Towards all-optical entangled BECs in microgravity

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Goal

Provide a compact and robust all-optical source for entangled ^{87}Rb atoms in microgravity environments.

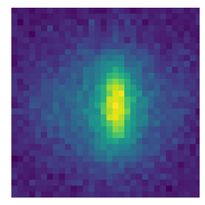
motivation

- Atom interferometers are high-precision sensors for acceleration, rotation and magnetic fields
- Possible space applications
- Improve sensitivity by surpassing SQL (entanglement)
- BEC's are used due to low expansion rate and macroscopic coherence length
- BEC preparation takes a lot of time → atom chips, ODT
- Atom chips reduce optical access in the science chamber → ODT

→ **Demonstrate fast BEC preparation in cODT in microgravity**

Status

- ☑ Build vacuum chamber
- ☑ MOT
- ☑ Molasses
- ☑ BEC
- ☑ Dipole trap test flight



- ☑ Transfer the system to the carrier
- ☑ BEC creation in microgravity
- ☐ Squeezing using entangled atoms
- ☐ **Entangled atoms in microgravity**

environment

- 4 s of free fall at 10-6 g possible
- Up to 100 repetitions a day feasible
- Max acceleration and deceleration of 5g during normal operation
- Max payload of about 550 kg
- 1 kW of cooling power available

Einstein-Elevator in Hannover

source: ITA LUH

Lift-off → **MOT** → **Molasses** → **Evaporation in cODT** → **BEC** → **Spin dynamics** → **State manipulation** → **Interrogation time** → **Detection** → **Landing**

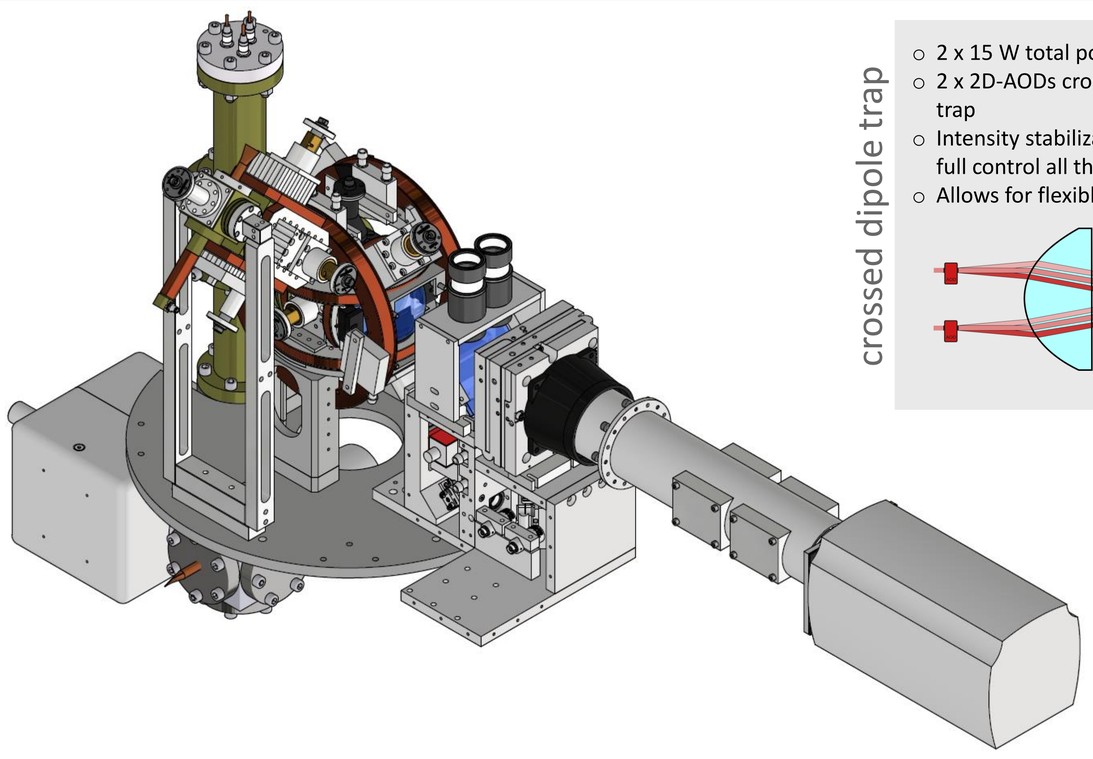
System

overview

- Atom oven provides steady source of ^{87}Rb
- 2D$^+$-MOT enables high loading rate (>1e9 atoms/s) connected to science chamber
- 3D-MOT chamber consists of 4 beams, with 2 being retro-reflected off mirrors to enable full spatial trapping in combination
- A total of 7 coils provide magnetic fields also for compensation, quantization and Stern-Gerlach type pulses
- All-optical approach to BEC creation via a crossed optical dipole trap (cODT) folded into the detection path
- State manipulation via microwave and rf antennas

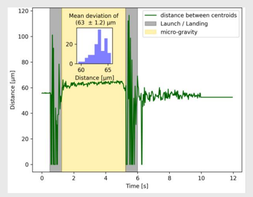
painted potentials

- Traps larger than 1 mm can be used to initially trap a large fraction of the available atoms
- Stroke reduction and intensity matching leads to phase space density increase
- BEC creation in less than 1s possible (see: Hetzel et al, "All-optical production of Bose-Einstein condensates with 2 Hz repetition rate", arXiv:2406.16488)
- Arbitrary potentials can be created at both AODs in both dimensions for exotic applications



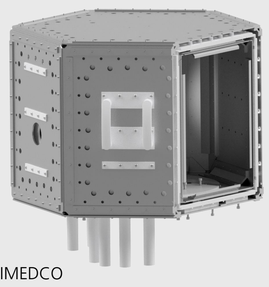
crossed dipole trap

- 2 x 15 W total power @1064 nm
- 2 x 2D-AODs crossing at 30° angle allow for 3D adjustment of the trap
- Intensity stabilization over many orders of magnitude to enable full control all the way to BEC creation
- Allows for flexible delta kick collimation



magnetic shielding

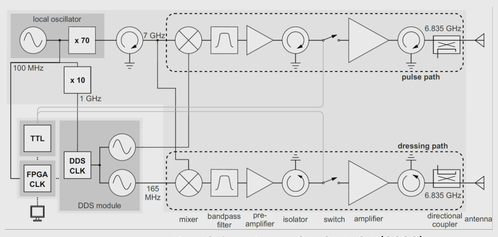
- Triple layer hexagonal shield (µ-metal, Al, µ-metal)
- Expected shielding factor > 5 000
- Remaining field strength of < 5 nT
- Degaussing coils for repetitive equilibration



In cooperation with IMEDCO

microwave source

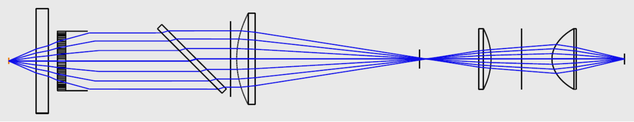
- Dynamic generation of highly stable MW pulses by combining a low-noise oscillator with a DDS



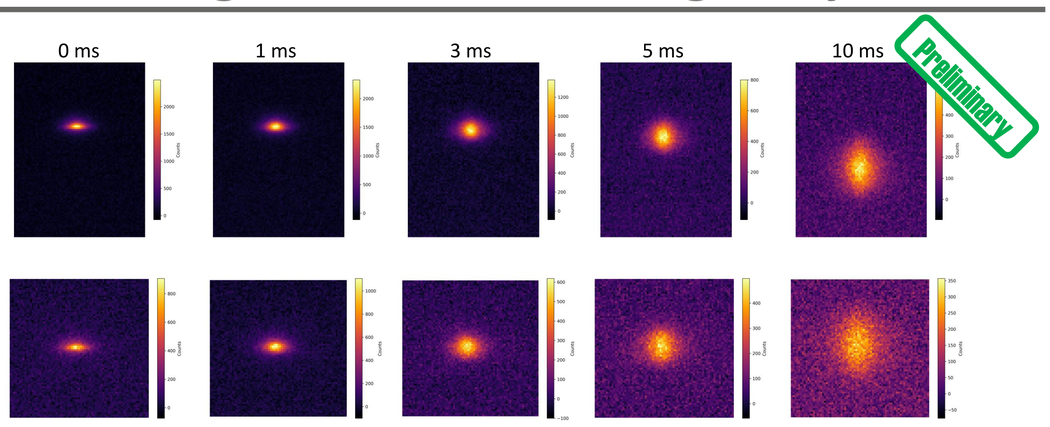
From: Rev. Sci. Instrum. 94, 074705 (2023)

detection system

- Detection via fluorescence imaging towards shot-noise limited measurements
- Image path shared with the optical dipole trap via a dichroic mirror
- High QE camera (>95%) tested for microgravity operation
- Secondary image detection via absorption imaging allows for 2D information



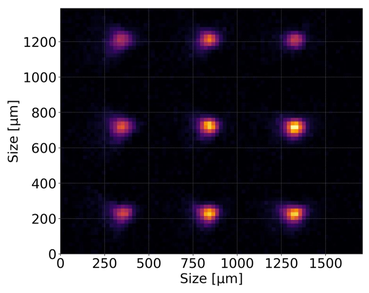
BEC generation in microgravity

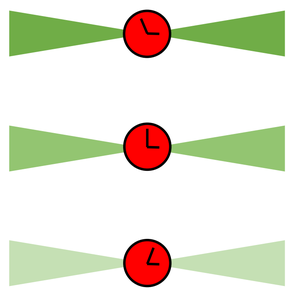


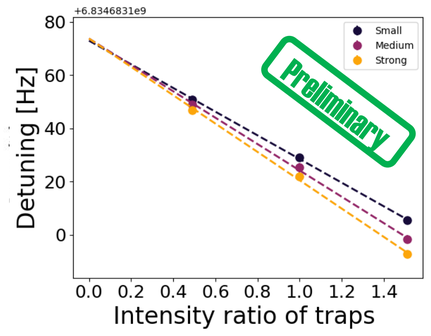
- Aspect ratio flip as a proof of BEC creation
- First BEC fully created all-optically in microgravity

see Condon et al. Phys. Rev. Lett. 123, 240402 (2019) for a similar experiment where the BEC was created in an Einstein-Elevator and operated in microgravity

Application example







- BEC arrays in dynamically painted optical potentials
- Ramsey clock experiments in multiple traps

see Stolzenberg et al. Phys. Rev. Lett. 134, 143601 (2025) for a comparably generated BEC array, which is used for inertial sensing

Recent publications

INTENTAS - an entanglement-enhanced atomic sensor for microgravity

All-optical production of Bose-Einstein condensates with 2 Hz repetition rate

Robust and compact single-lens crossed-beam optical dipole trap for Bose-Einstein condensation in microgravity

in cooperation with:

supported by: German Aerospace Center (Deutsches Zentrum für Luft-und Raumfahrt, DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz , BMWK) Grant No. 50WM2174, Grant No. 50WM2175, Grant No. 50WM2176, Grant No. 50WM2177, Grant No. 50WM2178 (INTENTAS) and Deutsche Forschungsgemeinschaft (DFG) under Germany's Excellence Strategy within the Cluster of Excellence QuantumFrontiers (EXC 2123, Project ID 390837967)