7th European Conference on Trapped Ions

Contribution ID: **111** Type: **Poster**

Spin squeezing and entanglement generation in two-dimensional ion crystals with up to 105 ions

Tuesday, 26 September 2023 19:30 (2 hours)

Linear strings of trapped ions in radio-frequency traps are a well-established platform for quantum simulation of magnetism. However, linear strings feature some drawbacks, among them difficulties in scaling the system size beyond 50 ions or the inability to investigate spin models in more than one dimension where many exotic quantum phenomena are expected to manifest. Here we present our novel ion trap apparatus which is capable of trapping and coherently manipulating two-dimensional ion Coulomb crystals of up to 105 $^{40}Ca^{+}$ ions. In the first part we will briefly present techniques to cool and control large planar ion crystals as well as some experiments to characterize their properties. We find that rf-induced heating and melting due to background collisions are no obstacles for quantum simulation experiments. We characterize the trapping potentials as well as the spatial crystal configurations by an analysis of crystal images and prove that we are able to mitigate configuration changes to realize stable confinement of large crystals. Furthermore, we show that precise control of the crystal orientation allows for minimizing micromotion seen by the out-of-plane motional modes similar to the level achieved in linear strings, and demonstrate simultaneous preparation of all 105 modes close to the motional ground state by means of electromagnetically induced transparency cooling [1]. In the second part we present global coherent manipulation of a ground-state Zeeman qubit – in which we encode the spin - by means of Raman transitions. Employing bichromatic Raman beams enables coupling of the spin state to the out-of-plane motional modes and the realization of the long-range transverse-field Ising model. To assess the performance of our quantum simulator and to prove multi-partite entanglement we implement a recently developed protocol to create spin-squeezed states, a valuable tool in quantum-enhances metrology [2]. Despite not having infinite-range interactions at hand, we show that operating the simulator in the power-law XY regime yields an evolution being well-approximated by the one-axis twisting model. This enables the creation of highly-squeezed states with Wineland parameters of more than 8dB for up to 105 particles and unambiguously verifies multi-partite entanglement in planar ion crystals.
[1] D. Kiesenhofer, H. Hainzer et al., PRX Quantum 4, 020317 (2023)
[2] J. Franke et al., arXiv: 2303.10688

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Session Classification: Tuesday Poster