

#### An efficient Zeeman slower for the ROYMAGE transportable Ytterbium clock

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# An efficient Zeeman slower for the ROYMAGE transportable Ytterbium clock



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### Motivation : apply quantum sensors to Earth Sciences

□ Optical Lattice Clocks allow a control of **18 significant digits** (10<sup>-18</sup>) of their frequency, with a statistical resolution of a few  $10^{-16}/\sqrt{\tau}$ , with  $\tau$  the integration time.

 $\Box$  As predicted by Einstein, atomic frequencies  $\nu$  are sensitive to the local gravitational potential W and therefore to the altitude.

□An atomic clock travelling in the field can be used to perform a cartography of the geopotential, by remote comparisons with ~12 existing optical clocks in Europe, connected by ultrastable fiber links.

**REFIMEVE+** network and international links to NMI





# Zeeman slower with permanent magnet (simulation)

□ Zeeman slower skeleton is based on the next three totally-related parameters:

- Velocity capture, being higher velocity the ZS is able to cool down.
- Maximum (des)acceleration, defined by the cooling laser intensity.
- Length of the ZS, defined as the minimum distance to stop atoms at v=0m/s.



#### Magnetic field along Zeeman axis





□ The Equipex **REFIMEVE+** disseminates a **1542 nm** ultrastable IR carrier throughout France, with connections to corresponding networks in Germany, UK and Italy.

# Impact of dead time on the clock short term stability

□ When interrogating the clock transition the result is judged by two criteria :

- The uncertainty, or how close we believe the corrected measured frequency is to the 'ideal' unperturbed value, and it will be reflected by how well are known the corrections made due to systematical effects shifting this frequency.
- The stability, when the values of repeated measurements are clustered close together and have minimal scatter over time.



Short term limiting effect as function of the dead time 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 ⊺<sub>Rabi</sub>=150 ms Laser's Flicker floor = 8x10<sup>-16</sup> 1.×10<sup>-</sup> ∽ 5.×10<sup>-1</sup> Dick Effect Rabi case Presen Situatio Target of 1.×10<sup>-</sup> this work QPN for 10<sup>4</sup> atoms 3 5.×10⁻ Detection noise for a resolut of 10<sup>2</sup> atoms over 10<sup>4</sup> atoms 0.8 0.5 Dead Time (s)

Loading as fast as the coherence of the laser will reduce it

The project aims at loading >10<sup>4</sup> atoms into the optical trap in <150 ms.

# Cold Yb source design and simulation

blue 2D-MO

- Design main points [2]:
  - Optical molasses for transverse velocity reduction.
  - Zeeman slower for longitudinal velocity reduction.
  - 2D MOT for cold atomic flux collimation.
  - 3D MOT prior to loading into an optical trap.

# First stages of the clock

### <u>Oven</u>



#### □ Ytterbium flux source :

- Oven containing ytterbium metal.
- Collection of microtubes at the oven output.
- □ The atomic flux is defined by the dimension of the microtubes and the oven temperature.

- Difficult to calculate the position of the magnets.
- Use much more magnets, it is heavier.
- Magnetic shield is 100% needed.
- Long decay of magnetic gradient along optical path. Short decay of magnetic gradient along optical path.
- Use 100% of the laser power.
- Easy to calculate the position of the magnets.
- Less magnets are needed, it lighter.
- The magnetic shield is most likely not necessary.
- Use 50% of the laser power.

# Winner Zeeman Slower —— Transversal

□ Maximum acceleration at the beginning and two screws at the end to control of the velocity output by modifying the radial distance of the last two magnets.

- Simulated Annealing to find the global optimum configuration of the array.
- □ Since the proposed array is symmetric, rotations will not change the shape of the magnetic field.

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- □ Longitudinal spectroscopy at 399 nm :
- Fit model : convolution between a lorentzian and a modified gaussian profile [1].
- Quantitative fits give :
- T<sub>longit</sub>= 712 K (440 °C)

• Most probable velocity : 322 m/s

Atomic beam divergence [2]: 5.4-6.8 ° (half angle)

### **Transverse cooling (simulation)**



□Proposed scheme : three atoms-light interraction zone with a gradient in detuning (spacial-distribution detuning).

#### **Optimized results :**

□ In order to have a maximum radius of 8 mm, we can reflect trajectories with initial radial velocity up to 18 m/s.



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EURAMET

XZ Plane (Y=0) . B<sub>z</sub> Field [mT]

[1] J. Vanier and C. Audoin, The Quantum Physics of Atomic Frequency Standards. Adam Hilger, 1989. [2] E. Wodey et. al., J. Phys. B: At. Mol. Opt. Phys., vol. 54, p. 035301, 2021. [3] Ian R, Hill et. al., J. Phys. B: At. Mol. Opt. Phys. Vol. 47, p. 075006, 2014.