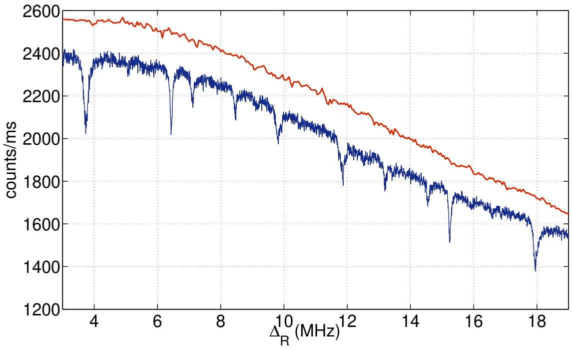
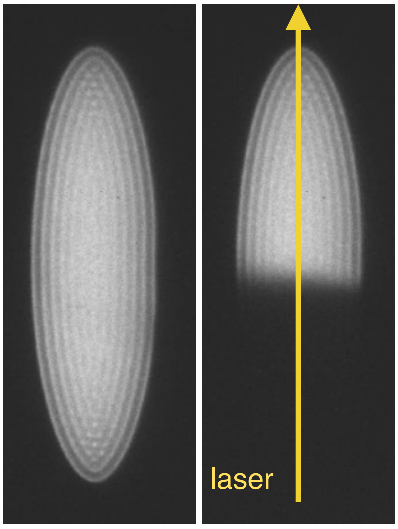
PhD project :
Enhancing high precision laser spectroscopy by the control of the self-diffusion in a laser-cooled ion cloud seen as a non-neutral plasma

SUPERVISOR : CAROLINE CHAMPENOIS
MAIL : CAROLINE.CHAMPENOIS@UNIV-AMU.FR
TEL : +33 413946413
LAB : PHYSIQUE DES INTERACTION IONIQUES ET MOLÉCULAIRES, MARSEILLE, CAMPUS DE SAINT-JÉRÔME.
WEB PAGE OF THE CIML GROUP : HTTPS://PIIM.UNIV-AMU.FR/EN/RESEARCH/SEVEN-TEAMS-AND-ONE-OPERATION/CIML-TEAM/

Atomic coherence has proven to be an efficient tool for achieving control of the interaction between electromagnetic fields, like laser electric fields, and an atomic sample. By dressing trapped atoms with three coherent photons that design a N-scheme within its internal structure, we are able to create a new eigenstate of the {atom+photons} system. This eigenstate, which is a coherent superposition if the dressed atomic eigenstates, is stable and observable if the three involved lasers, obey a three-photon resonance condition, are phase coherent, and address atoms with a negligible Doppler effect. When these conditions are fulfilled, the dressed atoms are set in this new state that is transparent to the laser lights. This gives rise to a sudden drop of the laser induced fluorescence and the building up of this "dark state" has a signature in the collected signal, like illustrated in the following spectrum where different Zeeman sub-states contribute to the signal [1].



We work with calcium ions Ca+, laser-cooled in a radio-frequency trap. As they reach temperatures lower than 1 K, they bunch in the trapping potential well and arrange in a stationary structure that minimise the {trapping+Coulomb repulsion} potential energy, to form what is called a Coulomb crystal. An example of these structures is shown on the figure obtained by the image of their induced fluorescence on a CCD camera. The left picture is formed by several hundreds of ions, laser cooled to less than 100 mK. On the right picture, the three lasers are going through the atomic sample with their frequencies obeying the three-photon resonance condition. The trapping of part of the ions in a dark state is observed through the dark portion of the cloud. The dark and bright ions segregate because of the radiation pressure induced by the laser-cooling process which acts only on the bright ions.



The observation of a dark line in the fluorescence can be understood as the results of the **quantum interference** between two excitation paths that is responsible for coherent population trapping. In Ca+ ion, the resonance is referenced to a magnetic dipole transition at 1.82 THz and the THz frequency is encoded in the combination of the frequency of the three involved optical fields [3]. These frequencies lie in the visible and near-infrared domain, spanning more than one octave. The required phase coherence and frequency relevance between the three lasers is built by a simultaneous lock on an **optical frequency comb** stabilised onto an ultra-stable laser, developed in the group [4]. Thanks to the connection of our experiment to the Refimeve+ network, which delivers an ultra-stable and accurate optical frequency reference, we now make absolute measurements of the THz transition frequency at the Hz level. This daily absolute calibration of the whole frequency chain allows us to explore the potential of the three-photon dark line for high precision measurements.

The diffusion of bright and dark ions induced by the state-selective radiation pressure that is observable through their spatial segregation needs to be understood and controlled to mitigate its impact on the THz frequency metrology. This platform offers a unique tool to measure self-diffusion coefficient within the laser-cooled trapped ion cloud which is a practical realisation of a finite size One Component Plasma (OCP) where the role of the neutralising particles is played by the confining potential. The OCP is a reference model in the study of strongly coupled Coulomb systems [5]. Its figure of merit is the plasma parameter which is the ratio between Coulomb potential energy and thermal kinetic energy of the ions. With the control on Doppler laser cooling and on the steepness of the trapping potential, the plasma parameter of our finite OCP can be experimentally tuned over several orders of magnitude spanning gas, liquid and crystal phases of the plasma. Our set-up, where the relevant time scales and the strength of the pressure force can be tuned by the numerous atom-laser interaction parameters is one of the few systems where diffusion coefficient in a strongly correlated OCP at equilibrium can be measured [6].

The **ambitious project** we propose relies on the control of a quantum linear superposition of dressed states and plane to take advantage of the offered frequency comparison to advance our control of the systematic effects that shift the frequency of the THz line. This control involves the study of the interplay between the ion dynamics within the cloud and the ion internal dynamics under quantum interference effects. These should lead to advances in THz frequency metrology and in the study of diffusion of charged particles within strongly correlated sample. To conduct this project which is mainly experimental, numerical simulations of the atom-laser interaction and molecular dynamic simulation of the ion-diffusion could also be run within the group. A strong collaboration with specialists of charged particle dynamics is already active to guide this study.

The **acquired skills** concern ion trapping in radio-frequency linear traps, atom-laser interaction (coherent processes and cooling), data acquisition and processing, optical frequency metrology with an optical frequency comb, and model for diffusion in a finite system.

REFERENCES :

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