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

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1. RAMAN SIDEBAND COOLING PULSE PARAMETERS AND SEQUENCE

Here, we list the full Raman sideband cooling (RSC) pulse parameters and sequence used to obtain the result in the manuscript. A step of RSC contains a Raman pulse and an optical pumping pulse. The full RSC sequence includes about 1000 pulses in 100 ms.

1.1. Optical pumping parameters

The optical pumping is performed with a σ^--polarized beam aligned with an 8.8 G bias magnetic field. There are two frequencies in the beam: one is on resonance with the $|F=2, m_F=-1\rangle$ of $3^2S_{1/2}$ to $|F'=2, m_{F'}=-2\rangle$ of $3^2P_{1/2}$ D1 transition and the other is on resonance with the $|F=1, m_F=-1\rangle$ of $3^2S_{1/2}$ to $|F'=2, m_{F'}=-2\rangle$ of $3^2P_{3/2}$ D2 transition. All optical pumping pulses have the length of $40\,\mu$s with a scattering rate of 0.14 MHz for atoms in $|F=1, m_F=-1\rangle$ and a scattering rate of 0.39 MHz for atoms in $|F=2, m_F=-1\rangle$.

1.2. Raman pulse parameters

Each Raman pulse in the cooling sequence is followed immediately by an optical pumping pulse. The full parameters for the Raman pulses, including the cooling "axis", the sideband "order (Δn)", the cooling frequency "δ'", the carrier ($\Delta n = 0$) frequency "δ'_0", the pulse "duration", the pulse strength in "Ω_0", and the beam of which a non-uniform "power ramp" is applied, are listed in 9 groups below. The applied cooling frequency, δ', is the two-photon detuning given relative to the zero-field $F=1$ and $F=2$ hyperfine splitting of 1.7716261288(10)GHz [1]. Due to the Stark shifts of the Raman beams, the carrier transition, δ'_0, varies with the power of the Raman beams. δ'_0 is given also relative to the zero-field hyperfine splitting. The strength of the pulses given in Ω_0 determines the two-photon Rabi frequency, $\Omega_{n,\Delta n} = \Omega_0\langle n|e^{i\vec{k}\cdot\vec{r}}|n+\Delta n\rangle$. We adopt the convention that a π-pulse between state n and $n+\Delta n$ requires a duration $\pi/\Omega_{n,\Delta n}$. The difference between δ' and δ'_0 gives the motional sideband frequency, δ. Many Raman pulses include a "power ramp" with a Blackman envelope [2] to minimize off-resonant excitations. Because each Raman pulse is a product of two spatial- and temporal-overlapped laser beams, the "power ramp" is applied only to the beam that has the smaller light shift (we label the beam by the corresponding F number) while the other beam has a square-pulse shape. For a Raman pulse with a power ramp, the Rabi frequency gives the arithmetic mean over the duration of the pulse.

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1.2.1. Group 1

This group is repeated 5 times.

Axis	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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.

Axis	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (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

[1] D. A. Steck, Tech. Rep. (2010), URL http://steck.us/alkalidata.
[2] M. Kasevich and S. Chu, Phys. Rev. Lett. **69**, 1741 (1992).