Motional Ground-State Cooling Outside the Lamb-Dicke Regime – Supplemental material

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1. RAMAN SIDEBAND COOLING PULSE SEQUENCE

1.1. Optical pumping parameters

The optical pumping is done with a σ^- polarized beam aligned with the bias magnetic field. There are two frequencies in the beam that are on resonance with the $|F=2, m_F=-1\rangle$ to $|F'=2, m_{F'}=-2\rangle$ D1 transition and the $|F=1, m_F=-1\rangle$ to $|F'=2, m_{F'}=-2\rangle$ D2 transition respectively. All optical pumping pulses have the same length of 40μs with a $|F=1, m_F=-1\rangle$ scattering rate of 0.14 MHz and a $|F=2, m_F=-1\rangle$ scattering rate of 0.39 MHz.

1.2. Raman pulse parameters

Each of the Raman pulse in the cooling sequence is followed immediately by an optical pumping pulse with the parameters given above. The parameters for the Raman pulses are different between different groups and are listed below. The full Rabi frequency is the two-photon Rabi frequency Ω excluding the matrix element from wavefunction overlap. For a Raman pulse with a power ramp, the full Rabi frequency gives the arithmetics mean over the duration of the pulse. The power ramp field gives, if any, the beam (in terms of their corresponding F number) that ramps with a Blackman profile during the pulse [4]. δ' is the two photon detuning relative to the zero field hyperfine splitting of 1.7716261288(10)GHz. All of the relative detunings are negetive indicating that the frequency difference is smaller than the zero field hyperfine splitting. A more negative number corresponds to lower order cooling sidebands and a more negative number corresponds to higher order ones. δ'_0 the relative detuning for the carrier with the specific powers in the Raman beams.

1.2.1. Group 1

This group is repeated 5 times.

Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
x	-2	-17.6375	-18.42	25	$2\pi \times 34$	F1
y	-2	-17.2825	-18.47	25	$2\pi \times 34$	F1
x	-1	-18.03	-18.42	25	$2\pi \times 34$	F1
y	-1	-17.875	-18.47	21	$2\pi \times 34$	F1

1.2.2. Group 2

This group is repeated 5 times.

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Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
z	-8	-17.966	-18.506	80	$2\pi \times 14$	
x	-2	-17.6375	-18.42	25	$2\pi \times 34$	F1
z	-7	-18.0335	-18.506	80	$2\pi \times 14$	
y	-2	-17.2825	-18.47	25	$2\pi \times 34$	F1
z	-8	-17.966	-18.506	80	$2\pi \times 14$	
x	-1	-18.03	-18.42	25	$2\pi \times 34$	F1
z	-7	-18.0335	-18.506	80	$2\pi \times 14$	
y	-1	-17.875	-18.47	21	$2\pi \times 34$	F1

1.2.3. Group 3

This group is repeated 6 times.

Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
z	-7	-18.0335	-18.506	80	$2\pi \times 14$	
x	-2	-17.6375	-18.42	25	$2\pi \times 34$	F1
z	-6	-18.101	-18.506	80	$2\pi \times 14$	
y	-2	-17.2825	-18.47	25	$2\pi \times 34$	F1
z	-7	-18.0335	-18.506	80	$2\pi \times 14$	
x	-1	-18.03	-18.42	25	$2\pi \times 34$	F1
z	-6	-18.101	-18.506	80	$2\pi \times 14$	
y	-1	-17.875	-18.47	21	$2\pi \times 34$	F1

1.2.4. Group 4

This group is repeated 7 times.

Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
z	-6	-18.101	-18.506	80	$2\pi \times 14$	
x	-2	-17.6375	-18.42	25	$2\pi \times 34$	F1
z	-5	-18.1685	-18.506	60	$2\pi \times 14$	
y	-2	-17.2825	-18.47	25	$2\pi \times 34$	F1
z	-6	-18.101	-18.506	80	$2\pi \times 14$	
x	-1	-18.03	-18.42	25	$2\pi \times 34$	F1
z	-5	-18.1685	-18.506	60	$2\pi \times 14$	
y	-1	-17.875	-18.47	21	$2\pi \times 34$	F1

1.2.5. Group 5

This group is repeated 7 times.

Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
z	-5	-18.1685	-18.506	90	$2\pi \times 17$	F2
x	-1	-18.03	-18.42	38	$2\pi \times 34$	F1
z	-4	-18.236	-18.506	75	$2\pi \times 17$	F2
y	-1	-17.875	-18.47	25	$2\pi \times 34$	F1
z	-5	-18.1685	-18.506	90	$2\pi \times 17$	F2
x	-1	-18.03	-18.42	43	$2\pi \times 34$	F1
z	-4	-18.236	-18.506	75	$2\pi \times 17$	F2
y	-1	-17.875	-18.47	28	$2\pi \times 34$	F1

1.2.6. Group 6

This group is repeated 8 times.

Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
z	-4	-18.236	-18.506	75	$2\pi \times 17$	F2
x	-1	-18.03	-18.42	38	$2\pi \times 34$	F1
z	-3	-18.3035	-18.506	60	$2\pi \times 17$	F2
y	-1	-17.875	-18.47	25	$2\pi \times 34$	F1
z	-4	-18.236	-18.506	75	$2\pi \times 17$	F2
x	-1	-18.03	-18.42	43	$2\pi \times 34$	F1
z	-3	-18.3035	-18.506	60	$2\pi \times 17$	F2
y	-1	-17.875	-18.47	28	$2\pi \times 34$	F1

1.2.7. Group 7

This group is repeated 10 times.

Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
z	-3	-18.3035	-18.506	60	$2\pi \times 17$	F2
x	-1	-18.03	-18.42	38	$2\pi \times 34$	F1
z	-2	-18.371	-18.506	60	$2\pi \times 17$	F2
y	-1	-17.875	-18.47	25	$2\pi \times 34$	F1
z	-3	-18.3035	-18.506	60	$2\pi \times 17$	F2
x	-1	-18.03	-18.42	43	$2\pi \times 34$	F1
z	-2	-18.371	-18.506	60	$2\pi \times 17$	F2
y	-1	-17.875	-18.47	28	$2\pi \times 34$	F1

1.2.8. Group 8

This group is repeated 10 times.

Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
z	-2	-18.371	-18.506	60	$2\pi \times 17$	F2
x	-1	-18.03	-18.42	38	$2\pi \times 34$	F1
z	-1	-18.4385	-18.506	60	$2\pi \times 17$	F2
y	-1	-17.875	-18.47	25	$2\pi \times 34$	F1
z	-2	-18.371	-18.506	60	$2\pi \times 17$	F2
x	-1	-18.03	-18.42	43	$2\pi \times 34$	F1
z	-1	-18.4385	-18.506	60	$2\pi \times 17$	F2
y	-1	-17.875	-18.47	28	$2\pi \times 34$	F1

1.2.9. Group 9

This group is repeated 40 times.

Axis	Order	δ' (MHz)	δ'_0 (MHz)	Time (μs)	Full Rabi frequency (kHz)	Power ramp
z	-1	-18.3615	-18.429	70	$2\pi \times 9$	F2
z	-1	-18.3615	-18.429	100	$2\pi \times 9$	F2
x	-1	-18.03	-18.42	38	$2\pi \times 34$	F1
z	-1	-18.3615	-18.429	70	$2\pi \times 9$	F2
z	-1	-18.3615	-18.429	100	$2\pi \times 9$	F2
y	-1	-17.875	-18.47	25	$2\pi \times 34$	F1
z	-1	-18.3615	-18.429	70	$2\pi \times 9$	F2
z	-1	-18.3615	-18.429	100	$2\pi \times 9$	F2
x	-1	-18.03	-18.42	43	$2\pi \times 34$	F1
z	-1	-18.3615	-18.429	70	$2\pi \times 9$	F2
z	-1	-18.3615	-18.429	100	$2\pi \times 9$	F2
y	-1	-17.875	-18.47	28	$2\pi \times 34$	F1

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