Atom Interferometry In Free Fall

A. Landragin and the QUANTUS and ICE teams

Systèmes de Référence Temps-Espace

Le progrès, une passion à partager

Context

- ✓ First atom interferometer: 1991

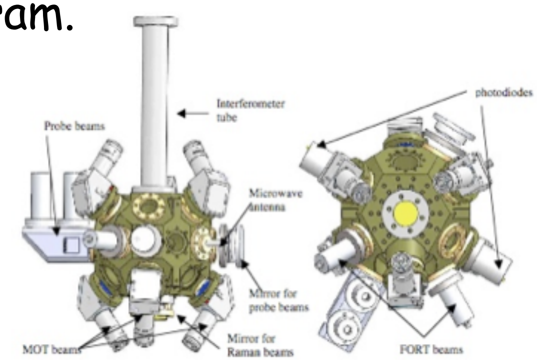
- ✓ First proposal to ESA of Atom Interferometry for a test of fundamental Physics: 2000 (HYPER)
- ✓ Development of ground experiment (gyro, gravimeter, gradiometer…)

- ✓ National programs to develop Atom Interferometry in 0-g (2005-06):

  - QUANTUS program by DLR in Germany
  - ICE Program by CNES in France

- ✓ Other propositions for COSMIC vision 2007 and 2011

- ✓ ESA program (SAI based Italy (G. Tino) 2007: merging national expertise on a ground demonstrator in the frame of the ELIPS program.



AI in Free Fall

National programs to develop Atom Interferometry in 0-g (2005-06):

- QUANTUS program by DLR in Germany
- ICE Program by CNES in France

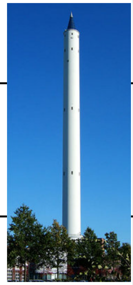
Means:

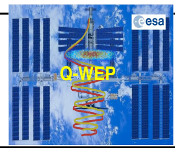
- developing the technology (increasing TRL levels)
- improving science knowledge of cold atom interferometry in Free Fall

Goal: to prepare for next calls

Platforms for experiments in extended free fall

platform	µg-quality [g]	µg-duration
ground	10^{-6}	1-2 seconds
droptower	10^{-6}	4.8 s, 9s with catapult
airplanes	10^{-2}	20 seconds
ballistic rockets	10^{-5}	up to 6 minutes
space carrier	10^{-6}	3 days
ISS	10^{-4}	days to years
Dedicated satellite	10^{-7}	2-5 years





Outline

1. ICE : test of EP in 0-g plane
2. QUANTUS: Chip based AI in free fall
3. Conclusion

Outline

1. ICE : test of EP in 0-g plane
2. QUANTUS:
3. Conclusion

The I.C.E. project:
Towards a test of the Universality of Free Fall with atoms in 0-G plane

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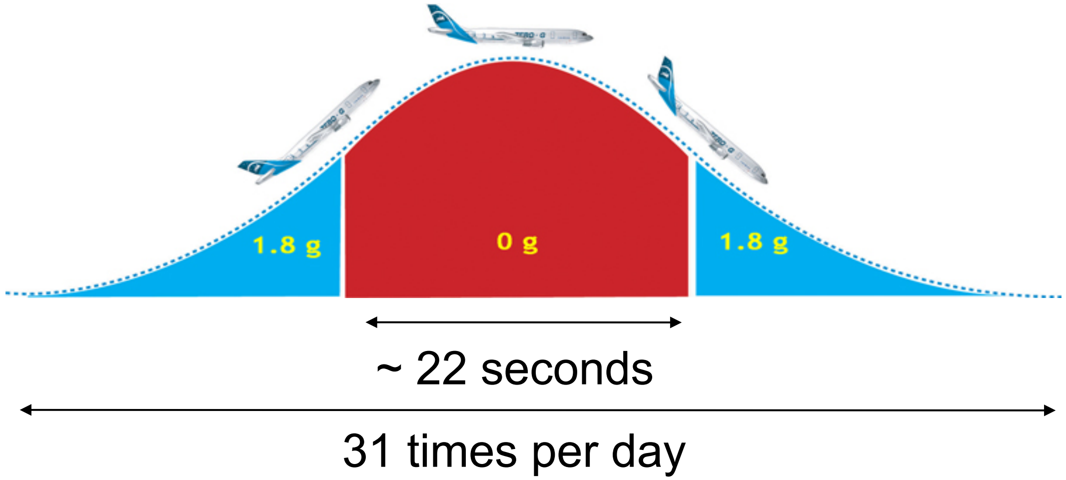
LNE-SYRTE, Observatoire de Paris

The I.C.E. setup in the flying lab

- Demonstrator for test of EP in Free fall in 0-g plane
- Choice of the ^{87}Rb and ^{39}K atoms: ratio of mass and composition
- Fiber laser sources @ 1560 nm and 1534 nm, second harmonic generation → 780 and 767 nm for cooling and manipulating atoms
(Reliability of telecom lasers)
- 4 racks, 700 kg, 1000 W power consumption

An aircraft as experimental platform

Novespace A300-0g Airbus (Bordeaux, France)



- 3 flight days in a campaign: microgravity total time ~ 30 minutes
- Measurement during 1-g and 0-g phases
- Rate of measurement: 500 ms (40 measures per parabola)

Experimental conditions

Transportability

Laboratory →plane

Thermal environment

5°C → 30°C

Stabilization duration

<3h

Vibrations

0,5 $m.s^{-2}$ in flight+ shocks (transport, takeoff, landing)

Modular experiment

Passive pumping for the vacuum system

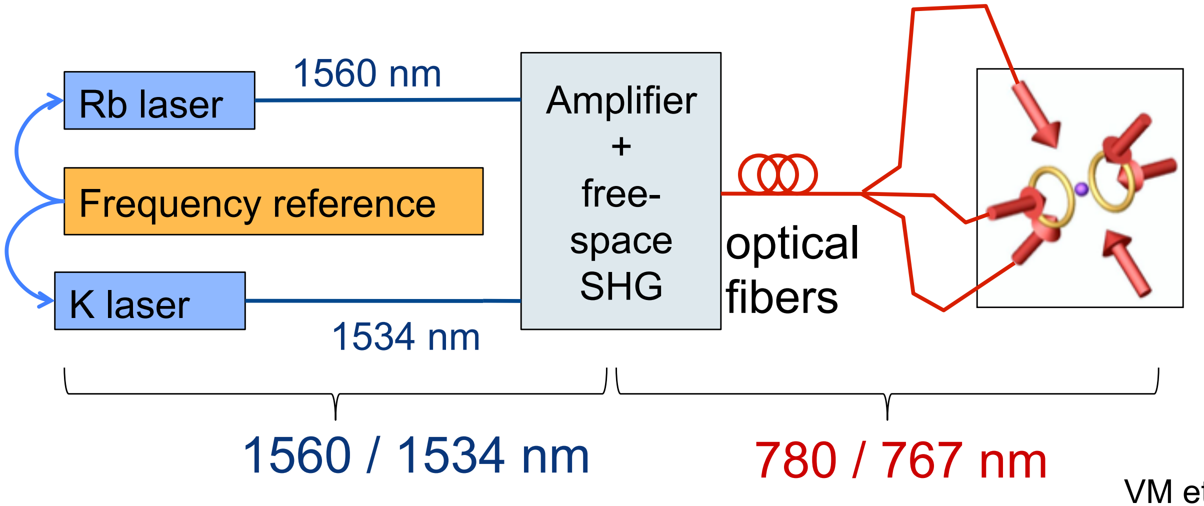
Laser system: telecom + frequency doubling

fibered, robust

…

Laser system

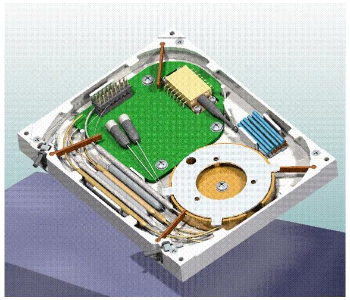
- Two-wavelength laser system
  - Rb : 780 nm
  - K : 767 nm
- Second Harmonic Generation from telecom lasers @ 1560 and 1534 nm
  - Fibered qualified components
  - Robust against temperature fluctuations and vibrations
- Common frequency reference
  - Self-referenced optical frequency comb (Menlo Systems)

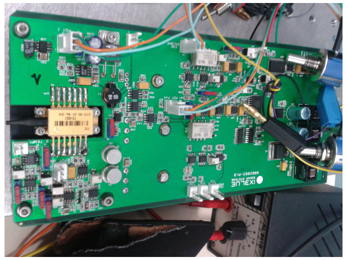


VM et al. Opt. Lett. **36**, 21 (2011)

Telecom components

- Transportable, robust, no problem with vibrations (no mechanical thickness, good for weight)
- Long lifetimes (25 years)





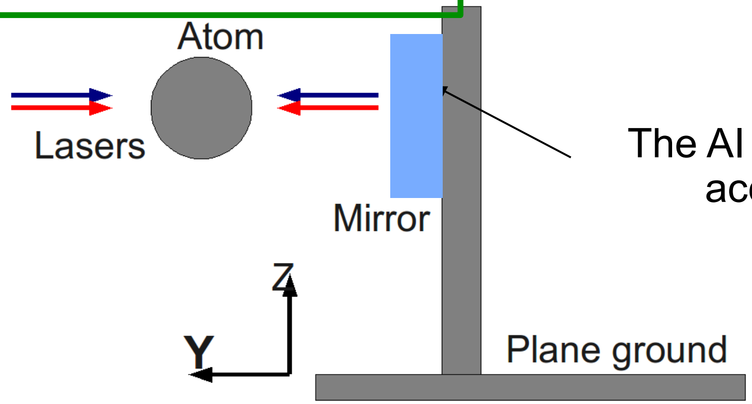
- Very convenient for modifications and assembling (fiber soldering, no global mechanical design modification)

- Wide and established market : no supply concern for the next 50 years
- Telcordia qualified (very demanding standard but nothing for radiation)
- Tests on temperature, aging, vibration, humidity…

Precise acceleration measurements with Rb

Problem: large acceleration fluctuations $\delta a_m \sim 0.5\ m.s^{-2}$

$$\sigma_\Phi = k.T^2.\sigma_a > \pi$$



AI output signal:

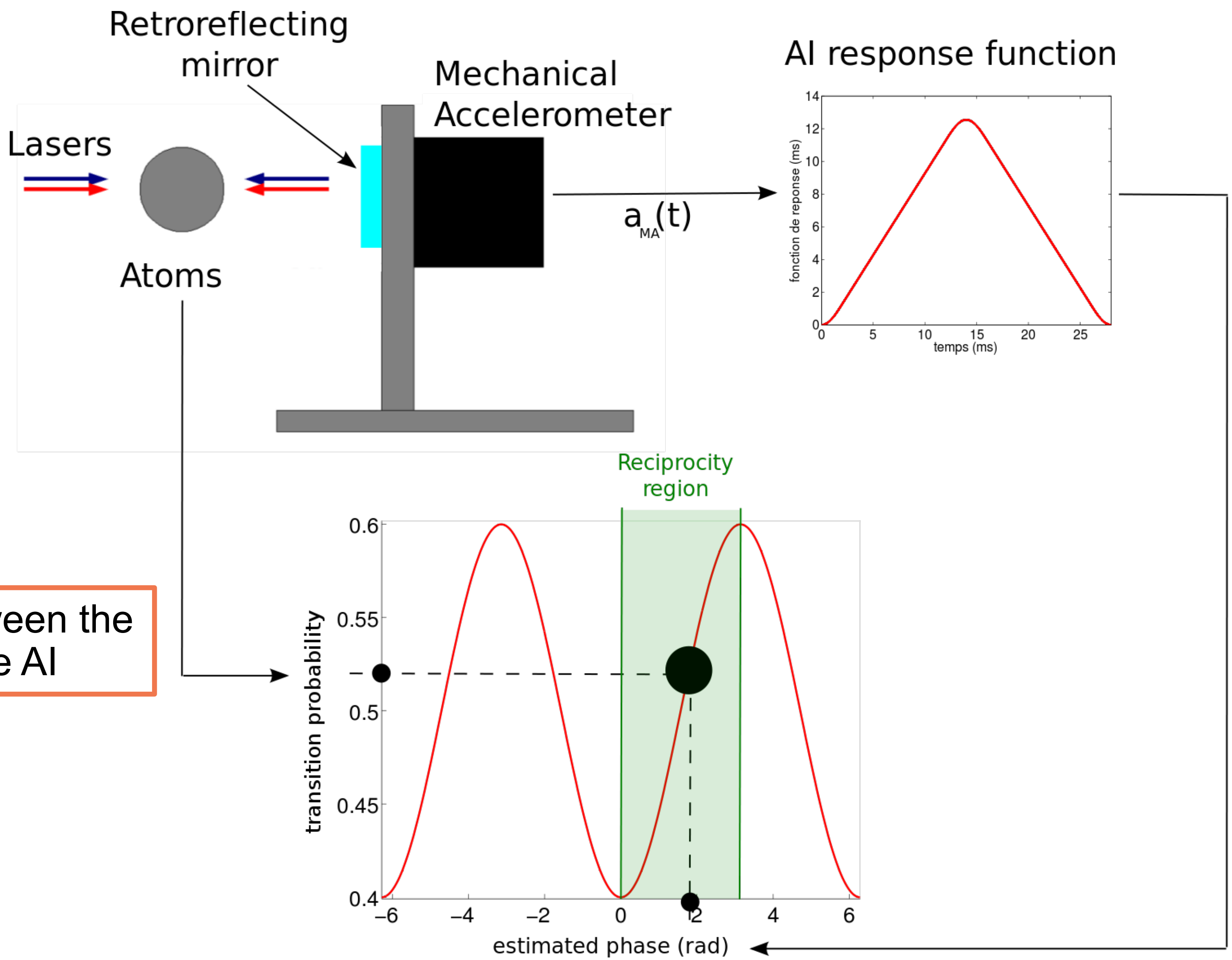
$$P = P_0 - A\cos\Phi$$

Link is lost if Φ>π
(non-reciprocal response of the AI)

Solution to overcome the non-reciprocity problem:

1. Use an external device to measure the coarse accelerations
2. Use the AI for the high resolution measurement

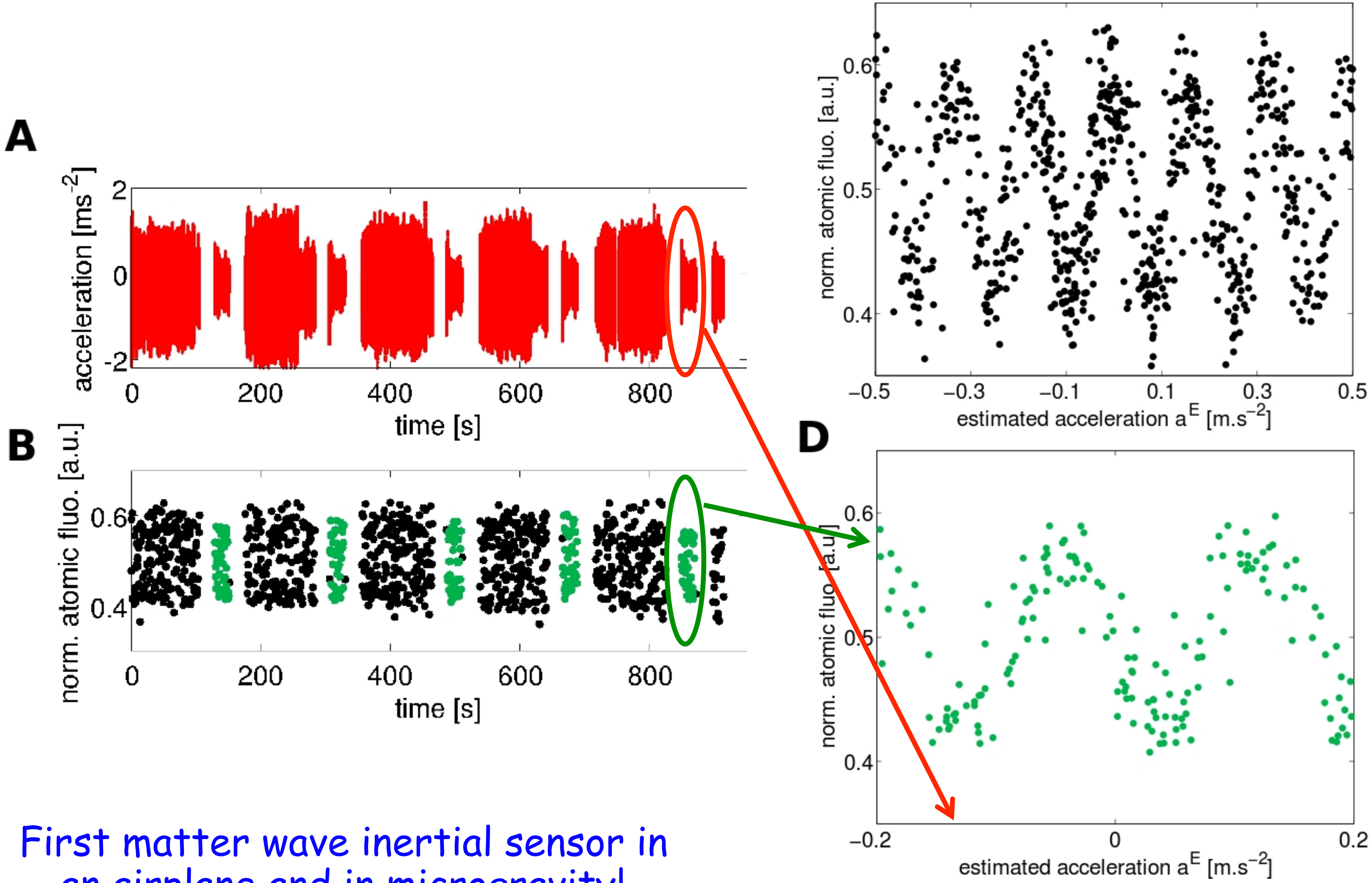
Correlation method



Correlation between the MAs and the AI

From S. Merlet, et al.
Metrologia 46 (2009), 87–94

MAs-AI correlations



1-g

0-g

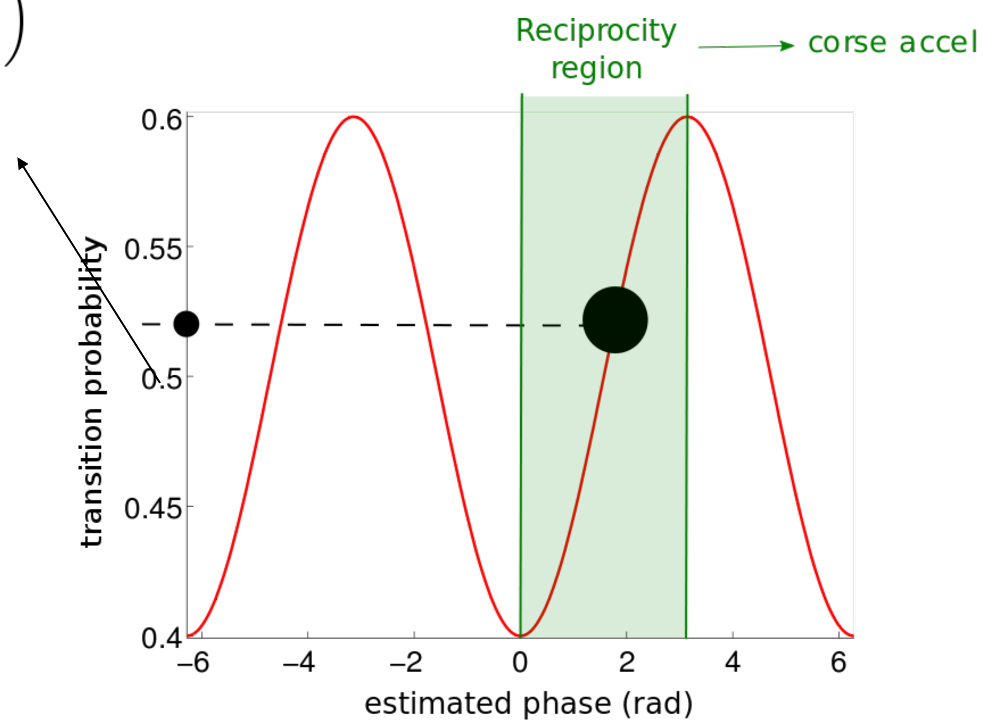
First matter wave inertial sensor in an airplane and in microgravity!

R. Geiger et al, Nature Comm. **2**, 474 (2011)

Two-step acceleration measurement

✓ Coarse measurement with the MAs → fringe number where the AI operates every shot
✓ Fine measurement with the AI, within its reciprocity region

$$\tilde{a}(t_i) = \frac{1}{kT^2} \arccos\left(\frac{P_0 - P(t_i)}{A}\right)$$



Acceleration sensitivity determined by:
- Interrogation time (T)
- SNR of the interferometer

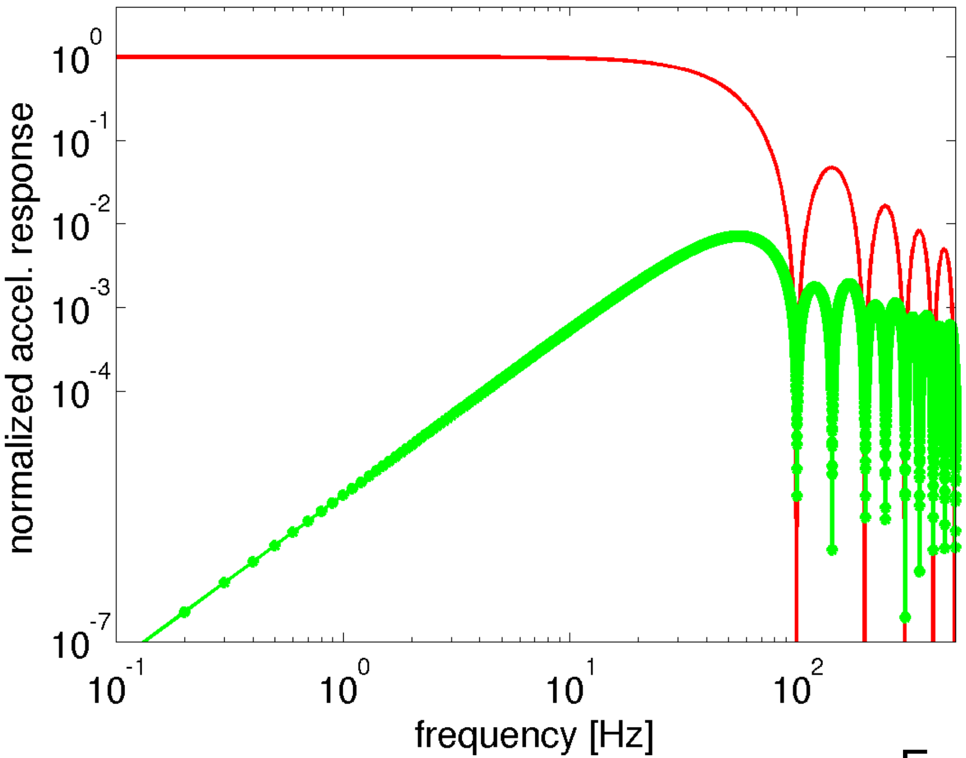
Resolution of the accelerometer: 300 times below the vibrations level in the plane!
Final sensitivity of 2.10^{-4} $m.s^{-2}.Hz^{-1/2}$

Limited by performances of the MAs at low frequencies

Vibration rejection in a two-species AI

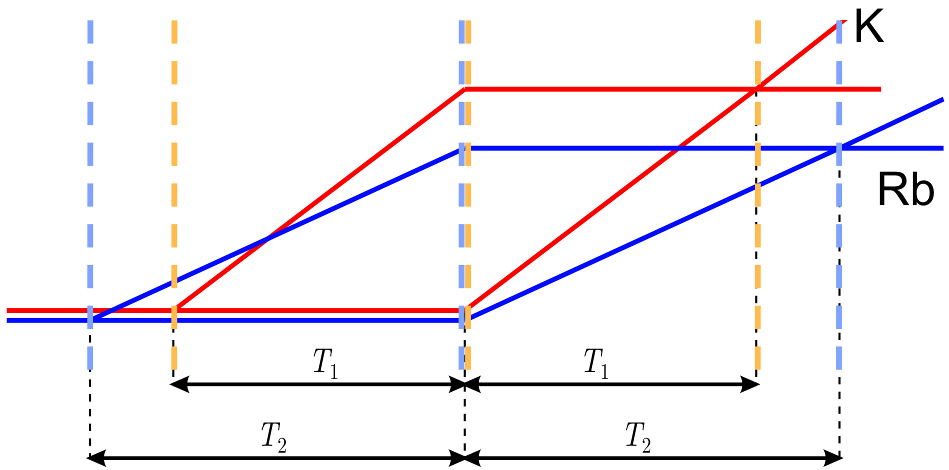
Close interrogation wavelengths:
λ_{Rb}= 780 nm / λ_K = 767 nm

→ Almost simultaneous operation
→ efficient vibration noise rejection



K- and Rb- interferometers with equal scale factor:

$$k_1 T_1^2 = k_2 T_2^2 = \mathcal{S}$$

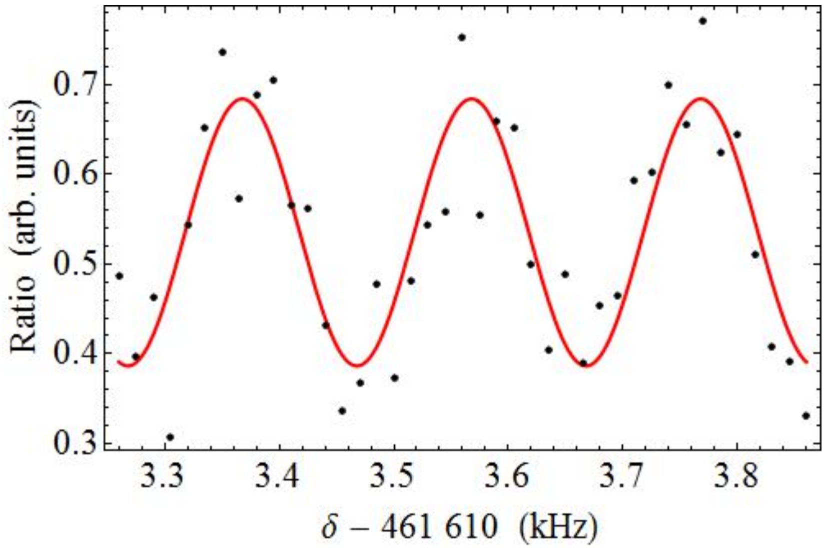


Expected rejection efficiency in the plane > 300

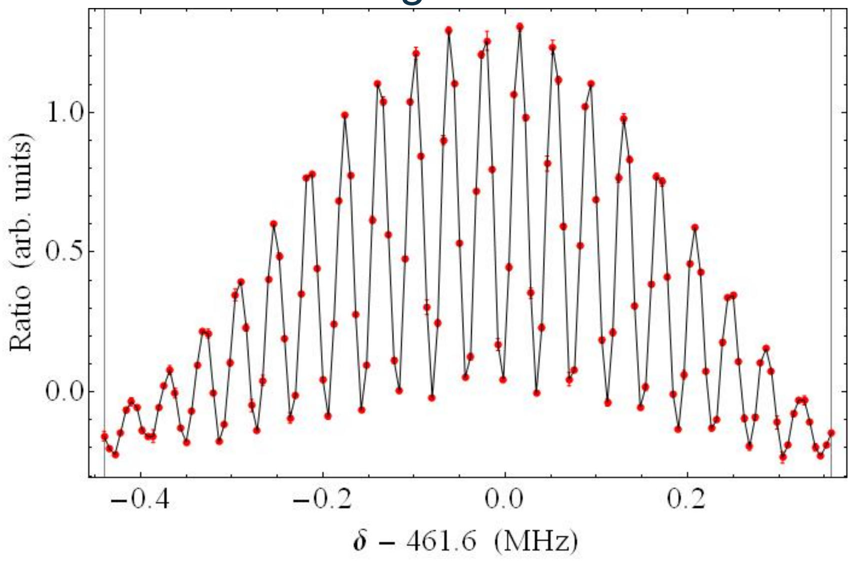
G. Varoquaux et al. NJP **11**, 113010 (2009)

Ramsey fringes with 39K in 0-g

In 0-g



On ground



T=5 ms

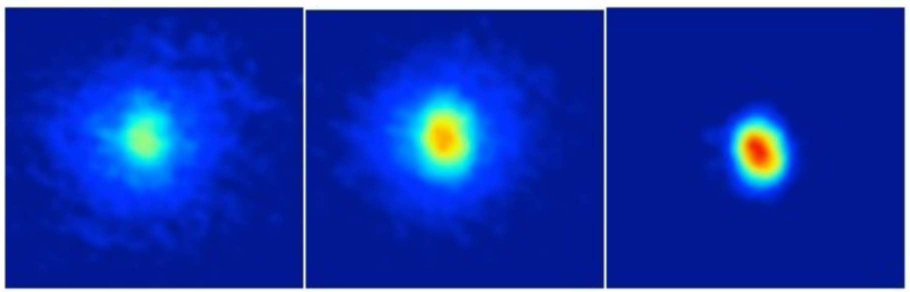
Co-propagating Raman transition (σ+-σ+ polarization)

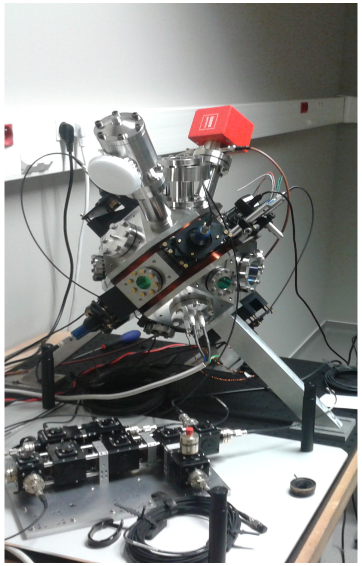
"Clock": π/2-π/2 interferometer

T_{max}= 15 ms in the plane

Next step under preparation

- Demonstrate K interferometer in 0-g (next week?)
- Dual interferometer Rb/K in 0-g plane
- Use of Ultra cold atoms in Dipole trap for extended time dual specie atom interferometry (use of same telecom laser for Dipole trap)





J.-F. Clément, et al. PRA 79 061406(R) (2009)

Outline

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2. QUANTUS: Chip based AI in free fall
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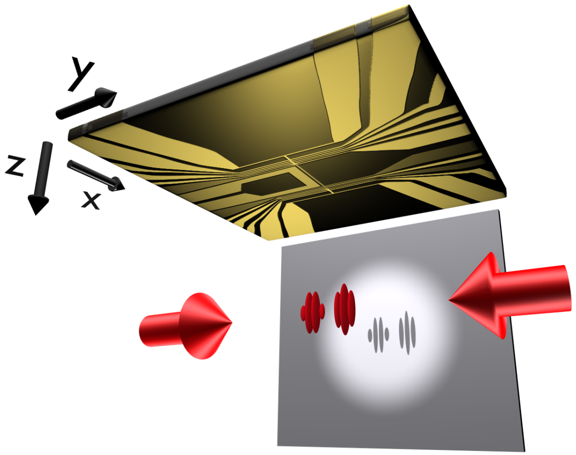
QUANTUS

Chip-based AI in extended free fall



QUANTUS

Leibniz Universität Hannover

MPQ

ZARM

DLR

ECOLE NORMALE SUPERIEURE

HUMBOLDT-UNIVERSITÄT ZU BERLIN

UH

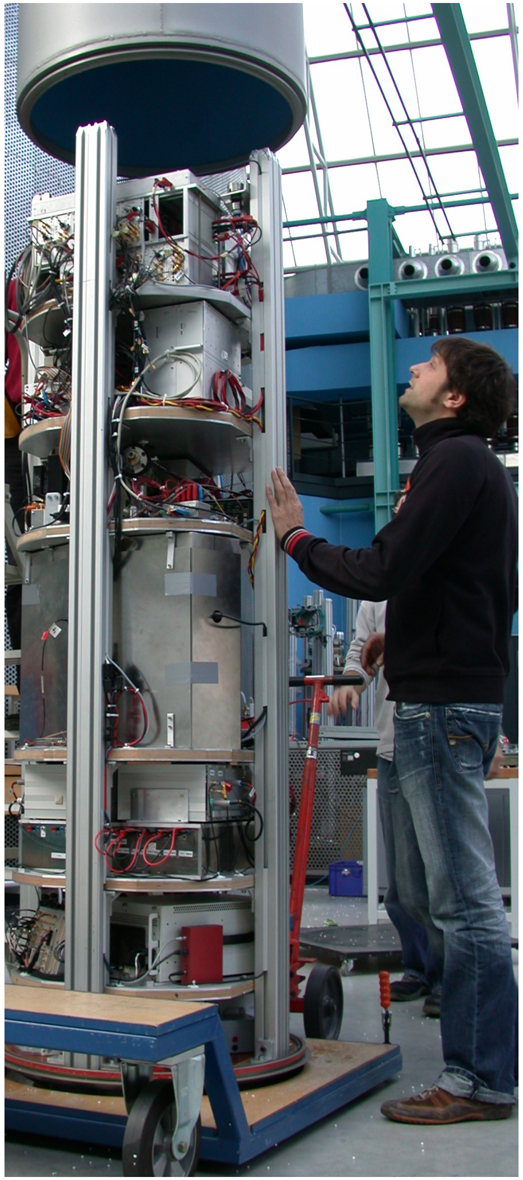
FBH

UNIVERSITÄT ULM · SCIENDO · DOCENDO · CURANDO ·

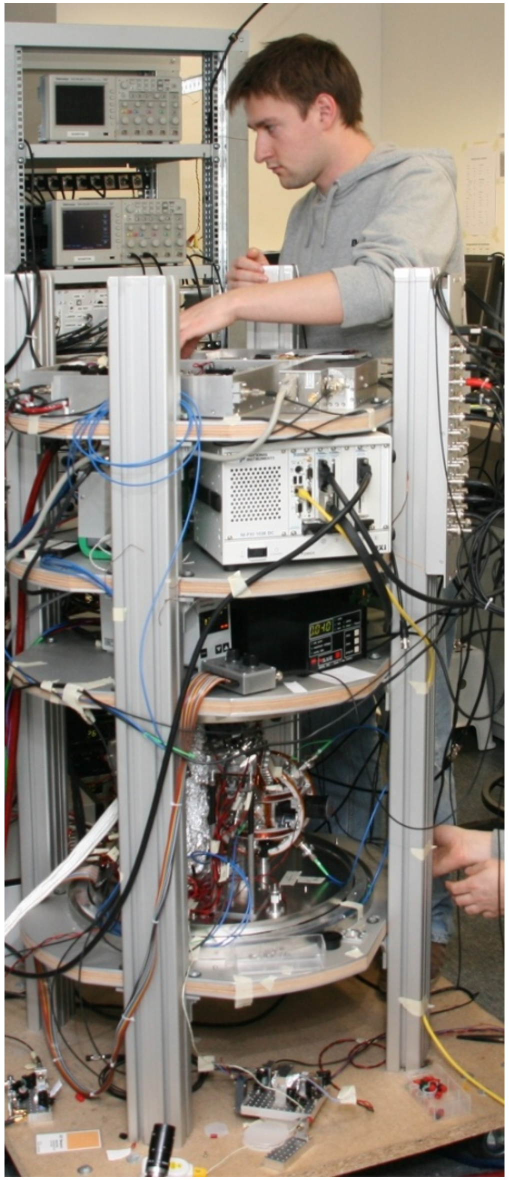
TECHNISCHE UNIVERSITÄT DARMSTADT

QUANTUS

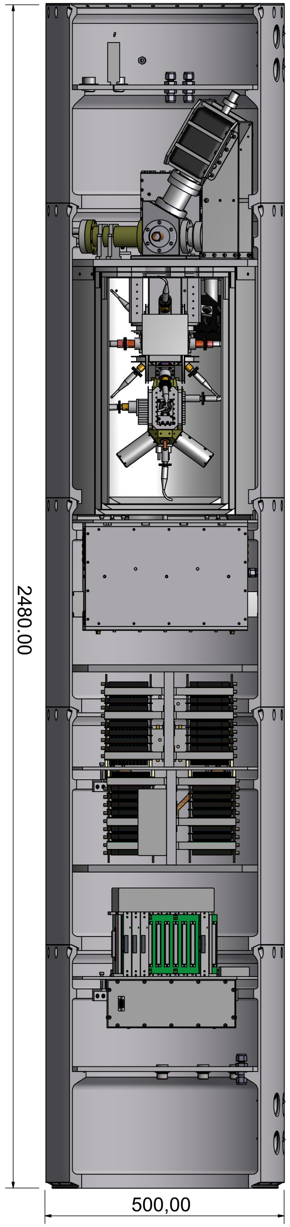
QUANTUS I



QUANTUS II

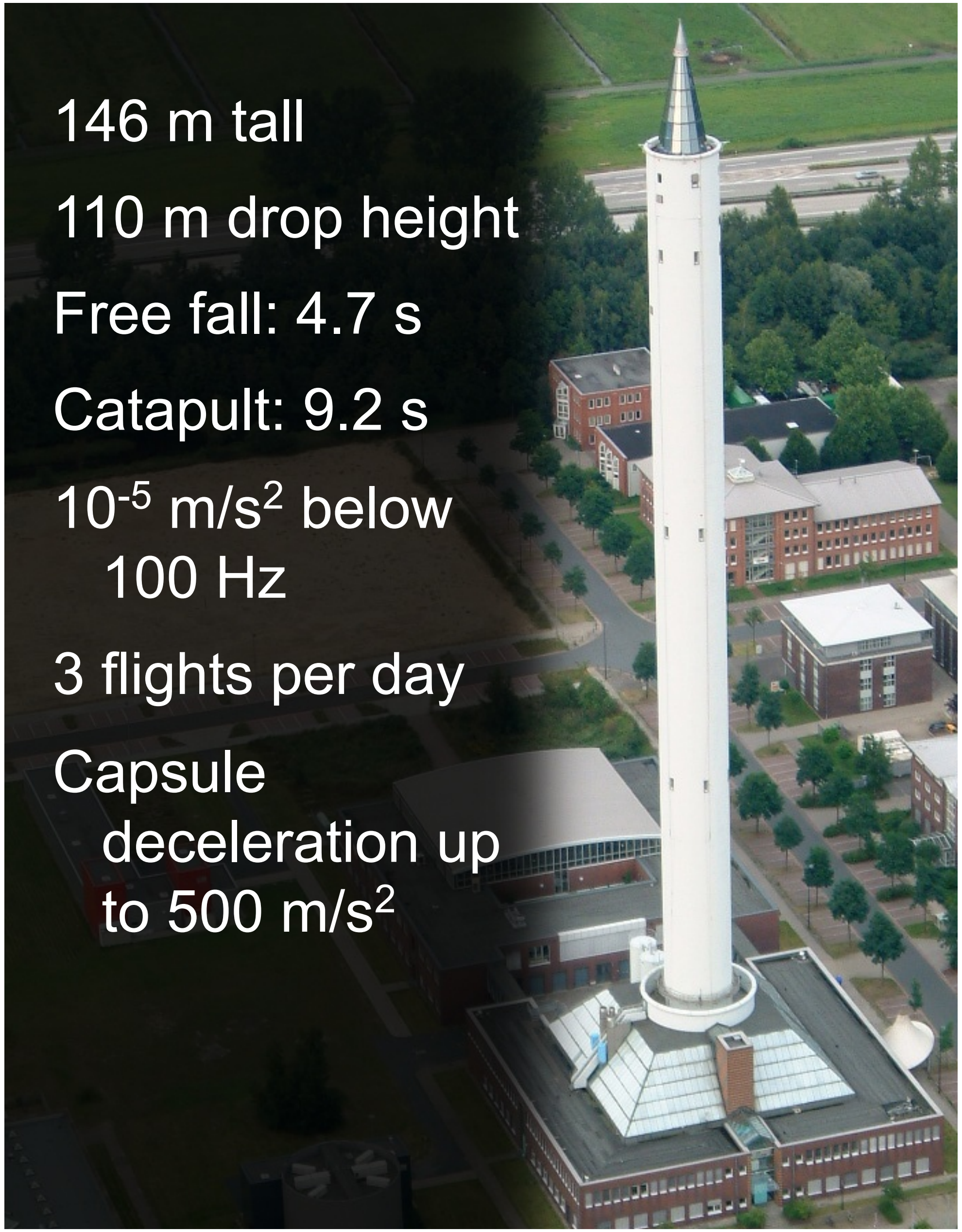


MAIUS

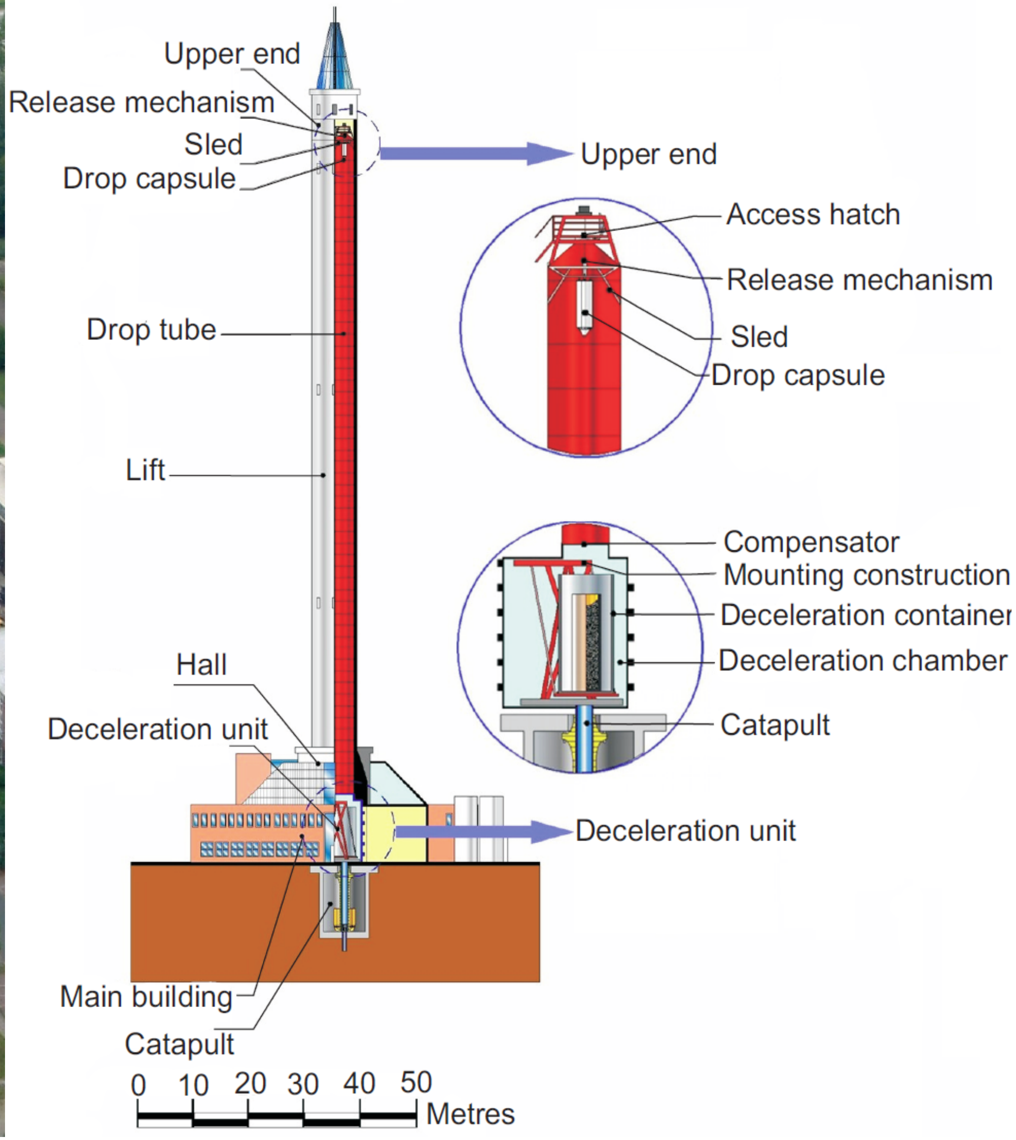


QUANTUS

The ZARM drop tower Bremen



- 146 m tall
- 110 m drop height
- Free fall: 4.7 s
- Catapult: 9.2 s
- 10^{-5} m/s^2 below 100 Hz
- 3 flights per day
- Capsule deceleration up to 500 m/s^2



QUANTUS

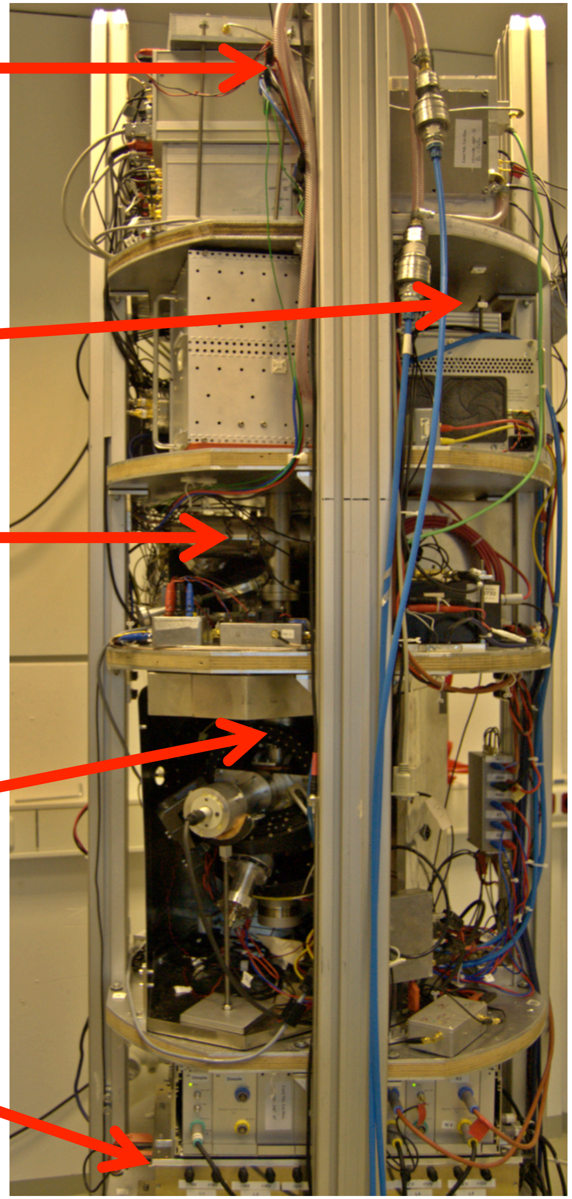
Laser system

Control system

Ion Getter Pump and electronics

Vacuum chamber

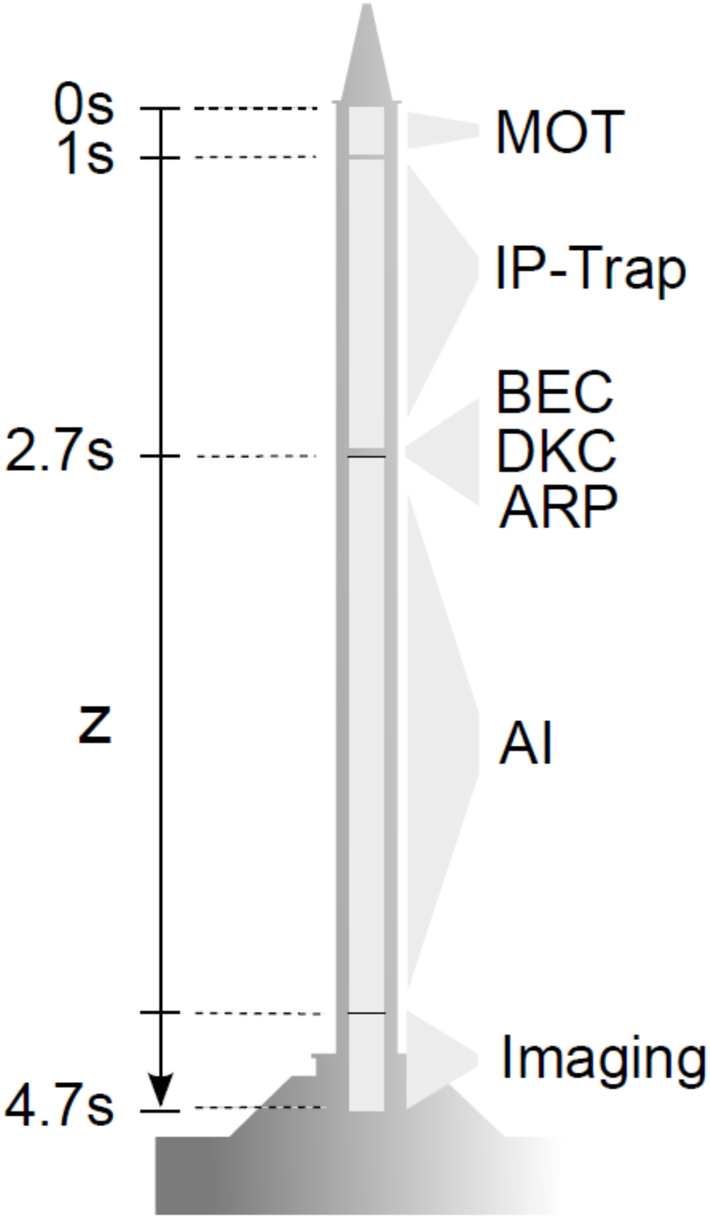
Batteries



Payload:
Diameter 0.6 m
Height 1.73 m
Weight < 234 kg

QUANTUS I

Drop-tower experiment



BEC by the numbers

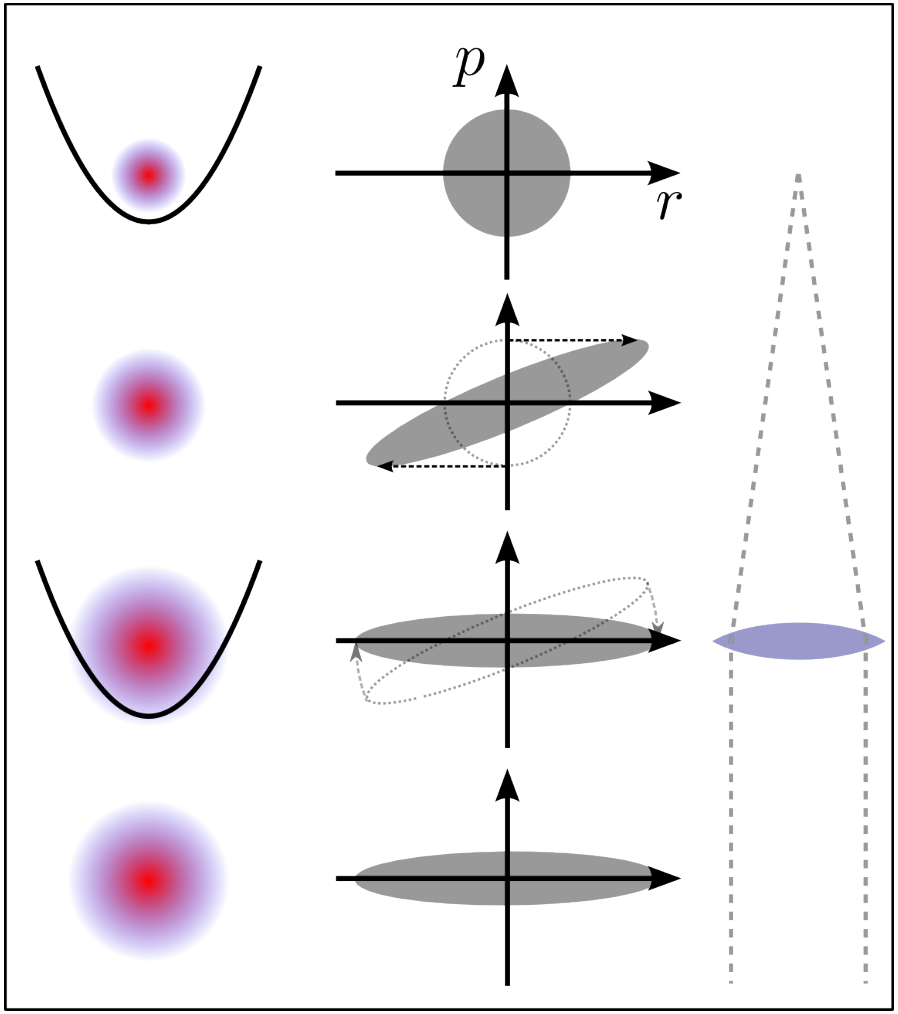
- 10^7 atoms in the MOT
- $5{\cdot}10^6$ in the magnetic IP trap
- 10^4 in the BEC after ~1.5 s evaporation
- 10 Hz to 30 Hz trap frequencies
- 10 nK kinetic energy
- $F = 2$, $m_F = 2$ state

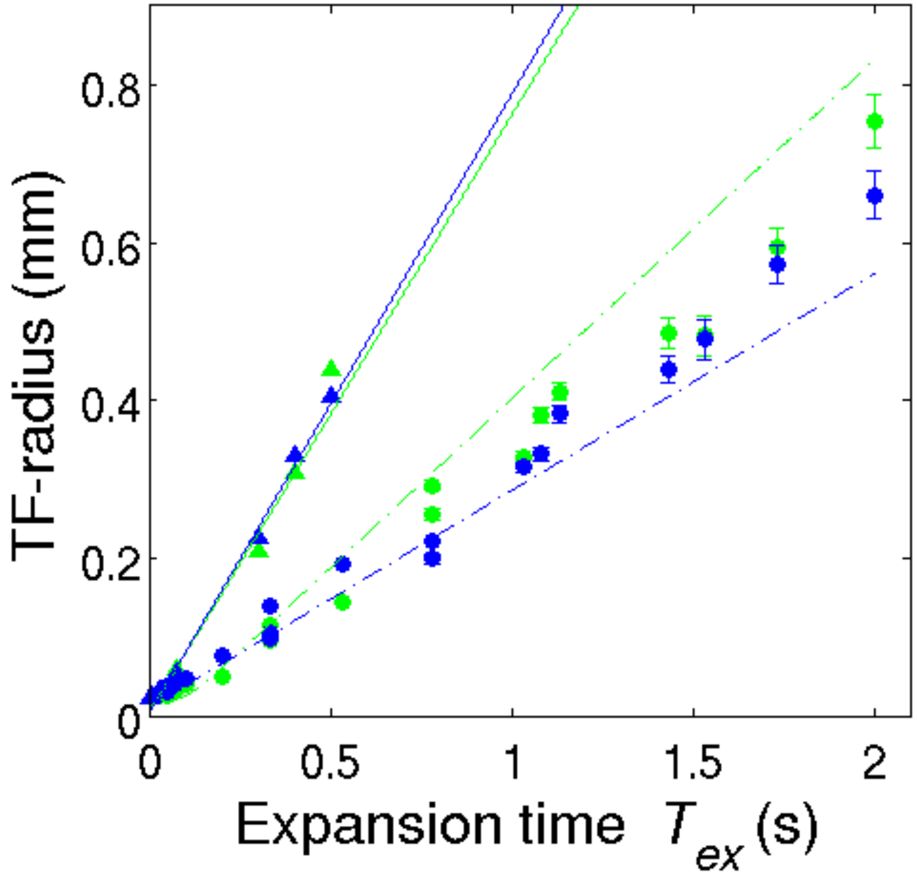
van Zoest et al., *Science* **328**, 1540 (2010)
H. Müntinga et al., PRL 110, 093602 (2013)

QUANTUS I

QUANTUS

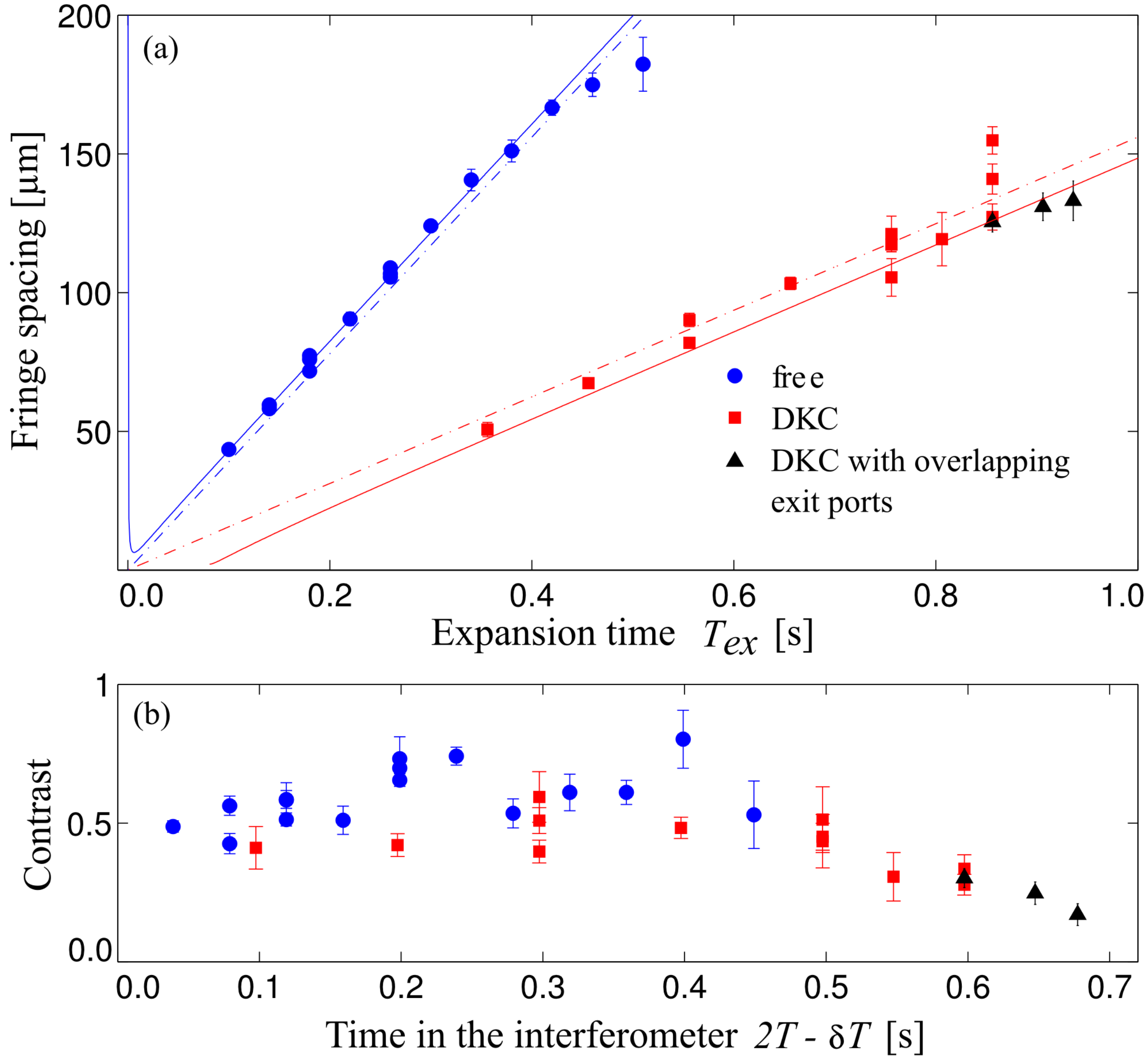
Delta-kick cooling

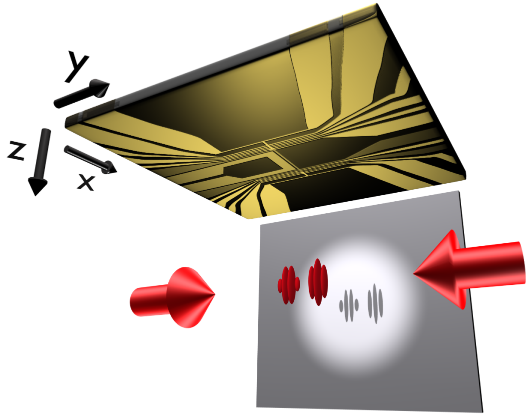


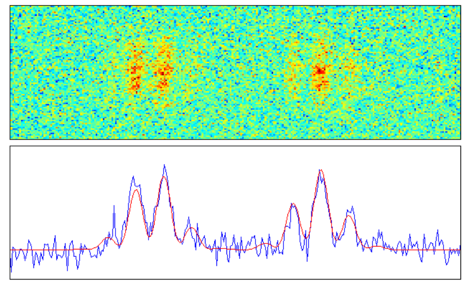


QUANTUS I

Interferometry in µg

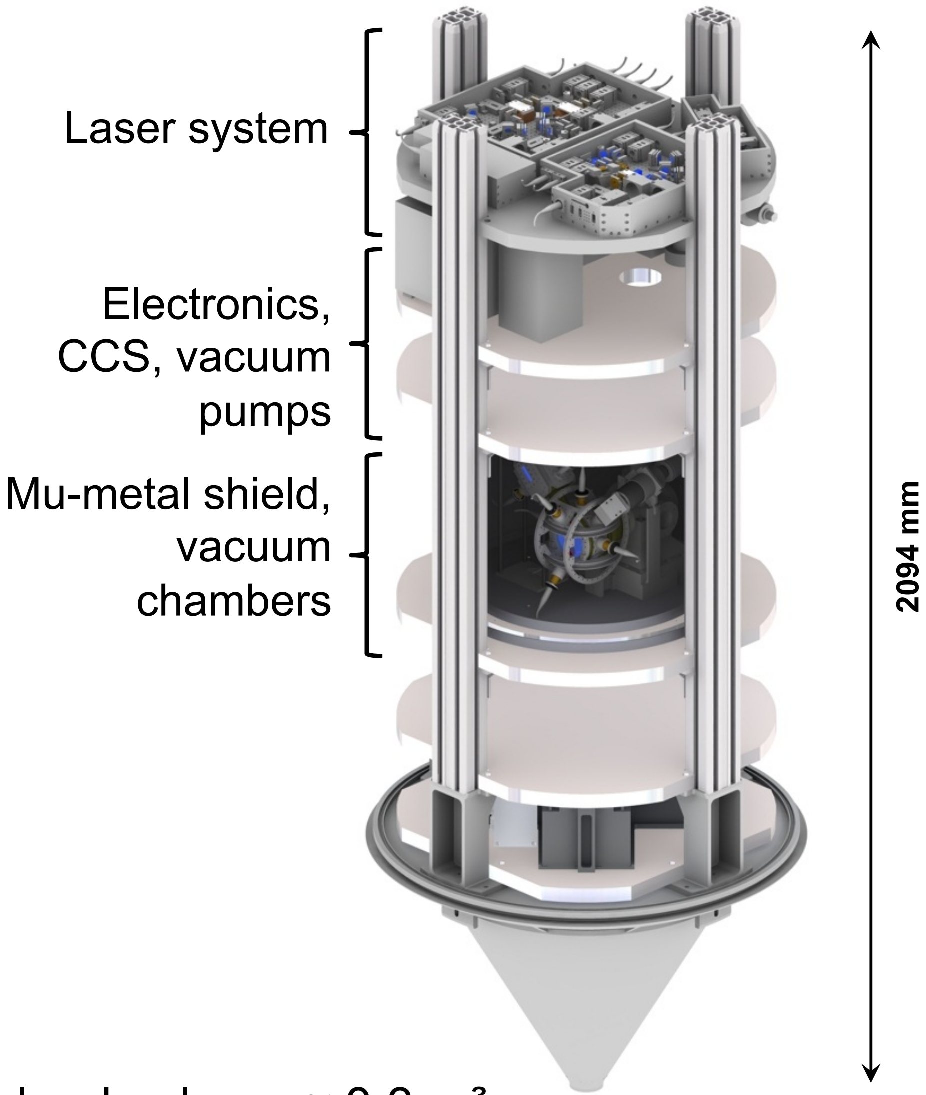


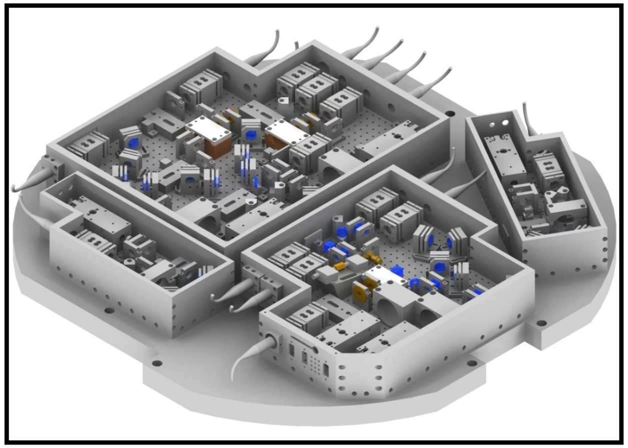




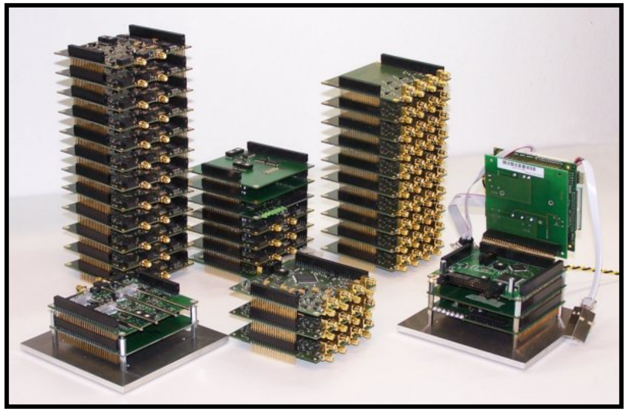
QUANTUS I

Catapult-capable capsule





Compact laser system for manipulation and detection of $^{87}Rb/^{40}K$

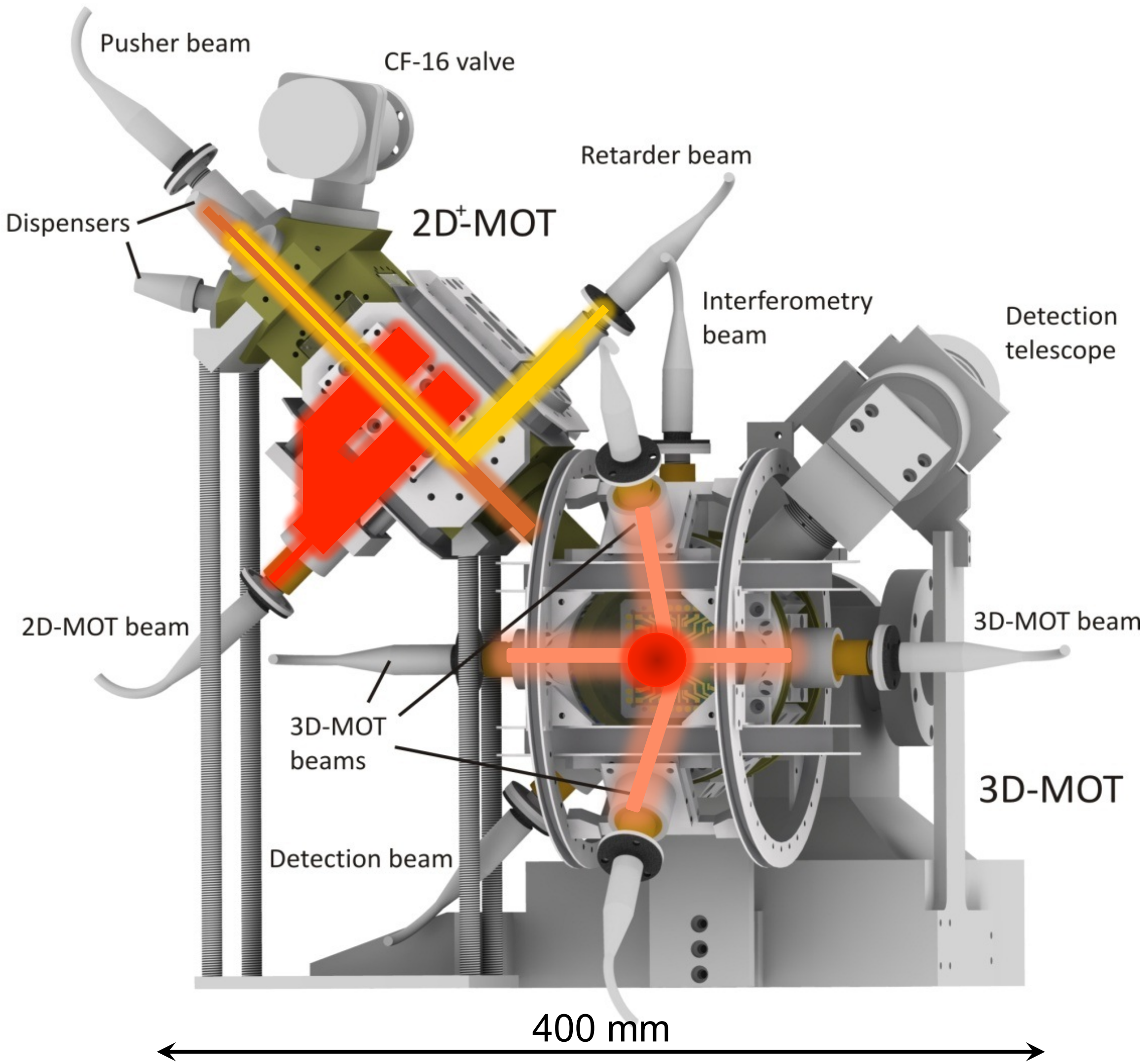


Stackable and miniaturized electronics

- Payload volume ≈ 0.3 m³
- Payload mass of 163.8 kg

QUANTUS II

MOT loading



Characteristics:

- Double-MOT-system
- Mirror MOT setup
- MOT quadrupole field formed by a mesoscopic U structure @9A and a bias field

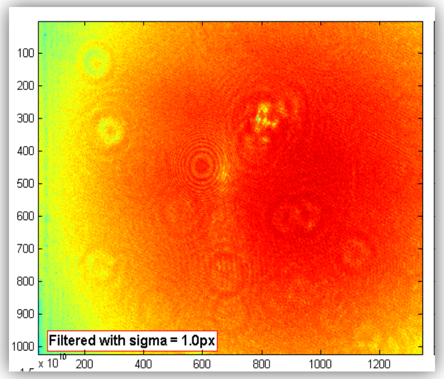
Performance:

- $2D^+$-MOT flux: $1,4x10^9$ @1s
- N_{max}: $2,5x10^9$ @5s

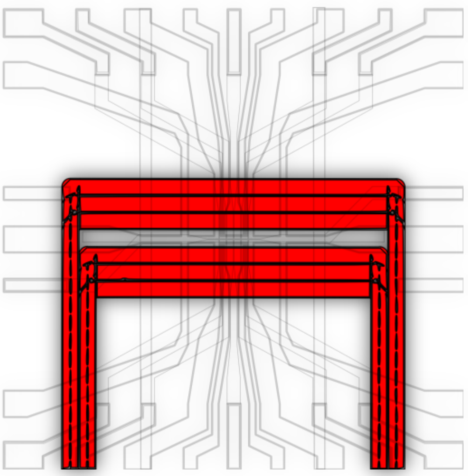
QUANTUS II

Chip trap

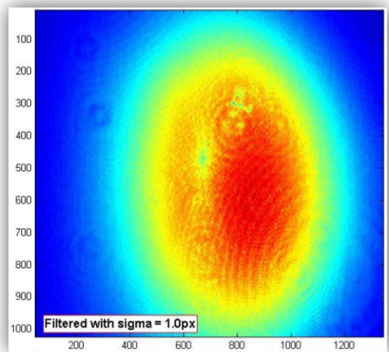
MOT



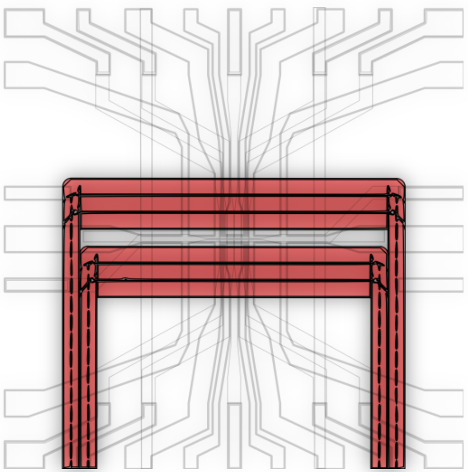
~10^9 atoms
T = 200µK



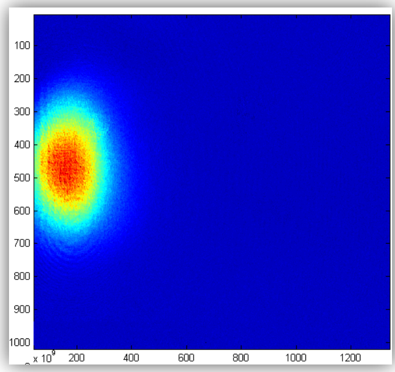
CMOT/Molasses



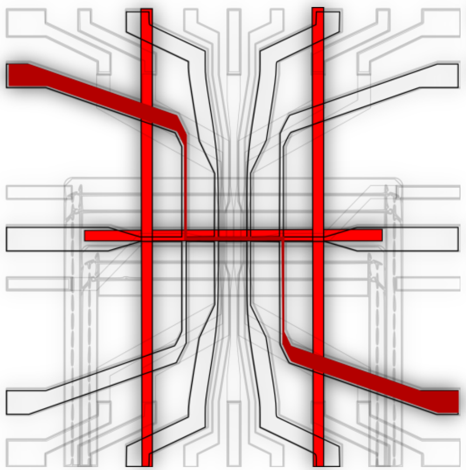
~10^9 atoms
T = 20µK



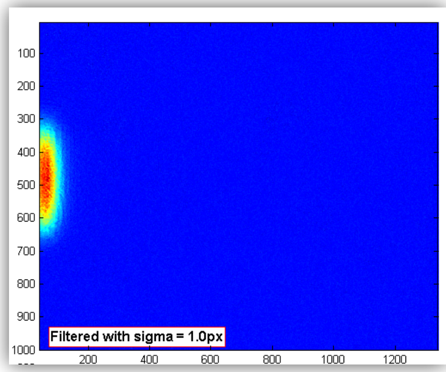
Meso-H/Base Chip



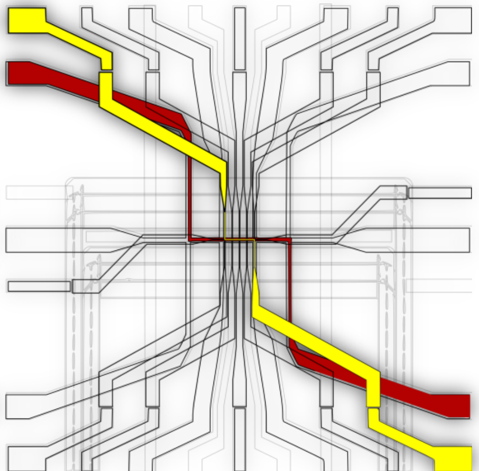
$2 \cdot 10^8$ atoms
T = 40µK



Base/Science Chip



$8 \cdot 10^7$ atoms
T = 60µK

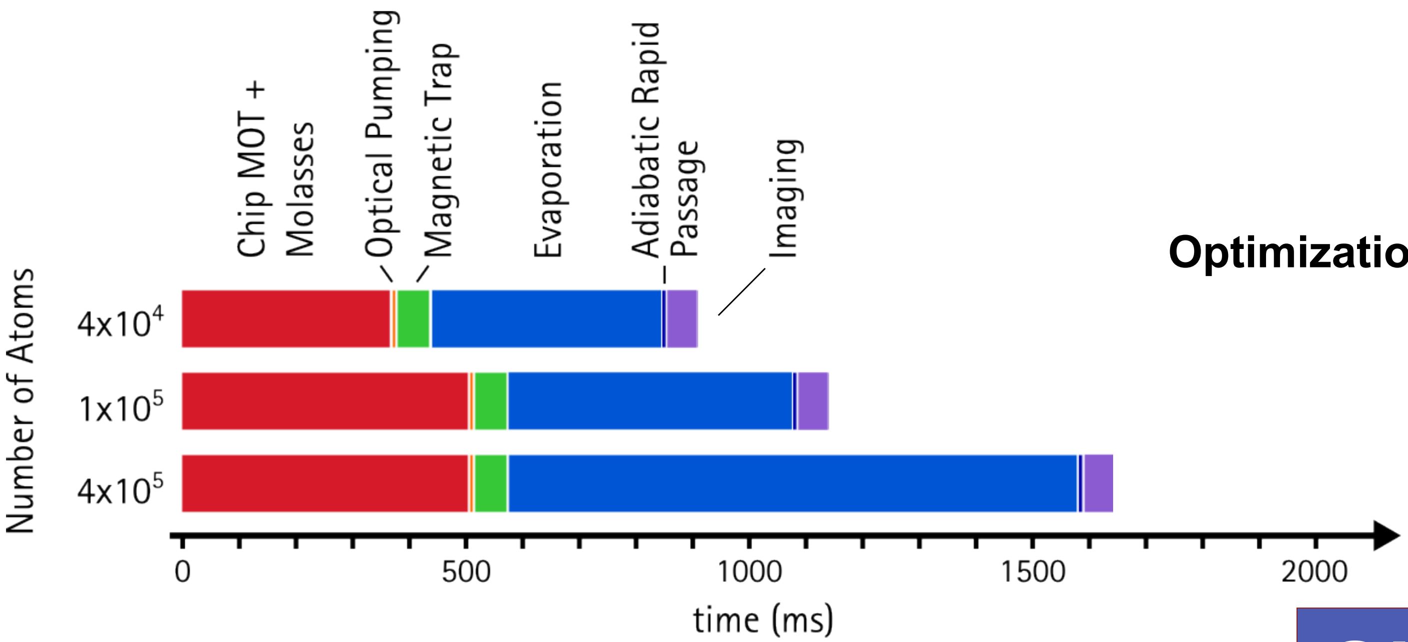


QUANTUS II

Evaporation & BEC

Particle number in dependence of total cycle time:

- Largest BEC: $5x10^5$ atoms in 3.5s
- Optimal BEC: $4x10^5$ atoms in 2s
- Fastest BEC: $4x10^4$ atoms in 1s

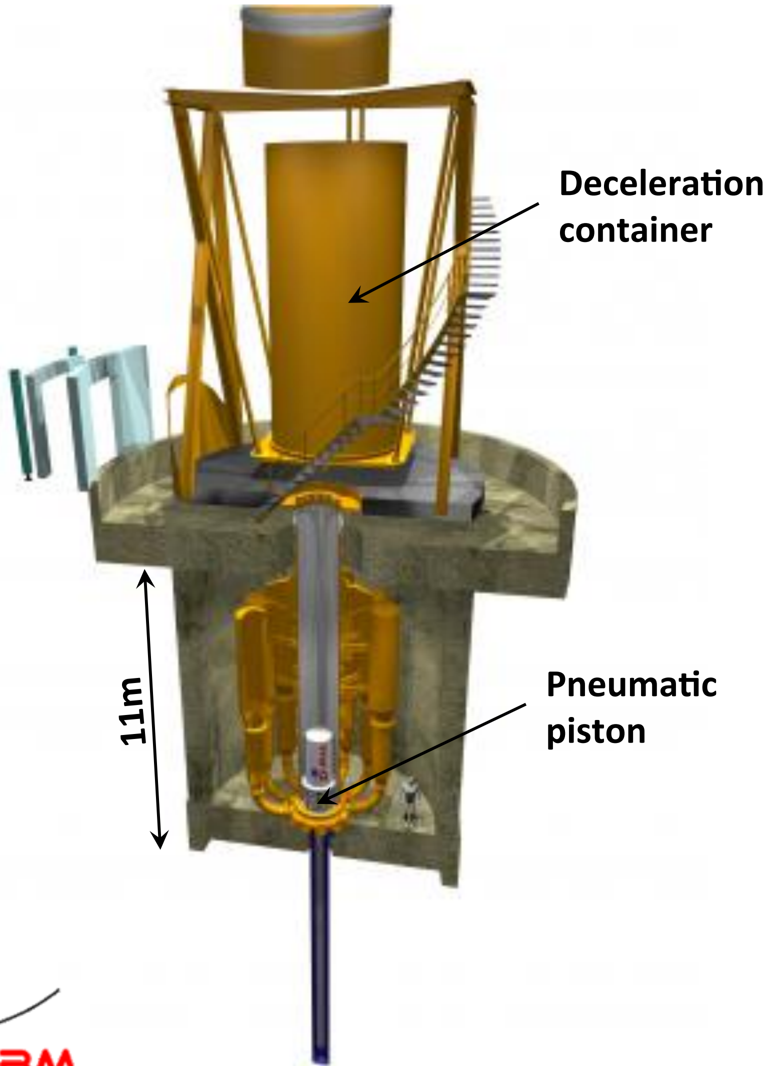


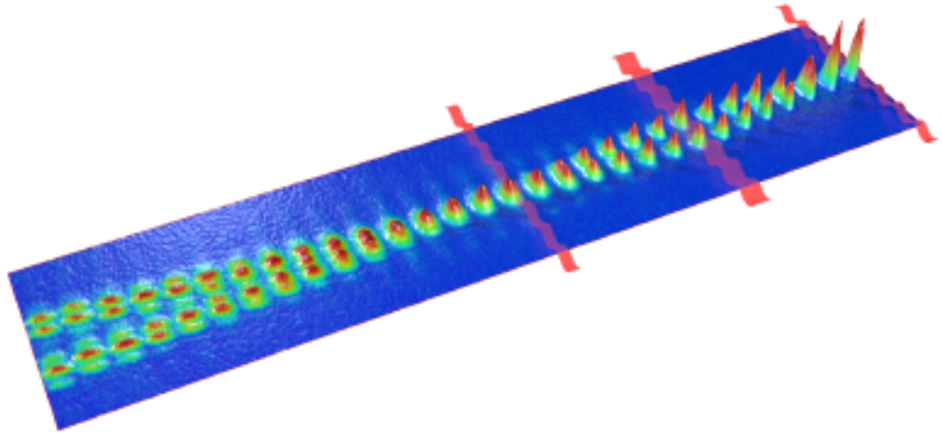
Optimization ongoing!

QUANTUS II

QUANTUS

Next step:
extended interferometry times in a catapult launch

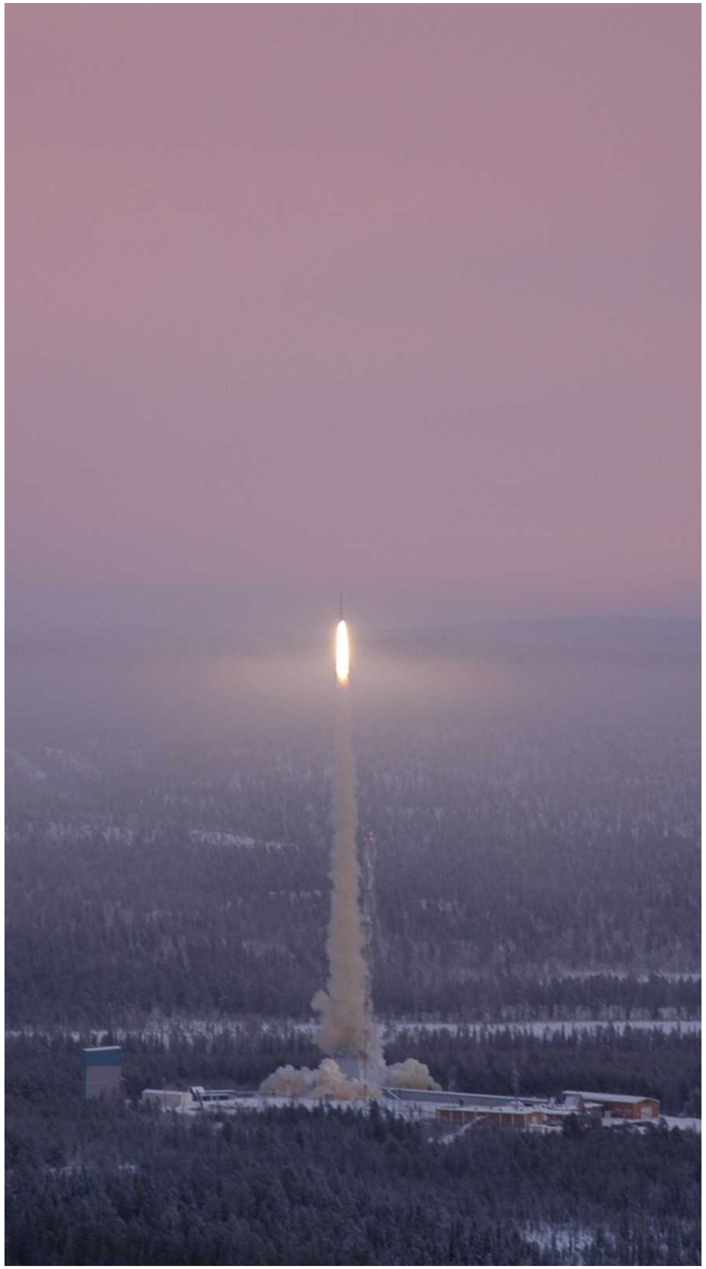




ZARM

QUANTUS II

MAIUS: BEC in Space



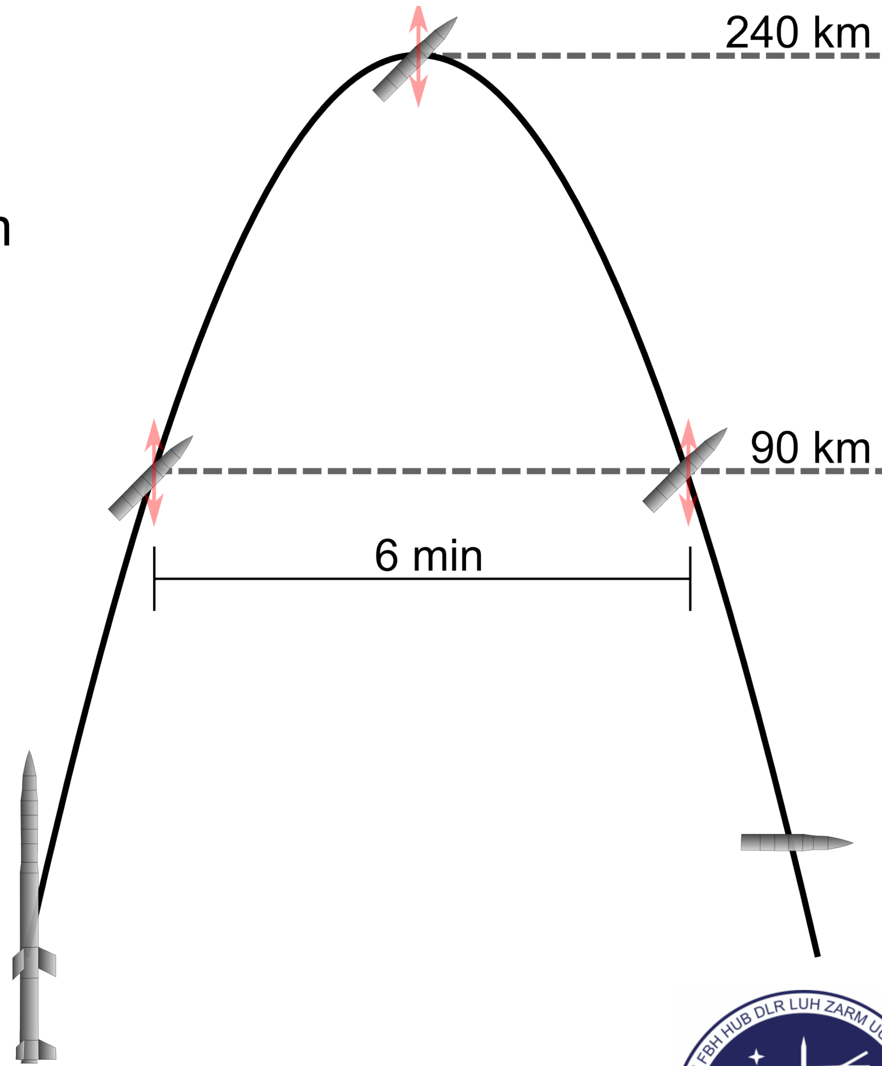
Objectives:

- Proof of concept of a rocket-borne atom optical experiment
- Automated operation of a Bose-Einstein-Condensate in space
- Demonstration of a Bragg-based atom interferometer

MAIUS: BEC in Space

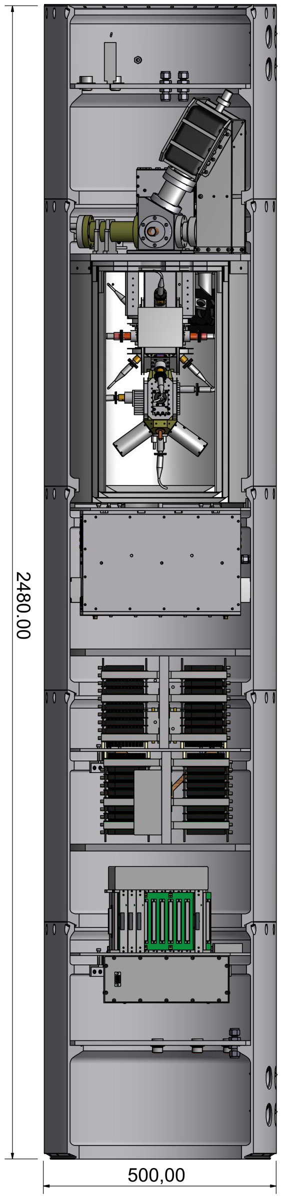
- Platform: VSB-30
- 400 kg pay load with apogee at 240 km
- 6 minutes of µg ($<10^{-6}\ g_0$)
- Orientation stabilization
- Residual rotation rate < 0,03 Deg/s

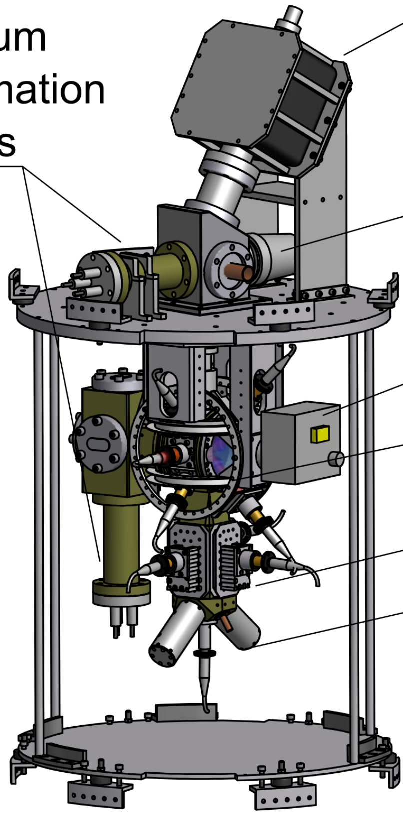
Source: DLR-MORABA



MAIUS Payload

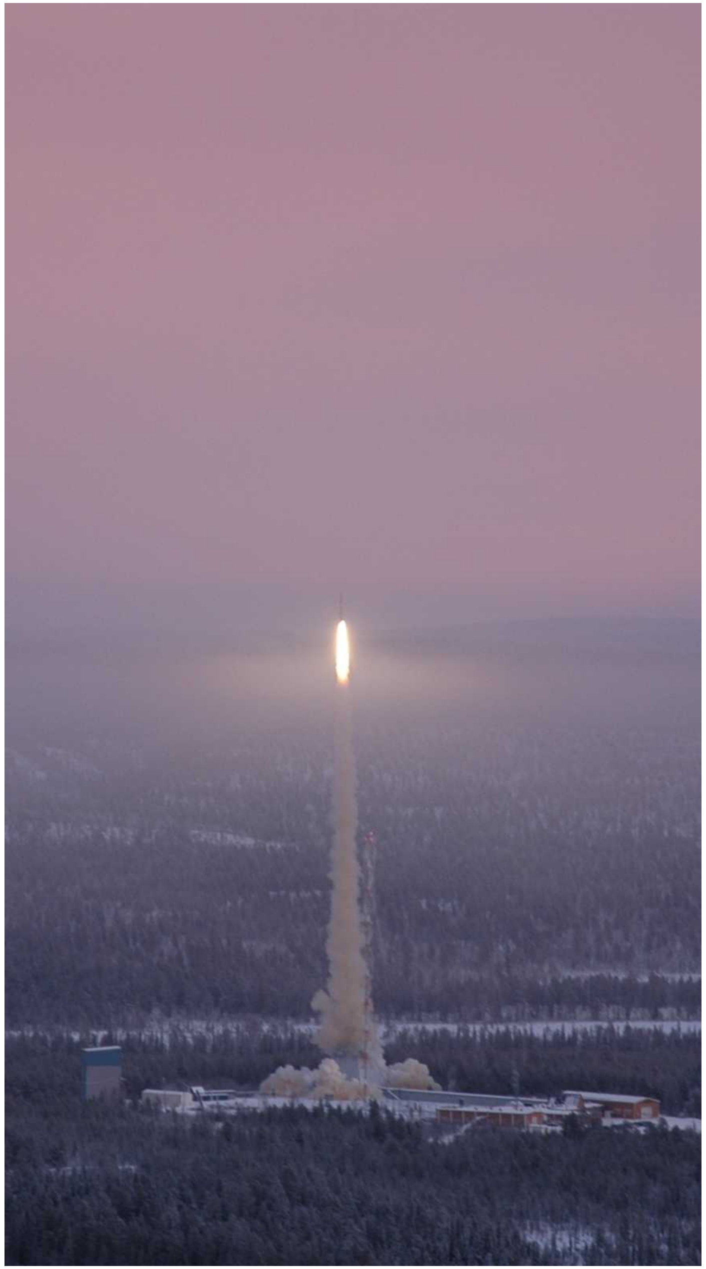
- Umbilical Section
- Experiment Section
- Laser section
- Electronics Section
- Battery section





QUANTUS

MAIUS: BEC in Space



Launch
November 2014
ESRANGE, Sweden

UHH FBH HUB DLR LUH ZARM UULM TUDA
MAIUS
Materiewellen Interferometrie unter Schwerelosigkeit

Outline

1. ICE:
2. QUANTUS:
3. Conclusion

Conclusion

- Two projects with similar goals but different approaches
  - ICE:
    - 0-g Plane
    - Telecom lasers
    - Dipole Trap
    - Interferometers and ultra-cold atoms
  - QUANTUS:
    - Bremen Tower
    - Semi-conductor diode lasers
    - Magnetic trap on chip
    - Ultra-cold atoms and Interferometers

- Technologies and concepts used for the definition of the AI in STE-QUEST

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