09/2022

# Factsheet

## macQsimal

**M**iniature **A**tomic vapor-**C**ell **Q**uantum devices for **S**ensIng and **M**etrology **A**pp**L**ications

QUANTUM FLAGSHIP

# Key facts

## Project coordinator

The project was coordinated by **Dr Jacques Haesler,** CSEM SA, Centre Suisse d'Electronique et de Microtechnique SA (CSEM), Neuchatel, Switzerland.

## Project duration

The macQsimal project was launched on **1 October 2018 and ran till 31 July 2022**.

## Project budget

The macQsimal project received **10.2 million € funding** from the EU as one of 25 projects within the first phase of the Quantum Flagship with a total budget of 1 billion €.

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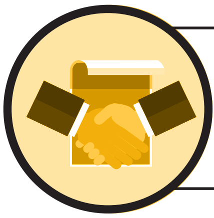
## Overcoming the limits of conventional sensing with quantum technologies

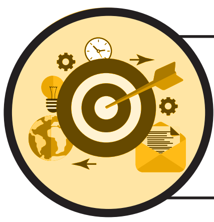
The understanding and application of physical laws in the microscopic realm was coined the first quantum revolution. Today, manipulating quantum effects in customized systems and materials enables the second quantum revolution.

# macQsimal



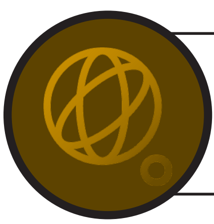
**Project consortium**

The macQsimal project brought together **14 partners** covering the entire value chain, from fundamental science to industrial deployment.



**Funding programme**

The macQsimal project has received funding from the European Union's Horizon 2020 research and innovation programme under **grant agreement No 820393**.



**Part of the Quantum Flagship**

The QF **launched in 2018** under the Horizon 2020 Framework Program has been one of the largest and most ambitious research initiatives in the European Union.

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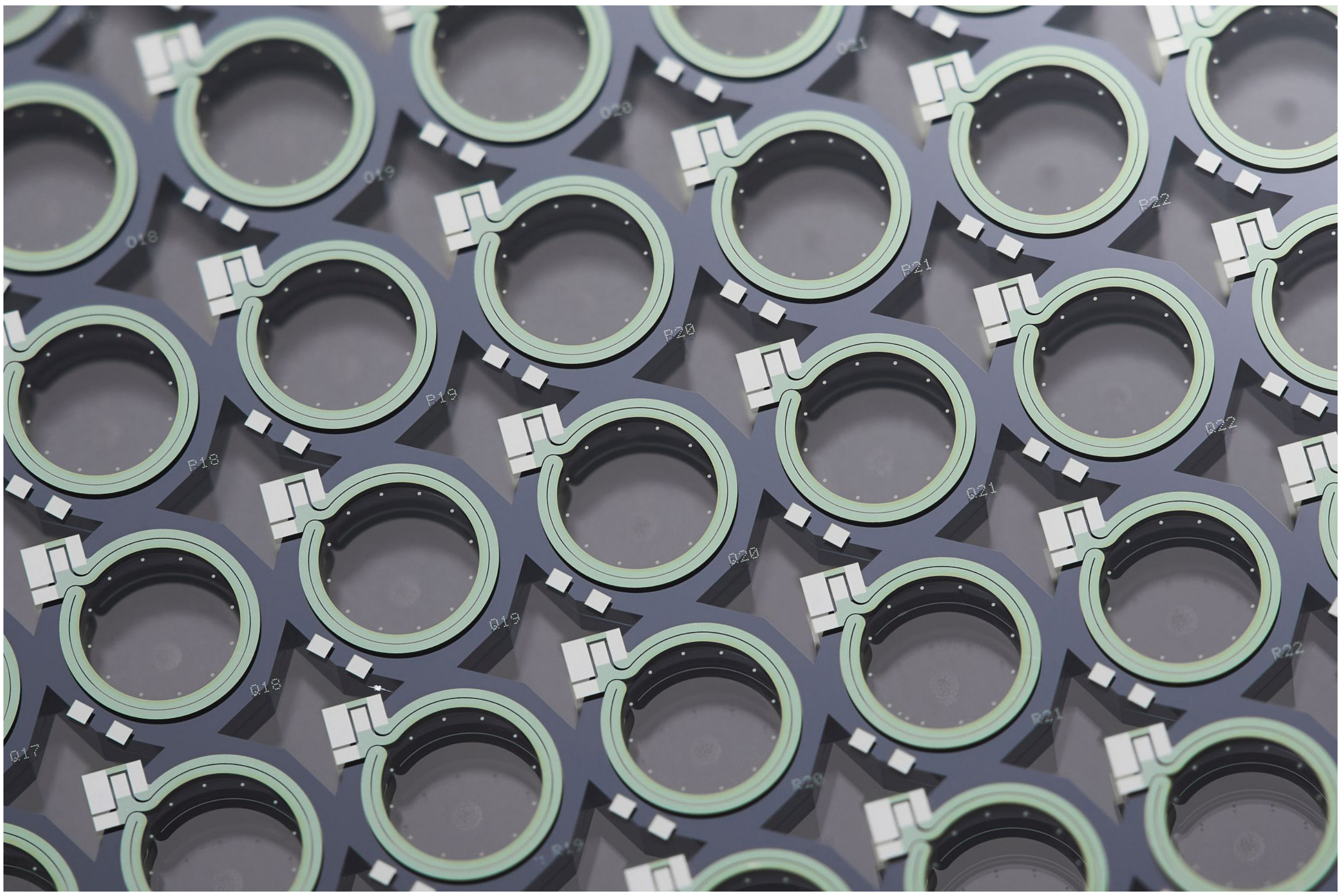
As a project under the Quantum Flagship (QF) of the European Commission, macQsimal was at the forefront of European efforts to push the boundaries for this new technology. In particular, the consortium has worked to exploit the potential of atomic vapor cells to provide the general public with a new generation of ultra-efficient sensors.
These sensors were developed in five application areas: miniaturized optically pumped magnetometers, miniature atomic clocks, compact atomic gyroscopes, GHz and THz magnetic and electric field sensors, and gas sensors. These applications were selected because they have a strong potential for industrial and commercial valorization in Europe in the next five to ten years.

# Systems design and cells fabrication



**Wafer with vapor cells designed for application in miniaturized atomic clocks (MAC) (pictures - CSEM)**

[Watch the session from the macQsimal scientific symposium]

The key elements of the project are atomic vapor cells realized as integrated microelectromechanical systems (MEMS) fabricated at the wafer level. The choice of atomic vapor cells makes coherent quantum processes available to different applications: advanced cell-based sensors optimally exploit single-particle coherence, with the potential to harness also multi-particle quantum coherence for even greater sensitivity. Fabricating such atomic vapor cells as MEMS allows for high-volume, high-reliability and low-cost deployment of miniaturized, integrated sensors, critical to wide-spread adoption.

Quality, reproducibility, and tracking are key aspects in the fabrication of MEMS atomic vapor cells for industrial and research applications.

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**Atomic vapor cells and systems**
**preliminary designs and cells fabrication**

Micro-fabricated (MEMS) alkali vapor cells are at the heart of the miniaturization of atomic devices such as atomic magnetometers, atomic gyroscopes and atomic clocks.

The fabrication process followed well-established steps ensuring the high-quality vapor cells used in macqsimal applications.

## Fabrication process

CSEM has established and optimized a patented fabrication process to produce atomic vapor cells, in a reliable and industrial way. This technique is identic to the technique used in foundries allover the world to produce integrated electronic circuits. Hence, we can produce a large number of vapor cells at once on a single 150mm diameter wafer. As an example, individual vapor cells for the atomic clock have a typical size of 4 by 4mm, so that more than 700 units fit on a single wafer. The silicon cell core contains a cavity which is closed on both sides with a glass lid.
MEMS atomic vapor cells were desiged and fabricated in different geometries to meet specific requirements of macQsimal applications.

**Fabrication process and quality check in the state-of-the-art cleanroom at CSEM**

**STEPS**

The fabrication includes photolithographic patterning and plasma etching of cavities in a 150mm diameter silicon wafer. A first glass wafer is aligned to the silicon cavity wafer and hermetically sealed with the cavity wafer by anodic bonding. The sandwich structure is irradiated under UV light which results in decomposition of the rubidium azide sealed inside the cavities into metallic rubidium and nitrogen. Then the triple wafer stack is diced into individual vapor cells.

# Applications

**In the macQsimal project, partners collaborated closely to design, develop, miniaturize and integrate advanced quantum-enabled sensors with outstanding sensitivity, to measure physical observables in five key areas:**

- **magnetic fields**
- **time**
- **rotation**
- **electro-magnetic radiation**
- **gas concentration**

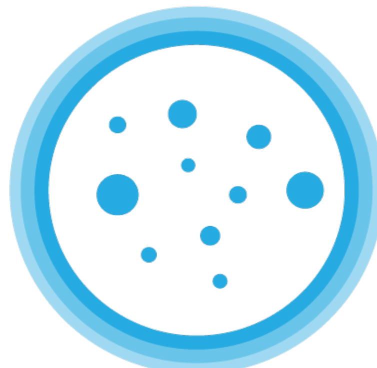
## Optically-Pumped Magnetometers

Optically pumped magnetometers (OPMs) are high-sensitivity quantum sensors that take advantage of the unique alkali vapor properties and their interaction with external magnetic and laser fields to detect magnetic fields with unprecetended sensitivity. With their high sensitivity, OPMs can measure the fields produced by electrical currents within the human brain, enabling bio-magnetic applications, such as magnetoencephalography (MEG).

## Miniturized Atomic Clocks

Atomic clocks are oscillators providing a signal with exquisite frequency stability, derived from ultra-stable alkali atomic transitions in a controlled environment. A miniature atomic clock (MAC) combines the advantages of reduced size, weight and power with superior timing accuracy over quartz-based technologies. MACs have the potential to improve the performance of secure telecommunication systems or Global Navigation Satellite System instruments.

# Applications



### Miniaturized Atomic Gyroscopes

Atomic gyroscopes are highly sensitive quantum devices that use the nuclear spins in an atomic gas for rotation measurement. Using lasers and magnetic fields, we initialize coherent precession of the atomic spins around a static magnetic field.
New quantum gyroscopes are more drift stable than ever before, paving the way for fully inertial navigation and improved safety in highly autonomous driving.

### GHz/THz sensor & imager

Gigahertz (GHz) fields, also called microwaves, are are a very important part of modern technology. For example, cellphones and wireless communication devices use microwaves.
Terahertz (THz) waves form a part of the electromagnetic spectrum in the frequency range from 100 GHz to 10 THz. THz waves are able to penetrate materials, much in the way that X-rays do, but they are low-energy radiation and therefore safe to use.

### Rydberg-based gas sensors

Rydberg states are atoms with electrons excited to high principal quantum numbers. Rydberg excitation and subsequent ionization are promising to be used as a new method to develop trace gas sensors at ppb sensitivities and yet highly selective. The flexibility offered by such a Rydberg gas sensor will benefit current small-sized and integrable systems that are now limited to a few gases of interest.

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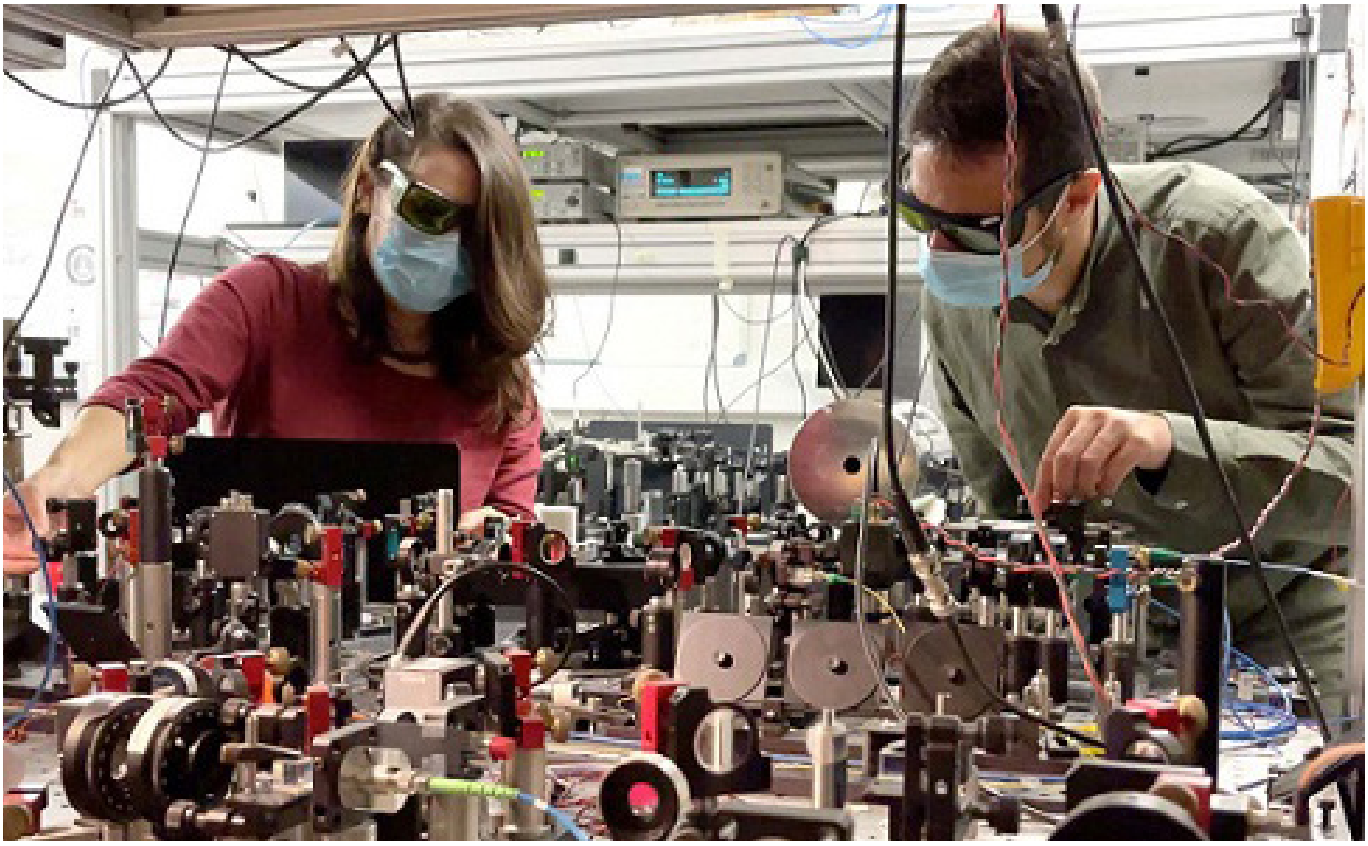
# Optically-pumped Magnetometers



**Dr Charikleia Troullinou and Dr Vito-Giovanni Lucivero from Fundacio Institut de ciencies fotoniques (ICFO) working with squizeed light magnetometer setup**

**Read more here**

**Watch the session from the macQsimal scientific symposium**

In the macQsimal project we were developing and validating specific wafer-fabricated MEMS atomic vapor cells for two different systems operating in two different regimes: high density and low density OPMs. Following the design, development and characterization, a compact, high temperature, high-density OPM prototype was sucessfuly produced and validated in the context of medical application in magnetoencephalography (MEG). MEG is an imaging technique for investigating human brain function by measuring the weak magnetic fields generated by electric currents in neurons. The room-temperature low-density OPM demonstrator was based on specifically designed atomic vapor cells with targeted sensitivity range for a different medical application, magneto-cardiography (MCG).

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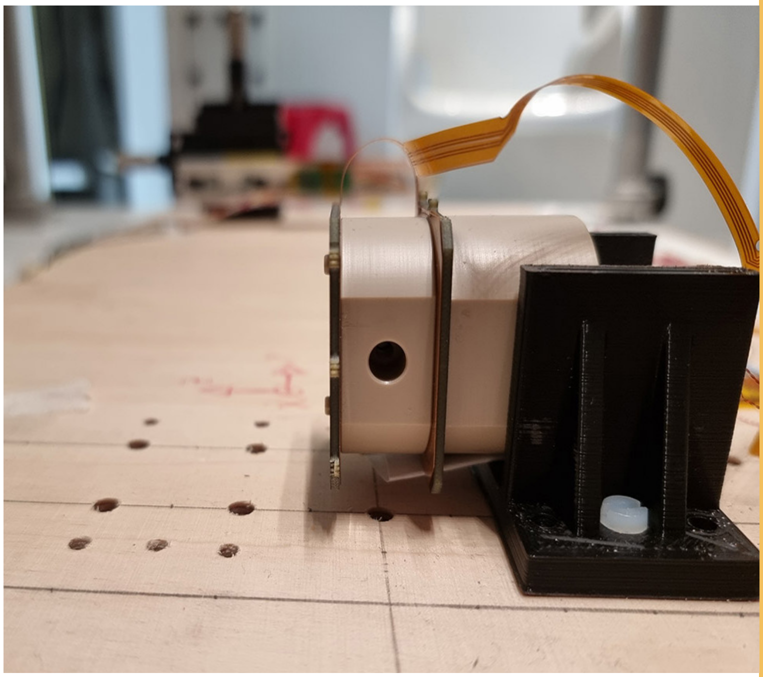
**Optically-pumped magnetometers**

Magnetic fields carry important information in biomedicine, in geophysics and in space science. Magnetometers are developed to make that information available to us.

OPM sensors have strengths and weaknesses when compared to superconducting sensors. In the macqsimal project we addressed challenges and met the project objectives.

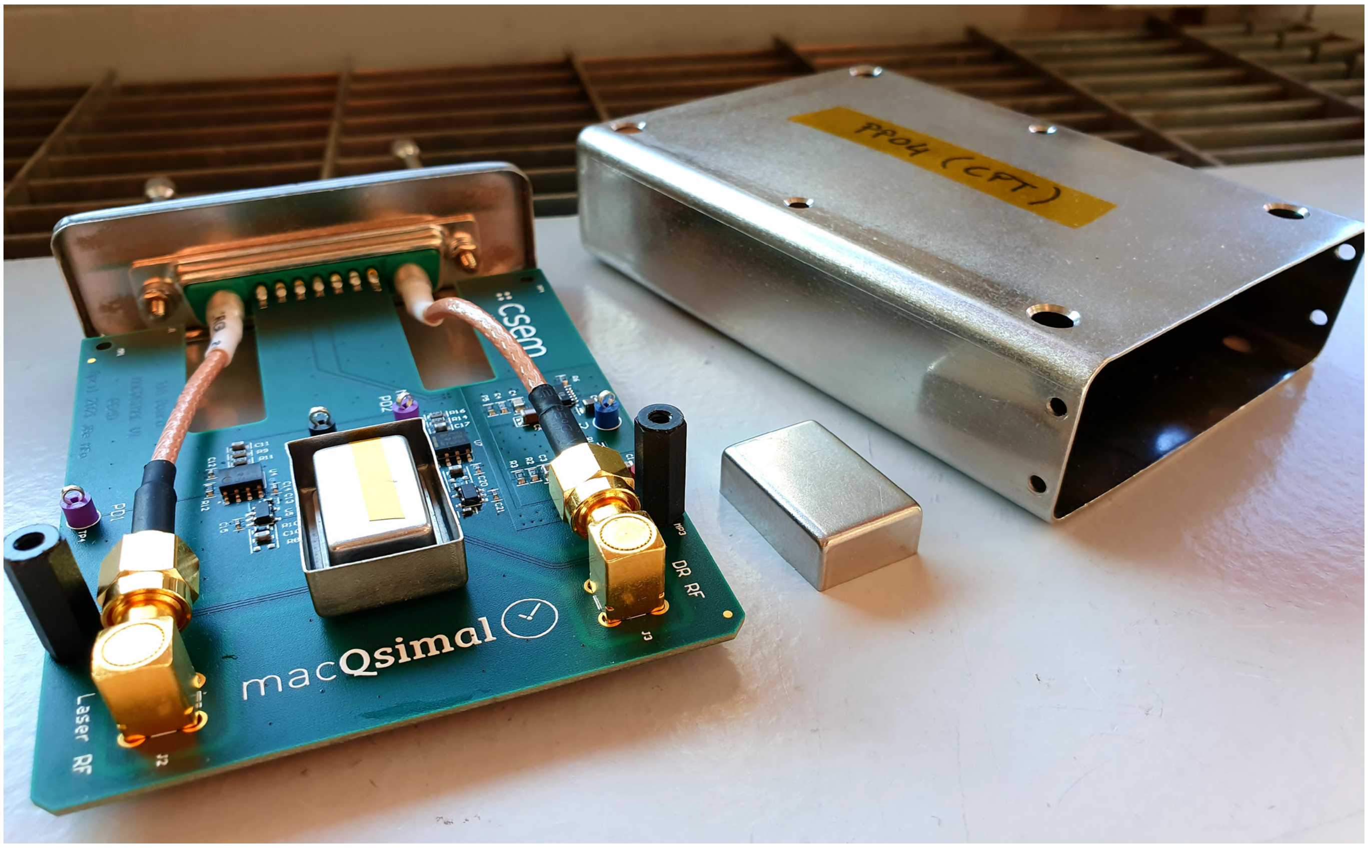


**The vapor cell oven on the OPM test bench (picture - Aalto University)**

## Key achievements

- Successful tests of the high-density OPM demonstrator show performance metrics suitable for the MEG application
- Development of two control and measurement systems for high-density OPM demonstrator
- Development of a highly sensitive OPM that is optimised for detection of biological signals with high temporal and spatial resolution
- A novel approach to suppress atomic saturation allowing to measure conductivities lower compared to state-of-the-art experiments
- Design and set up of an OPM demonstrator with a metal-free sensor head that was able to measure in real time the magnetic field of an MRI sequence of clinical relevance
- Development of a design for a manufacturable prototype OPM
- Novel methods in quantum-enhanced OPM, such as demonstrated optical and spin squeezing

# Miniaturized Atomic Clocks




**Physics package (PP) mounted on the testbed printed circuit board (PCB) (pictures - CSEM and Orolia)**

[Watch the session from the macQsimal scientific symposium]()

The physics package (PP) is a key element of a MAC: it provides all the interaction tools between the clock control electronics and the atoms. First, all building elements were validated and the base package components pre-assembled. Then the assembly of the main optoelectronics components was made by VTT, including the laser, the atomic vapor cell and the photodiode. The optical waveguide was integrated later by CSEM. The essential step in the development of MACs is the hermetic encapsulation of the PP. After assembly, the PP was transferred to Orolia for final encapsulation and integration with the Orolia electronics package. Finally, the fully integrated MAC was successfully tested under air and in a vacuum simulating both ground- and space applications.

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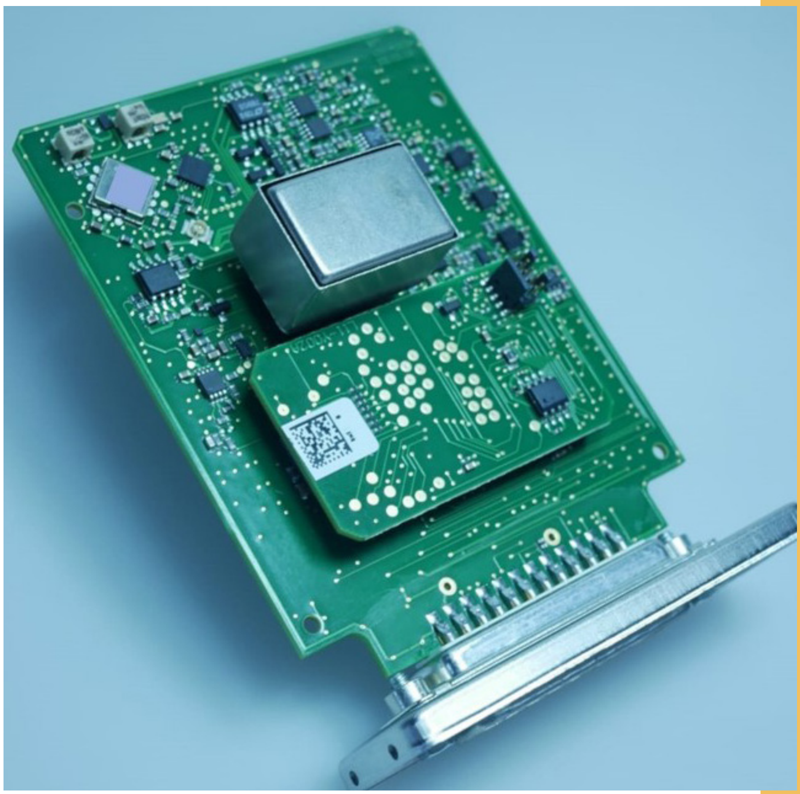
Miniaturized Atomic Clocks

The applications of atomic clocks are diverse and range from underwater oil prospection to telecommunication network synchronization and are also used in satellites in space.

CSEM recently patented a low-cost ultra-flat miniature atomic clocks PP that combines the advantages of reduced size, weight, and power, with superior timing accuracy over high-end quartz-based technology.

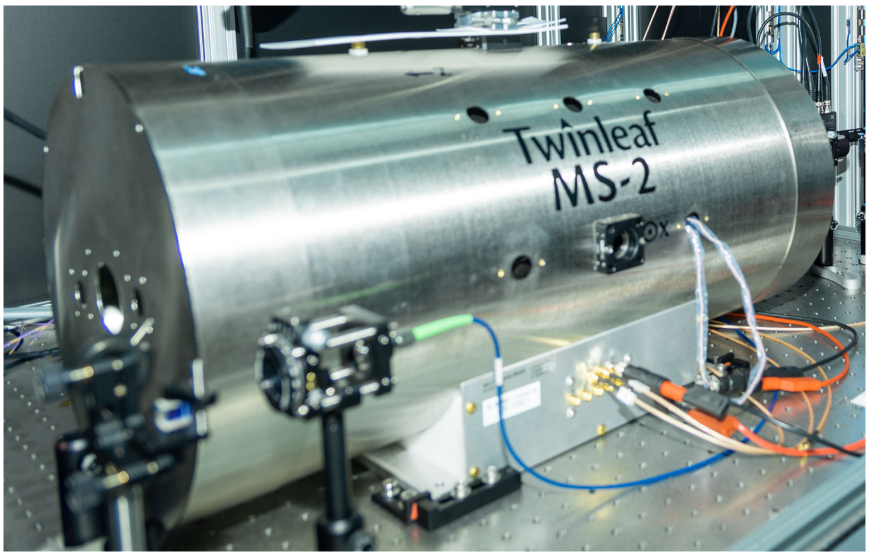


**Miniaturized atomic clock combining the physics package (PP) and electronics package (EP)**

## Key achievements

- Functionalized MEMS atomic vapor cell design for miniature atomic clocks (MAC)
- Fabrication of the MAC MEMS atomic vapor cells at the wafer-scale
- Demonstration of state-of-the-art MAC cells frequency drift performance
- Validation of the reproducibility of the MAC physics package fabrication process
- Development and validation of dedicated MAC electronics
- Successful production of 4 system-level MAC prototypes
- Strong reduction of light-shift effects in the µ-POP scheme
- Development of the µ-POP clock, a tabletop clock demonstrator of a pulsed optical-microwave double resonance clock

# Miniaturized Atomic Gyroscopes




Laboratory setup of an atomic gyroscope developed at Bosch corporate research (picture above - Martin Stollberg/Bosch)

Glass-blown vapor cells of different geometries containing rubidium and xenon (picture University of Neuchatel)

[Watch the session from the macQsimal scientific symposium]

First generations of atomic gyroscopes used handmade glass cells - limited in both miniaturization and cost reduction. In macQsimal, we deployed vapor cells fabricated using cost efficient MEMS processes. We successfully designed and built up a proof-of-principle demonstrator, integrating the optical, magnetic and electrical components on one platform. The macQsimal partners from Bosch leading the task on the the miniaturized atomic gyrocsope developed the electronics and software of the system.
To realize an atomic gyroscope with a vapor cell, we started with the initialization step, aligning the spins of the atoms with a laser along its direction. In the detection step, we applied a constant well-defined magnetic field and to avoid disturbance by external magnetic fields, the cell was placed in a magnetic shield.

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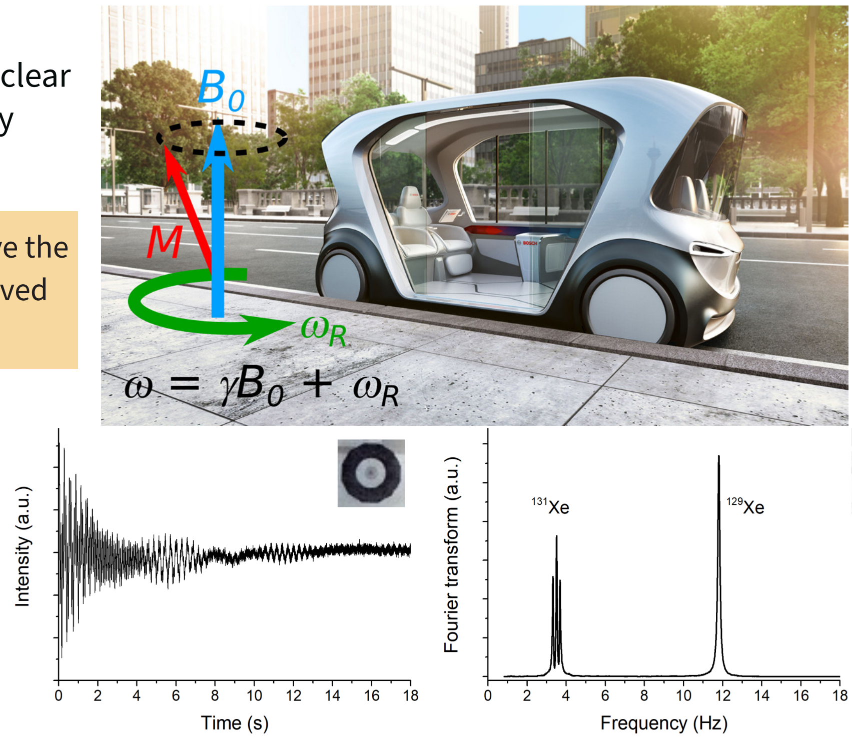
**Miniaturized Atomic Gyroscopes**

Atomic gyroscopes employ noble-gas nuclear spins with long coherence times as highly precise rotation sensors.

> Miniaturized atomic gyroscopes could pave the way for fully inertial navigation and improved safety in highly autonomous driving.

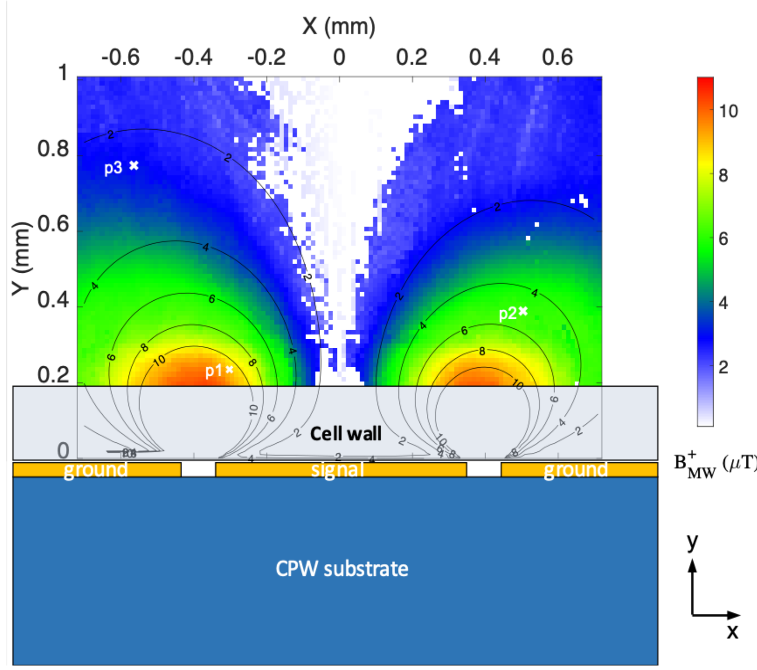



**Noble gas nuclear spin precession is the basis of high-performance atomic gyroscopes (picture Tobias Gramsch/Bosch)**

# Key achievements

- Fabrication, characterization and optimization of atomic MEMS and glass vapor cells
- Measurement of Larmor precession of noble-gas nuclear spins with coherence times of serval seconds
- Sealing of MEMS vapor cells in a low temperature cofired ceramic package allowing for good thermal and mechanical isolation
- Set-up of a table-top experiment for vapor cell characterization and proof-of-principle tests via application of an emulated rotation rate
- Novel approach in the assessment and benchmarking of the gyroscope bandwidth
- Development of a system model of an atomic gyroscope
- Design and implementation of control, driving and readout electronics

# GHz/THz sensor & imager




**Setup for high-resolution imaging of GHz fields (picture above on the left - University of Basel)**

**Imaging results based on frequency-omain Rabi spectroscopy and electromagnetic simulation (picture above on the right- University of Basel)**

**Watch the session from the macQsimal scientific symposium**

In the macQsimal project we were also using atoms to image high-frequency electromagnetic fields in the gigahertz (GHz) and terahertz (THz) frequency range. Partners from the University of Basel demonstrated a microwaves magnetic near-field imaging technique based on frequencydomain Rabi spectroscopy, using a compact MEMS atomic vapor cell as an imaging sensor. Rubidium atoms contained in the ultra-thin MEMS atomic vapor cell were used to respond to the microwave fields with their atomic quantum states.

The principle of THz imaging used by researchers from Durham University was based on the use of Rydberg atoms to perform THz-to-optical frequency conversion, meaning converting difficult-to-detect THz radiation into easy-to-detect optical photons.

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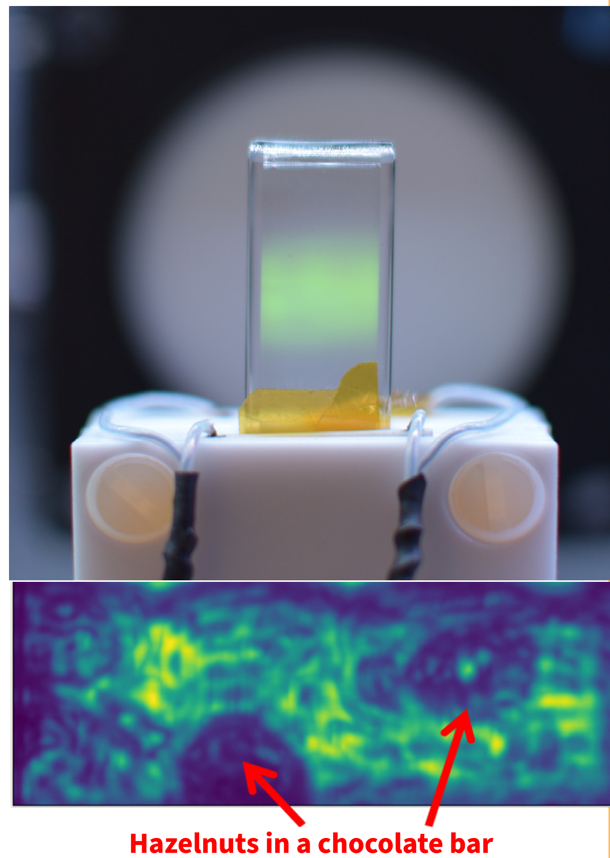
**GHz/THz sensor & imager**

Microwaves are used for communication, for navigation, for radar and in medical applications. THz radiation can be applied in fields such as process monitoring, food safety, security screening and renewable energy technologies.

Using atoms to image high-frequency electromagnetic fields in the GHz and THz frequency range partners pursue applications in collaboration with industry to build up on the macQsimal achievements.

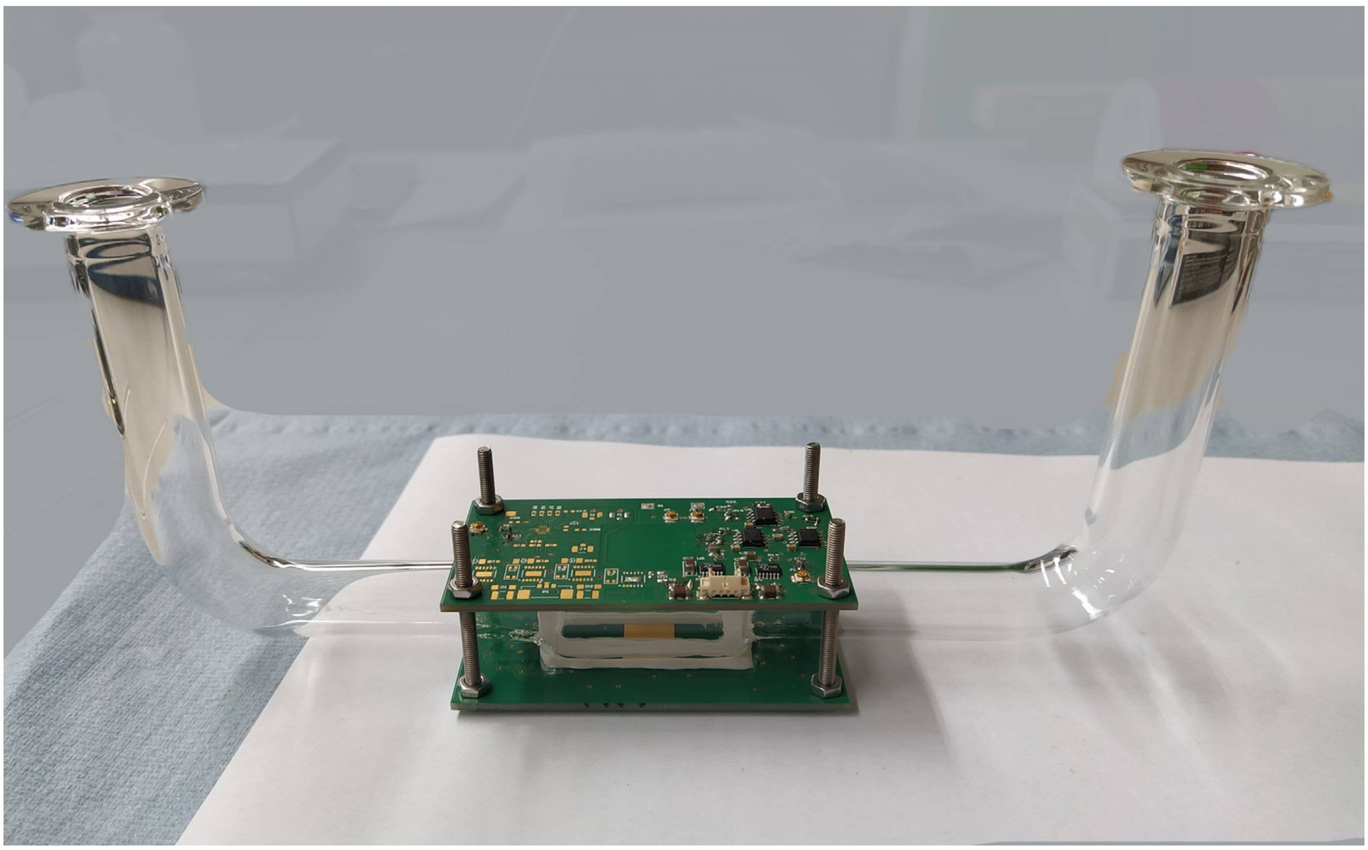



**THz fluoresence and imaging of a chocolate bar (pictures - Durham University)**

## Key achievements

- An atomic GHz imaging device demonstrator operating with MEMS vapor cells was built, tested and validated
- Atomic spectrum analyzer operation mode was demonstrated and identified as the most relevant and promising for applications in the microwave communications industry
- A Rydberg-based THz imager was demonstrated, tested and validated, showing high sensitivity, bandwidth, and spatial resolution
- Calibrated THz electric field sensing was demonstrated providing a new tool for metrology in the terahertz frequency range.

# Rydberg-based gas sensors



**Vapor cells with integrated electronics for direct current detection of highly excited nitric oxide molecules (pictures - University of Stuttgart)**

[Watch the session from the macQsimal scientific symposium]

The swift development of narrowband lasers, especially in the ultraviolet domain, allows expanding the proficiency of atomic vapor spectroscopy to molecular gases. With a multi-step excitation scheme, partners from the University of Stuttgart could realize high-lying Rydberg states of nitric oxide (NO) with unmatched precision. In combination with integrated electronics, a direct current of ionized molecules was detected, making the whole system a highly sensitive detector for NO. Besides this, precision spectroscopy of molecules is also of fundamental interest in macQsimal. To this end, we were able to perform sub-Doppler-spectroscopy which offered insights into the fine structure of NO.

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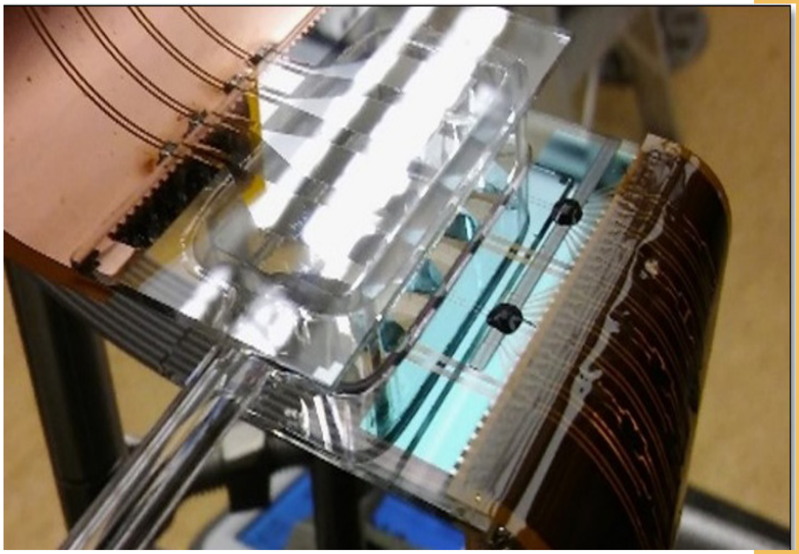
**Rydberg-based gas sensors**

Nitric oxide is an important tracer gas for inflammatory diseases, like asthma. Trace gas sensing of NO for medical applications based on precision spectroscopy in gas cells with integrated electronic was one of the macQsimal's recognized innovations.

Novel CW-lasers were used in macQsimal to precisely excite high-lying electronic states of nitric oxide. These fragile objects ionize by collisions with a background gas and can be directly detected as a current.



**Glass vapor cells used for Rydberg-based gas sensor prototype**

# Key achievements

- Performed Sub-Doppler spectroscopy of nitric oxide
- Realization of Rydberg states of nitric oxide
- Direct current detection of Rydberg states
- Realization of integrated vapor cells with onboard electronics
- Development of large bandwidth and low current trans-impedance amplifiers
- Performance test of rubidium in nitrogen resulted in ppb sensitivities
- Exploring the Potential to extend this scheme to other relevant molecules

# Impact

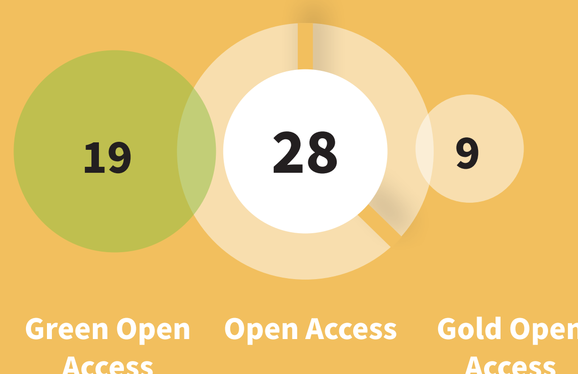
The macQsimal consortium ensured that all the results produced within the project are available to the scientific community and industry for further uptake. The consortium members supported by accelopment Schweiz AG took every opportunity to share the knowledge and innovations through developed communication and through dissemination of project results. In this way, macQsimal strongly contributed to strenghtening the European research capacity. The main avenues of dissemination the project results included:

- Peer-reviewed scientific publications
- Public and confidential deliverables
- Presentations and talks at international and national conferences
- Poster presentations
- Participation in industry events
- Organisation of macQsimal workshops, the scientific symposium and other events
- Public deliverables
- Educational material and videos

## KEY INNOVATIONS

- **Miniature magnetometer for brain imaging**
- **Compact shoe-box size NMR gyroscope**
- **Chip-scale atomic clock**
- **Novel GHz spectrum analyzer demonstrator**
- **Novel THz imaging technique**

## PUBLICATIONS



# The macQsimal team


The project's closing ceremony was held at the University of Neuchâtel, on 20–21 June through a symposium open to the public and an event held as part of the university's Temps, Sciences et Société (Time, Science, and Society) conference series. During the final meeting, partners presented the key achievements, shared challenges and debated the future of quantum sensing. The event was also an excellent opportunity for the announcement of the macQsimal YouTube channel.

All videos developed within the project as part of the communication and dissemination strategy led by accelCH are now available for those interested in science, quantum and technology.

# The macQsimal consortium

Aalto Korkeakoulusaatio SR - AALTO
accelopment Schweiz AG - accelCH
Robert Bosch GmbH - BOSCH
Centre national de la recherche scientifique - CNRS
Centre Suisse d'électronique et de microtechnique SA - CSEM
Fundacio Institut de ciencies fotoniques - ICFO
Elekta OY - MEGIN
Orolia Switzerland SA - OROLIA
Universität Stuttgart - STUTT
Kobenhavns Universitet - UCPH
University of Durham - UDUR
Universität Basel - UNIBAS
Universite de Neuchâtel - UNINE
Teknologian tutkimuskeskus VTT Oy - VTT

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