Thermometry of a single ion by high-resolution imaging

Bharath Srivathsan[1], Martin Fischer[1,2], Lucas Alber[1,2], Markus Weber[1],
Markus Sondermann[1,2] and Gerd Leuchs[1,2,3]

[1]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany
[2]Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Department of Physics, Staudtstr. 7/B2, 91058 Erlangen, Germany
[3]Department of Physics, University of Ottawa, 25 Templeton Street, Ottawa, Ontario K1N 6N5, Canada

In experiments devoted to the interaction of a single atom with tightly focused light, the extent of a trapped atom's probability distribution in position space can play a decisive role: Once the light is focused such that the width of the spatial intensity distribution at the focus is on the order of the width of the atomic distribution, the atom averages over the focal intensity distribution. Thus the atom experiences a lower electric field on average and the interaction efficiency is reduced. This can also occur for an atom cooled to the Doppler limit [1, 2], depending on parameters such as trap frequencies and spectral width of the transition driven during laser cooling. In order to quantify this effect, the motional temperature of the atom has to be determined.

Here, we present an experimental scheme based on high resolution imaging of a single ion trapped at the focus of a parabolic mirror [3]. This high resolution stems from the large depth of the parabolic mirror in comparison to its focal length. Furthermore, collecting photons scattered by the ion from almost full solid angle yields a large signal-to-noise ratio.

We collect the fluorescence photons scattered during laser cooling and refocus them on an electron-multiplying charge-coupled device (EMCCD) camera. The intensity distribution measured on the EMCCD chip is given by the convolution of the point-spread function (PSF) of the imaging system with the spatial probability distribution of the ion. Accounting for the width of the PSF and the magnification of the imaging system, we infer the extent of the trapped atom in position space and the average number of motional quanta of the corresponding thermal state. At the Doppler limit, which corresponds to a temperature of about 470 μK for the used Ytterbium ions, our measurement scheme is not yet at its limit and still operational. This opens up the possibility to measure temperatures well below the Doppler limit, though not at the motional ground state.

We also perform such measurements by varying the detuning or the power of the cooling laser. Fitting the prediction of a standard model for laser cooling [4] to the measured widths of the ion images we infer the anomalous heating rate, cf. Fig 1. Anomalous heating is inherent to all ion traps, and there exist several schemes to quantify the associated heating rate. The benefit of our method is that it is applied in the steady state of interacting with the cooling laser, therefore not requiring to first let the ions heat up as in a well-established earlier scheme [5].

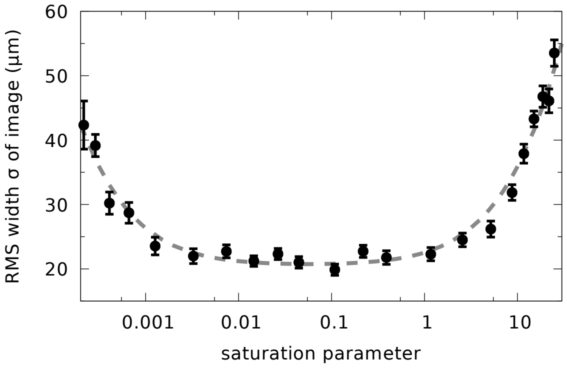

Figure 1: Width of the distribution of refocused fluorescence photons as a function of saturation parameter, measured at half-linewidth detuning. Symbols denote measurement results, the gray line represents the result of fitting our model to the data. The extracted anomalous heating rate is 1.54 ± 0.15 quanta per ms. The smallest observed width corresponds to a temperature which is 16% above the Doppler limit for the used ion species and trap parameters.

---

[1] Alber L, Fischer M, Bader M, Mantel K, Sondermann M, and Leuchs G. Journal of the European Optical Society-Rapid Publications **13**, 14 (2017).

[2] Fischer M, Srivathsan B, Alber L, Weber M, Sondermann M, and Leuchs G. Applied Physics B **123**, 48 (2017).

[3] Maiwald R, Golla A, Fischer M, Bader M, Heugel S, Chalopin B, Sondermann M, and Leuchs G. Phys. Rev. A **86**, 043431 (2012).

[4] Stenholm S. Rev. Mod. Phys. **58**, 699 (1986).

[5] Wesenberg J. H, Epstein R. J, Leibfried D, Blakestad R. B, Britton J, Home J. P, Itano W. M, Jost J. D, Knill E, Langer C, Ozeri R, Seidelin S, and Wineland D. J. Phys. Rev. A **76**, 053416 (2007).