Single Atom Sub Atto-Newton Force Sensor in Three-Dimensions

E.W. Streed[1,2], V. Blūms[1], M. Piotrowski[1,3], M. I. Hussain[1], B. G. Norton[1], S. Connell[1,3], S. Gensemer[1,3], M. Lobino[1,4]
[1]*Centre for Quantum Dynamics, Griffith University, Brisbane, Australia* [3]*Institute for Glycomics, Griffith University, Australia*
[3]*CSIRO Pullenvale, Australia* [4]*Queensland Micro and Nanotechnology Centre, Griffith University Australia*
e.streed@griffith.edu.au

Abstract: Ultra-sensitive force measurements are crucial for physics. Nanometer precision displacement measurements of a Paul trapped $^{174}Yb^{+}$ ion provides force sensitivities below aN/√Hz. Accuracy was verified by measuring the 95 zN cooling laser light force pressure.
OCIS codes: (100.6640) Super resolution; (050.1970) Diffractive Optics; (140.3320) Laser Cooling

1. Introduction

Trapped atomic ions are a well-isolated quantum systems that is extensively used for applications in quantum information technologies and precision metrology. The strong Coulomb interaction with the ion's charge provides a high sensitivity to applied electric fields. A force sensor based on the motion of an ion crystal in a harmonic trap [1] has previously achieved a sensitivity of 390±150 yN/√Hz in one dimension, with its spatial resolution limited by the ensemble extent. Large numerical aperture optics imaging of trapped ions allows stochastic type super-resolution localization with nanometer scale accuracies [2]. The time-averaged nature of these imaging measurements allows a greater flexibility in the measurement bandwidth and allows them to estimate the mean location of the ion with an accuracy that exceeds the extent of the short-timescale thermal fluctuations or even the single measurement quantum ground state.

2. Experimental Method

A $^{174}Yb^{+}$ ion laser cooled at 369.5 nm in a needle style Paul trap was imaged using a 0.64 numerical aperture microfabricated phase Fresnel lens [3] at 400x with 20-30 s exposures onto an EMCCD camera. As shown in Figure 1 defocusing the image provided sensitivity to displacements in the third dimension by calibrated measurement of the ion image spot width. The ion spot centroids were fit to ± <1 nm and the spot widths to ± <2 nm using a Gaussian profile. Using Hooke's law $F=m\omega^2x$ with the known secular trap frequencies and ion mass translates displacements into forces. The applied force was calculated by alternating measurements of the ion's reference position without the applied force and the ion's position with the applied force on.

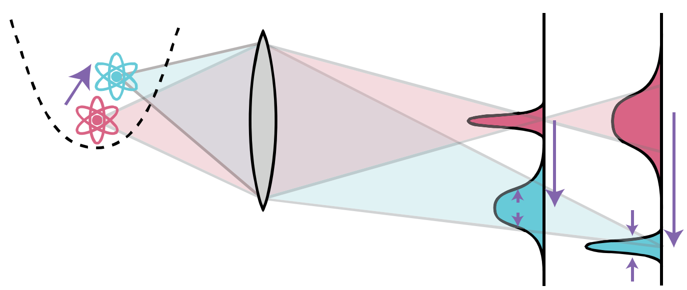

Figure 1. Imaging the displacement of a trapped ion in three dimensions.

3. Results

Slow drifts in the reference location of the ion with an extent of ~ 100 nm were observed over 2000 s and corrected out from the applied force measurements through 3rd order spline interpolations. The measured trap frequencies of 800 kHz, 829 kHz, and 1601 kHz, corresponding to spring constant values of 7.29±0.02 zN/nm, 29.22±0.04 zN/nm, and 7.83±0.02 zN/nm respectively. The largest value of the spring constant corresponds to the direction parallel to the trapping needles x, where the confinement is stronger and the trapping frequency higher. We could not determine the orientation of the two weaker trapping axes with respect to our imaging system and this introduces a systematic error in our force measurement of ±7%.

We determined the sensitivity of our system by varying the voltage on a stray electric field compensation electrode and measuring the resulting shift in ion position. Varying the voltage by up to 1V resulted in a displacement of up 250 nm in the x direction and 3750 nm in the y direction. A linear fit of displacement vs. voltage included both small and large voltage differences and from the y-intercept residuals a sensitivity of 372±9 zN/√Hz in the x direction and 335 or 359 ± 14 zN/√Hz in the y direction was determined, the later ambiguity arising from the trap axes orientation ambiguity.

To measure the z axis focusing direction displacement requires defocusing the imaging system slightly so that the variation in ion image spot waist can be calibrated against the focal axis displacement. This also provides a cross check as the width in the two axes provides two independent measures of the displacement. Our compensation electrode configuration was nearly planar and so required larger voltage range on our main test compensation electrode and synchronous operation of multiple other compensation electrodes to minimize the ion's lateral displacement, which introduces aberrations if the movement is too significant. Aberrations artificially increase the ion's spot width and would require a higher order de-convolution to extract usable position data. A voltage range of up to 7 V displaced the ion 700 nm in the focusing direction, resulting in a sensitivity of 779 or 836±42 zN/√Hz

The absorption recoil of photons from our laser cooling beam provides a directional spontaneous force on the atoms which is proportional to the scattering rate. We calibrated our force by measuring the saturation curve (Figure 2a) and then measuring the ion's displacement as a function of the applied spontaneous light force (Figure 2b). The measured displacement agrees with our calculated light force of 95 zN. This is a direct, real time measurement of the force, and does not involved using time of flight evolution to integrate up the momentum transfer into a detectable signal such as when observing the recoil of atoms from a laser illuminated Bose-Einstein condensate.

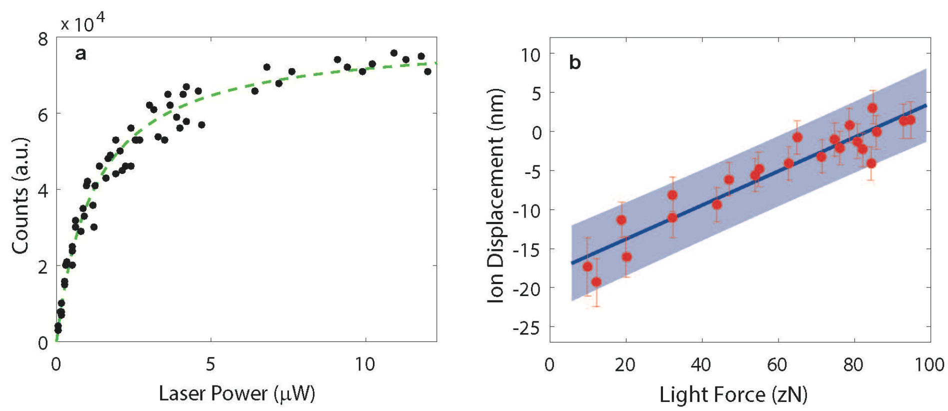

Figure 2. A. Calibration of scattering rate via the saturation curve. B. Ion displacement as a function of applied light force.

4. Discussion

The sensitivity of our measurements is bounded at the short time-scale by the resolving power and collection efficiency of our imaging optics. The long-term sensitivity is limited by drifts in the system, most likely due to a combination of slow changes to the stray electric field within the trap and mechanical/thermal drifts in the externally mounted needle trap nano-positioning system or optical imaging system. A ion trap purpose designed for force sensing would operate at lower secular frequencies to maximize displacements relative to force and be optimized for mechanical stability in both the trap electrodes and the associated imaging chain. Changes to the trap geometry would eliminate the problematic near degeneracy of the y and z axis trap frequencies which are a source of systematic ambiguity.

5. References

[1] Biercuk, M. J., Uys, H., Britton, J. W., VanDevender, A. P. & Bollinger, J. J. "Ultrasensitive detection of force and displacement using trapped ions." Nature Nanotech. **5**, 646–650 (2010).
[2] Wong-Campos, J. D., Johnson, K. G., Neyenhuis, B., Mizrahi, J. & Monroe, C. "High resolution adaptive imaging of a single atom." Nature Phot. **10**, 606-610 (2016).
[3] Jechow, A., Streed, E. W., Norton, B. G., Petrasiunas, M. J. & Kielpinski, D. "Wavelength-scale imaging of trapped ions using a phase Fresnel lens." Opt. Lett. **36**, 1371–1373 (2011).