Image Processing Towards Multi-ion Optical Clock

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Optical clocks are pushing the limits of the precision humanity has been able to achieve. Through the latest and most innovative technologies[1] and theories, the accuracy and stability of such devices continue to improve. Yet, the crucial feedback from an ion to the clock laser on its frequency is, in principle, limited by how fast one can obtain spectroscopic data. Using multiple ions in a linear Coulomb crystal (Fig. 1), enables simultaneous ion probing, thus offering a great advantage for the laser's stability by increasing the feedback rate.

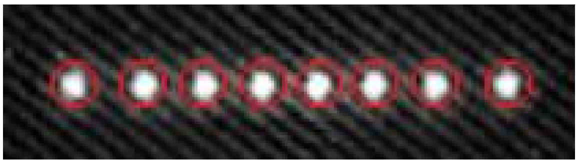

Fig. 1: Linear Coulomb crystal of eight $^{40}Ca^+$ ions and regions of interest around them. Independent data analysis of each of the ions in real-time makes various spectroscopic experiments possible. Most of the experiments depend of fast readout of ROI's intensity.

In this setup, we focus on $^{40}Ca^+$ ions trapped and laser-cooled in a linear Paul trap. The typical process of a clock laser optical frequency lock on the clock transition of the trapped ion is based on the real-time signal from a Single-Photon Avalanche Diode (SPAD). However, with our algorithm implemented into a software utility together with cutting-edge hardware, such as Andor iXon Ultra 897 EMCCD offering frame rates above 1 kHz with single-photon level sensitivity, we can analyze Rabi oscillations (Fig. 2) in real-time as well as in individual ions. This complex arrangement provides superior information about the clock transition frequency of individual ions and trap's properties in various positions, e.g. the heating rate of ions or magnetic sensitivity.

Although there are significant challenges like background noise or position-dependent quadrupole frequency shift compared to single ion detection on the SPAD detector, simultaneous precision spectroscopy on multiple ions opens up the door for significant stability improvements and an entirely different class of experiments.

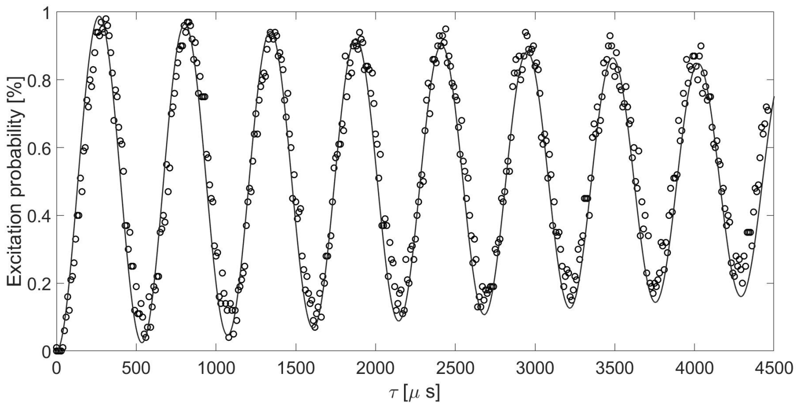

Fig. 2: Rabi oscillations of a single $^{40}Ca^+$ ion.

[1] Newman, Zachary L., et al. "Architecture for the photonic integration of an optical atomic clock." Optica 6.5 (2019): 680-685.