

Metrology of microwave fields with cold Rydberg atoms

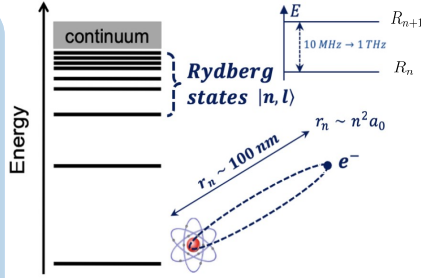
R. Granier, R. Duverger, Q. Marolleau, A. Bonnin, C. Blanchard, N. Zahzam, Y. Bidet, A. Bresson and S. Schwartz

DPHY, ONERA, Université Paris-Saclay, Chemin de la Hunière - BP80100, F-91123 Palaiseau, France

Motivation and context

Rydberg States

- Highly excited atomic states: $n \gg 1$
- Very large electric dipole moments making them very sensitive to external electromagnetic fields.
 $\langle R_n | \hat{d} | R_{n+1} \rangle \propto n^2$
- Polarizability: $\alpha \propto n^7$
- Long-lived atomic states suited for precision spectroscopy and coherent manipulation: $\tau_{lifetime} \propto n^3$



→ Tunable from the MHz to the THz domain (radio waves / micro-waves)

Room temperature Rydberg sensors

- Demonstrated sensitivity: $100 \text{ nV/cm}/\sqrt{\text{Hz}}$
- Limited spatial and spectral resolution
- High bandwidth

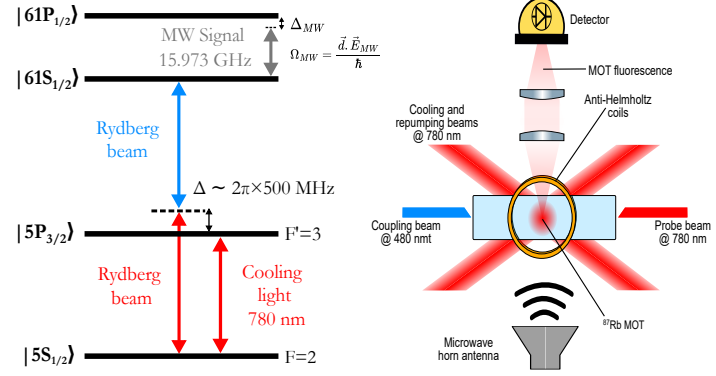
[Meyer et al., Assessment of Rydberg atoms for wideband E-field sensing. J. Phys. B 53, 034001 (2020)]

Cold Rydberg atoms sensors

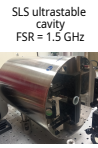
- High linearity
- High resolution
- Long-term stability
- High sensitivity
- Low bandwidth

Towards a new generation of electromagnetic sensors with high sensitivity and spatial resolution

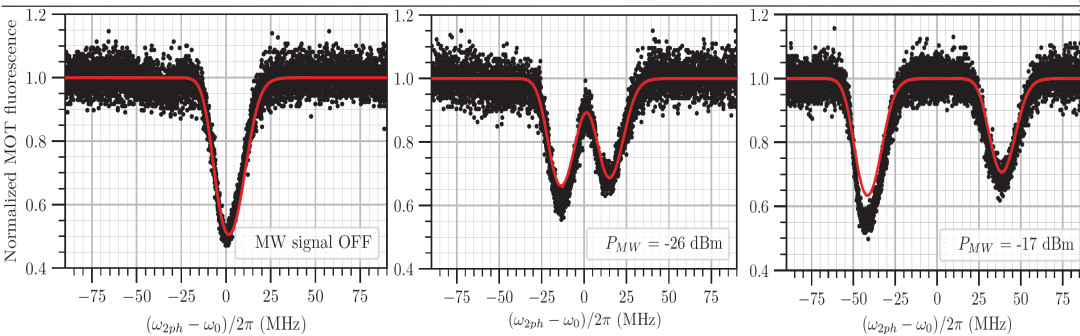
Experimental setup



- Telecom doubled laser system for 780nm light.
- Injection-locking laser source (by Moglabs) for the 480nm light.
- Fast Pound-Drever-Hall Locking of Rydberg lasers on an ultrastable cavity.



Rydberg Trap loss spectroscopy



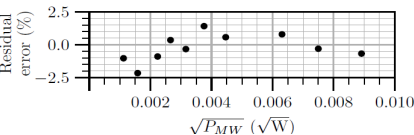
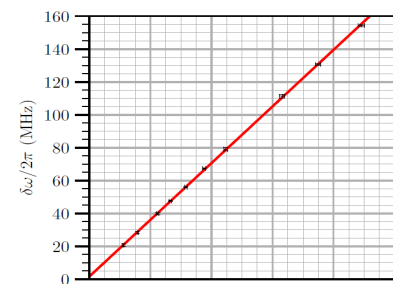
Increasing MW power

Autler-Townes splitting

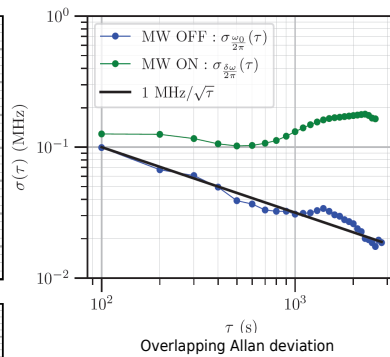
$$\omega_{\pm} = \omega_0 - \frac{\Delta_{MW}}{2} \pm \frac{1}{2} \sqrt{\Omega_{MW}^2 + \Delta_{MW}^2}$$

$$\delta\omega = \omega_+ - \omega_- \propto \Omega_{MW} \quad (\Delta_{MW} = 0)$$

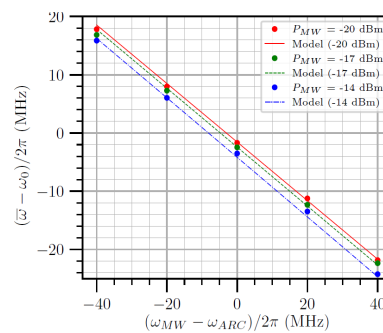
$$\bar{\omega} = \frac{\omega_+ + \omega_-}{2} \propto \frac{\Delta_{MW}}{2}$$



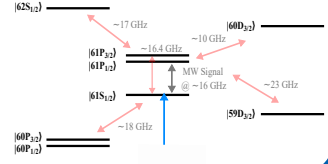
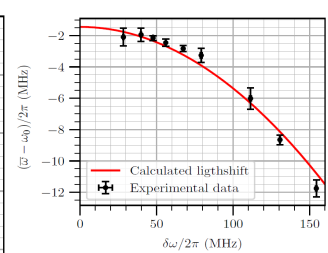
→ High linearity.



- Long-term stability.
- High resolution: $5 \mu\text{V/cm}$
- Sensitivity: $247 \mu\text{V.cm}^{-1}.\text{Hz}^{-1/2}$

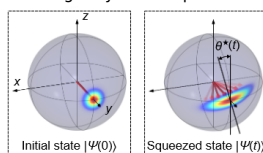


→ presence of lightshifts resulting from adjacent energy levels: $\delta_i^{LS} = \sum_j \frac{|\Omega_{ij}|^2}{4\Delta_{ij}}$



Perspectives

- Sequencing of the MOT and optimization of trap loss peaks width.
- Implementation of the optical tweezers: spatial resolution of $\sim \text{few } \mu\text{m}$
[Broaays and Lahaye, Many-body physics with individually controlled Rydberg atoms, Review article, Nature Physics (2020)]
- Quantum Metrology: harness entanglement to overcome the standard quantum limit:
 - Rydberg induced spin-squeezing
 - Explore the large variety of metrologically-useful quantum states



Bornet, Guillaume, et al. "Scalable spin squeezing in a dipolar Rydberg atom array." arXiv preprint arXiv:2303.08053 (2023)

$$\Delta E = \frac{1}{n^2} \frac{\hbar}{a_0 e \tau} \sim \frac{1}{n^2} \times 1.2 \text{ V/m/shot}$$

$$\sim 5 \mu\text{V/cm/shot}$$

Applications

- Fundamental Physics:
 - Rydberg thermometry to mitigate blackbody shift in optical lattice clocks
 - Measuring the cosmic MW background
 - Electromagnetic fields imaging
 - New types of THz detection
- New concept of "antenna/radar"?
 - Telecommunications?
 - Hybridization of classical and quantum sensors, such as atomic clocks or gravimeters.
 - High bandwidth (Rydberg EIT in a hot vapor cell)
 - Long-term stability (Rydberg cold atoms)