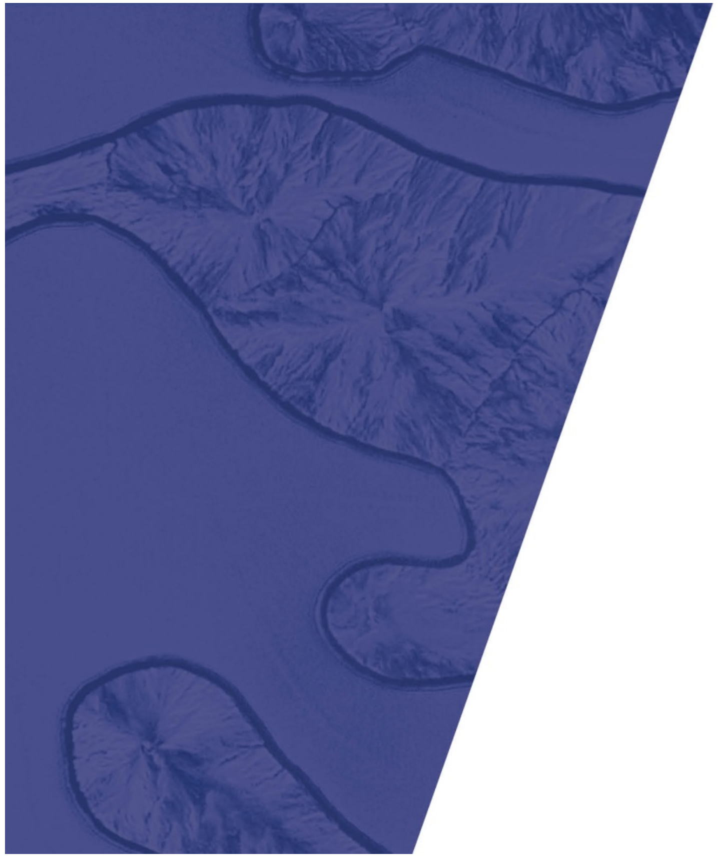
Welcome to Today's Webinar!



GENERATION AND MANIPULATION OF BOSE-EINSTEIN CONDENSATES IN SPACE

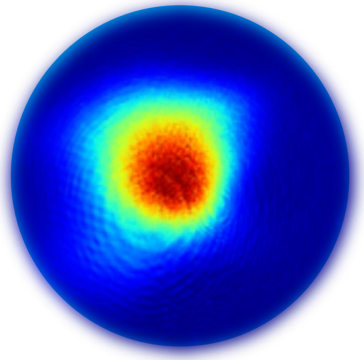
16 April 2021 • 9:00 EDT (UTC -4:00)

OSA Optical Cooling and Trapping Technical Group

Technical Group Executive Committee

Markus Krutzik
Chair of the OSA Optical Cooling and Trapping Technical Group

Victoria Henderson
Co - Chair



NN
Could be you? Please contact us!

About the Optical Cooling and Trapping Technical Group

Our technical group focuses on the physics of laser cooling, electromagnetic trapping and other radiative manipulation of neutral atoms, ions, dielectric particles and nanostructures.

These fundamental studies are used to develop applications to new kinds of physics measurements and processes such as high resolution spectroscopy, atomic clocks, atomic collisions, atom optics.

Our mission is to connect the 900+ members of our community through technical events, webinars, networking events, and social media.

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.osa.org/ot
- On LinkedIn at https://www.linkedin.com/groups/5081944/
- Email us at TGactivities@osa.org (or markus.krutzik@fbh-berlin.de)

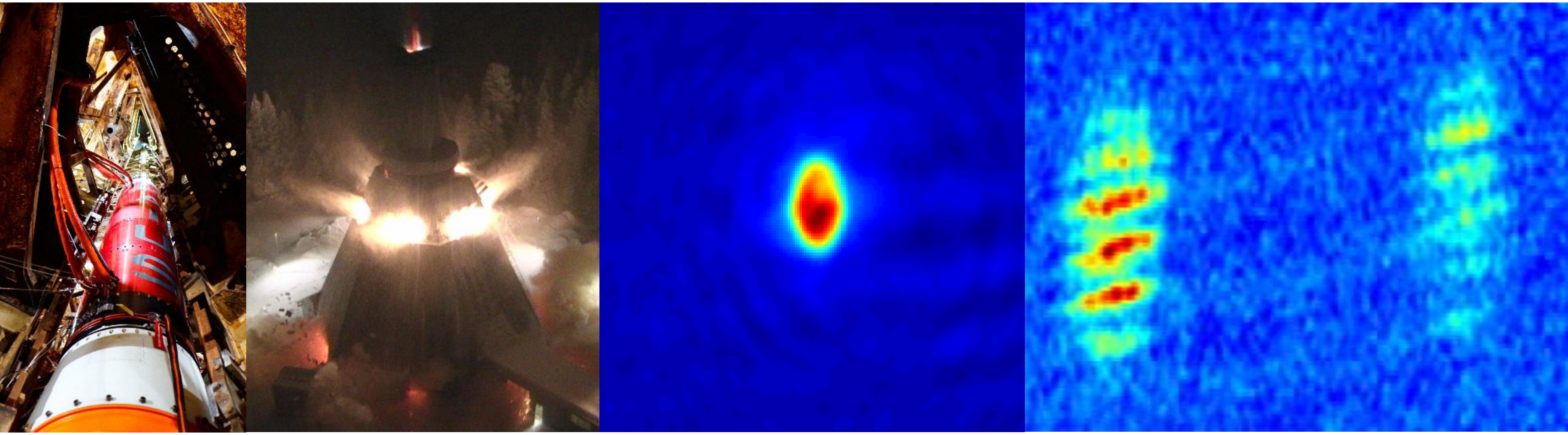
Today’s Speaker

Maike Lachmann

Leibniz University of Hannover

Short Bio:

- PostDoc working on atom-optical experiments in microgravity environments
- Scientific lead for upcoming space missions that plan to perform dual-species atom interferometry on-board a sounding rocket.
- During PhD she already participated in the sounding rocket mission MAIUS-1 demonstrating BEC creation and matter-wave interferences in space for the first time.



Generation and Manipulation of Bose-Einstein Condensates in Space

MAIKE DIANA LACHMANN

Atom interferometry in space

Tests of fundamental physics

Universality of free fall

Search for dark energy

Determining fundamental constants

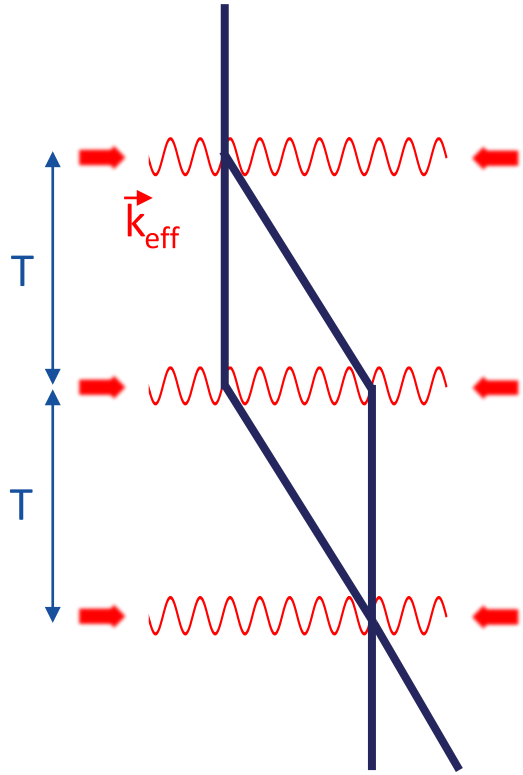
Applications

Navigation

Geodesy

Detection of gravitational waves

Atom interferometry for precision measurements



Sensitivity scales with $k_{eff}T^2$

- large momentum transfer
- extension of T
  - long baselines
  - free falling laboratories
  - ➢ small volume
  - ➢ reduced kinematics of source
  - ➢ Low background noise

Free Falling Laboratories

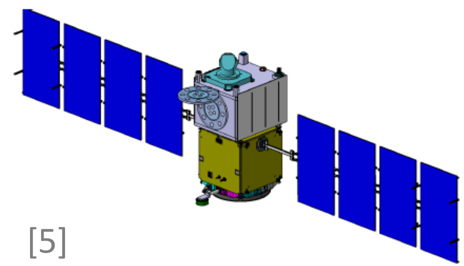
space
µg time > 6 min

Sounding rocket

[4]

International Space Station (ISS)

Satellite



[5]

time

today

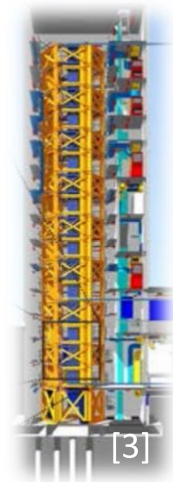
[1]

Passive drop tower

Parabola flight

[2]

ground-based
µg time < 22 s



[3]

Active drop tower

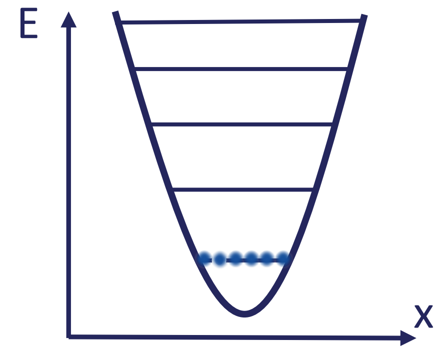
[1] Holger Ahlers, Hauke Müntinga
[2] V. Pletser *et al. Microgravity Sci. Technol.* **28,** 587–601 (2016).
[3] 2017 Christoph Lotz et al., Sciendo. License. BY-NC-ND 3.0
[4] NASA: https://www.nasa.gov/images/content/155384main_jsc2006e33314_high.jpg
[5] ESA: https://sci.esa.int/web/ste-quest/-/49355-ste-quest-mission-proposal

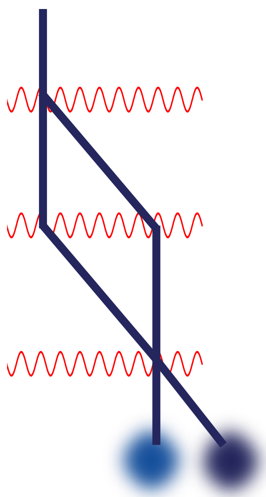
Bose-Einstein condensates

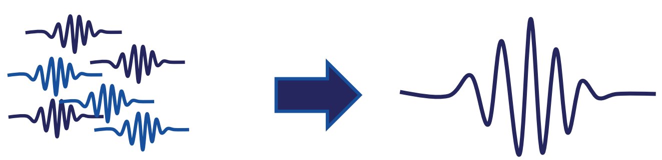
- Macroscopic population of ground state at high phase space densities

- Narrow momentum distribution and small initial size
  - Increased beam splitter efficiencies
  - Smaller disturbances due to wave front errors
  - Higher density during detection
  - Separation of output ports

- macroscopic coherence

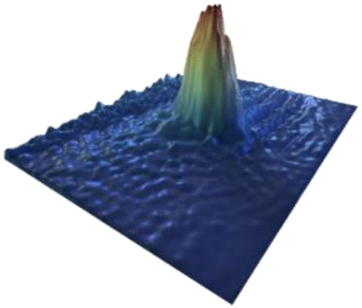






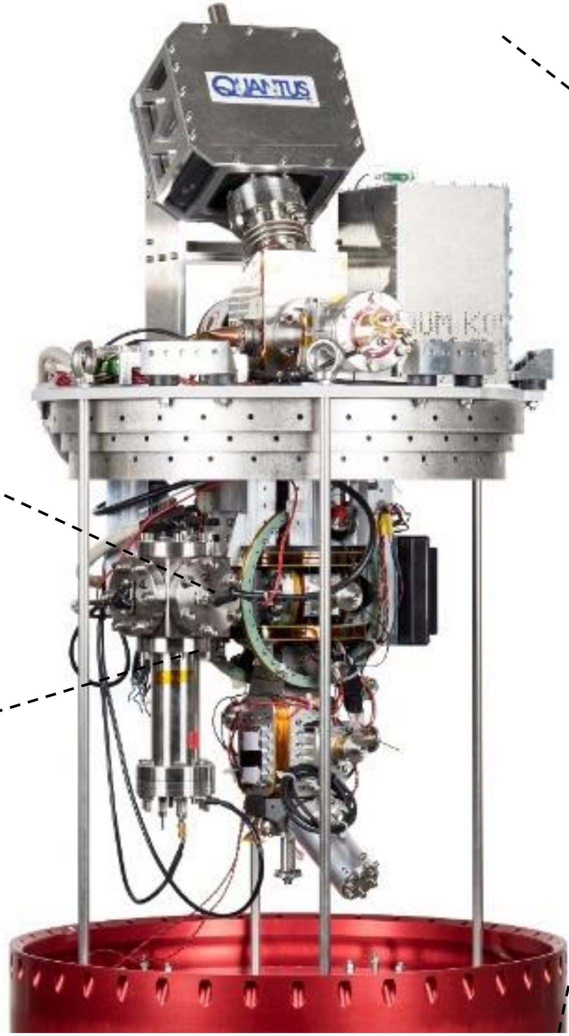
Outline

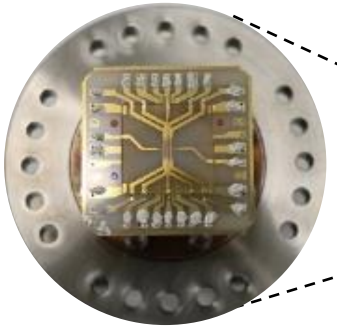
- Setup
- Preparation of ultracold ensembles in space
- Interaction of light and matter wave
- Atom interferometry
- Outlook

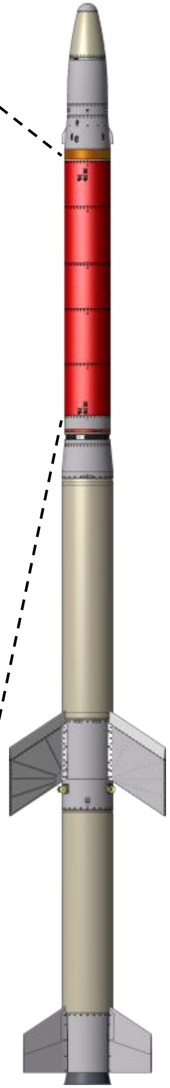


Setup MAIUS-A

Atom chip apparatus







Sounding rocket of type VSB-30

Requirements for scientific payload:

- Compact: Ø 0.5 m x 2.8 m
- Robust
- Small mass
- Low power consumption
- Autonomous operation

- Kubelka-Lange, A. et al. *Rev. Sci. Instrum*. **87**, 063101 (2016).
- Grosse, J. et al. *J. Vac. Sci. Technol. A* **34**, 031606 (2016).

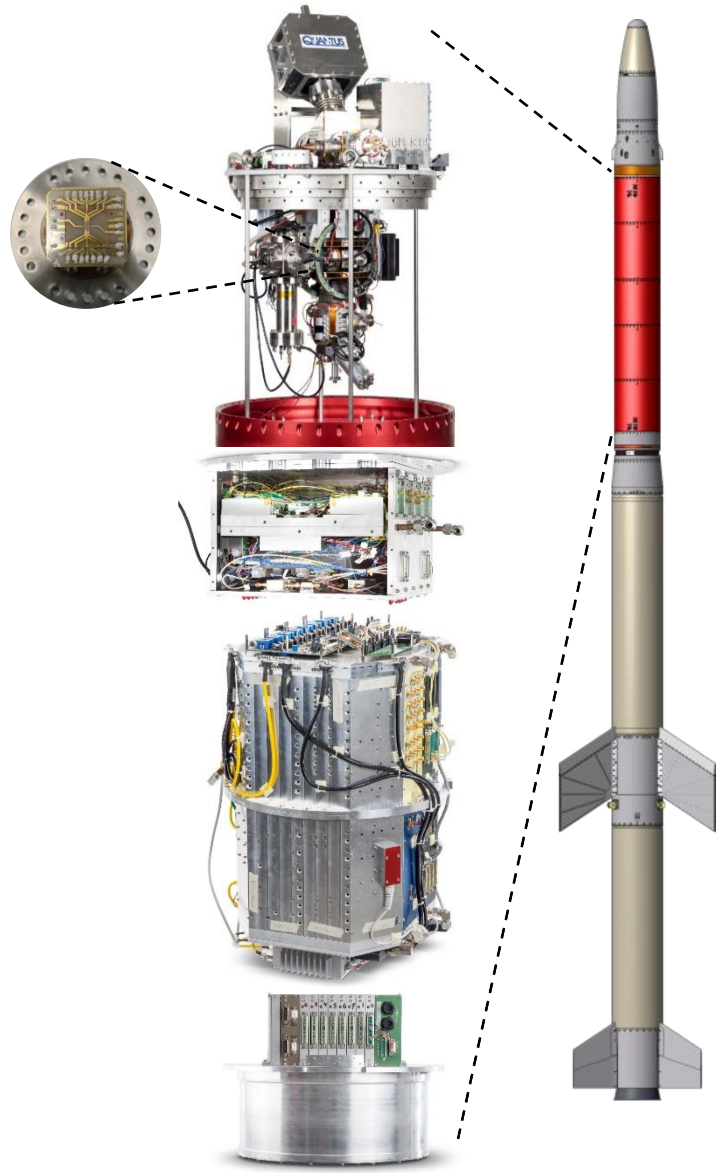
Setup MAIUS-A

Atom chip apparatus

Laser system

Control electronics

Battery module



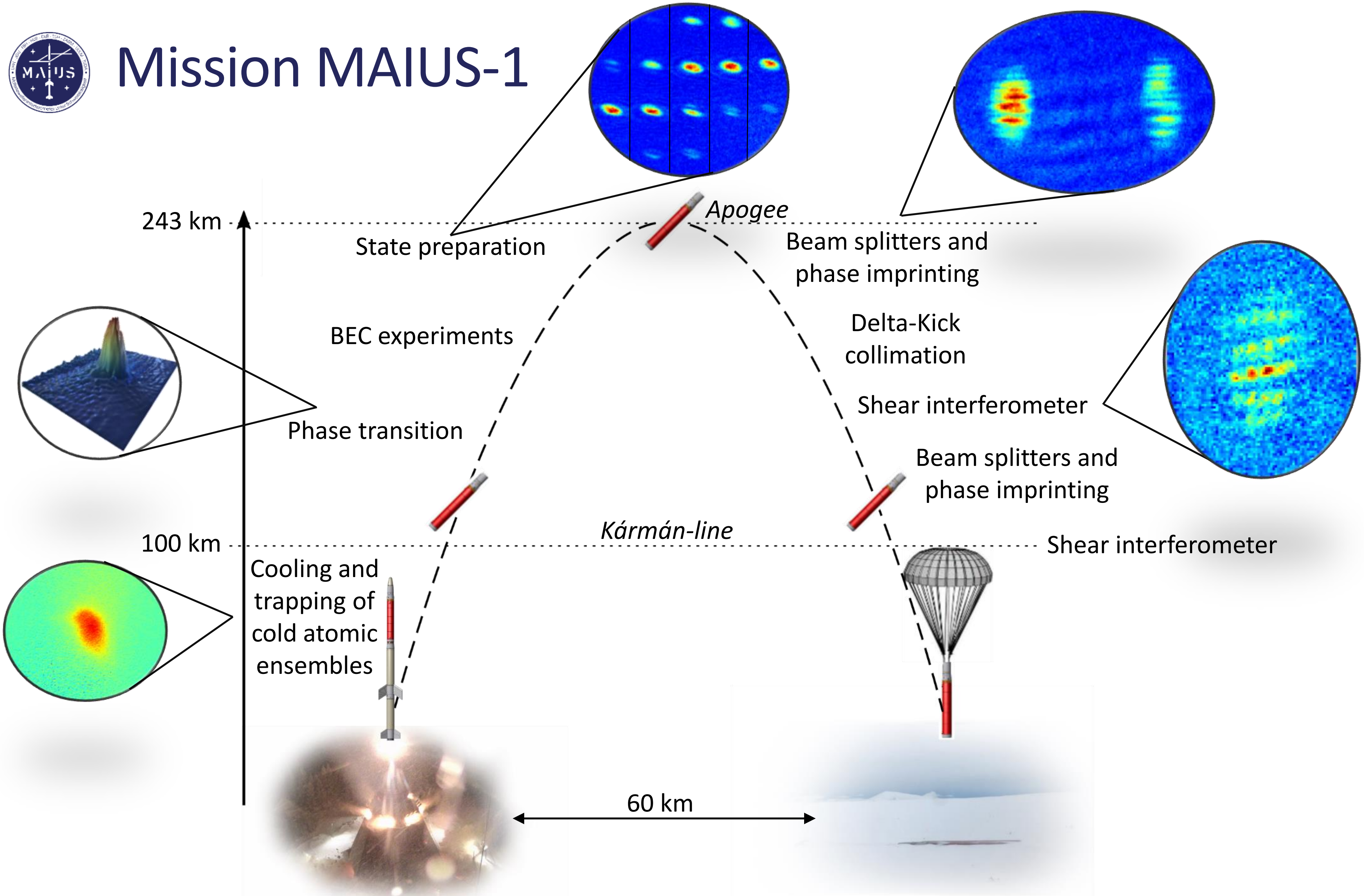
Sounding rocket of type VSB-30

Requirements for scientific payload:

- Compact: Ø 0.5 m x 2.8 m
- Robust
- Small mass
- Low power consumption
- Autonomous operation

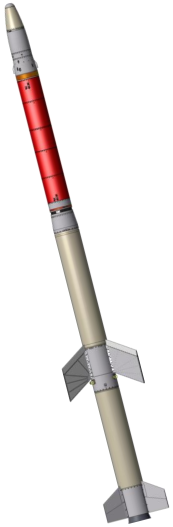
- Kubelka-Lange, A. et al. *Rev. Sci. Instrum*. **87**, 063101 (2016).
- Grosse, J. et al. *J. Vac. Sci. Technol. A* **34**, 031606 (2016).
- Schkolnik, V. et al. *Appl. Phys. B* **122**, 217 (2016).

Mission MAIUS-1

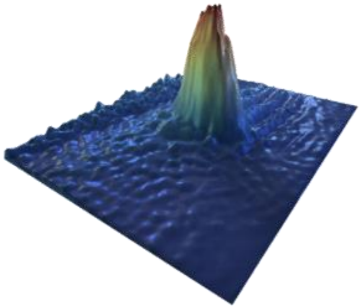


23.01.2017 Launch: 03.30 am CET Landing: 03.47 am CET 110 experiments

Outline

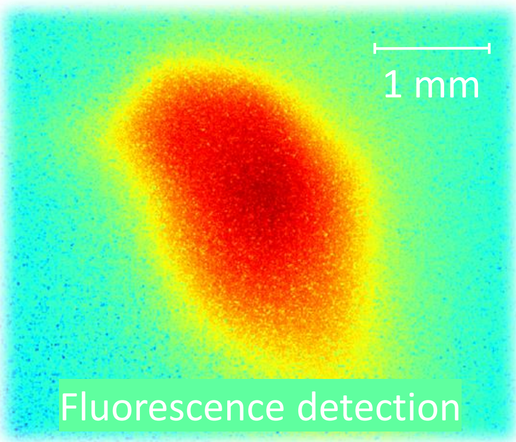


- Setup
- Preparation of ultracold ensembles in space
- Interaction of light and matter wave
- Atom interferometry
- Outlook

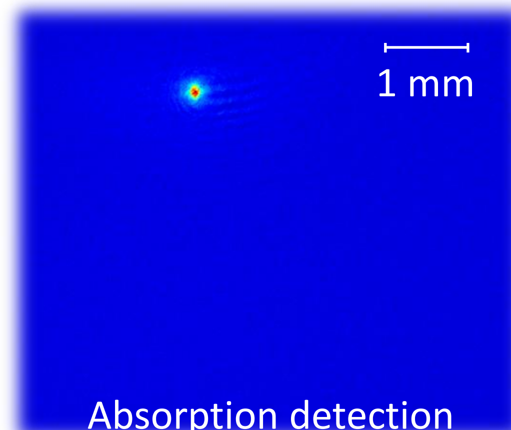


Creation of Bose-Einstein condensates

Thermal ensemble → Magneto-optical trap → Optical molasses → Optical pumping → Magnetic trap → Evaporation → Bose-Einstein condensate



BEC-flux of 10^5 atoms in 1.6 s

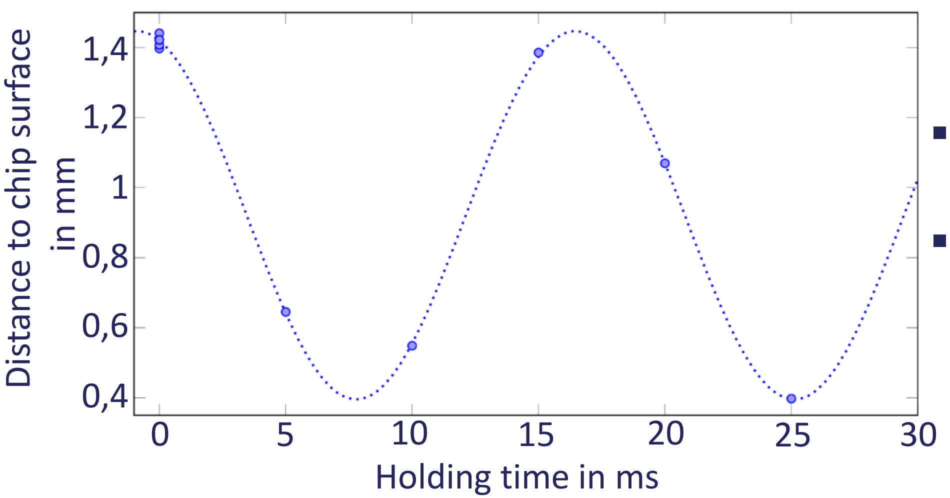


Becker, D., Lachmann, M. D., Seidel, S. T., et al. *Nature* **562,** 391–395 (2018).

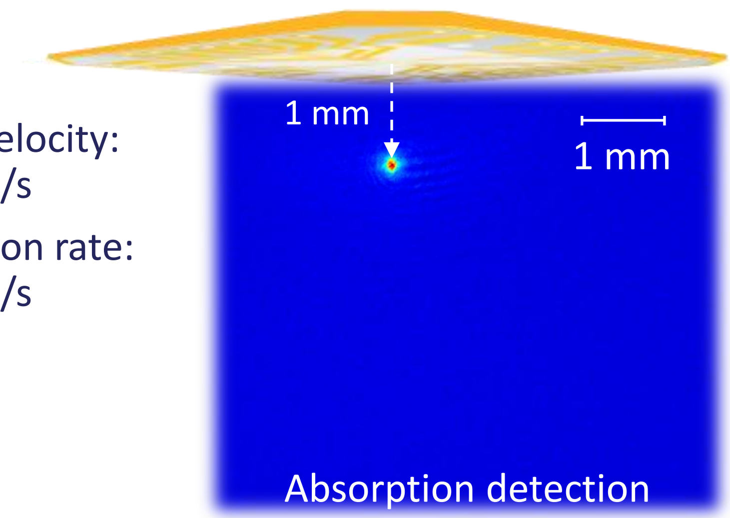
Creation of Bose-Einstein condensates

Thermal ensemble → Magneto-optical trap → Optical molasses → Optical pumping → Magnetic trap → Evaporation → Bose-Einstein condensate

10^5 atoms in 1.6 s

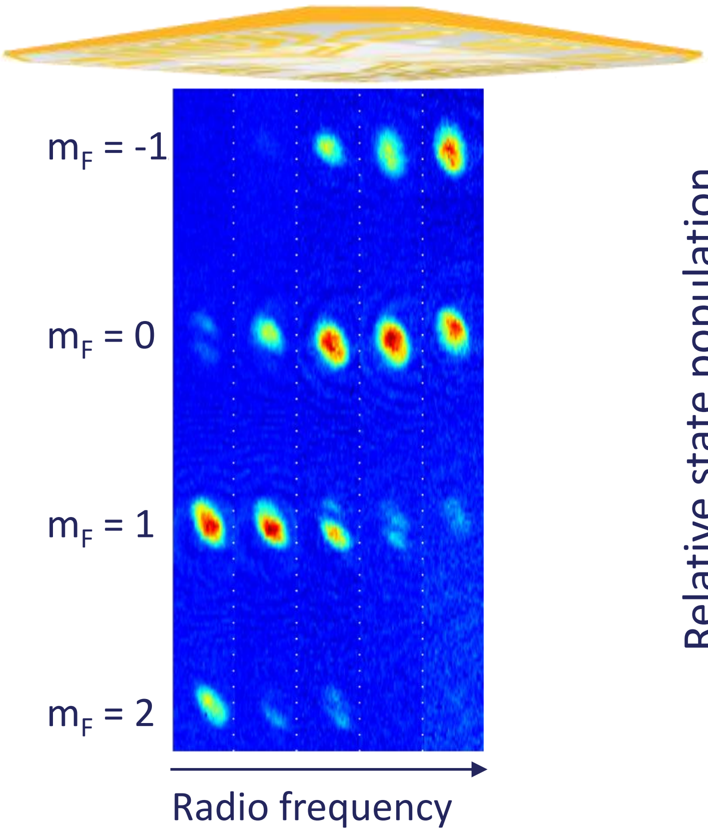


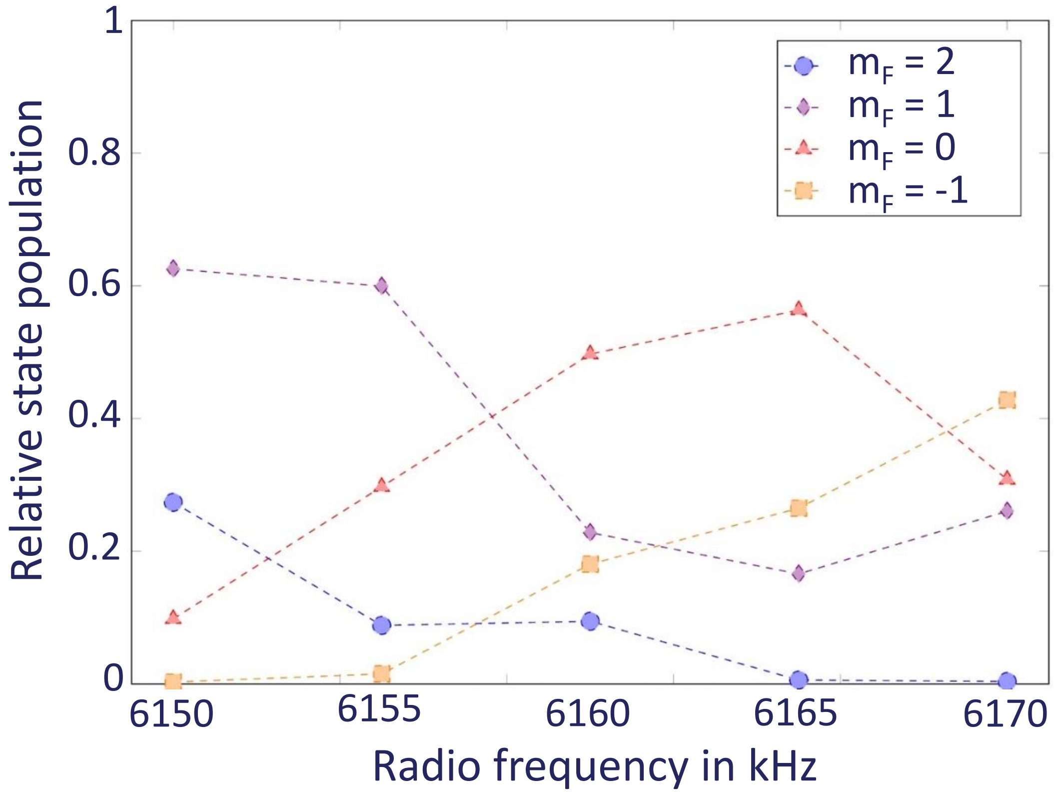
- Initial velocity: 8.8 mm/s
- Expansion rate: 3.3 mm/s



Becker, D., Lachmann, M. D., Seidel, S. T., et al. *Nature* **562,** 391–395 (2018).

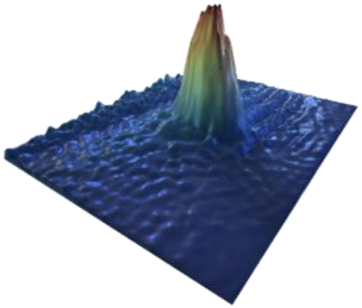
State preparation - Adiabatic rapide passage





Outline

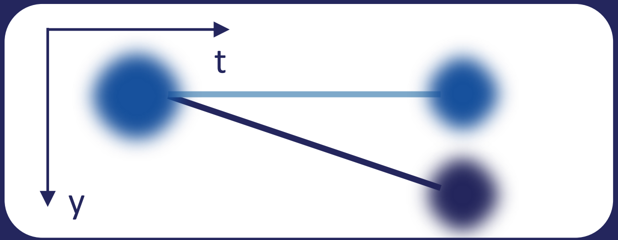
- Setup
- Preparation of ultracold ensembles in space
- **Interaction of light and matter wave**
- Atom interferometry
- Outlook



Manipulation of matter waves using light

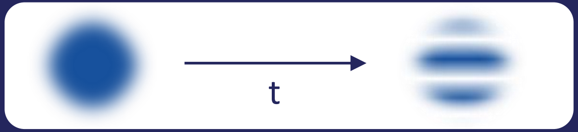
Superposition of momentum states

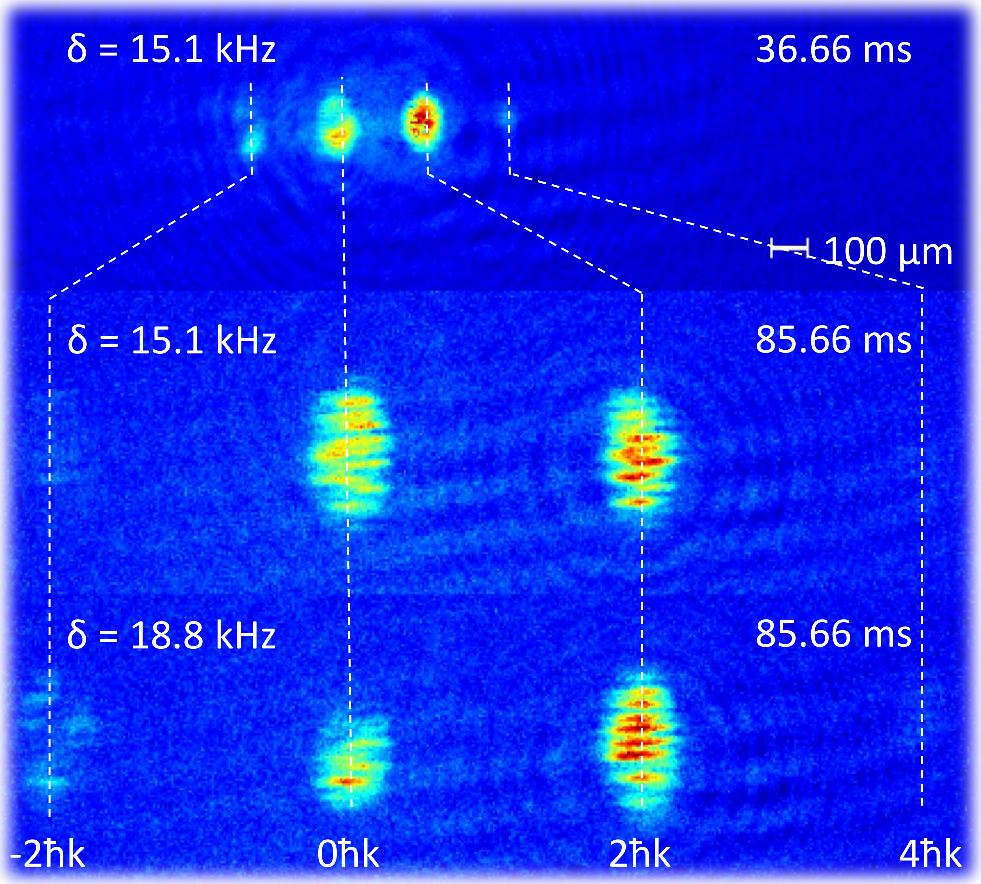
- Multiple-photon processes
- Spatial separation after TOF



Phase imprinting

- Imprinting of phase distribution on wave packet
- Spatial phase gradients define momentum distribution
- Modulated density distribution after TOF

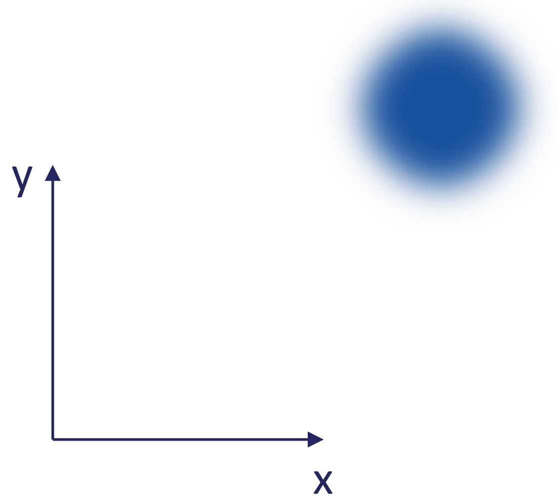




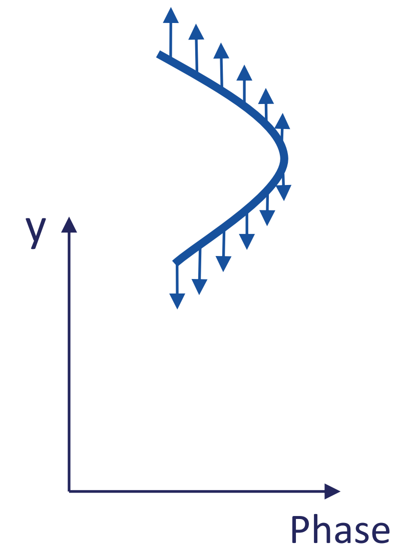
Single interaction, without Stern-Gerlach separation
k: wave number
ħ: Planck constant
δ: differential frequency of light fields

Phase imprinting

2D spatial density distribution

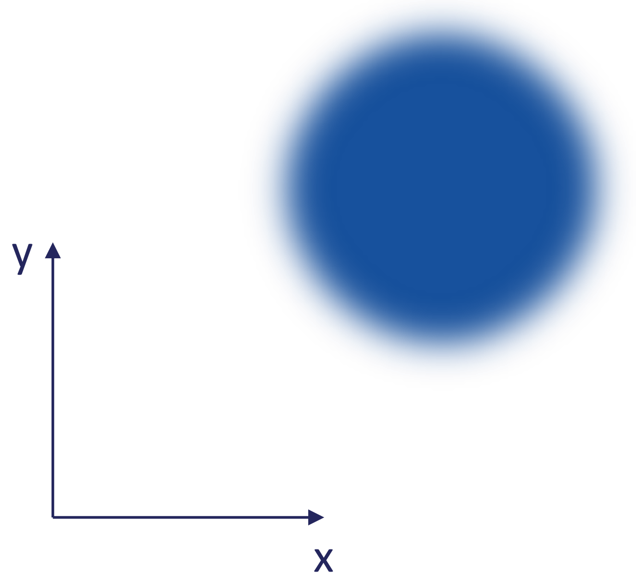


1D phase distribution

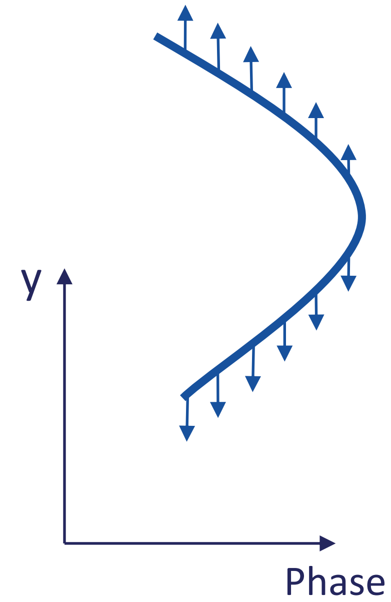


Phase imprinting

2D spatial density distribution



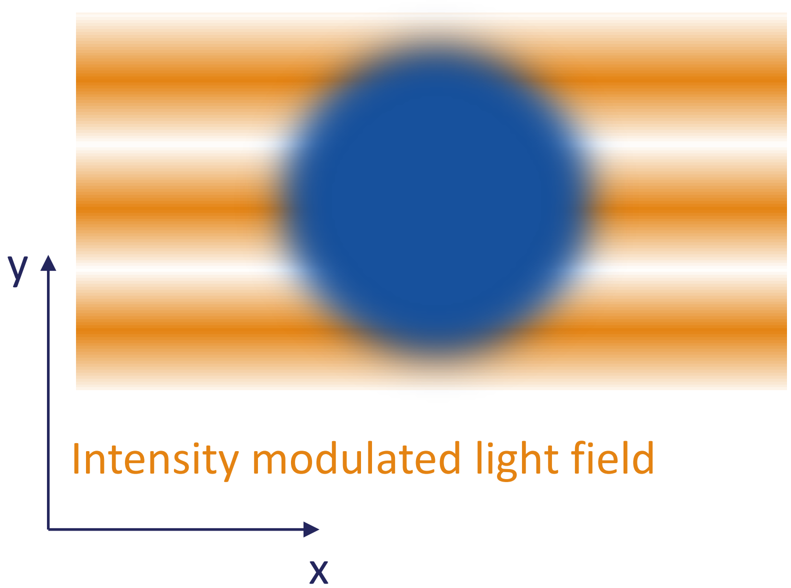
1D phase distribution

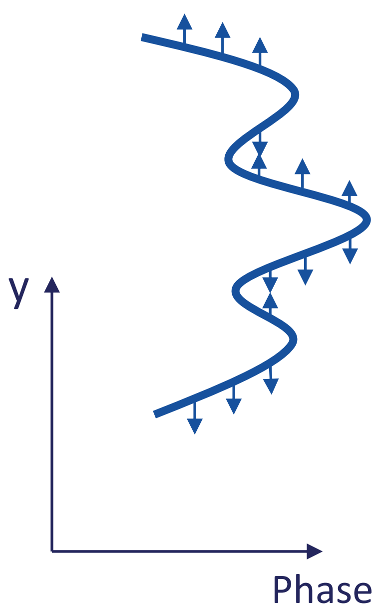


Phase imprinting

2D spatial density distribution

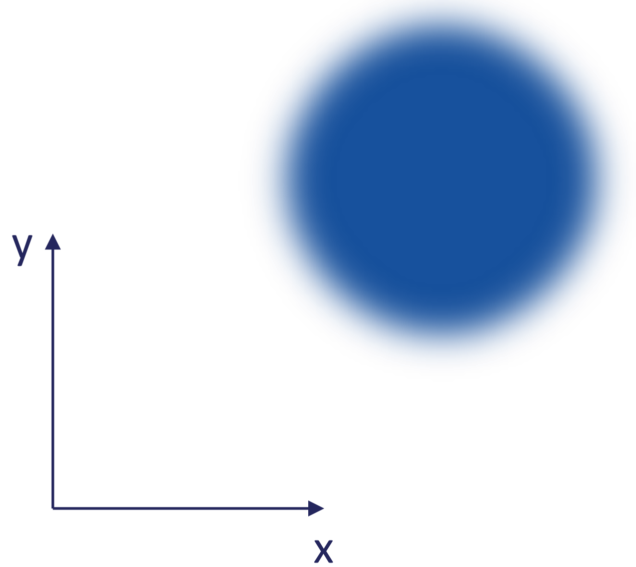
1D phase distribution



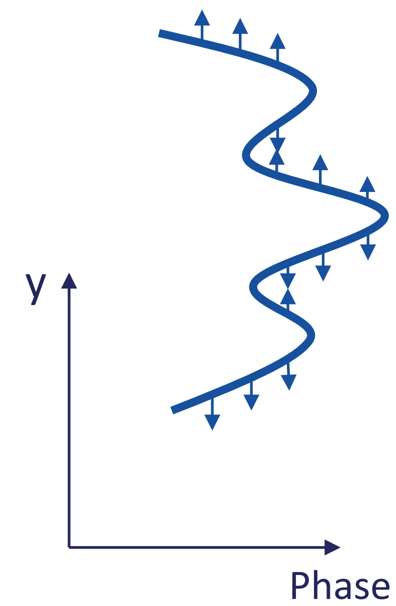


Phase imprinting

2D spatial density distribution

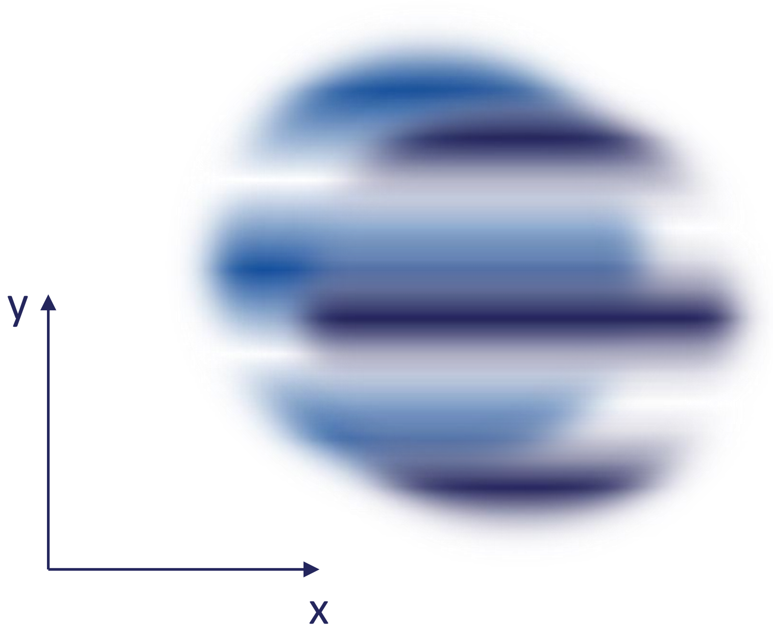


1D phase distribution

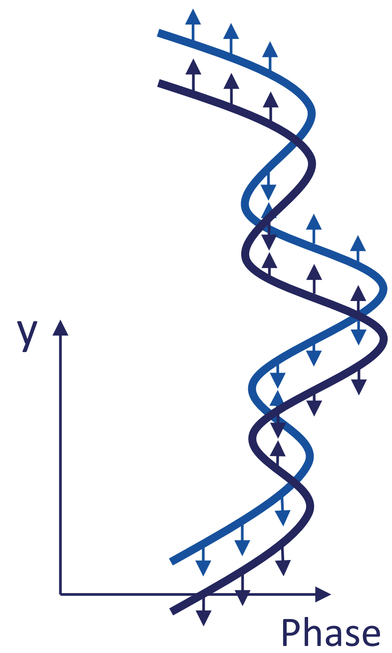


Phase imprinting

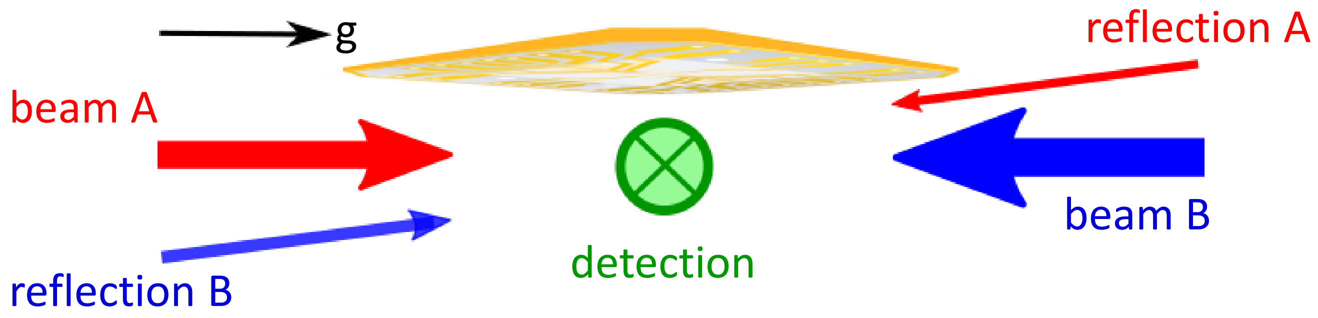
2D spatial density distribution



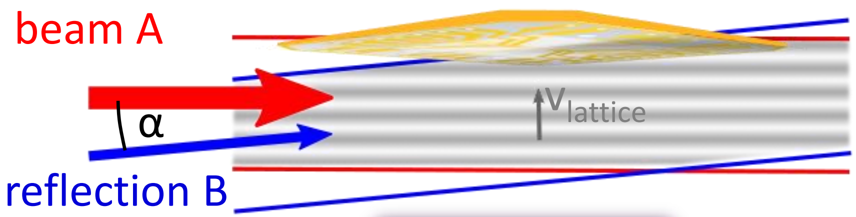
1D phase distribution

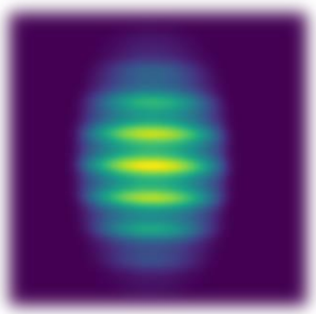


Light configuration

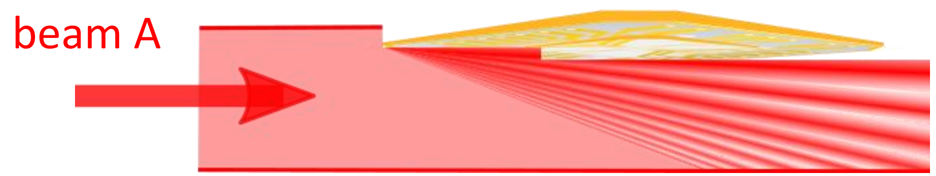


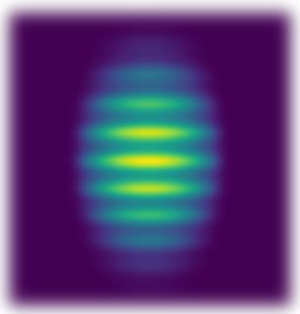
Running lattice





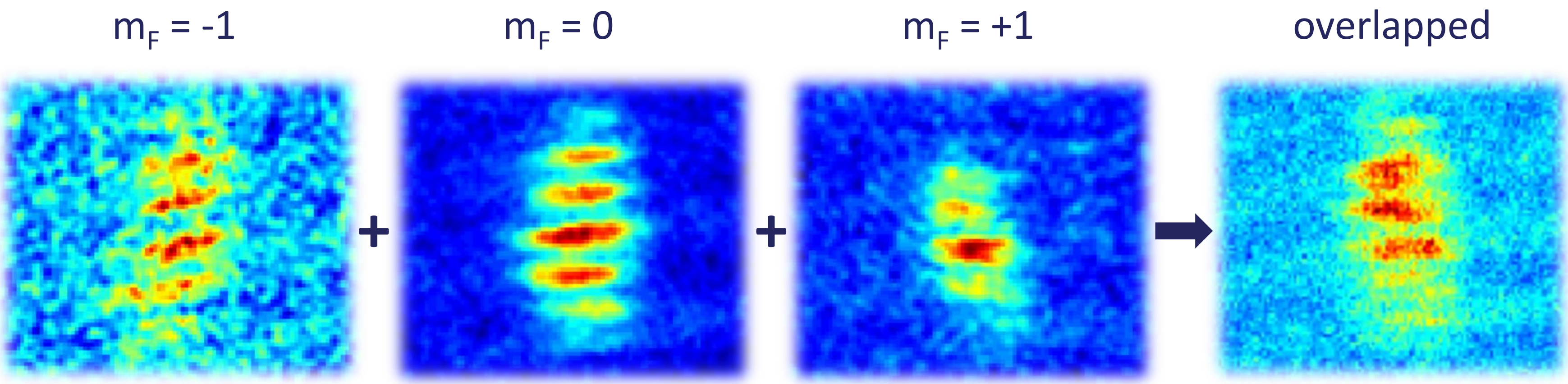
Diffraction on chip edges





Lachmann, M. D., Ahlers, H., et al. *Nature commun* **12,** 1317 (2021).

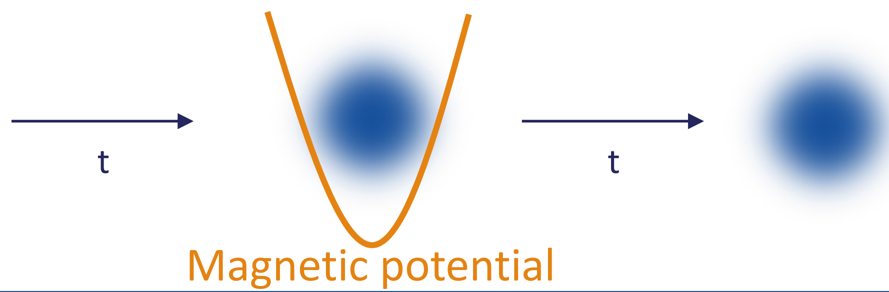
Analysis of environment



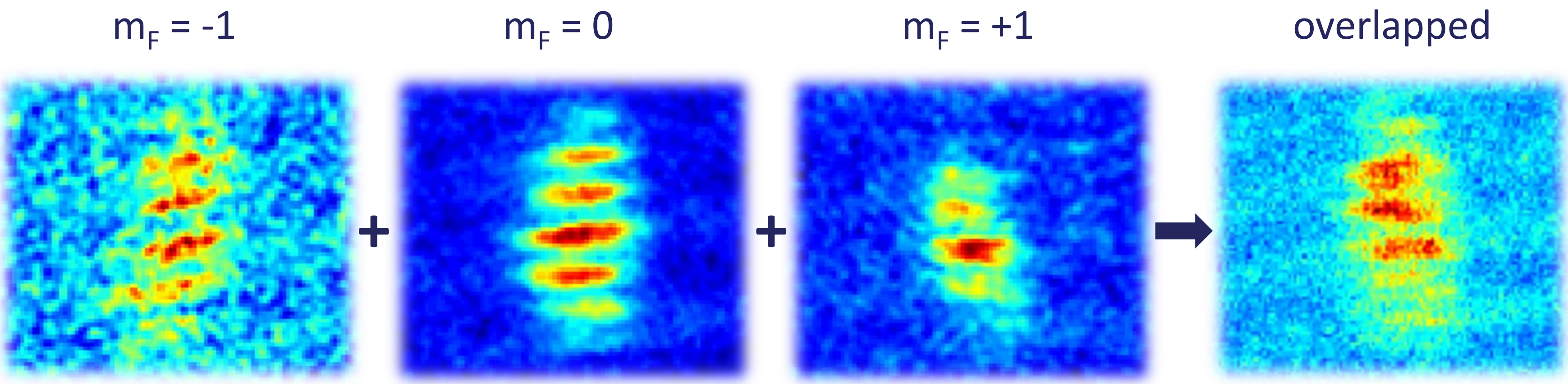
Rotation can be caused by magnetic field curvature with around 3.5 µT/mm^2

Applications for this method:

- Rotations visible
- Shearing visible → characterization of Delta-Kick collimation



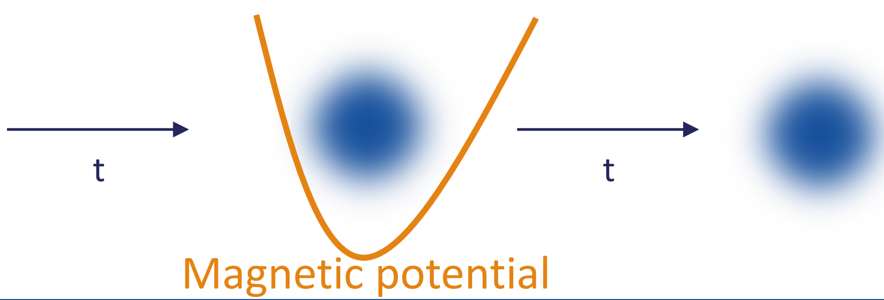
Analysis of environment



Rotation can be caused by magnetic field curvature with around 3.5 µT/mm^2

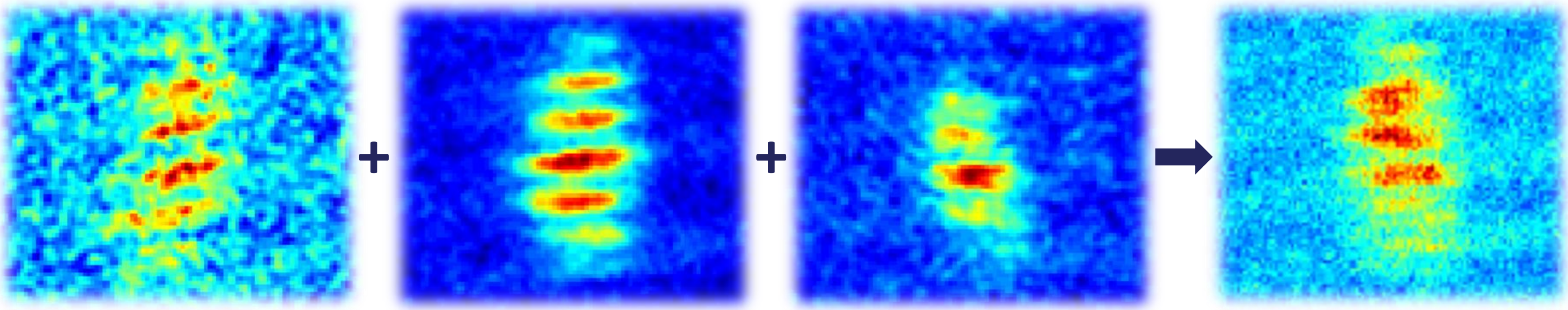
Applications for this method:

- Rotations visible
- Shearing visible → characterization of Delta-Kick collimation



Analysis of environment

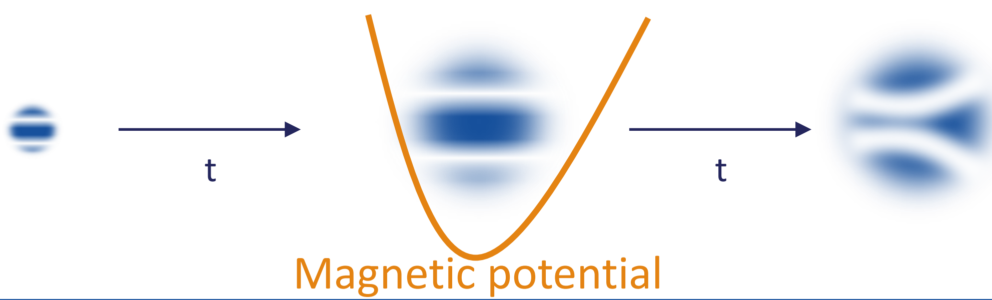
$m_F = -1$ | $m_F = 0$ | $m_F = +1$ | overlapped



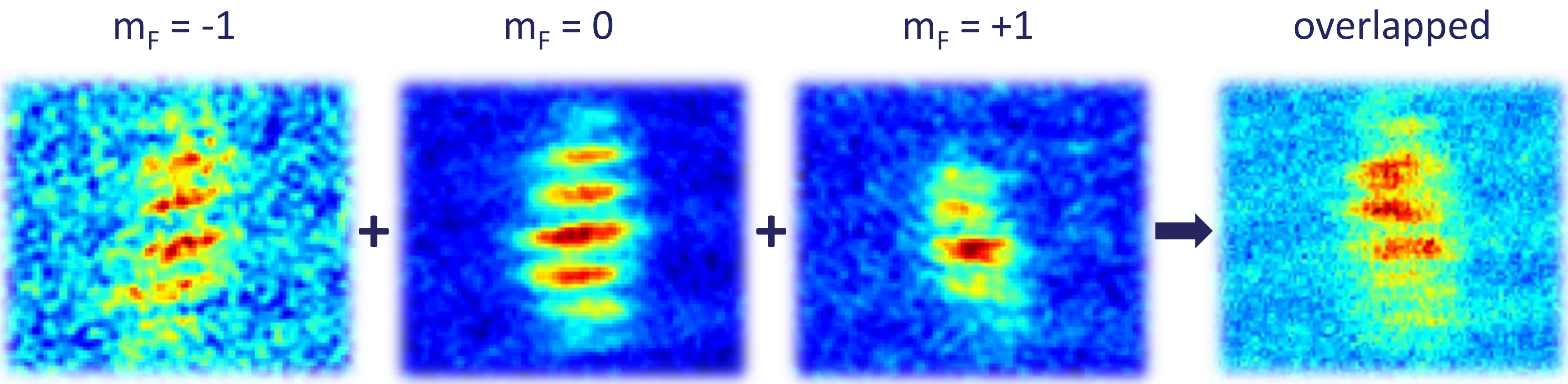
Rotation can be caused by magnetic field curvature with around 3.5 μT/mm²

Applications for this method:

- Rotations visible
- Shearing visible → characterization of Delta-Kick collimation



Analysis of environment

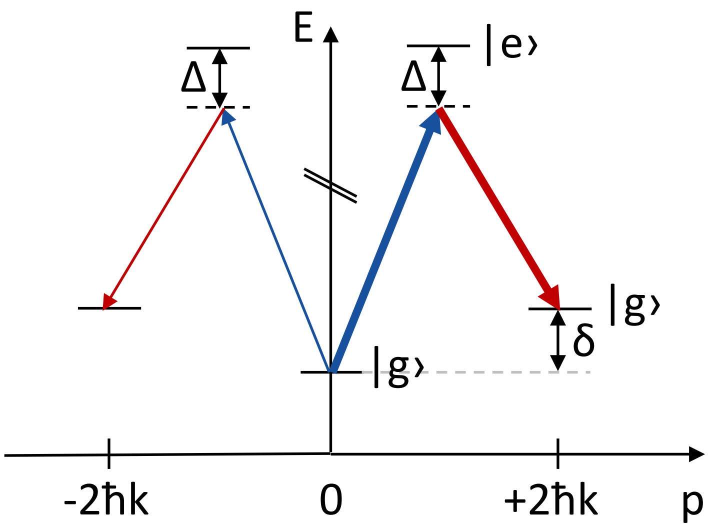


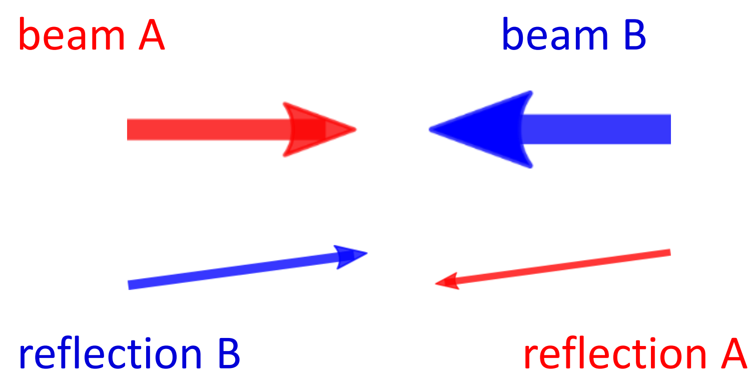
Rotation can be caused by magnetic field curvature with around 3.5 µT/mm^2

Applications for this method:

- Rotations visible
- Shearing visible → characterization of Delta-Kick collimation
- Small movements of different components relative to each other better visible than with envelope → analysis of differential forces
- Extension to different atomic species

Bragg diffraction

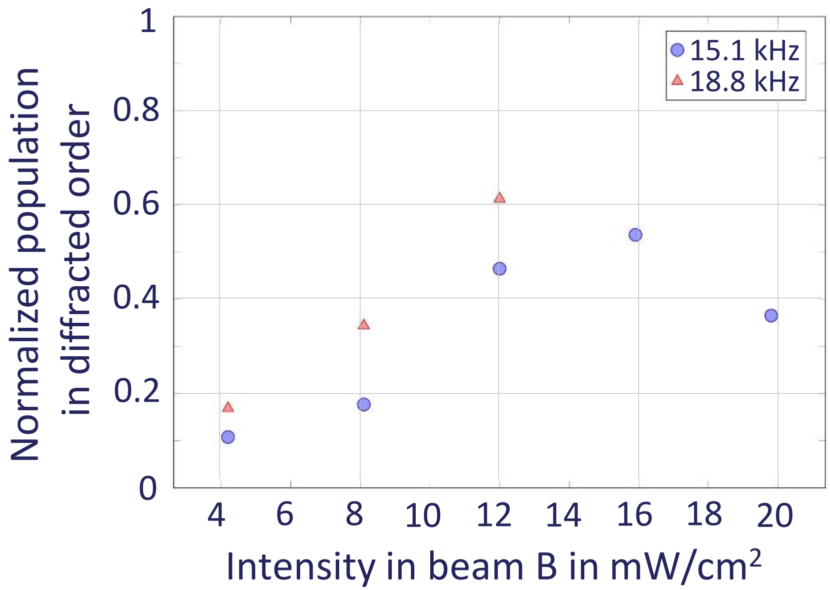




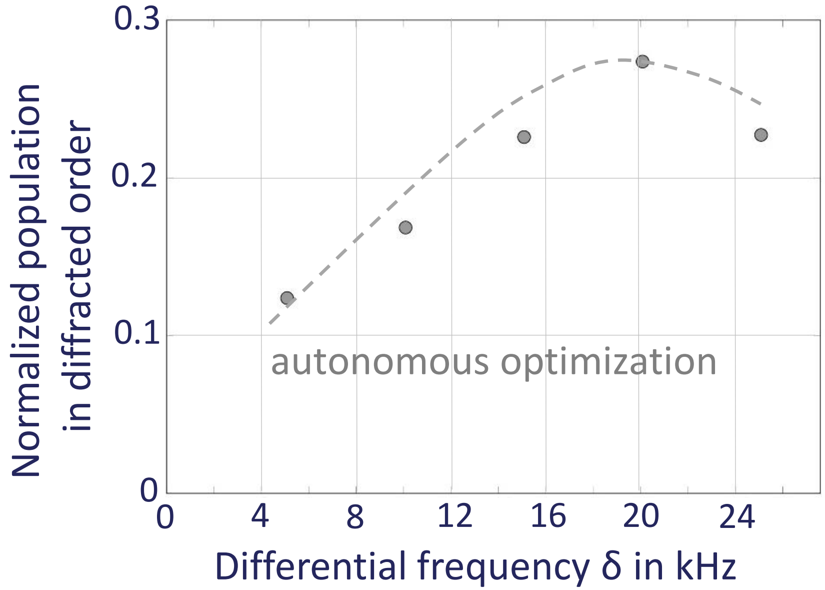
Δ: detuning to atomic transition
δ: Differential frequency ν_A-ν_B
ħ: Planck constant
k: wave number

Bragg diffraction

Rabi oscillation:

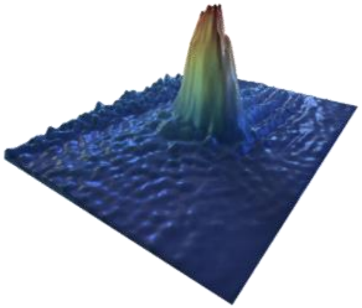


Bragg resonance:

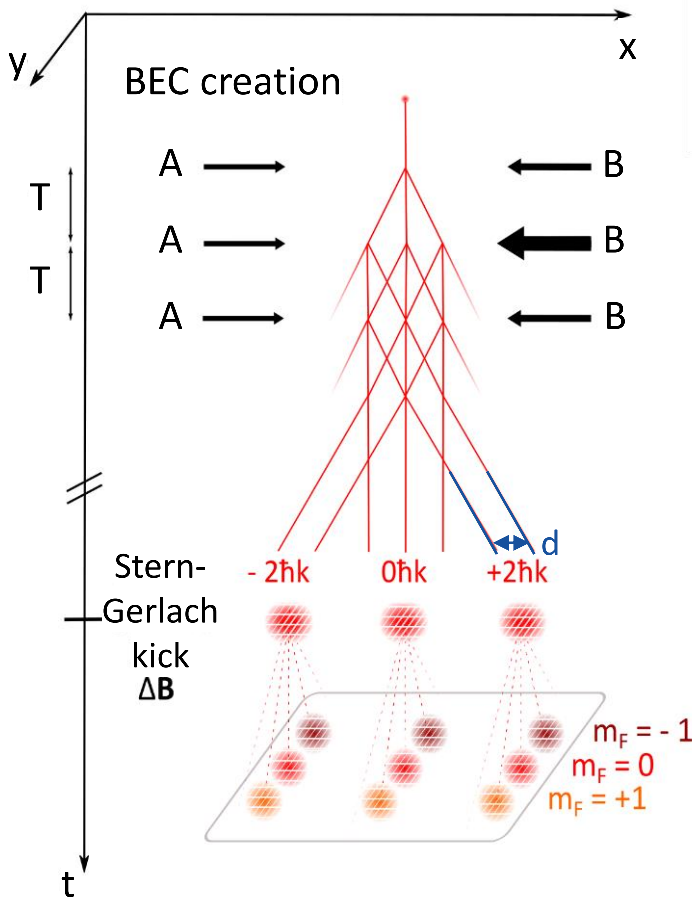


Outline

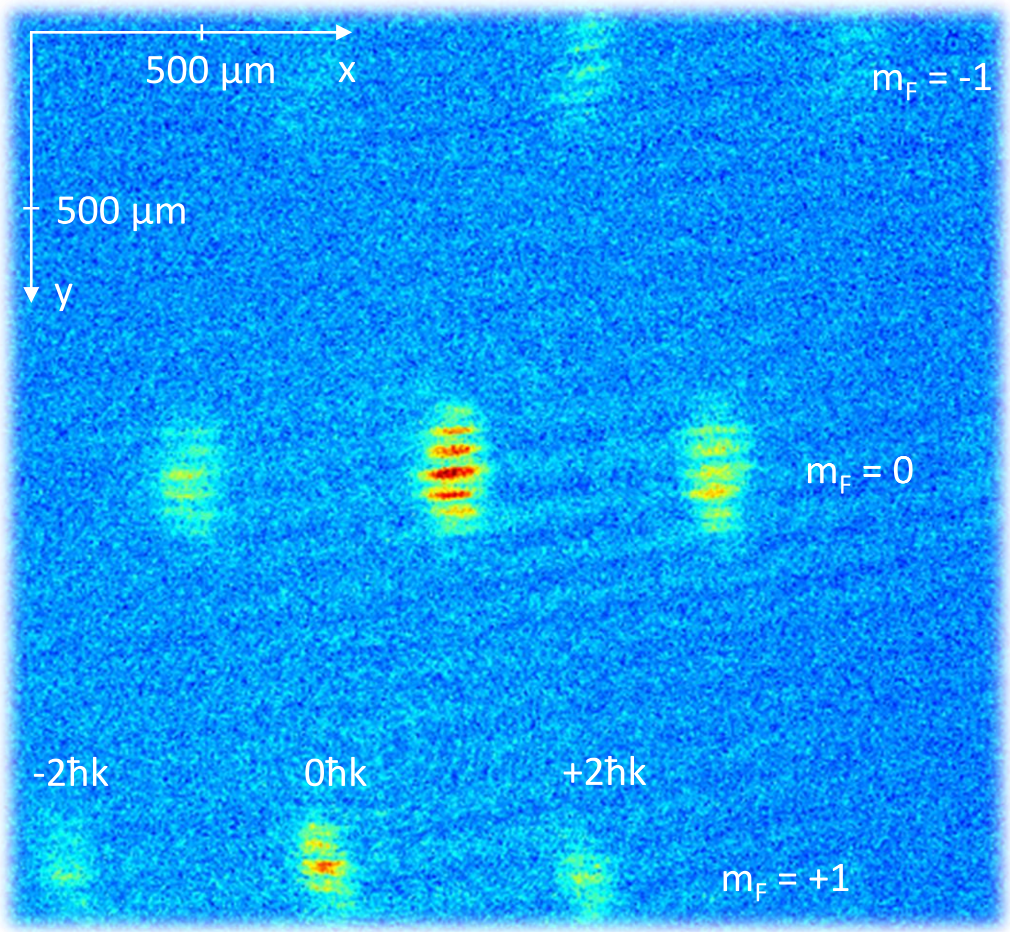
- Setup
- Preparation of ultracold ensembles in space
- Interaction of light and matter wave
- Atom interferometry
- Outlook



Shear interferometry with matter waves in space

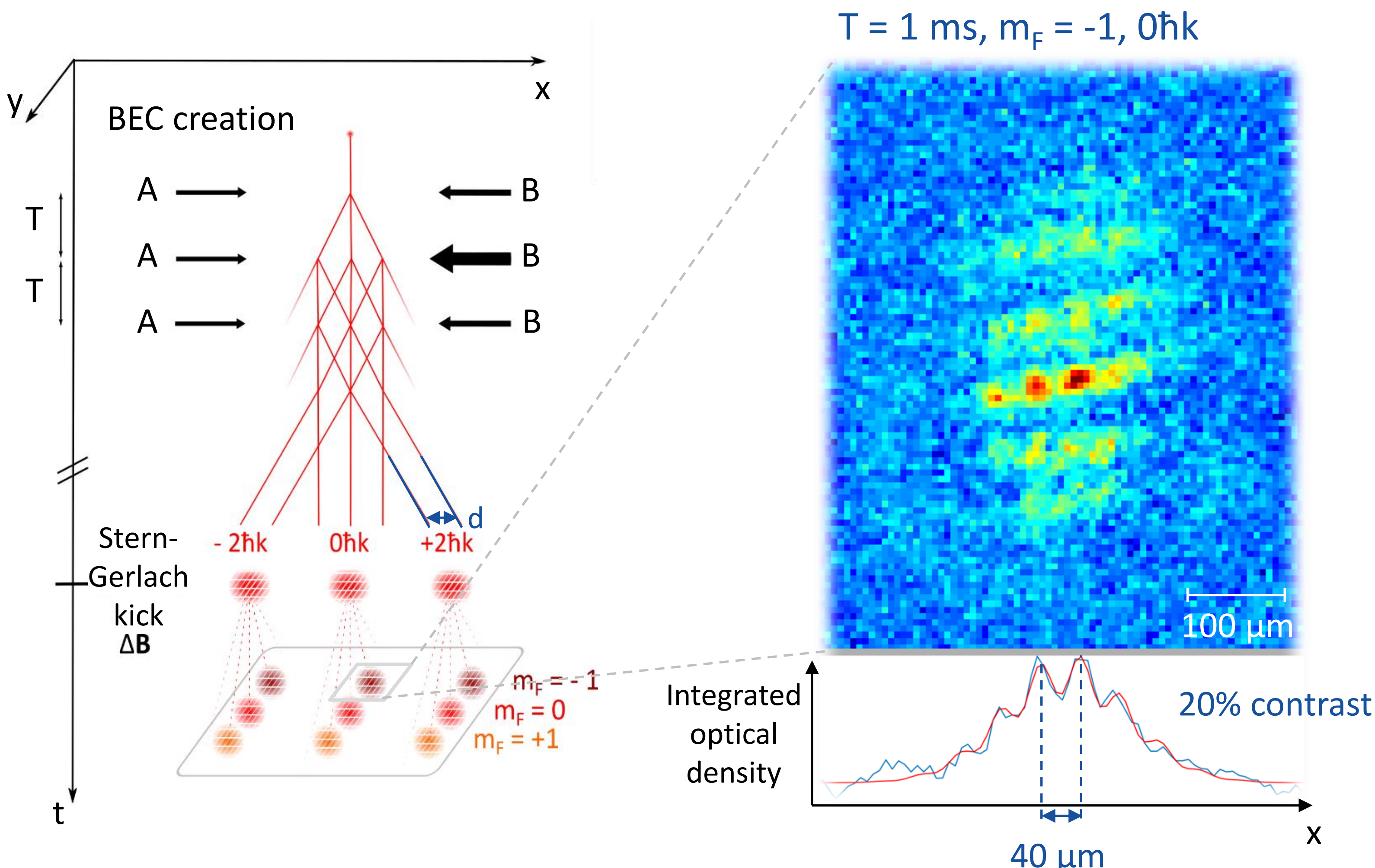


T = 2 ms



Lachmann, M. D., Ahlers, H., et al. *Nature commun* **12,** 1317 (2021).

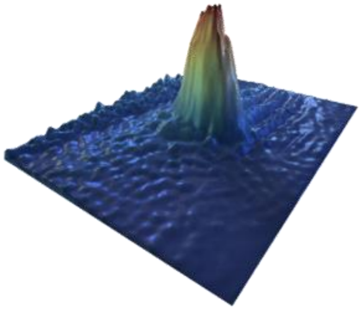
Shear interferometry with matter waves in space



Lachmann, M. D., Ahlers, H., et al. *Nature commun* **12,** 1317 (2021).

Outline

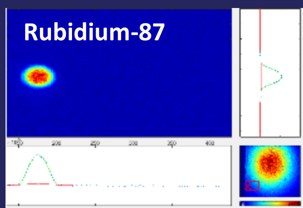
- Setup
- Preparation of ultracold ensembles in space
- Interaction of light and matter wave
- Atom interferometry
- Outlook

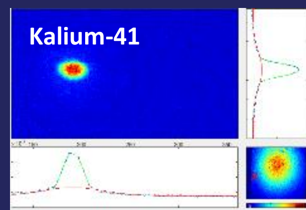


Outlook: follow up missions

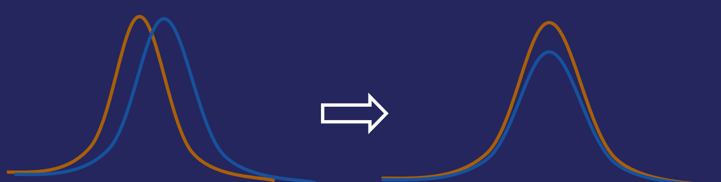
MAIUS-2

- two-species Bose-Einstein condensates

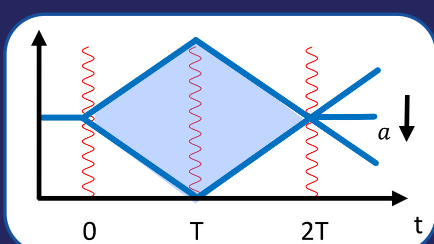




- Studies of mixtures

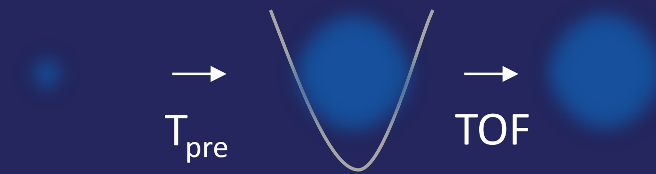


- Sequential interferometry
  - Symmetric Raman diffraction

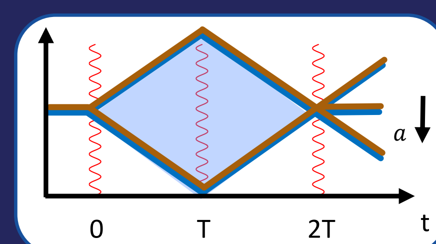


MAIUS-3

- Delta-Kick collimation for K and Rb



- Transport on atom chip for K and Rb
- Simultaneous two-species interferometry



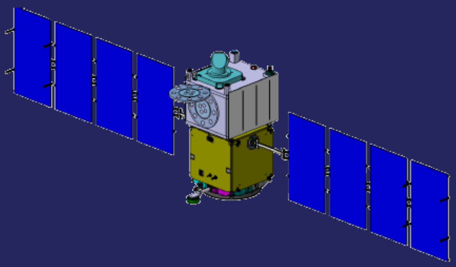
Outlook: Missions in orbit

BECCAL

- Experiments on the International Space Station (ISS)
- Multi-Functions and multi-purpose apparatus
- Studies
  - Many particle physics
  - Spheric potentials
  - Alternative radio frequency out couplings
  - Coherences of up to 5s
- Noise background

STE-QUEST

- Independent satellite
- BECs with 10^6 atoms of ^{41}K and ^{87}Rb
- Tests of the Universality of Free Fall with an Eötvös ratio $\eta < 1 \times 10^{-17}$



Source: White paper for the ESA Voyage 2050 long term plan August 5, 2019

Questions?
Remarks?