Tailoring the All-To-All Interaction of Trapped Ions

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For quantum computation and -simulation, all-to-all connectivity between spin-1/2 systems (qubits) mediated by a long-range interaction can significantly speed up quantum algorithms and enable efficient encoding of fault-tolerant logical qubits [1–3]. Here, we present three methods for tailoring the interaction between (pseudo-)spins that are coupled via an all-to-all Ising-type interaction.

Firstly, we introduce a method to synthesize an arbitrary interaction matrix. This method is applicable to any Ising-coupled system, independent of the physical mechanism that induces the coupling. Here, we demonstrate it using laser cooled trapped $^{171}\mathrm{Yb}^+$ ions with qubits encoded into hyperfine states of their electronic ground states. The interaction in a quantum register of four ions is provided by magnetic gradient induced coupling (MAGIC) [1, 4–9]. Therefore, all coherent operations can be performed using RF radiation. We demonstrate how to tune the interaction between the qubits using a novel pulsed dynamical decoupling scheme while simultaneously preserving the coherence of the qubits. Thus, we create, for instance, non-interacting subregisters or equalize all pairwise couplings [10].

Secondly, the matrix characterizing the spin-spin interaction can be tailored by modifying the electrostatic trapping potential confining trapped ions. We developed a numerical method to design and optimize electrode shapes that determine the trapping potential in 2D ion traps. Thus, we obtain the ion positions, mode structure, and effective interaction matrix with low control-voltage requirements [11]. While we focus on linear trap segments, the same approach can also be applied to more elements such as junctions in scalable ion-trap chips.

Thirdly, we present the design and implementation of quasi-two-dimensional micromagnets tailored to generate an inhomogeneous static magnetic field necessary for MAGIC [12]. We integrate the magnet design into a 2D Paul trap that is split into two types of regions: An interaction zone and a cooling/readout zone. The mi-cromagnets are meticulously designed to produce high field gradients for an effective all-to-all interaction while maintaining a low absolute field strength within the qubit interaction zones. In the cooling/readout zones the magnets generate a homogeneous magnetic field to facilitate laser cooling on larger ion crystals. Furthermore, the magnetic field orientation is optimized to support both σ- and π-polarized RF-driven resonances in $^{171}\mathrm{Yb}^+$ ions.

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