Cold Atoms in Space: German activities and perspective

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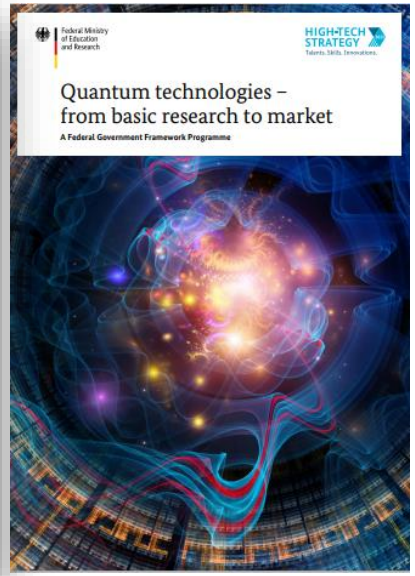
Community Workshop on Cold Atoms in Space

(Space) Quantum Technologies in Germany

German Space Agency at DLR

Federal Ministry for Economic Affairs and Energy

2010: German Space Strategy



2018: German Federal Framework Programme Quantum technologies

Programmatic Objectives

- Scientific excellence „made in Germany“
- Enhancing the physical understanding of our world
- Strengthening German industry
- Advancing technology developments
- Strengthening STEM fields
- „Benefit on earth“

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Quantum Technologies for Space – subject areas

Fundamental physics	→	Gravitational waves, dark matter, EEP tests …
Quantum sensing/ metrology	→	acceleration, magnetic fields… inertial navigation, clocks…
Quantum communication	→	Quantum key distribution, Quantum repeater,…
Quantum computing & simulation	→	Cross-section technology; No direct space application (low TRL)

- 2004: QT activities started at the German Space Agency, **science-driven**
- 2021: QT in departments Research & Exploration, Satellite communication, Satellite Navigation and Earth Observation

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Infrastructures for experiments and technology development

- Stand-alone µ-g experiments and step-by-step development of QT for space

- Experiments and technology demonstration on multiple microgravity platforms
  - Bremen Drop tower/Einstein elevator
  - Parabolic flights
  - Sounding rockets
  - Suborbital platforms
  - Small satellites
  - International Space Station

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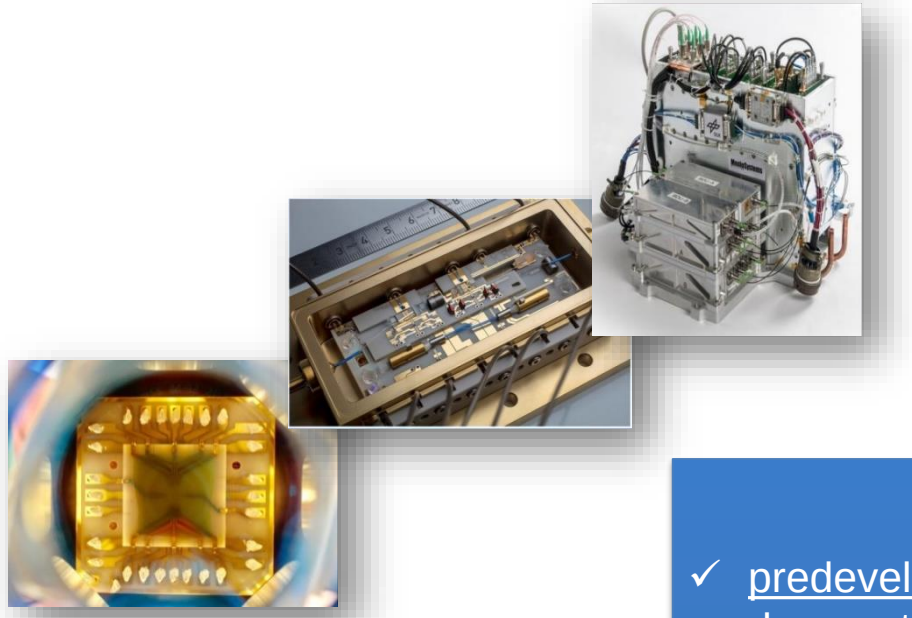
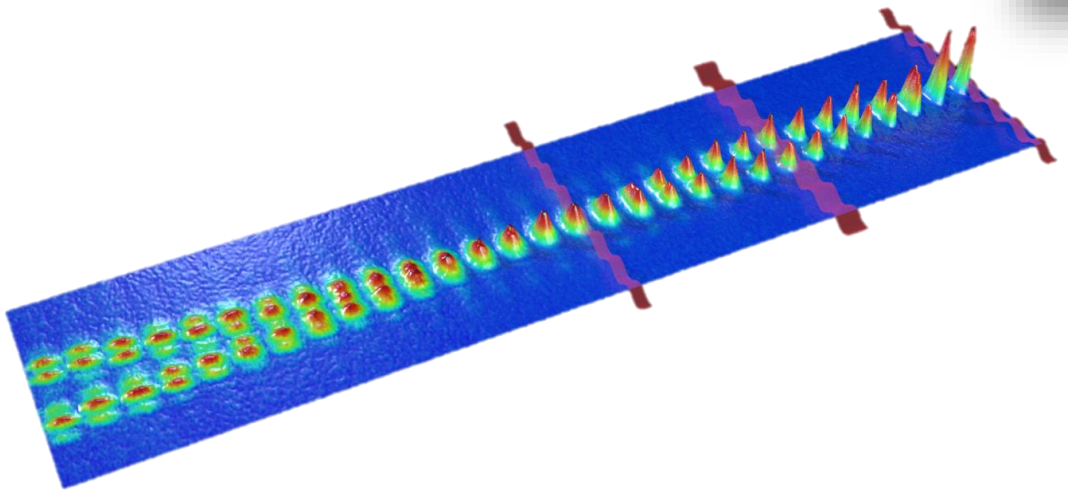
Quantum technologies in the research and exploration department

- ✓ Fundamental physics
  - Matter wave interferometry
  - ultra-cold quantum gas
  - tests of theory of relativity
  - Dark energy / dark matter
  - Quantum entanglement
  - …





- ✓ predevelopments and technology demonstration for space applications
  - Quantum sensors
  - Laser modules
  - Frequency combs
  - Clock prototypes
  - Atomic chips
  - Optical dipole traps
  - Single photon sources
  - Quantum memory
  - …

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Atom Interferometry for Quantum Sensing Activities

- **Funding of Quantum Sensing / Atom Interferometry Projects for space started in 2004. German researchers have continually expanded and demonstrated their expertise since**

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German Space Agency

QUANTUS drop tower project, started 2004, ongoing
- First BEC under µg 2007

PRIMUS drop tower project, started 2009, ongoing
- 2014: first Quantum EEP test in a lab with 2 different atomic species
- Development of all-optical traps as alternative trap technology

MAIUS sounding rocket programme, started 2014, ongoing
- First BEC in space, 2017
- MAIUS-2 launch 2022

CAL, NASA cold atom experiment on ISS, started 2018, German contribution to CUAS consortium
- First BEC on the ISS, 2018

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Current and Future Activities in Quantum Sensing

INTENTAS Einstein elevator project, started 2021

- surpass the standard quantum limit in a compact and robust atomic sensor with entangled atomic ensembles

BECCAL, US-German cooperation, 2025+

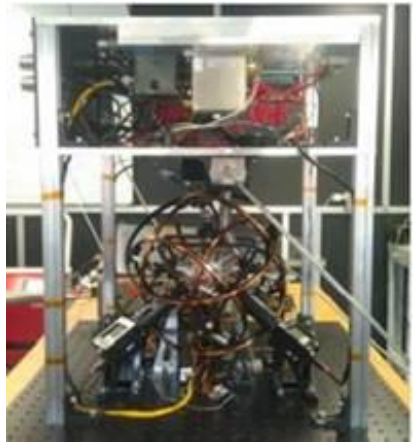
- Future cold atom research on ISS (quantum optics, atom optics and atom interferometry experiments with cold and condensed atoms (Bose-Einstein-condensates)
- Pathfinder for next-generation quantum sensors
- Fundamental research, e.g. Einstein tests, search for dark matter, gravitational waves, stability of fundamental constants

DESIRE Einstein elevator project, started 2021

- Collaboration with NASA/JPL
- Dark energy search with atom interferometry

Quantum Sensing

Current activities (application-oriented)



Quantum Inertial Sensing Systems

- Algorithms to analyse inertial measurements of quantum sensors
- Development of hybrid 1-axis quantum sensors and performance demonstration, preparation for 6-axis sensor and miniaturization
- Compact hybrid 3-axis quantum sensor based on cold atoms

French-German cooperation “QUANTA”, 2019-

- CARIOQA-Study: Pathfinder Mission for demonstrating the operation of a Quantum Accelerometer on a satellite.

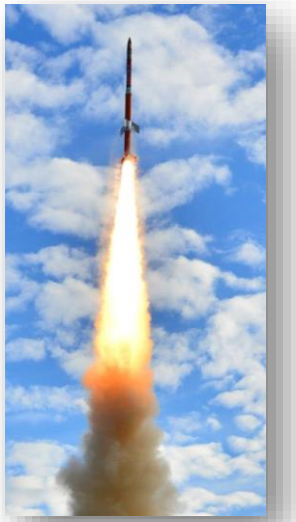
Space Optical Clocks

Heritage

FOKUS

Prototype development for optical clocks in space

- Start of development of a fiber laser-based frequency comb for space applications, 2013
- First frequency comb + Rb spectroscopy in space: proof of concept on sounding rockets, 2015



KALEXUS

- 2nd frequency comb prototype + K spectroscopy in space, 2016

- Improved comb + iodine clock prototype in space, 2018

MenloSystems

JOKARUS

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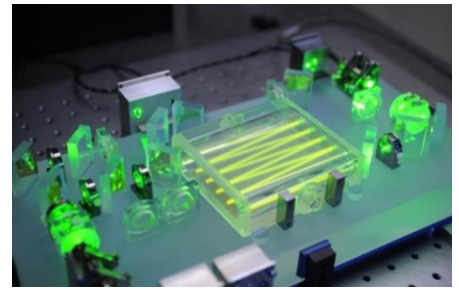
Space Optical Clocks

Current



Prototype of **Sr-clock**, 2023:
Based on Ramsey-Bordé Interferometry on thermal Sr beam

- Laser chip technology, Miniaturised optical setups for the physics package
- Increase TRL of frequency comb

Key Technologies for **Rb-2-Photon-Clocks** on Satellites:
High potential for SWaP budget reduction, stability and accuracy

- Increase TRL of frequency comb
- Physics package: Miniaturisation, energy efficiency
- Micro-integrated lasers (towards monolithic integration)

Developments towards highly compact optical space clocks
Evaluation of optical clock (elements) for 2nd next generation Galileo

Micro-integrated lasers

Space Optical Clocks / Metrology
Current & Perspectives

SOLIS 

Development of prototype of **Sr-lattice clock**, started 2021:

- highly-precise clock for fundamental science, relativistic modeling, optical frequency metrology

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Outlook

We strive to

- expand quantum technologies as an important pillar of our programme beyond the current „quantum hype“

- support further development of space-QT towards higher TRLs for application
  - in GNSS
  - earth observation
  - exploration
  - fundamental physics (dark energy, tests of physical theories, gravitational wave detection,…)

- continue successful actitivies: harness the knowledge and expertise gained in the last 2 decades
- In orbit demonstration / validation: push the technology beyond „the valley of death“ (e.g. Satellite missions for fundamental physics and earth observation)
- Support development of key components and miniaturisation (laser, atom chips, frequency combs…)
- Team up with European / international partners
- Push the boundaries even further in both fundamental physics and QT applications

Thank you for your kind attention!

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