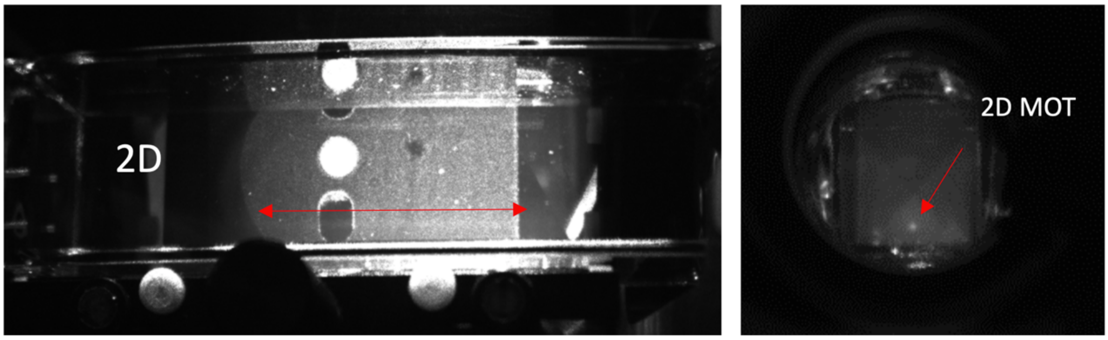

Figure 3. Photograph of the 2D gMOT viewed from the side (left) and along its axis (right). The 2D gMOT is only weakly observed, due to the dynamic nature of the atoms passing out of the cooling region.

5.3 3D gMOT

The project has demonstrated for the first time that cold-atom clouds with $>10^8$ atoms are possible using the gMOT platform. The research program has identified the potential to increase to 10^9 cooled and trapped atoms.

Parameter	Value
3D-grating period	1189 nm
3D-grating duty cycle etched:unetched	60:40
3D-grating coating	100 nm Al
3D-grating size	20 mm x 20 mm

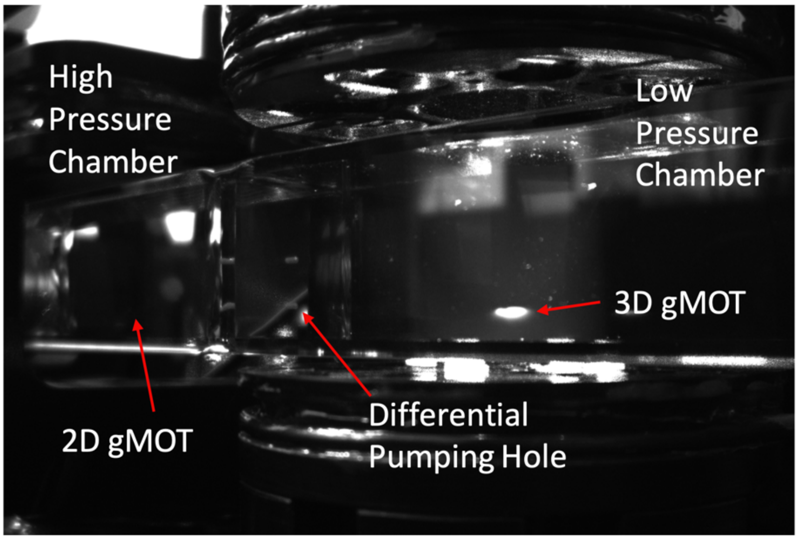

Figure 4. Photograph showing the position of the 2D and 3D gMOTs, with atoms being transferred from the former to the latter through the differential pumping hole. The 3D gMOT provides trapping in addition to cooling, which is evident due to the vastly increased signal compared with the 2D gMOT.

5.4 Optical molasses

The apparatus achieves atomic temperatures of 20 μK for atomic clouds with $\geq 10^8$ atoms, and temperatures below 5 μK for atom numbers in the range of 10^7 atoms. These temperatures are directly comparable to the values that can be achieved in traditional 6-beam MOT geometries. MOTs that use retro-reflected beams are affected by shadowing, or spatially dependent loss of light from the MOT itself, which makes it extremely difficult to achieve temperatures as low as observed in this project.

5.5 Optical dipole trap

In the project we have demonstrated the single-beam and crossed-beam optical dipole traps. As expected, loading directly from the cold atom cloud was results in a limited atom number due to the imperfect spatial overlap between the atoms and the trapping potential. By rastering, i.e., repeatedly rapidly scanning the position of the optical dipole trap, it was possible to increase the number of atoms load into the trap, at the cost of a reduced trap depth. The ability to dynamically control the raster parameters provides the capability of recovering the trap depth once atoms have been loaded by reducing the range over which the position is scanned.

6 Review

The targeted parameters were known to be challenging from the start project. However, the project has resulted in a combined apparatus, shown in Figure 5, that has demonstrated the ability to cool and trap large numbers of atoms in a relatively simple experimental geometry.

The method has demonstrated the capability for significant reductions in SWaP of the core systems. The Strathclyde group have demonstrated the operation of a device of volume 100 mℓ, which contains the complete vacuum, magnetic, and cooling-optics for cooling and trapping 10^7 atoms. Further progress possibilities are outlines in the associated roadmapping documents.

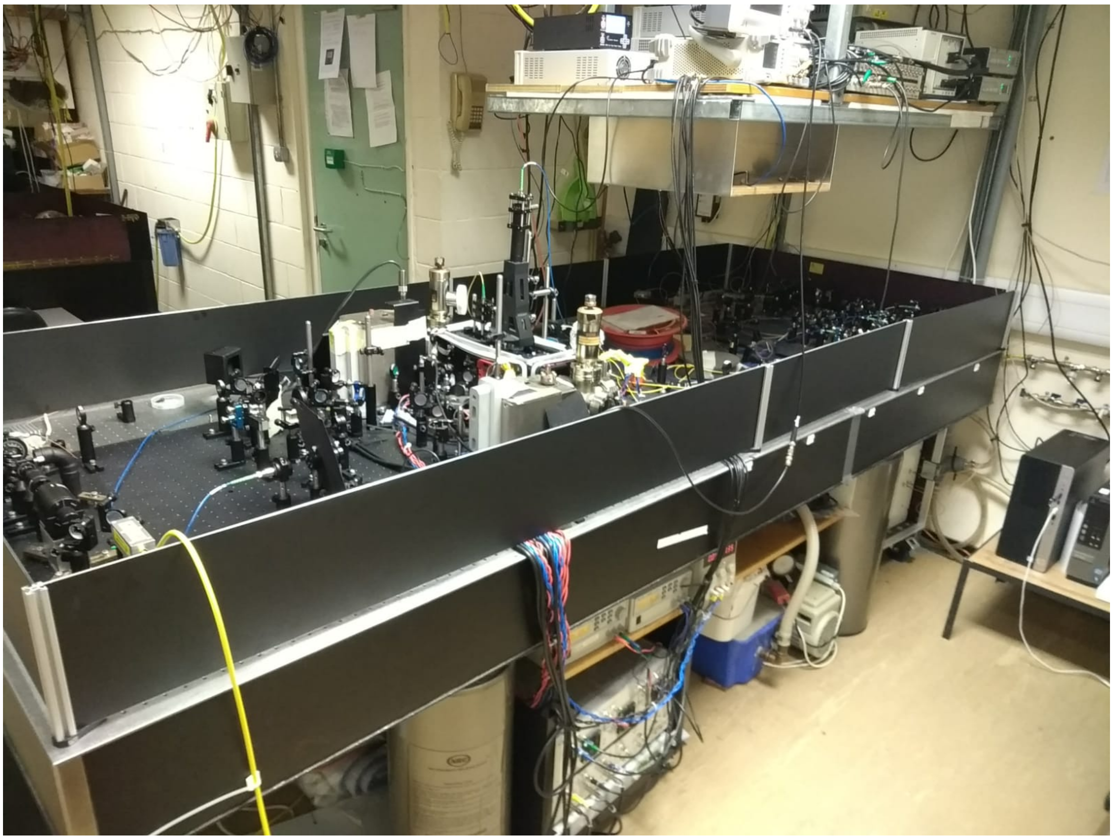

Figure 5 Photograph of apparatus with the full optical assembly

The final goal of the project, the attainment of BEC, was not achievable within the project. Early delays in recruiting an experienced researcher on the project affected the initial progress. Unforeseen technical issues that would have required major engineering changes limited the attainable atomic densities. However, practical methods to overcome these have been identified and could be applied to the apparatus.