Quantum simulation with 2d crystals in a novel rf trap

Dominik Kiesenhofer[1,2], Artem Zhdanov[1], Helene Hainzer[1,2], Tuomas Ollikainen[1,2], Matthias Bock[1,2] and Christian Roos[1,2]

1 Institute for Experimental Physics, University of Innsbruck
2 Institute for Quantum Optics and Quantum Information (IQOQI) Innsbruck

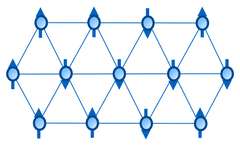
erc IQI universität innsbruck
FWF Österreichischer Wissenschaftsfonds
beyondC

2D Crystals

Why 2D ???

1. **Overcoming scalability issues** with linear chains:
   *) Axial heating
   *) Single-ion addressing
2. **Investigate 2D models**

Model:
2D spin lattice



= Large number of interacting spins

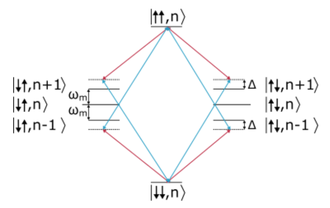
Quantum Simulation

Transverse Ising Hamiltonian

$$H = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x + B\sum_i \sigma_i^z$$

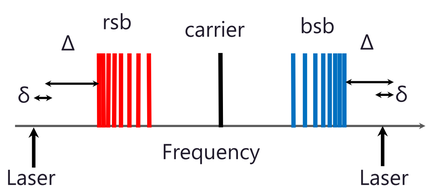
$$J_{ij} \propto \frac{1}{|i-j|^\alpha} \qquad \text{Tunable interaction: } 0 < \alpha < 3 \qquad B = \delta/2$$

Tunable long-range spin-spin interaction using bichromatic light fields

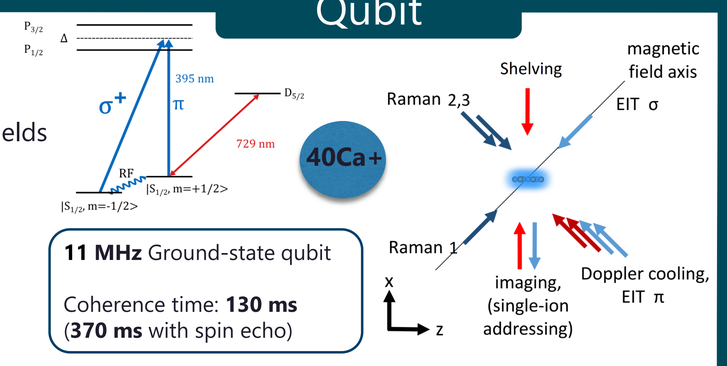


Mapping to trapped ions

- Spin-1/2 particles are encoded into the $4S_{1/2}$ ground- state manifold
- Manipulation via Raman transition
- Coupling to radial motional modes (**1D**) / **out-of-plane modes** (**2D**)



Qubit



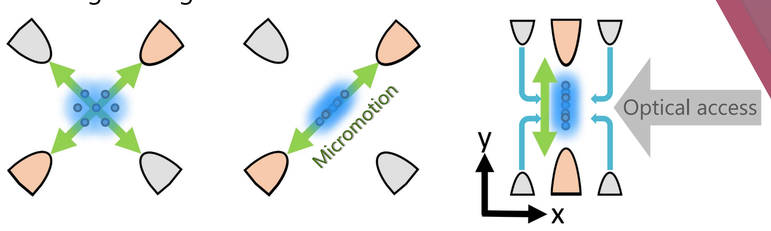
11 MHz Ground-state qubit

Coherence time: **130 ms** (**370 ms** with spin echo)

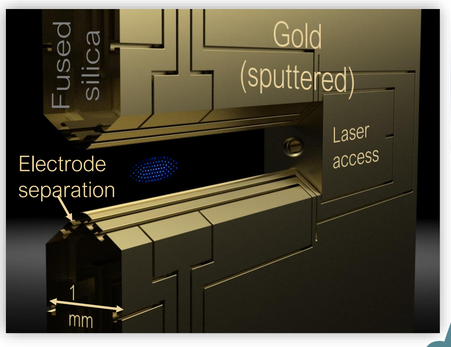
Our ion trap

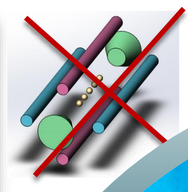
Challenges

- **Micromotion** in 2D crystals, because some ions are naturally away from the RF null
- **Changes of crystal structure** due to collisions with background gas



- Optical access perpendicular to micromotion; imaging and laser addressing perpendicular to crystal plane
- Macroscopic linear Paul trap (0.4 mm electrode-ion distance)



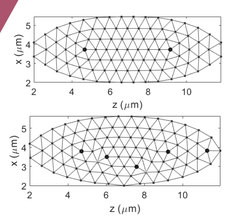


- Trap frequencies: 2.2 MHz at 43 MHz drive
- Heating Rate at 2.2 MHz: ~15 ph/s
- Subtractive 3D print (fused silica wafer)

Cooling & Stability

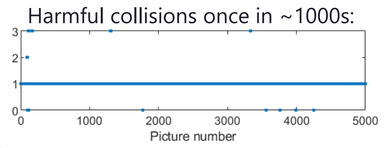
Crystal stability

- Stable crystals up to **105 ions**
- **>99% in the symmetric main configuration**

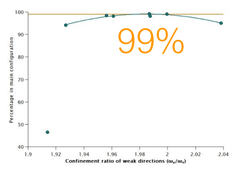


Clustering algorithm for config. analysis

Harmful collisions once in ~1000s:



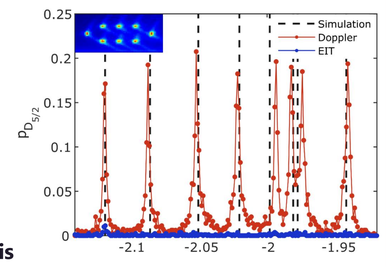
Optimization of trapping parameters:



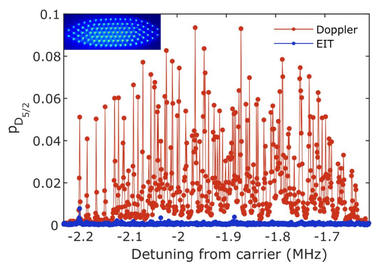
Ground-state preparation via EIT cooling

Fast multi-mode cooling of all out-of-plane modes in ~400 us

8 ions

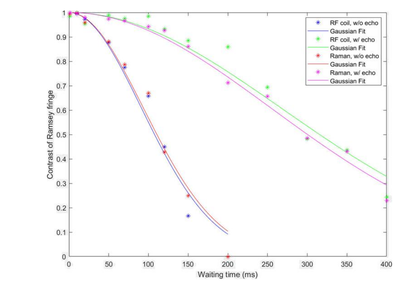


105 ions

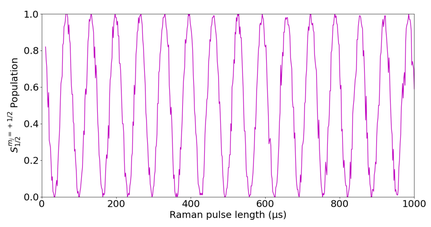


Qubit control

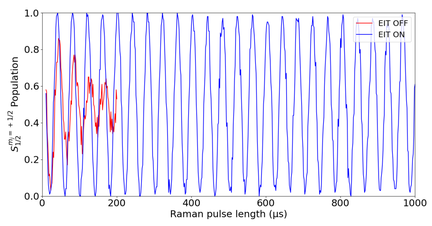
Coil drive VS **Raman drive** coherence



- High-power laser light at 396 nm creates **Raman interaction** to induce **qubit entanglement** via out-of-plane modes
  Rabi Frequency up to $\frac{\Omega}{2\pi}$ ~ 200 kHz
- RF coil **drives all ions** $4S_{1/2}$ state simultaneously



Rabi Flops driven by beams 2+3
$\Delta k = 0 \rightarrow$ **motional states invisible**

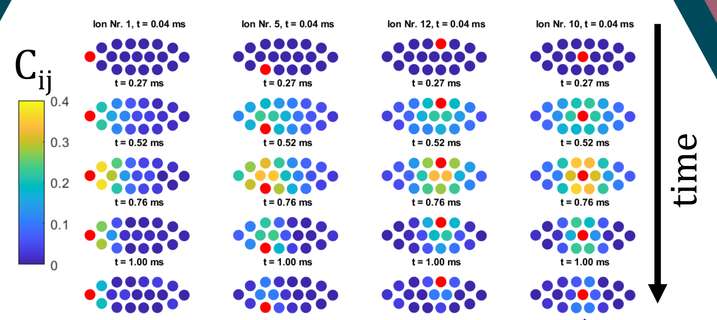


Rabi Flops driven by beams 1+2
$\Delta k \neq 0 \rightarrow$ **coupling to motional states**

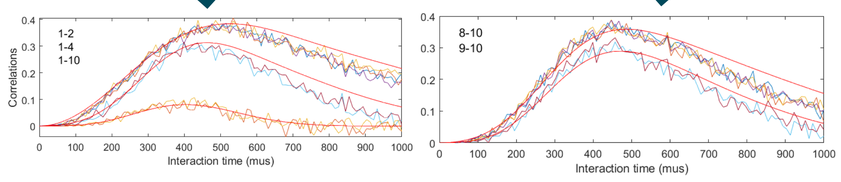
Build-up of spin-spin correlations during a global interaction pulse

- Pure Ising model (w/o center line det./transverse field)
- Analytical model based on sim. J_{ij} matrix matches data

$$H = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x + B\sum_i \sigma_i^z$$



Simulations agree with the measured correlation coefficients …

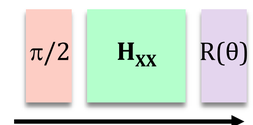


Spin squeezing

Goal: Using spin squeezing for benchmarking the entanglement in our system and investigating limits using a variational approach with classical optimization

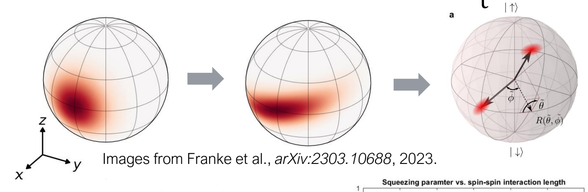
Realizing one-axis twisting (OAT) model via transverse-field Ising/XX Hamiltonian

$$\sum_{i<j} J_{ij}\left(\hat{\sigma}_i^+\hat{\sigma}_j^- + h.c.\right) \equiv \hat{H}_{\mathrm{PL-XX}}$$



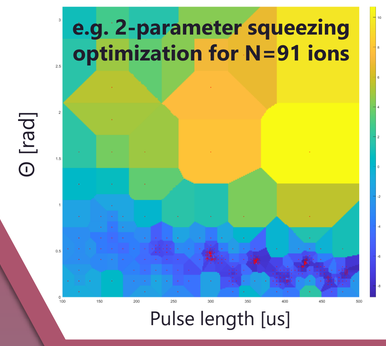
Spin squeezing (Wineland) parameter:

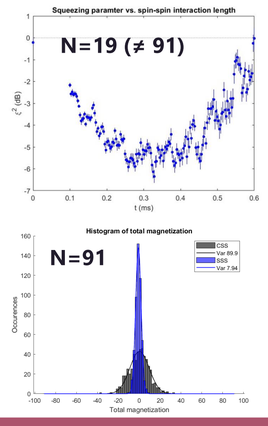
$$\xi = \min_{\mathbf{n}_\perp} \frac{\sqrt{N\langle(\Delta\hat{S}_{\mathbf{n}_\perp})^2\rangle}}{|\langle\hat{\mathbf{S}}\rangle|}$$



Images from Franke et al., *arXiv:2303.10688*, 2023.

Classical optimization algorithm searches for "global" minimum.





Thermometry

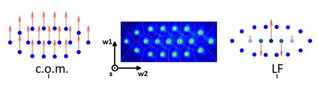
Sideband thermometry of a 19-ion crystal

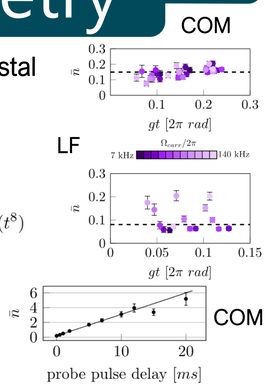
Vybornyi et al. "Sideband thermometry of ion crystals." *arXiv:2306.07880* (2023).

$$\frac{P_r(\bar{n},t)}{P_b(\bar{n},t)-P_r(\bar{n},t)} = \mathcal{R}_t(\bar{n})$$

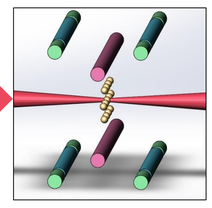
$$\mathcal{R}_t(\bar{n}) = \bar{n}+(gt)^2\mathcal{P}_2(\bar{n})-(gt)^4\mathcal{P}_3(\bar{n})+(gt)^6\mathcal{P}_4(\bar{n})+o(t^8)$$

Determine mean phonon numbers for COM and lowest frequency mode

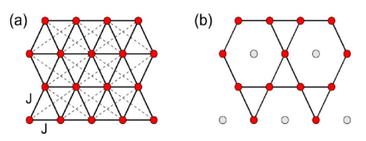




Outlook



To be implemented



Addressing with 2D AOD 729 nm laser light induces **phase shifts on individual ground state qubits** and shelves ions to $3D_{5/2}$ state for lattice structuring

Spin-spin correlations

Achievements

- Trapping stable 2D ion crystals with **up to 105 ions**
- **Fast cooling** of all out-of-plane modes close to motional ground state
- **130 ms** ground-state qubit coherence time (**330 ms** with spin echo)
- **Spin squeezing of ~ -6.5 dB** for with a 19-ion crystal and **< -9.0 dB** for a 91-ion crystal

Upcoming Goals

- **Spin squeezing of larger crystals (~ 100 ions) and optimization of multi-layer sequences**
- **Individual qubit control** with 2D-addressed 729nm laser beam
- **(Variational) Quantum Simulations of 2D Spin Models**

2D Publications:

- Joshi, M. K., et al. "Polarization-gradient cooling of 1D and 2D ion Coulomb crystals." *New Journal of Physics* 22.10 (2020): 103013.
- Hainzer, Helene, et al. "Correlation spectroscopy with multi-qubit-enhanced phase estimation." *arXiv preprint arXiv:2203.12656* (2022).
- Kiesenhofer, Dominik, et al. "Controlling two-dimensional Coulomb crystals of more than 100 ions in a monolithic radio-frequency trap." *PRX Quantum* 4.2 (2023): 020317.
- Vybornyi, Ivan, et al. "Sideband thermometry of ion crystals." *arXiv preprint arXiv:2306.07880* (2023).

Want to know more?