MON 6: QIP Implementations: Trapped Ions

Time: Monday 14:15–16:15 Location: ZHG007

MON 6.1 Mon 14:15 ZHG007

Quantum Information Processing with Trapped Rydberg Ions — •Katrin Bolsmann[1,2], Thiago L. M. Guedes[1,2], Joseph W. P. Wilkinson[3], Igor Lesanovsky[3,4], and Markus Müller[1,2] — [1]Institut für Quanteninformation, RWTH Aachen University — [2]PGI-2, Forschungszentrum Jülich — [3]Institut für Theoretische Physik, Universität Tübingen — [4]School of Physics and Astronomy, University of Nottingham

Combining the strong, long-range interactions of cold Rydberg atoms with the controllability of trapped ions, trapped Rydberg ions provide a promising platform for scalable quantum information processing. As demonstrated in a breakthrough experiment (Zhang et al., Nature 580, 345, 2020), microwave dressing of Rydberg states induces permanent rotating dipole moments leading to strong interactions between highly excited ions. Due to the separation of timescales, the fast electronic dynamics of Rydberg ions decouple from the slower motional modes of the linear Coulomb crystal, which typically mediate entangling gates in ground-state ion systems. Therefore, Rydberg ions enable significantly faster gate operations.

In this talk, we will discuss how the unique features of trapped Rydberg ions can be used to realize fast and high-fidelity entangling gates, along with the associated challenges and strategies to address them. We will present different types of gate protocols for two- and multi-qubit entangling gates with trapped Rydberg ions, analyze sources of infidelity, and compare the performance with other platforms based on neutral atoms and ground-state ions.

MON 6.2 Mon 14:30 ZHG007

Register-Based Trapped-Ion Quantum Processors with Near-Field Microwave Control — •Florian Ungerechts[1], Rodrigo Munoz[1], Janina Bätge[1], M.Masum Billah[1], Axel Hoffmann[1,2], Giorgio Zarantonello[1,3], and Christian Ospelkaus[1,4] — [1]Inst. f. Quantenoptik, Leibniz Universität Hannover — [2]Inst. f. Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover — [3]QUDORA Technologies GmbH — [4]Physikalisch-Technische Bundesanstalt

Trapped ions are a leading platform for quantum information processing, offering long coherence times, high gate fidelities, and unmatched quantum volume. Scalable architectures, such as the Quantum Charged Coupled Device (QCCD) architecture, enable all-to-all connectivity between atomic ion qubits in dedicated registers and can be implemented on microfabricated surface-electrode traps. However, as chip size increases, external free-space lasers become infeasible. To address this, quantum logic gates with chip-integrated microwave conductors have been demonstrated, also eliminating spontaneous emission as an intrinsic error source in laser-driven gates. Although shown individually, combining the QCCD architecture with the near-field microwave control technique into scalable devices is a current research topic. We present an overview of our recently developed surface-electrode traps for near-term quantum information processing with up to 50 atomic ion qubits. We compare the chip architectures and highlight the design of radiofrequency junctions, bucket-brigade storage registers, and chip-integrated microwave conductors.

MON 6.3 Mon 14:45 ZHG007

Framework for optimization of Paul trap design and control voltages for X-junction shuttling — •Andreas Conta, Ulrich Poschinger, and Ferdinand Schmidt-Kaler — Institut für Physik, Johannes Gutenberg-Universität Mainz

Trapped-ion quantum computing is a promising architecture for large-scale quantum computing. We aim to scale up the shuttling-based [1] approach. This requires complex multi-segmented traps that include junctions [2]. We present our work of a framework for optimization of trap designs and control voltages waveforms, with the goal of shuttling a linear crystals an X-junction. Commercially available tools are used to create parameterised models of traps and potentials of the electrodes [3]. Our custom Segmented Ion Trap CONtrol System (SITCONS) then performs a multipole expansion, thereby enabling the calculation of control voltages using quadratic programming. We analyse the influence of different trap designs and electrode shapes on the shuttling through an X-junction.

[1] Ruster et al., Phys. Rev. A 90, 033410 (2014)
[2] Delaney et al., Phys. Rev. X 14, 041028 (2024)
[3] Nullspace Inc., Nullspace ES [software], https://www.nullspaceinc.com/

MON 6.4 Mon 15:00 ZHG007

Generating arbitrary coupling matrices for multi-qubit quantum gates — •Patrick H. Huber, Dorna Niroomand, Markus Nünnerich, Patrick Barthel, and Christof Wunderlich — Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Germany

An always-on, all-to-all Ising-type interaction between qubits in a quantum register can be provided by the Magnetic Gradient Induced Coupling (MAGIC) approach to quantum computing with trapped ions [1,2]. In that case, the interaction strength between radio frequency(rf)-controlled qubits is determined by the trapping potential and the applied magnetic field gradient.

Here we present a novel method that allows for the tuning of the qubits' interaction without changing the trapping potential nor the magnetic field while simultaneously preserving the qubits' coherence. This method uses pulsed dynamical decoupling and is demonstrated experimentally in a quantum register of four qubits encoded into hyperfine states of the electronic ground state of laser-cooled $^{171}Yb^{+}$ ions . We synthesize an arbitrary coupling matrix within this quantum register and, furthermore, generate non-interacting subregisters. Thus, this method opens up a new path for efficiently synthesizing quantum algorithms when using an all-to-all Ising-type interaction between qubits.

[1] A. Khromova *et al.*, Phys. Rev. Lett. **108**, 220502 (2012). [2] P. Baßler *et al.*, Quantum **7**, 984 (2023).

MON 6.5 Mon 15:15 ZHG007

Fast radio frequency-driven entangling gates with trapped ions using rapid phase switching — •Markus Nünnerich, Patrick Huber, Dorna Niroomand, and Christof Wunderlich — Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Gemany

Entangling gates are a fundamental component of any quantum processor, ideally operating at high speeds in a robust and scalable manner. Here, we experimentally investigate a novel radio frequency (RF)-driven two-qubit gate with trapped and laser cooled $^{171}\mathrm{Yb}^{+}$ ions exposed to a static magnetic gradient field of 19 T/m that induces an effective qubit-qubit interaction (Magnetic Gradient Induced Coupling, MAGIC). The hyperfine states $|0\rangle \equiv |^2\mathrm{S}_{1/2}, \mathrm{F}=0, \mathrm{m_F}=0\rangle$ and $|1\rangle \equiv |^2\mathrm{S}_{1/2}, \mathrm{F}=1, \mathrm{m_F}=-1\rangle$ are used as qubits. We generate Bell states by applying continuously two RF driving fields, each one of them on resonance to one of the qubit transitions. By modulating the phase or amplitude of the driving fields, qubits are protected from addressing and RF amplitude fluctuations. In the experiments presented here, the phase of the driving fields varies periodically in discrete values, yielding effectively a sequence of back-to back dynamical decoupling pulses. By adjusting the Rabi frequency induced by the driving fields, the effective coupling of the qubits to the ions' motional state is changed, and the entangling gate speed can be varied between ≈ 4 ms and $\approx 300\mu$s. In currently used micro-structured traps with larger magnetic field gradients, gate speeds on par with laser-driven gates in trapped ions are expected.

MON 6.6 Mon 15:30 ZHG007

Scaling-up a trapped-ion quantum computer using MAGIC — •Saptarshi Biswas[1], Ivan Boldin[1], Benjamin Bürger[1], Friederike J. Giebel[3,4], Radhika Goyal[2], Patrick Huber[1], Eike Iseke[3,4], Lukas Kilzer[2], Nila Krishnakumar[3,4], Rodolfo Muñoz Rodriguez[1], Tobias Pootz[2], Kais Rejaibi[1], David Stuhrmann[2], Nora Daria Stahr[2,4], Jacob Stupp[2,4], Konstantin Thronberens[3,4], Celeste Torkzaban[2], Pedram Yaghoubi[1], Christian Ospelkaus[2,3,4], and Chritsof Wunderlich[1] — [1]Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Germany — [2]Gottfried Wilhelm Leibniz Universität, Hannover, Germany — [3]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [4]Laboratory of Nano and Quantum-Engineering, Hannover, Germany

We present the status of a cryogenic (4K) experimental set-up for quantum computing with radio frequency (rf)-controlled trapped ions. It incorporates a novel micro-structured planar Paul trap with integrated micromagnets and we report on the characterization of the first trap generation to be used in this set-up. The ions interact via magnetic gradient induced coupling (MAGIC).Also, progress in developing laser cooling techniques for mixed Yb^+-Ba^+ crystals is reported.

MON 6.7 Mon 15:45 ZHG007

Efficient simulation workflow for micro-structured planar Paul traps — •Kais Rejaibi, Dorna Niroomand, Patrick Huber, and Christof Wunderlich — Department of Physics, School of Science and Technology University of Siegen, 57068 Siegen, Gemany

Trapped-ion experiments require precise control of ion motion, minimal micromotion, and stable quantum state manipulation. To support this, we developed a simulation workflow based on the Boundary Element Method (BEM), which accurately models electric fields from complex electrode layouts, including junction-type planar Paul traps and designs using Magnetic Gradient Induced Coupling (MAGIC). The method handles open boundary conditions efficiently and is suitable for iterative design.

We use a solid harmonics decomposition to analyze the simulated fields. This helps us to identify and to reduce higher-order multipole components that can cause residual micromotion. In addition, we can add specific higher-order components in a controlled way to create interaction patterns for many-body quantum systems, for instance by shaping the effective J-coupling matrix between ions.

This approach-combining simulation, field analysis, and voltage control-helps us design planar Paul traps that support reliable ion transport through regions with varying magnetic fields. It improves design efficiency and supports the development of more capable systems for quantum information experiments.

MON 6.8 Mon 16:00 ZHG007

Micro-structured ion traps with integrated magnets for quantum science — •Benjamin Bürger, Patrick Huber, and Christof Wunderlich — Department of Physics, School of Science and Technology, University of Siegen, 57068 Siegen, Germany

We present the design and implementation of quasi-two-dimensional (2D) micromagnets tailored to generate an inhomogeneous static magnetic field. This field, when integegrated into a micro-structured ion trap, enables frequency-selective addressing of ions through radio frequency radiation (RF) and conditional quantum dynamics with trapped ions. We will integrate the magnet design into a planar Paul trap that is split into two types of regions: An interaction zone and a cooling/readout zone. The micromagnets are meticulously designed to produce high field gradients while maintaining a low absolute field strength, effectively minimizing decoherence induced by magnetic field noise within the qubit interaction zones. In the cooling/readout zones, the magnets are designed to generate a small homogeneous magnetic field to facilitate efficient Doppler cooling on larger strings. Furthermore, the magnetic field orientation is optimized to support both σ and π polarized RF-driven transitions in $^{171}Yb^+$ ions facilitating efficient cooling on the magnetic-field-insensitive π transition and utilizing the σ transition for gate operations.