Multi-Qubit Operations using Scalable Techniques

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Scalable quantum registers
- A scalable quantum register must implement all the operations required for QIP
- Must use scalable methods – operations should be combined with information transport.
- Must implement operations in a manner which is consistent with a large-scale device
- Should be verifiable – no hardware changes required for different tasks.

With trapped ions, one scalable architecture uses multi-zone traps – transport of qubits involves moving the qubit ions themselves

- Requires qubit states robust against environmental perturbations
- Requires recording prior to two-qubit gates due to imperfect control of transport and ambient heating (two-qubit gates only work for cold ions)

Multi-zone trap
- Time varying voltages applied to electrodes of a segmented trap allow us to move and separate chains of ions
- Qubits separated: Individual addressing
- Qubits trapped together: Two-qubit gates

Entangled Mechanical Oscillators
- After entangling the internal states of two beryllium ions, we can separate them, and use sympathetic cooling (see right) with Magnesium to null the ground state of motion in each trap
- We can then drive Rabi flopping on the motional sideband in each trap.

- By performing a “pi” pulse in each trap, we can map the internal state entanglement into the motional state.

\[ \frac{1}{2} (|0_A|0_B) + |1_A|1_B] \]

- We verify by reversing the mapping, and verifying the coherence element of the resulting spin density matrix.

Mapping in and out can be misleading – what if some population got left behind in the spin? We ensure that this doesn’t contribute to C, by “shelving” this population in a state which doesn’t interact with the phase-scanned analysis pulse.

Arbitrary Control of 2-qubits (universal 2-qubit QIP)
We implement an arbitrary unitary operation in SLOQ using two-qubits
- 15 free parameters are inputs to single qubit gates.
- 3 two-qubit gates required to reach all local equivalence classes.

We demonstrate arbitrary control by choosing at random a unitary operator and one of 16 input states.
We perform state-tomography on the output, and compare this to the ideal state.

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Smooth voltage supplies for fast transport of ions
Operation time limited by transport and cooling.
Currently: NI-6733 voltage supplies update at 500 kHz:
- Ion separation requires trap frequency to be lowered through 500 kHz, edge result in resonant motional excitation (open with filtering)
- Currently overcome this with ions of sympathetic cooling - takes time.

New home built supply: with update rate of 50 MHz >> all ion secular frequencies
- separation of two beryllium ions - record low amounts of heating!

Anharmonic trap potentials
Most work up until now assumes a harmonic potential well. This is generally a good approximation when the electrode size- and ion-electrode distance p is large compared to the extent of the ion crystal.
We observe effects on the motional modes due to higher order terms in the trapping potential, which will become more important with larger crystals and smaller traps.

The curvature of the potential is now different at each ion
Odd-order anharmonicity - asymmetry results in different potentials for the beryllium ions
For our four ion crystal
We observe beating when Rabi flopping on motional sidebands