PHD PROJECT DESCRIPTION

(4000 characters max., including the aims and work plan to de published online)

Project title: New experimental techniques for realizing ultra-strong optical dipole traps for molecules.

1.1. Project goals

- Understanding the physics of high-power optical cavities and the behavior of molecules in an ultra-strong optical dipole trap.
- Extend the ultra-strong laser-field experimental methodology from room temperature to the deep cryogenic regime.
- Demonstration of operation of ultra-strong dipole trap (with optical power at the level of 100 kW) in cryogenic environment that will be used to trap H_2 molecules.

1.2. Outline

Techniques for confining atoms in optical dipole traps have been widely used for the atoms that were pre-cooled in a magneto-optical trap [1]. This method allows for the significant improvement in linewidth measurements by isolating atoms from external disturbances during the interrogation procedure. This leads to unprecedented precision and paves the way for a variety of applications, including quantum sensing, tests of the Standard Model, and other areas of fundamental physics [2].

Over the past two decades, significant progress has been made to extend similar methods to molecules. However, there exist molecular species, such as CO, N_2, or H_2 in their electronic ground states, that do not respond to standard cooling and slowing techniques [3]. Recent major advances in laser and optical technologies have opened entirely new perspectives in this field [4, 5]. One of them is the proposal to create an optical trap deep enough to directly capture buffer-gas-cooled molecules [4]. This concept is based on the already demonstrated feasibility of generating 125 kW of optical laser power [5], which is sufficient to achieve trap depths of several kelvin, enabling potential pre-cooling with commercially available cryo-coolers.

This project will focus on trapping H_2 molecules using a novel approach. Instead of a static dipole trap, which requires a dissipation mechanism, we aim to create a non-conservative trap by dynamically switching the cavity high power laser field on and off. This method is inherently challenging. Our goal is to push the current technological limits of available laser power and optical components in the deep cryogenic regime. The project involves overcoming several significant technological challenges: high-power laser control, fast and synchronized switching, mirror surface heating [6], efficient heat extraction at cryogenic temperatures etc. Dynamically trapping H_2 molecules opens up the very promising possibility of improving measurements of the H_2 rovibrational transition by orders of magnitude compared to classically cooled, non-trapped gases [7]. This paves the way for state-of-the-art tests of QED at an unprecedented level of precision.

1.3. Work plan

- Literature review and the theoretical modeling of the high-power optical resonator at room temperature.
- Development of experimental techniques for mirror surface quality diagnosis and maintenance (to handle optical losses at ppm level)
- Design and construction of the high-power optical resonator operating at room temperature.
- Experimental characterization of the room-temperature optical resonator and the essential optical element in the setup.
- Construction of the high-power optical resonator operating at cryogenic temperatures.
- Experimental characterization of the cryogenic-temperature optical resonator for the prospective H_2 molecule trapping.

1.4. Literature (max. 7 listed as a suggestion for a PhD candidate preliminary study)

[1] R. Grimm, et al., Adv. At. Mol. Opt. Phys, 42, 95-170 (2000)
[2] A. D. Ludlow, et al., Rev. Mod. Phys. 87, 637–701 (2015).
[3] R.V. Krems, et al., *Cold Molecules Theory, Experiment, Applications* (2009)
[4] A. Singh, et al., Phys. Rev. Res. 5, 033008 (2023).
[5] C. Turnbaugh, et al., Rev. Sci. Instrum. 92, 053005 (2021).
[6] L. S. Meng, et al., *Opt. Express* 13, 10085–10091 (2005)
[7] K. Stankiewicz, et al., arXiv:2502.12703 (2025)

1.5. Required initial knowledge and skills of the PhD candidate

Skills and experience in experimental physics (in particular, in laser optical cavities technologies). Good knowledge of Matlab, LabView or Mathematica (or equivalent) software. Excellent problem-solving and communication skills. Written and verbal communication skills and presentation skills. Teamwork ability. Good command of the English language.

1.6. Expected development of the PhD candidate's knowledge and skills

Knowledge, skills and experience in molecular and optical physics, laser, vacuum and cryogenic technologies, and in experimental data analysis.