Advancing electric-field sensing through near-ground state cooling and beam position optimization in a Penning trap

Joseph H. Pham, Julian Y. Z. Jee, Robert N. Wolf, Michael J. Biercuk

ARC Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW 2006, Australia

email: jpha9875@uni.sydney.edu.au

Quantum sensing is a rapidly growing field that harnesses the properties of quantum mechanics to develop highly sensitive sensors. This project focuses on developing a Penning-trap-based quantum-sensing system to detecting ultra-weak electric fields. Such a system can potentially search for ultra-light, wave-like dark matter in the mass range of 1-10neV/c^2 [1].

To enhance the sensitivity of our Penning trap [2], we have implemented near-ground-state cooling through electromagnetically induced transparency cooling, ensuring operation within the Lamb-Dicke regime [3].

Furthermore, we have developed a laser beam delivery system based on compact piezo-actuated optical mirrors, which provides efficient beam position tuning. This system allows us to optimise the ratio of spin-spin interaction strength to spontaneous emission, a crucial factor for preparing entangled spin states.

Experimental results demonstrate a linear correlation between the angle of the entangling beam and the interaction strength, with a spin-dependent optical dipole force range of 15yN to 35yN, as seen in figure 1. These findings highlight the potential for further advancements in ion-trap-based quantum sensing and pave the way for developing highly sensitive sensors with applications in various fields, including precision measurements, quantum information processing, and fundamental physics research.

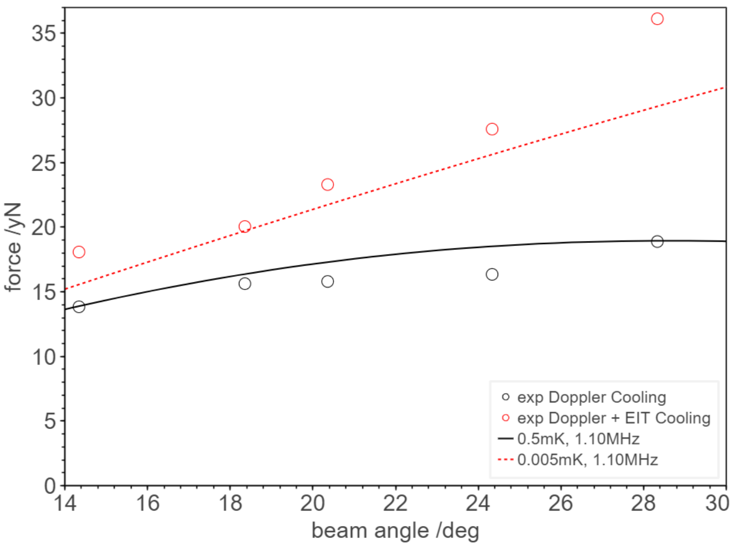

Figure 1: The spin-dependent optical dipole force at different beam angles, with the ions initially cooled with only Doppler or Doppler followed by EIT cooling. The dotted lines are the theoretical curves of the force at those angles and temperatures.

References

[1] Gilmore, K., Affolter, M., Lewis-Swan, R., Barberena, D., Jordan, E., Rey, A., & Bollinger, J. Quantum-enhanced sensing of displacements and electric fields with two-dimensional trapped-ion crystals. *Science*, *373*(6555), 673-678 (2021).

[2] Ball, H., Marciniak, C., Wolf, R., Hung, A., Pyka, K., & Biercuk, M.. Site-resolved imaging of beryllium ion crystals in a high-optical-access Penning trap with inbore optomechanics. *Review Of Scientific Instruments*, *90*(5), 053103 (2019).

[3] Jordan, E., Gilmore, K., Shankar, A., Safavi-Naini, A., Bohnet, J., Holland, M., & Bollinger, J. , Near Ground-State Cooling of Two-Dimensional Trapped-Ion Crystals with More than 100 Ions. *Physical Review Letters*, *122*(5), 053603 (2019)