# AMICC:  Advanced Micro-Cell atomic Clock
# Final Presentation – ESA NAVISP Program


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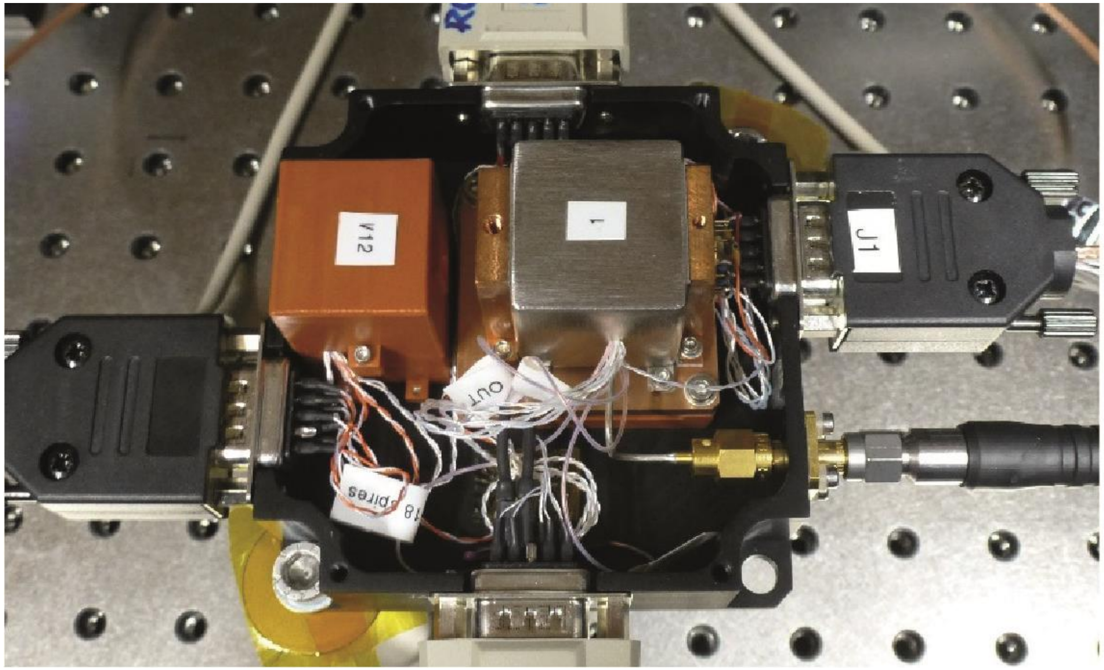
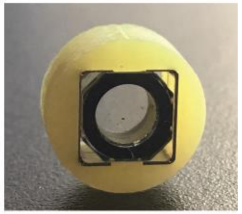


# Agenda

# 1. Project introduction

- NAVISP-EL1-32:

  ADVANCED CONCEPT FOR CHIP-SCALE ATOMIC CLOCKS

- **AMICC project:** Advanced Micro-Cell Atomic Clock
  ESTEC contract 4000129974/20/NL/LW

- Duration: March 2020 - June 2023

- Main contractor: **Laboratoire Temps-Fréquence**,

  University of Neuchatel (UniNE-LTF)

- Sub-contractor: **Microwave and Antennas Group** (MAG),

  Ecole Polytechnique Fédérale de Lausanne (EPFL),

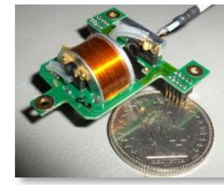
- Industrial Partner: **Micos** Engineering GmbH

# 1. Contractors' Background

**UniNE-LTF: Laboratoire Temps-Fréquence**

- Core competences: atomic clocks, lasers, optical technology
- Space atomic clocks heritage from Neuchâtel Observatory
- 10+ ESA projects since 2007 (foundation)
- 25+ national space / industry and European projects
- numerous fundamental research projects
- Collaboration with EPFL-MAG (ex LEMA) since < 2000





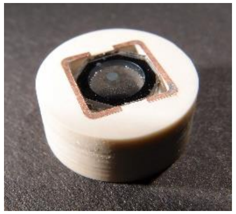


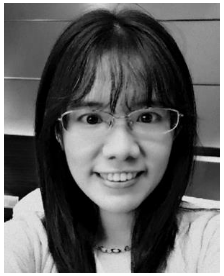


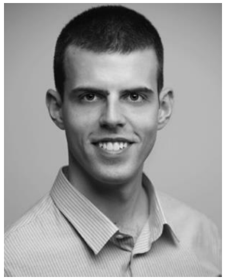
# 1. Sub contractors’ Background

**EPFL MAG: Microwave and Antennas Group**

- Core competences: passive microwave structures and antennas
- Heritage from EPFL-LEMA
- Long experience in ESA projects (since <2000)
- numerous fundamental and applied research projects with academic and industrial partners
- Collaboration with UniNe LTF since < 2000







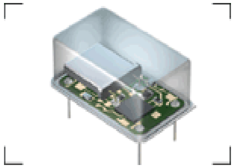
# Agenda

# 2. Motivation: Chip-Scale Atomic Clocks

⇨ Bring atomic timing precision to the size and power range previously covered by quartz oscillators

CSAC




| | Primary Standard | Commercial Cs Beam Clock | Compact Atomic Clock | Miniature Atomic Clock | Precision Quartz | Wristwatch Quartz |
|---|---|---|---|---|---|---|
| Accuracy: | $10^{-15}$ | $10^{-13}$ | $10^{-11}$ | $10^{-10}$ | $10^{-7}$ | $10^{-5}$ |
| Timing error: | 10ns/yr | 1µs/yr | 0.1µs/day | 1µs/day | 100µs/day | 1s/day |
| Size: | $10^7$ cm$^3$ | $10^4$ cm$^3$ | 100 cm$^3$ | 20 cm$^3$ | 1-10 cm$^3$ | 10 mm$^3$ |
| Power: | kW | 100's W | 1 W | 120mW | 100 mW | 10 µW |

⟵ Increasing performance, size, power, cost

⇨ **Low power consumption**: 100 mW ⇒ runs ≈ 1 week from a smartphone battery

Slide adapted from J. Kitching

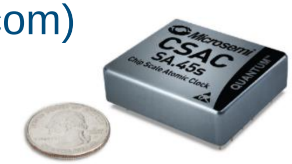
## 2. Project Motivation

- Importance of improved CSAC for PNT, secure telecom, and hold-over
- Existing low-power CSAC: alkali microcells + CPT interrogation
- Main CSAC challenges: thermal design + sensitivity
  long-term stability (timing error < 1 $\mu$s/day)

### Existing commercial products:

**Microchip SA.45**

(ex Microsemi / Symmetricom)




- $1 - 3 \cdot 10^{-10}$ @ 1 s
- Drift < $3 \cdot 10^{-11}$ /day
- 17 $cm^3$
- < 120 mW

**Safran mRO50**

(ex Orolia / Spectratime)


- $0.4 - 1 \cdot 10^{-10}$ @ 1 s
- Drift $1 \cdot 10^{-11}$ /day
- 50 $cm^3$
- 450 mW

⇨ **Need for new, advanced CSAC**

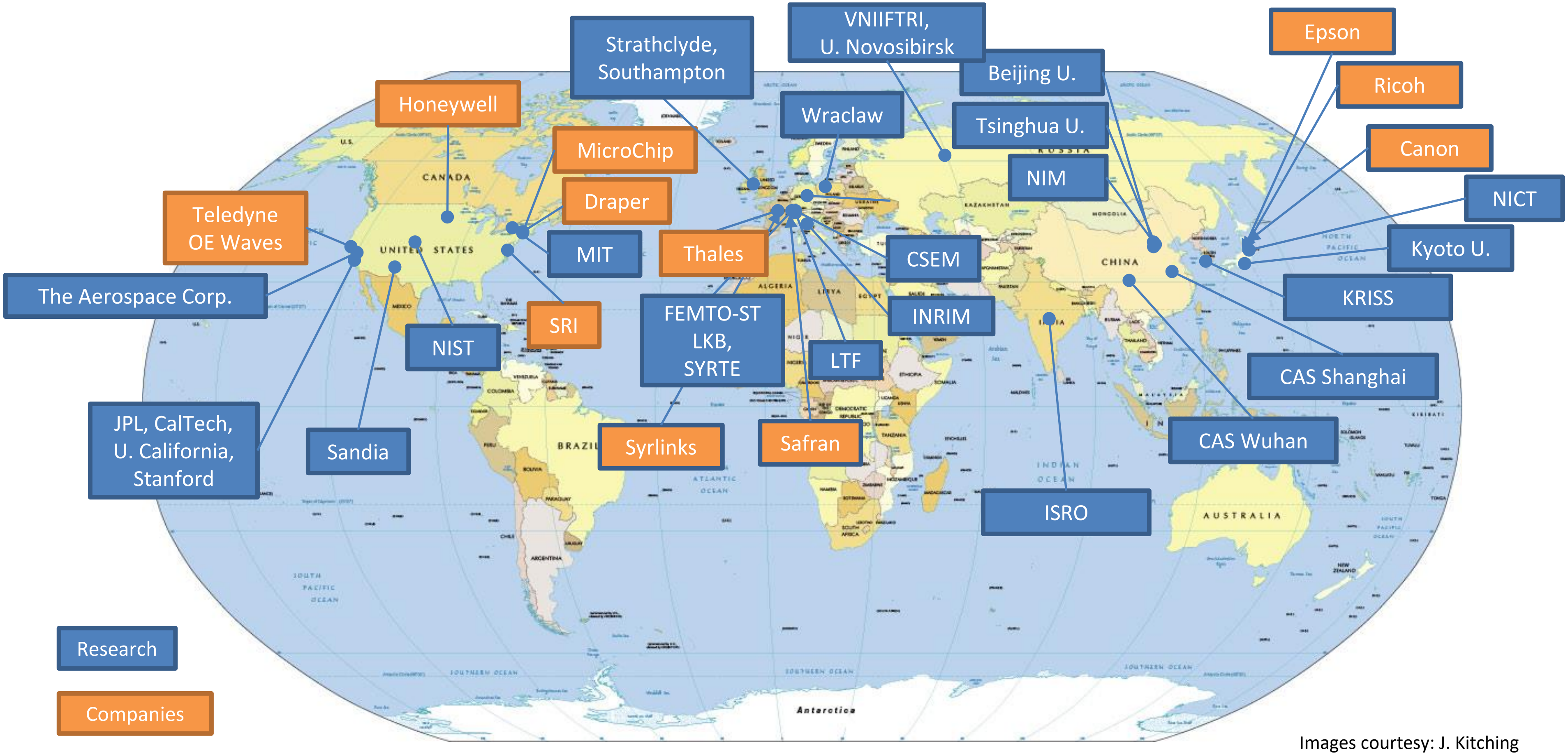
⇨ Aim for improved clock performances

- $1 \cdot 10^{-10} - 1 \cdot 10^{-11}$ @ 1 s
- **$1 \cdot 10^{-11} - 1 \cdot 10^{-12}$ / day**
- Timing error 1 – 0.1 µs/day
- Volume 5 – 10 $cm^3$
- Power 10 – 100 mW

# Agenda

1. Introduction
2. Motivation: miniature atomic clocks
3. **AMICC clock**
    a. **Selected clock scheme and design**
    b. Micro-Loop-Gap-Resonator
    c. AMICC clock demonstrator
    d. Results
4. Conclusions & outlook

# 3a. Advanced CSAC R&D activities




Images courtesy: J. Kitching

> 20 research groups worldwide
> 200 publications

# 3a. Advanced CSAC approaches

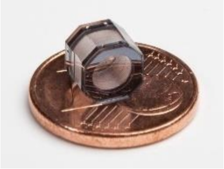
| Clock transition | Interrogation type | Stability | Maturity | Complexity | Clock Volume | Reliability / Lifetime |
|---|---|---|---|---|---|---|
| Optical | Trapped matter<br>e.g. single ion optical clock | $10^{-14}$-$10^{-15}\,\tau^{-1/2}$ | High | High | Typ. 0.5 $m^3$ | Trap lifetime ~1 day |
| | Two-photon transition atomic clock | $2 \times 10^{-12}\,\tau^{-1/2}$ | Medium | Medium | PP > 35 $cm^3$ | Cell lifetime > 10 years |
| Micro-wave | Trapped matter<br>e.g. Yb ion microwave Standard | $4 \times 10^{-12}\,\tau^{-1/2}$ | High | High | 70 $dm^3$ | Trap lifetime ~3 weeks |
| | Alkali-cell CPT<br>Coherent population trapping clock | Typ $10^{-10}\,\tau^{-1/2}$ | High | Low | 17-30 $cm^3$ | Cell lifetime > 10 years |
| | Alkali-cell DR<br>Double resonance atomic clock | $10^{-10} – 10^{-12}\,\tau^{-1/2}$ | High | Low | 51 $cm^3$ | Cell lifetime > 10 years |
| | Alkali-cell POP<br>Pulsed optical pumping atomic clock | $5 \times 10^{-13}\,\tau^{-1/2}$ | High | Low | PP < 1 $dm^3$ | Cell lifetime > 10 years |
| | NV in Diamond | $10^{-7}\,\tau^{-1/2}$ | Low | Low | No data | No data |
| | OCS<br>Chip scale molecular clock | $3 \times 10^{-9}\,\tau^{-1/2}$ | Medium | Low | PP > 20 $cm^3$ | Cell lifetime, no data |
| | Endohedral fullerene atomic clocks | No data | Low | Low | No data | No data |

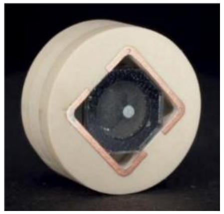
# 3a. Selected Solution

## Advanced Double-Resonance scheme for improved CSAC

- Alkali microcells + DR interrogation (RAFS heritage)
  - improved signal compared to CPT ⇒ short-term stability
  - Low light-shift effects ⇒ long-term stability, drift
- Simple scheme, few components ⇒ low-power solution

- Main technology components
  - Rb microcells (UniNE-LTF)
  - mm-scale microwave resonator (EPFL-MAG)
  - Laser interrogation: cw (selected) or pulsed, LTF high-perf clock heritage

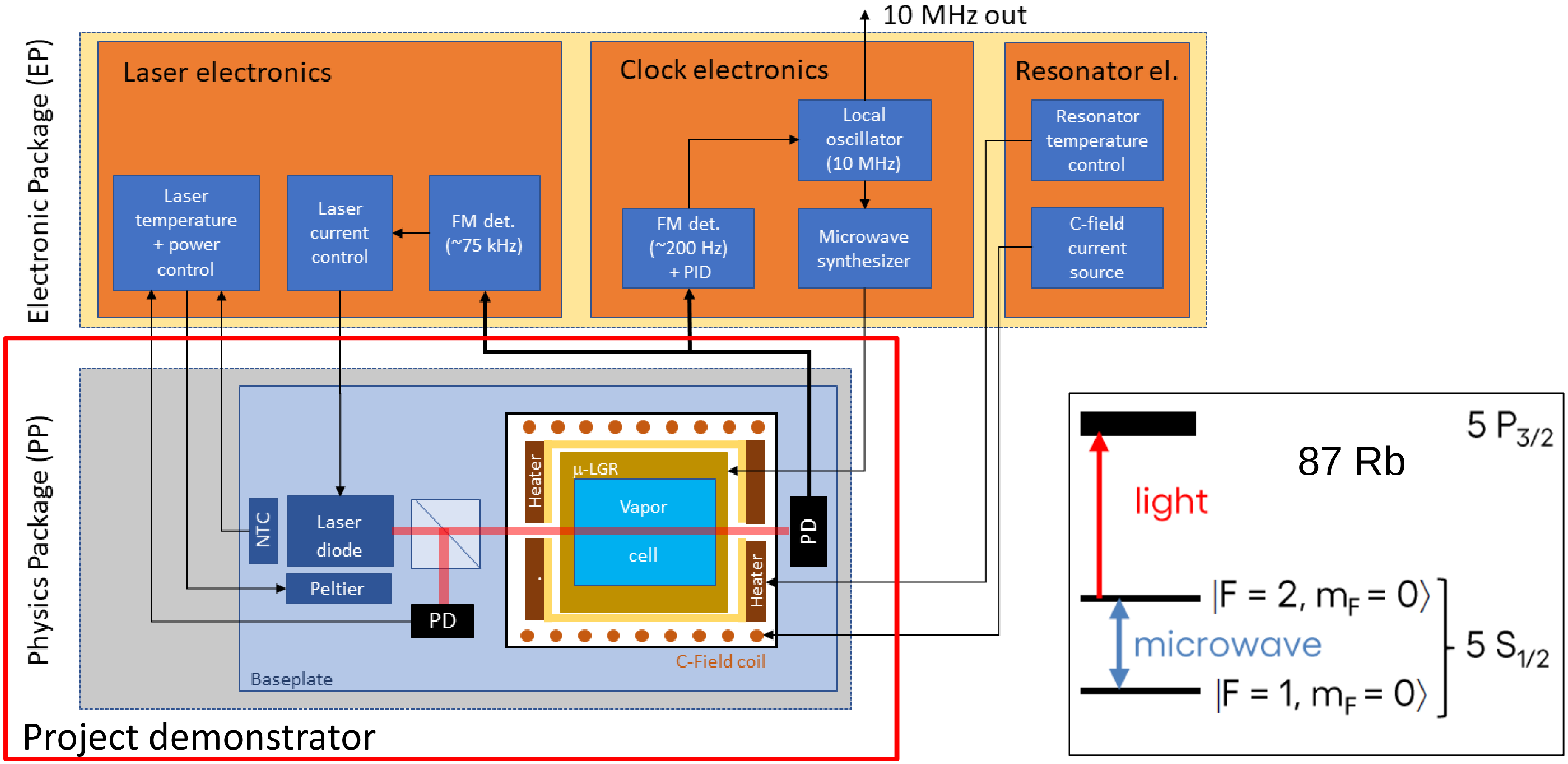




➢ Small size, simplicity, and target performance

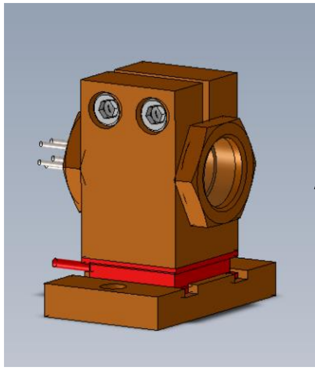
# 3a. AMICC Clock Scheme

## CW Double-Resonance microcell clock

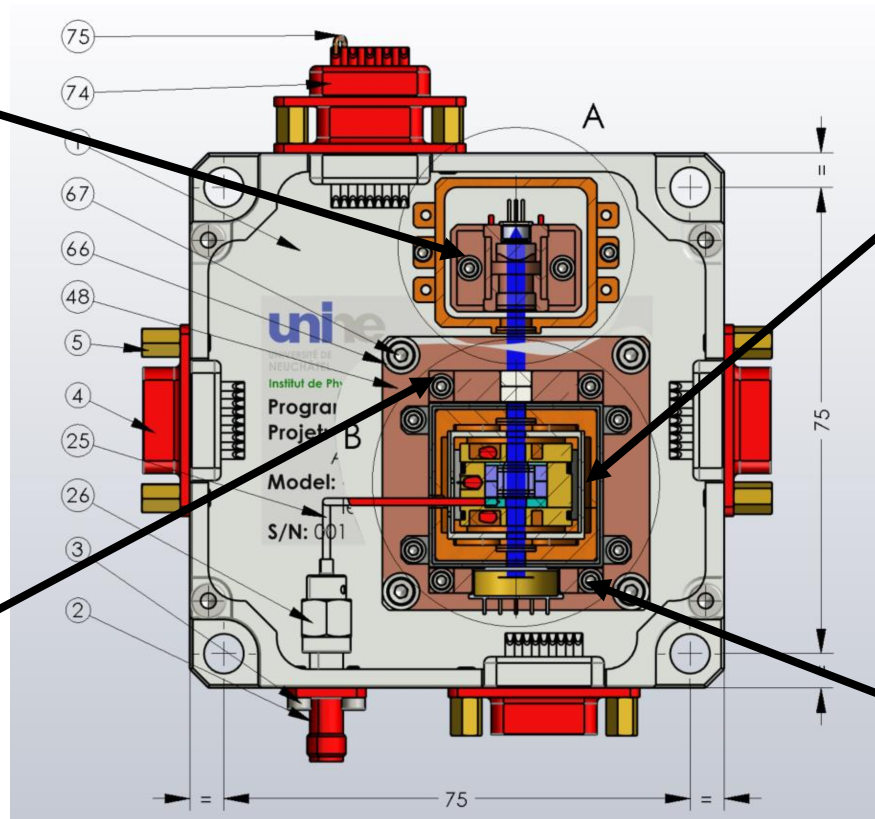


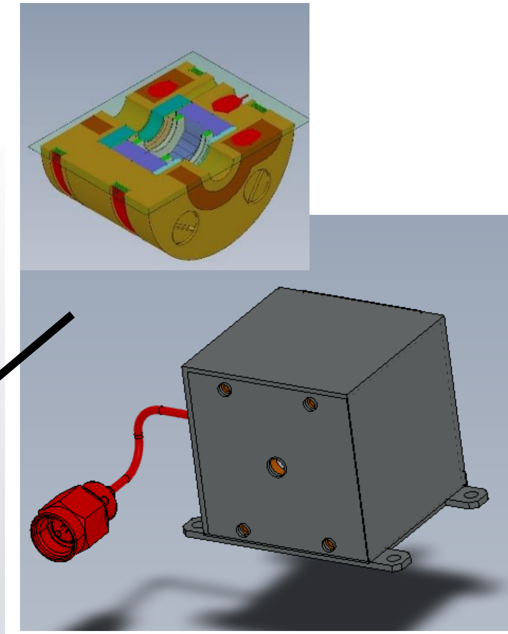

- 1 low-power laser diode, 1 Rb(nat) microcell, 1 miniature microwave resonator

## Demonstrator overview

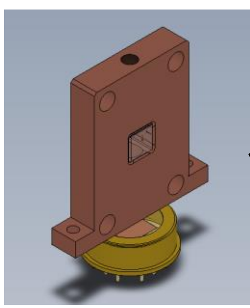


Integrated Light source module

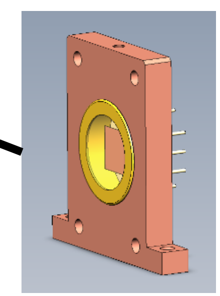


Atomic resonator module



Active power stabilization



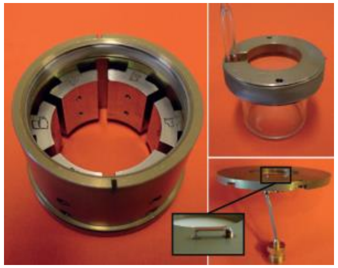
All-integrated photo-detector and preamp

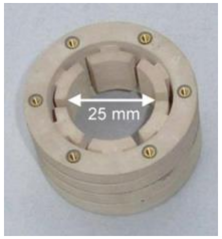
# Agenda

# 3b. Micro Loop-Gap resonator

- **Introduction & Review**

Challenge: miniaturize the cavity, while keeping the resonant frequency and the field orientation (FoF). Reminder : wavelength at 6.835 GHz is about 44 mm. Minimum radius of cylindrical cavity with the appropriate $TE_{011}$ mode: 27mm







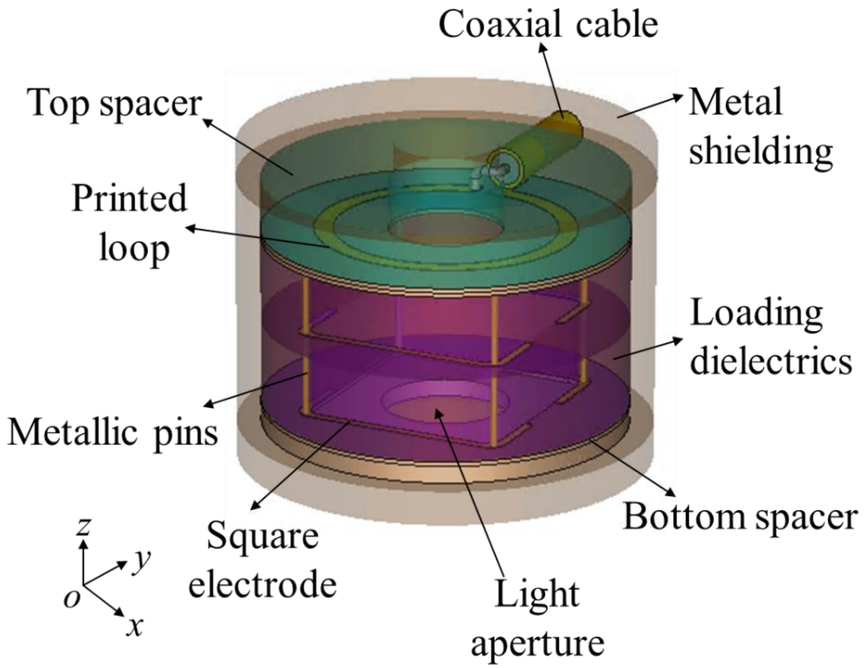

65cm$^3$ ~45cm$^3$ ~1cm$^3$ ~0.5cm$^3$

**LGR (Loop-Gap Resonator) technique** shows its advantages to achieve a **high field homogeneity** in **a sub-wavelength sized volume** for Rb atom transition of a CSAC at 6.853GHz.

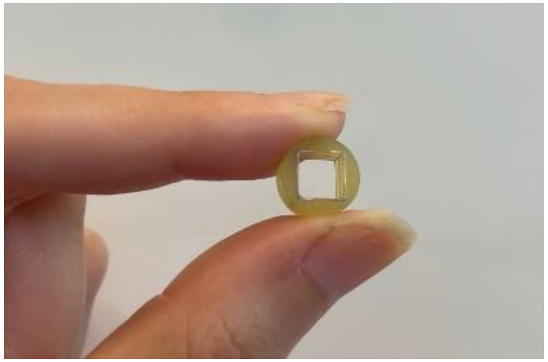
# 3b. Micro Loop-Gap resonator

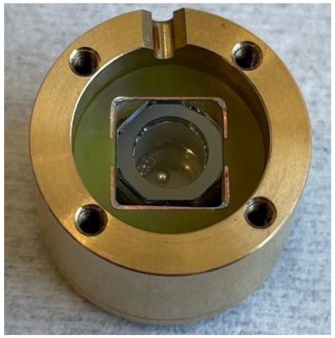
- **Tuning-free concept for μLGR design**

Key features: low cost, smaller volume, tuning free, excellent field homogeneity




Fabrication Prototypes

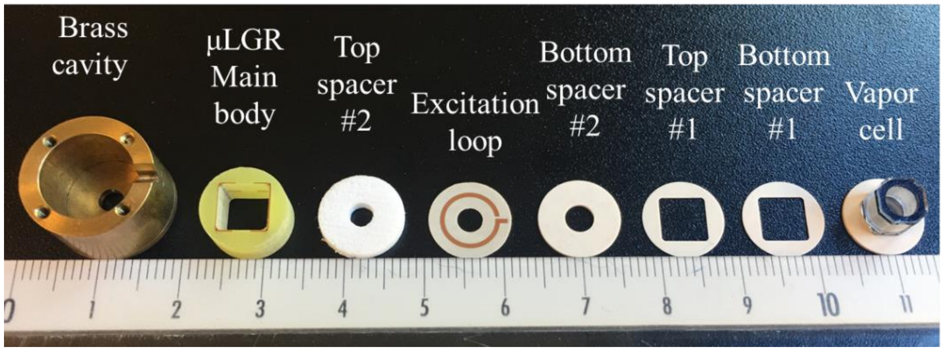


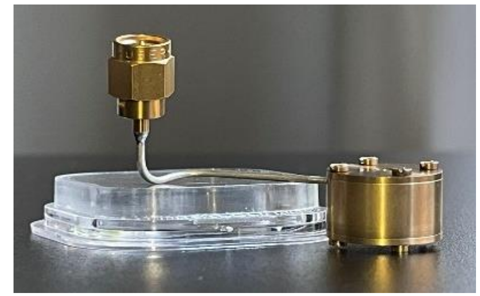


# 3b. Micro Loop-Gap resonator

- **Assembling & Performance Validation**

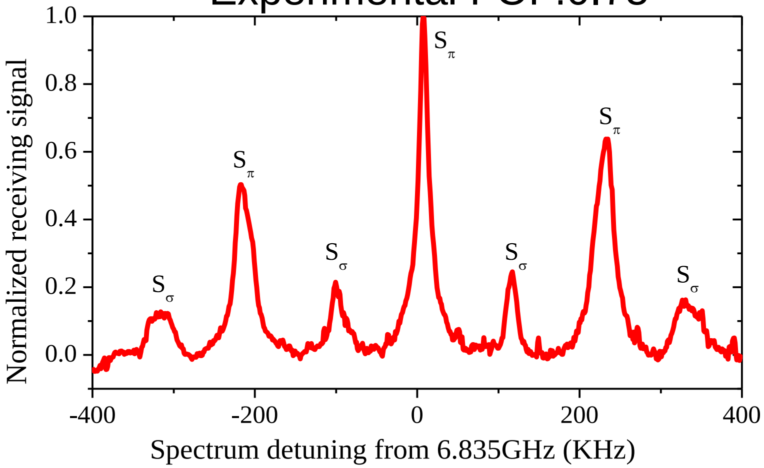
Assembling



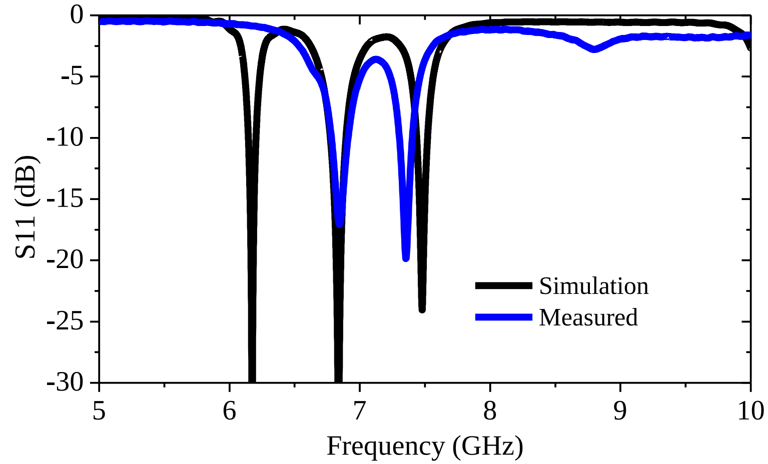



Measurement Performance

Experimental FOF:0.75




Cavity-cell assembly in high T (~109°C)



# 3b. Micro Loop-Gap resonator

- **Compliance wrt specifications**

| Specification | Specification value | Verification method | Test result | Pass / fail |
|---|---|---|---|---|
| Resonant frequency | 6.835 GHz ± 10 MHz | VNA | 6.843 GHz | Pass |
| FOF | ≥ 0.7 | At system level, spectroscopic | 0.75 | Pass |
| Loaded Q factor | 10 ~ 200 | VNA | 13 | Pass |
| Volume, with / without enclosure | < 5 $cm^3$ / < 1 $cm^3$ | Caliper | 0.65 $cm^3$ | Pass |
| Input impedance at resonance | 50 $\Omega$ | VNA | 50 $\Omega$ SMA connection | Pass |
| Bandwidth of \|S11\| < -10 dB | NA | VNA | 130 MHz | NA |
| Testing temperature T | 80°C ≤ T ≤ 110°C | Thermometer | ~109°C | Pass |

# 3b. Microwave resonator conclusions

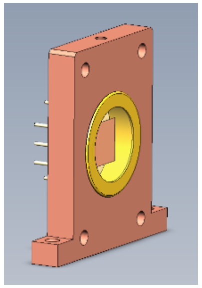
## Conclusions

- **Low cost**: benefited from common FR4 substrate and standard PCB fabrication technique
- **Smaller volume**: with dielectric loading, in line with CSAC goal
- **Tuning free**: simpler and robust clock system
- **Excellent field homogeneity**:  Support more atom transitions

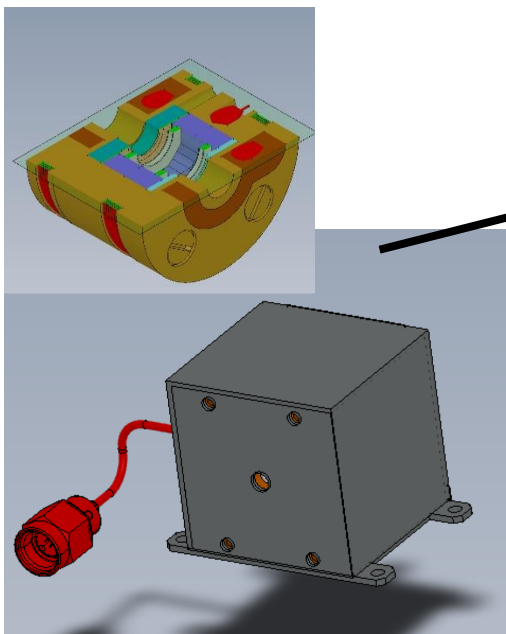
# Agenda

# 3c. Demonstrator PP design reminder

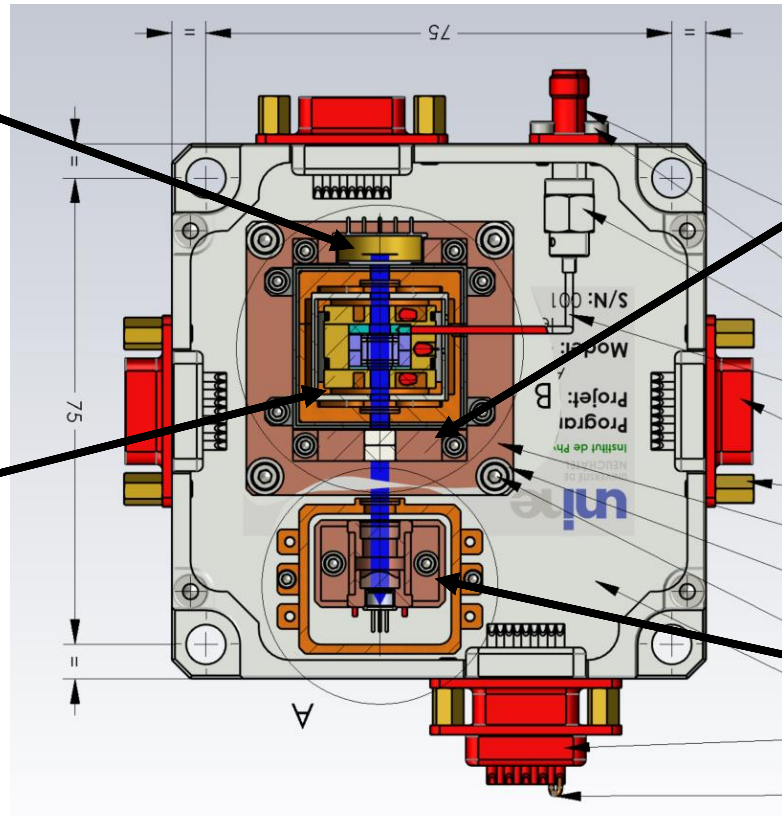
## Demonstrator PP overview

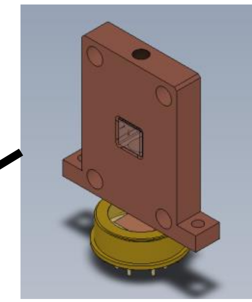


All-integrated photo-detector and preamp

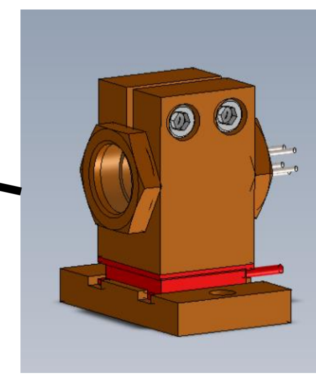


Atomic resonator module



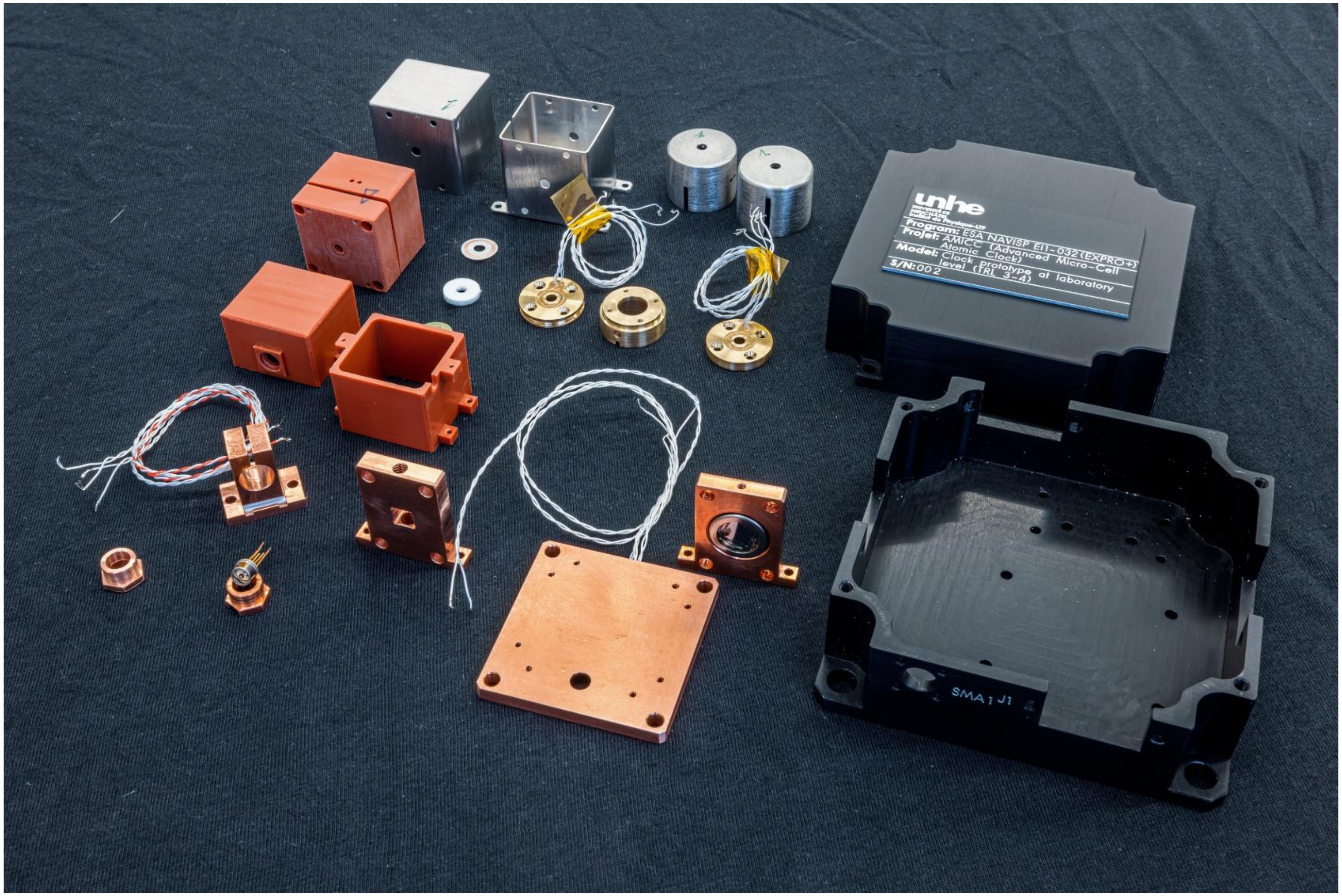
Active power stabilization



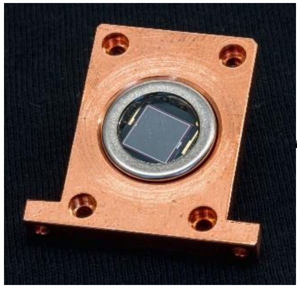
Integrated Light source module

# 3c. Demonstrator Manufacture

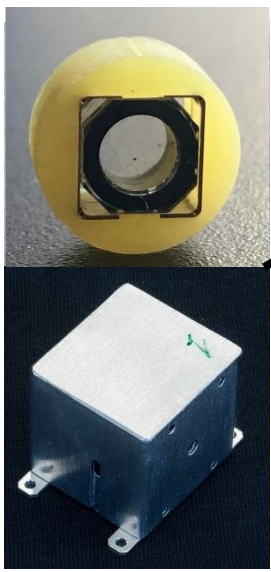
Demonstrator parts, mainly in-house machining and assembly



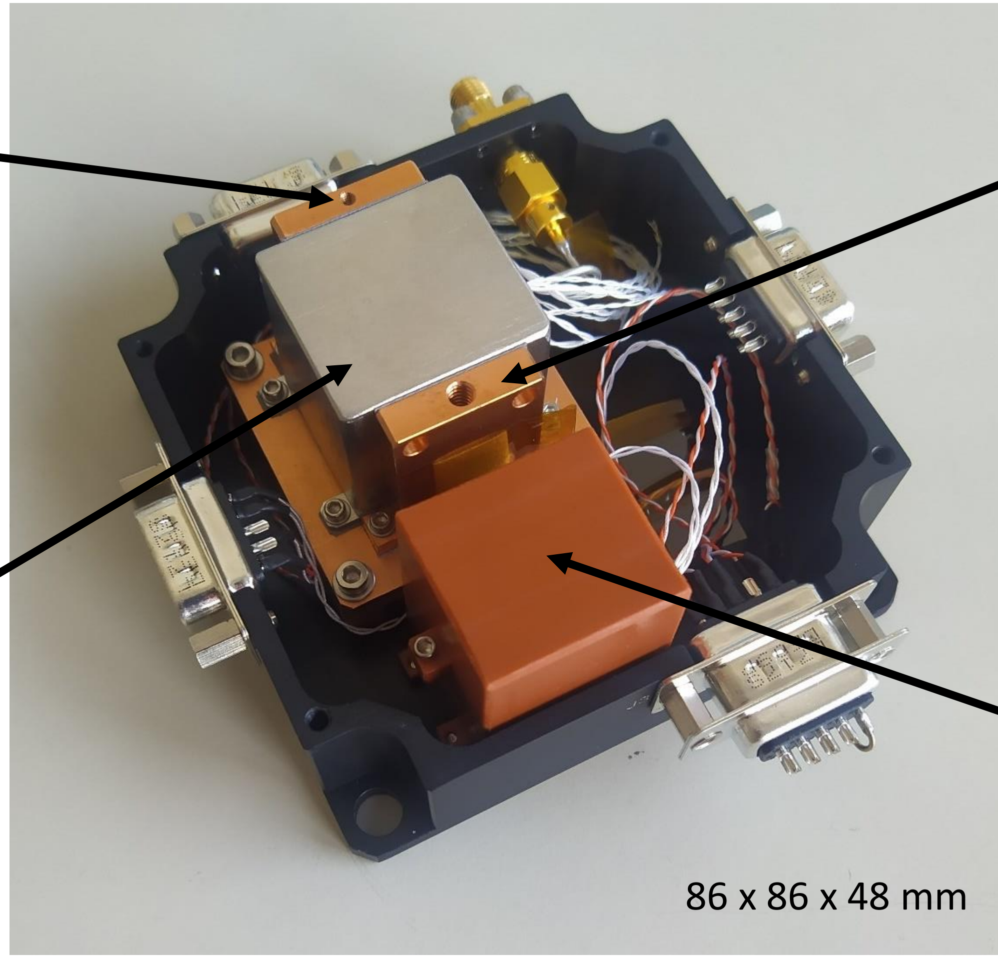
# 3c. Assembled Demonstrator PP

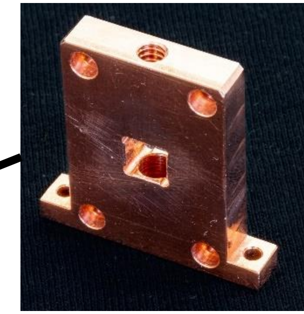


All-integrated photo-detector and preamp.

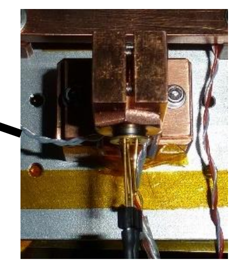


Atomic resonator module



Active power stabilization



Integrated Light source module

+ laboratory-type control electronics

# Agenda

1. Introduction
2. Motivation: miniature atomic clocks
3. AMICC clock
    a. Selected clock scheme and design
    b. Micro-Loop-Gap-Resonator
    c. AMICC clock demonstrator
    d. **Results**
4. Conclusions & outlook

# 3d. Clock signals

- Operating parameters

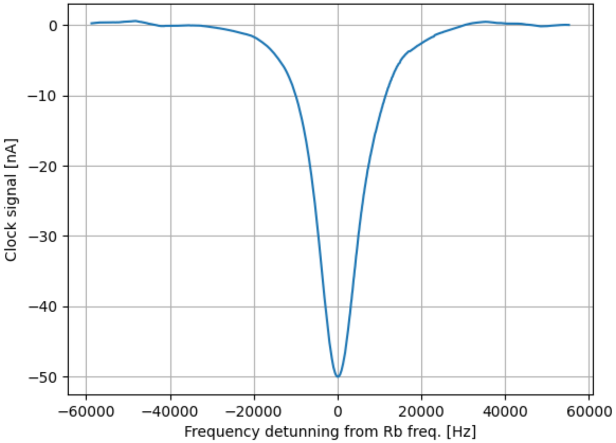
| | |
|---|---|
| Laser power | 10 µW |
| Microwave power | 100 µW |
| Cell temperature | 99 °C |

- Clock signal

FWHM = 11 kHz

Amplitude = 52 nA

Detection noise ≈ 1 pA $Hz^{-1/2}$

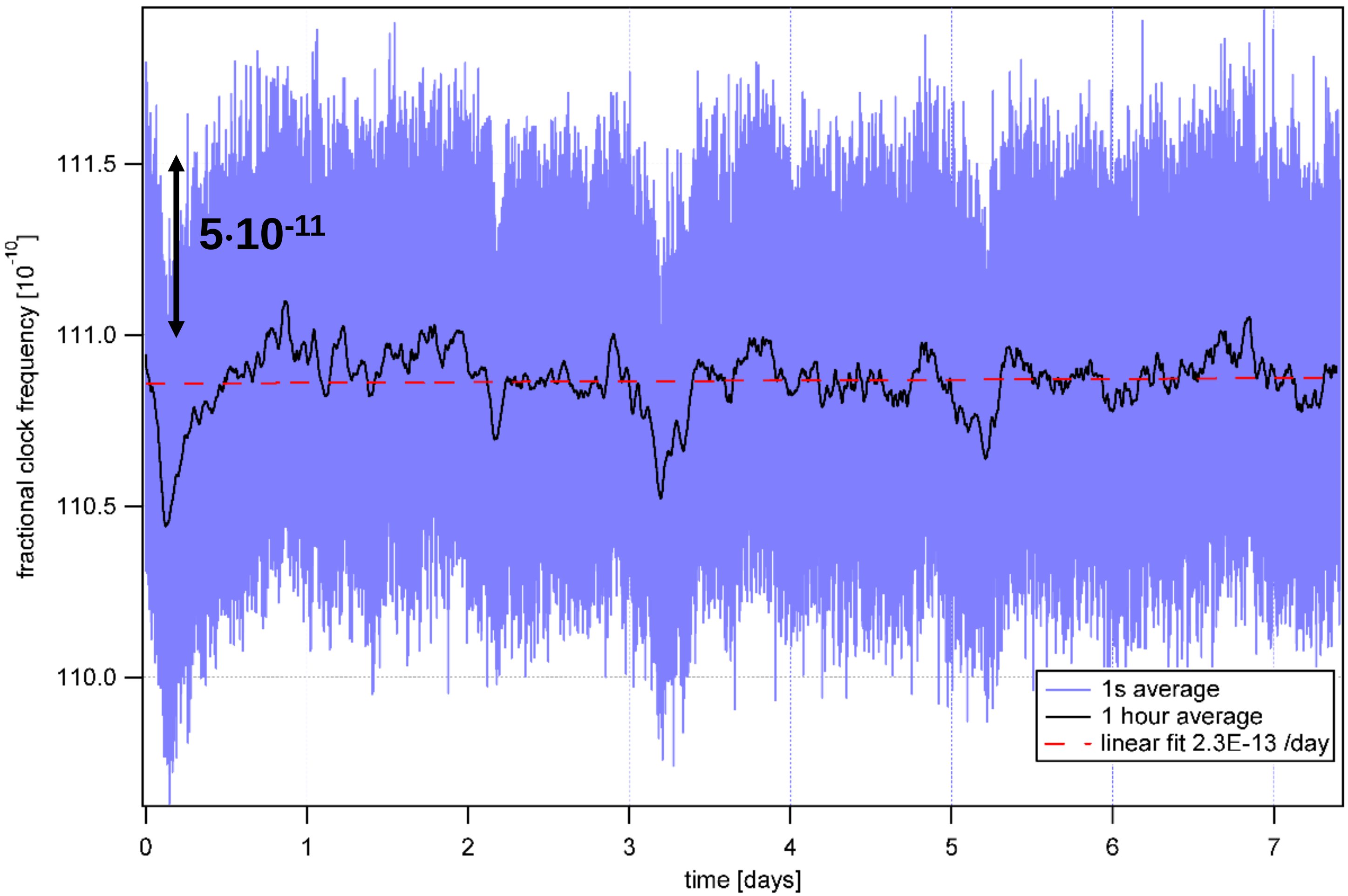



- Predicted signal-to-noise-limit

$\sigma_{SNR} = 2.5\times10^{-11}\ \tau^{-1/2}$

# 3d. Clock test results

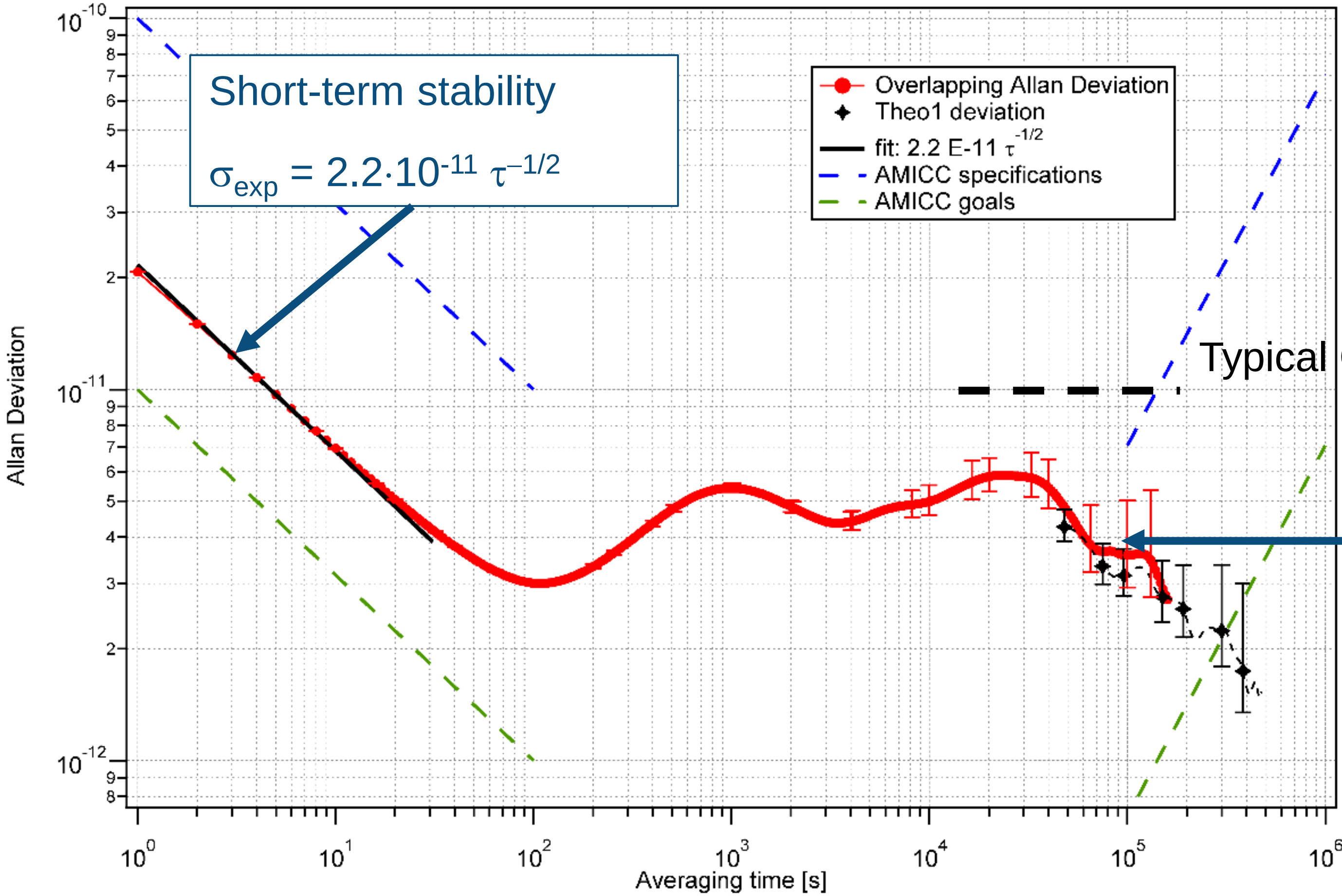
- Clock frequency (1-week run)




- ➢ Good stability
- ➢ No drift removed
- ➢ **Low drift, $2 \cdot 10^{-13}$ /day**

# 3d. Clock test results

- Allan deviation (1-week run)




- ➢ meets specifications
- ➢ No drift removal

≈ **$4\cdot10^{-12}$ @ 1 day**

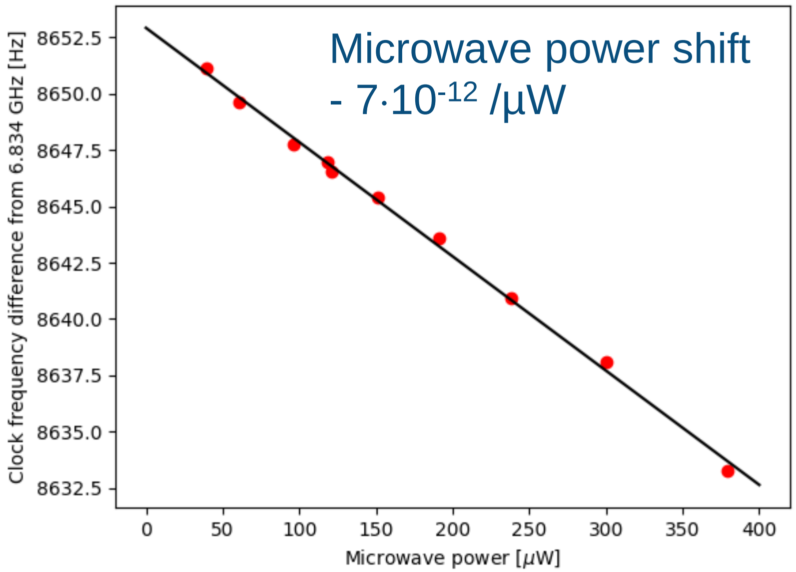
# 3d. Clock test results: short-term stability budget

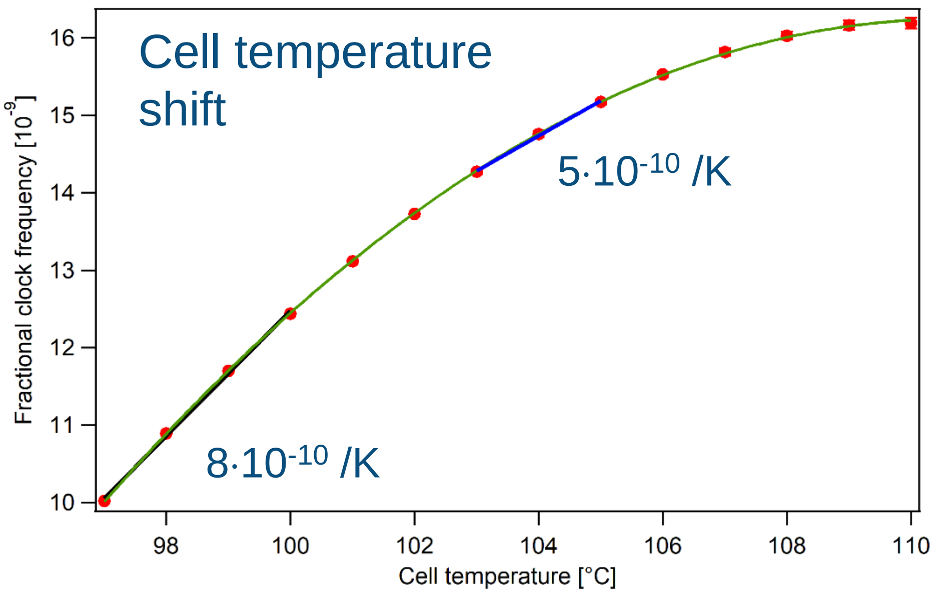
| Physical effect | Sensitivity Coefficient | | Physical Parameter | | Clock instability contribution at 1 s |
|---|---|---|---|---|---|
| | Unit | Value | Parameter | Fluctuation at 1 s | |
| **Detection noise limit** | - | - | - | - | **$2.5 \cdot 10^{-11}$** |
| **Of which shot-noise** | - | - | - | - | $6.5 \cdot 10^{-12}$ |
| **Intensity Light-Shift** | Fract. freq/uW | $5.5 \cdot 10^{-10}$ | Laser Intensity [μW] | $4.5 \cdot 10^{-3}$ | $3.8 \cdot 10^{-12}$ |
| **Frequency Light-Shift** | Fract. Freq /Hz | $9.9 \cdot 10^{-17}$ | Laser freq. [Hz] | $3.8 \cdot 10^{4}$ | $2.5 \cdot 10^{-12}$ |
| **2$^{nd}$ order Zeeman shift** | Fract. Freq/T | $1.7 \cdot 10^{-12}$ | Magnetic field [T] | $4.3 \cdot 10^{-10}$ | $2.5 \cdot 10^{-12}$ |
| **Microwave power shift** | Fract. freq/uW | $-7.4 \cdot 10^{-12}$ | Microwave power [uW] | $1.2 \cdot 10^{-2}$ | $9.0 \cdot 10^{-14}$ |
| **Estimated total** | | | | | **$2.5 \cdot 10^{-11}$** |
| **Measured** | | | | | **$2.2 \cdot 10^{-11}$** |

- Short-term stability is well understood
- Main current limitation is detection noise
- Measured stability is below estimate due to different cell temperature

# 3d. Selected systematic effects

- ➢ Characterize systematic shifts, for long-term instability budget
- ➢ Measure closed-loop clock stability for varying operation parameters



# 3d. Clock Metrology: Long-Term Stability Budget

| Physical effect | Sensitivity Coefficient | | Physical Parameter | | Clock instability contribution at $10^5$s |
|---|---|---|---|---|---|
| | Unit | Value | Parameter | Fluctuation at $10^5$s | |
| **Intensity Light-Shift** | Frac. Freq/µW | $5.5 \cdot 10^{-10}$ | Laser Intensity [µW] | $5.4 \cdot 10^{-4}$ | $3.0 \cdot 10^{-13}$ |
| **Frequency Light-Shift** | Frac. Freq/Hz | $9.9 \cdot 10^{-17}$ | Laser freq. [Hz] | $3.8 \cdot 10^{4}$ | $\mathbf{3.7 \cdot 10^{-12}}$ |
| **Temperature coefficient** | Frac. Freq/K | $8.0 \cdot 10^{-10}$ | Cell T [K] | $8.0 \cdot 10^{-4}$ | $6.4 \cdot 10^{-13}$ |
| **Microwave Power Shift** | Frac. Freq/µW | $7.4 \cdot 10^{-12}$ | Microwave Power [µW] | 0.2 | $1.5 \cdot 10^{-12}$ |
| **$2^{nd}$ order Zeeman shift** | Frac. Freq/T | $1.8 \cdot 10^{-4}$ | C-field [T] | $1.3 \cdot 10^{-9}$ | $2.3 \cdot 10^{-13}$ |
| **Total** | | | | | $\mathbf{4.1 \cdot 10^{-12}}$ |
| **Measured** | | | | | $\mathbf{3.6^{+1.5}_{-0.7} \cdot 10^{-12}}$ |

- Long-term stability is well understood
- Main current limitation is frequency light-shift
- $2^{nd}$ order Zeeman shift includes external field fluctuations (measured by locking to magnetically sensitive transition $m_F=1 \leftrightarrow m_F=1$)

# 3d. Clock Stability Summary

| Parameter | AO9952 spec | AO9952 goal | AMICC prototype | Compliance (wrt specs) |
|---|---|---|---|---|
| **Output frequency** | 10 MHz to 10 GHz | 10 MHz to 10 GHz | 10 MHz | Compliant |
| **Adev (1 s)** | $1 \cdot 10^{-10}$ | $1 \cdot 10^{-11}$ | $2 \cdot 10^{-11}$ | Compliant |
| **Adev (10 s)** | $3.2 \cdot 10^{-11}$ | $3.2 \cdot 10^{-12}$ | $7 \cdot 10^{-12}$ | Compliant |
| **Adev (100 s)** | $1 \cdot 10^{-11}$ | $1 \cdot 10^{-12}$ | $3 \cdot 10^{-12}$ | Compliant |
| **Adev (1 day)** | -- | -- | $4 \cdot 10^{-12}$ | NA |
| **Frequency drift** | $1 \cdot 10^{-11}$ /day | $1 \cdot 10^{-12}$ /day | $2 \cdot 10^{-13}$ /day | Compliant |
| **Timing error** | 1 µs/day | 0.1 µs/day | 0.17 µs/day | Compliant |

- Compliant with respect to baseline specifications
- Close to project goal specifications

# Agenda

1. Introduction
2. Motivation: miniature atomic clocks
3. AMICC clock
    a. Selected clock scheme and design
    b. Micro-Loop-Gap-Resonator
    c. AMICC clock demonstrator
    d. Results
4. **Conclusions & outlook**

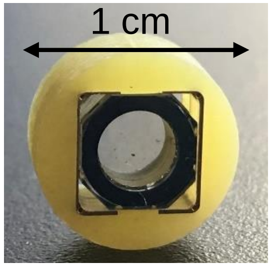
# 4. Conclusions

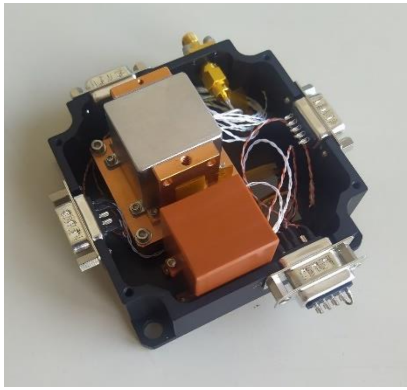
- Realized simple AMICC DR-clock concept, based on a novel µ-LGR resonator for microcells

- Very simple system ⇒ only 1 laser, 1 microcell, 1 µ-LGR
  ⇒ small PP, simple electronics
  ⇒ small and low power clock possible

- Compliant clock performance demonstrated

- Main long-term stability limit: frequency light-shift



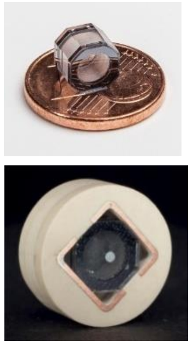
Next steps:

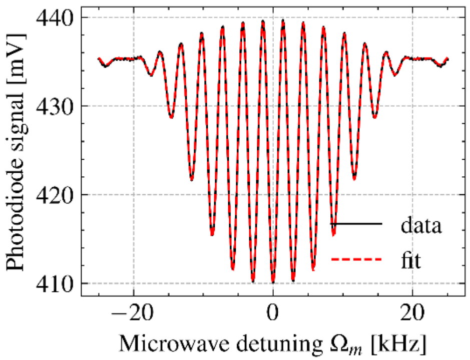
- Performance enhancement: pulsed µPOP clock (reduced light-shift)
- In parallel, industrialisation of the AMICC clock
- Size reduction with planar µ-LGR resonator

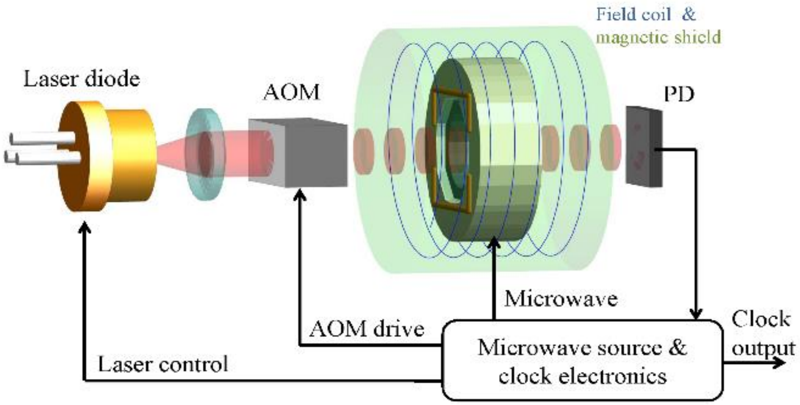
# 4. Outlook 1: µ-POP study

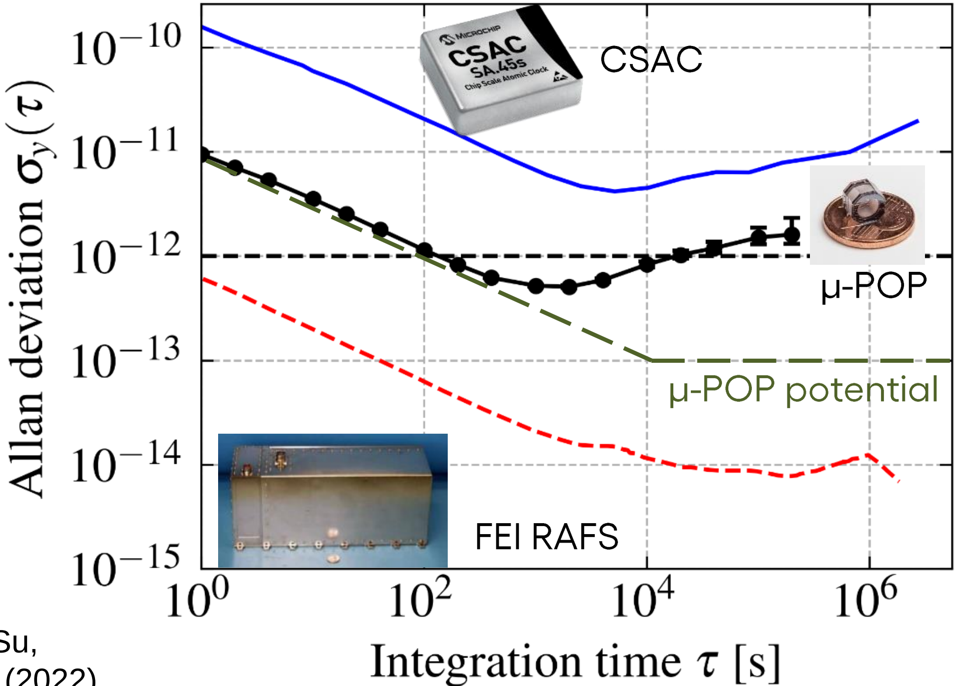
- **µ-POP clock study:**
  **First demonstration of Ramsey interrogation in a microcell**
- ≈ $10^{-12}$ stability @ 1 day
- $10^{-13}$ stability potential
- Reduced light-shift effects

➢ To be implemented on AMICC PP






E. Batori, C. Affolderbach, M. Pellaton, F. Gruet, M. Violetti, Y. Su,
A. K. Skrivervik, G. Mileti, Physical Review Applied 18, 054039 (2022)

# 4. Outlook 2: AMICC micro-clock development

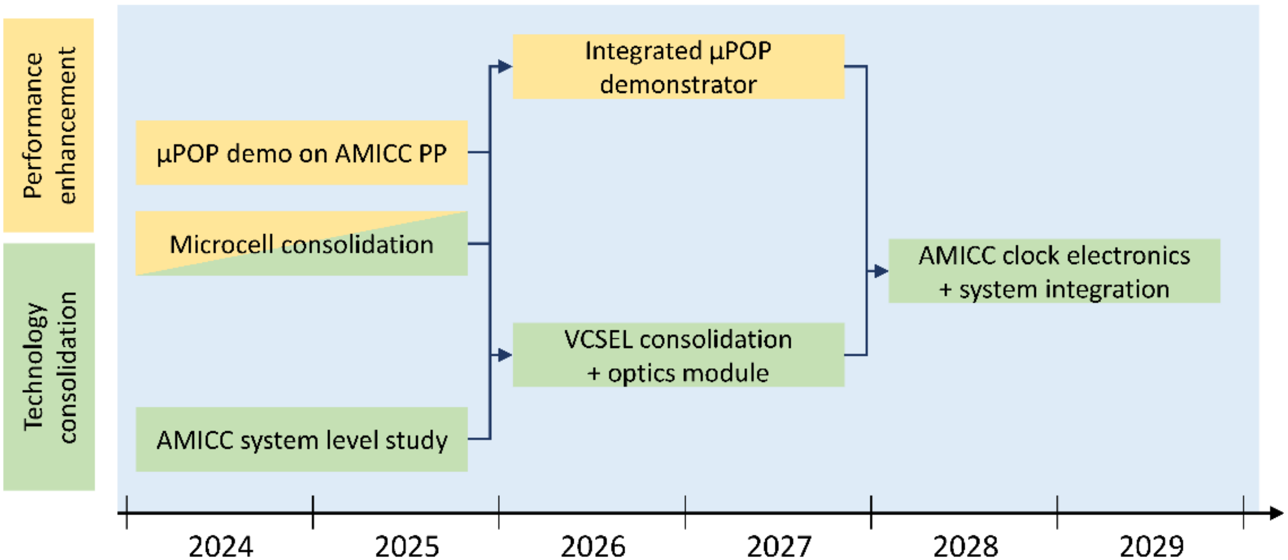
### Performance enhancement

- µPOP study on AMICC PP: improved long-term
- 87Rb cell implementation: improved signal

⇒ Improved clock stability

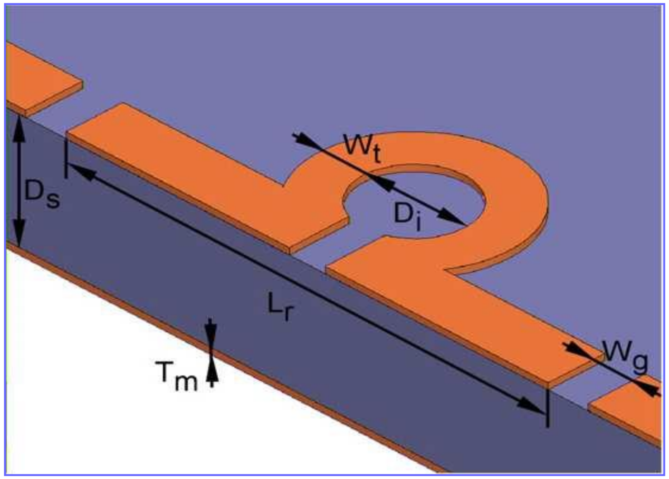
### Product development

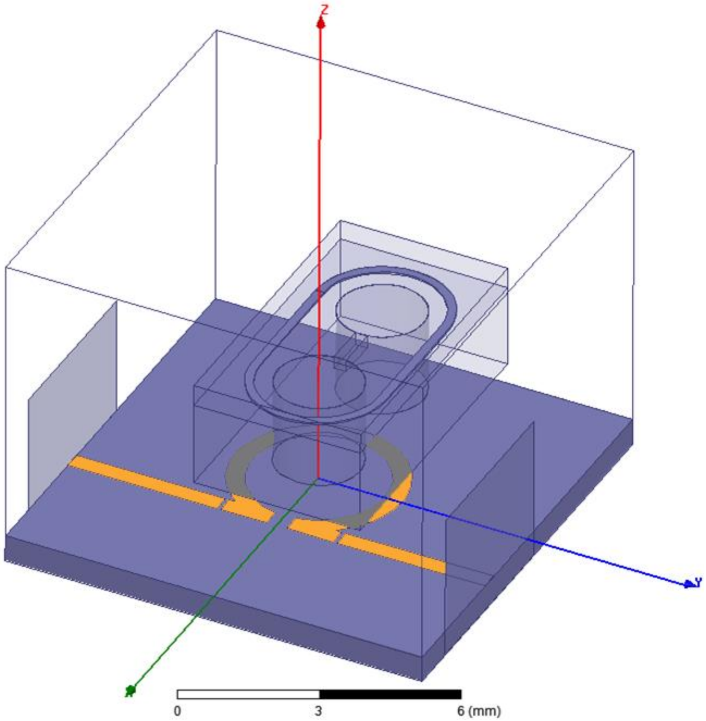
- VCSEL laser + optical module consolidation
- Clock electronics adaptation or development
- Product integration



# 4. Outlook 3: Flat vapour cells and planar resonators

- **Planar resonator for flat microcells**
- Suitable for on-chip integration
- Simple structure ☺
- Preliminary simulated FoF: 0.86
- Further reduced clock volume



# 4. Project publications

- Y. Su, C. Affolderbach, M. Pellaton, G. Mileti and A. K. Skrivervik, "**A Wide-Frequency-Tuning Micro-Loop-Gap Resonator for Miniature Rubidium Vapor-Cell Atomic Frequency Standards**," IEEE Trans. Microwave Theory and Techniques 2023, doi: 10.1109/TMTT.2023.3276194.
- Y. Su, M. Pellaton, C. Affolderbach, G. Mileti, M. Veljovic and A. Skrivervik, "**Characterization of Microwave Substrates for High Accuracy and Long-Term Stability Using Full-Wave Microstrip Ring Resonator Method**," Proc. 2021 European Microwave Conference (EuMC), London UK, 2022, pp. 421-424, doi: 10.23919/EuMC50147.2022.9784190.
- Y. Su, C. Affolderbach, M. Pellaton, G. Mileti and A. K. Skrivervik, "**Mode Suppression and Homogeneous Field Bandwidth Enhancement of Tuning-Free Micro-Loop-Gap Resonator Using FR4 Loading Technique for Chip-Scale Rubidium Clock**", submitted to IEEE Transactions on Microwave Theory and Techniques, 27.06.2023.
- M. Pellaton, C. Affolderbach, E. Batori, G. Mileti, Y. Su, M. Violetti, A. K. Skrivervik, "**LEMAC: LTF-EPFL Miniature Atomic Clock - current status**", Proc. European Frequency and Time Forum 2022, Paris FR, poster 5066.
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- E. Batori, C. Affolderbach, M. Pellaton, F. Gruet, M. Violetti, Y. Su, A. K. Skrivervik, G. Mileti, "**µPOP Clock: A Microcell Atomic Clock Based on a Double-Resonance Ramsey Scheme**", Physical Review Applied 18, 054039 (2022).

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