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Advances in Penning trap ion imaging and control for quantum sensing and simulation

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Coherently manipulated crystals of ions in a Penning trap are a promising candidate for near-term quantum simulation of complex many-body phenomena and the search for dark matter using quantum sensing [1]. At the University of Sydney, we developed a Penning trap to perform such experiments with crystals containing hundreds of beryllium ions [2]. This contribution introduces this system and two major technical innovations supporting these applications. First, we have implemented a high bandwidth time-correlated single-photon-counting camera, which allows efficient single-ion detection in 2D ion crystals, a prerequisite to investigate spatial correlations in many-body quantum systems. Ion positions are localised using an artificial neural network. We achieve a spin-state detection fidelity of 94(2)% [3]. Next, we describe a laser beam delivery system based on compact piezo-actuated optical mirrors, which allow an efficient beam-position tuning inside the room-temperature bore of a superconducting magnet. This system enables in situ maximization of the ratio of coherent spin-spin interaction strength to spontaneous emission in laser-mediated interactions. Using this system, we demonstrate long-range entanglement with a variable coupling strength.
[1] M. Gärttner et al., Nat. Phys. 13, 781 (2017); K. A. Gilmore et al., Science 373, 673 (2021)
[2] H. Ball et al., Rev. Sci. Instrum. 90, 053103 (2019)
[3] R. N. Wolf et al., arXiv:2303.10801

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