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

Y. Yu,* N. R. Hutzler,† J. T. Zhang, L. R. Liu, T. Rosenband, and K.-K. Ni‡
Department of Chemistry and Chemical Biology,
Harvard University, Cambridge, Massachusetts, 02138, USA
Department of Physics, Harvard University, Cambridge, Massachusetts, 02138, USA and
Harvard-MIT Center for Ultracold Atoms, Cambridge, Massachusetts, 02138, USA
(Dated: April 16, 2018)

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 540 pulses in 53 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 $30\,\mu$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 6 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.

---

*Electronic address: yichaoyu@g.harvard.edu
†Present address: California Institute of Technology, Division of Physics, Mathematics, and Astronomy. Pasadena, CA, 91125
‡Electronic address: ni@chemistry.harvard.edu

1.2.1. *Group 1*

This group is repeated 4 times.

Axis	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (kHz)	Power ramp
x	-2	19.625	18.649	44.1	$2\pi \times 23$	F1
y	-2	19.615	18.648	28.6	$2\pi \times 35$	F1
x	-1	19.130	18.649	36.9	$2\pi \times 23$	F1
y	-1	19.615	18.648	24.0	$2\pi \times 35$	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	-5	19.030	18.605	81.5	$2\pi \times 16$	F2
x	-2	19.625	18.649	44.1	$2\pi \times 23$	F1
z	-4	18.940	18.605	76.3	$2\pi \times 16$	F2
y	-2	19.615	18.648	28.6	$2\pi \times 35$	F1
z	-5	19.030	18.605	81.5	$2\pi \times 16$	F2
x	-1	19.130	18.649	36.9	$2\pi \times 23$	F1
z	-4	18.940	18.605	76.3	$2\pi \times 16$	F2
y	-1	19.130	18.648	24.0	$2\pi \times 35$	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	-4	18.940	18.605	76.3	$2\pi \times 16$	F2
x	-2	19.625	18.649	44.1	$2\pi \times 23$	F1
z	-3	18.858	18.605	70.2	$2\pi \times 16$	F2
y	-2	19.615	18.648	28.6	$2\pi \times 35$	F1
z	-4	18.940	18.605	76.3	$2\pi \times 16$	F2
x	-1	19.130	18.649	36.9	$2\pi \times 23$	F1
z	-3	18.858	18.605	70.2	$2\pi \times 16$	F2
y	-1	19.130	18.648	24.0	$2\pi \times 35$	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	-3	18.858	18.605	70.2	$2\pi \times 16$	F2
x	-2	19.625	18.649	44.1	$2\pi \times 23$	F1
z	-2	18.773	18.605	62.7	$2\pi \times 16$	F2
y	-2	19.615	18.648	28.6	$2\pi \times 35$	F1
z	-3	18.858	18.605	70.2	$2\pi \times 16$	F2
x	-1	19.130	18.649	36.9	$2\pi \times 23$	F1
z	-2	18.773	18.605	62.7	$2\pi \times 16$	F2
y	-1	19.130	18.648	24.0	$2\pi \times 35$	F1

1.2.5. Group 5

This group is repeated 10 times.

Axis	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (kHz)	Power ramp
z	-2	18.773	18.605	62.7	$2\pi \times 16$	F2
x	-1	19.130	18.649	36.9	$2\pi \times 23$	F1
z	-1	18.685	18.605	52.5	$2\pi \times 16$	F2
y	-1	19.130	18.648	24.0	$2\pi \times 35$	F1
z	-2	18.773	18.605	62.7	$2\pi \times 16$	F2
x	-1	19.130	18.649	70.0	$2\pi \times 23$	F1
z	-1	18.685	18.605	52.5	$2\pi \times 16$	F2
y	-1	19.130	18.648	46.0	$2\pi \times 35$	F1

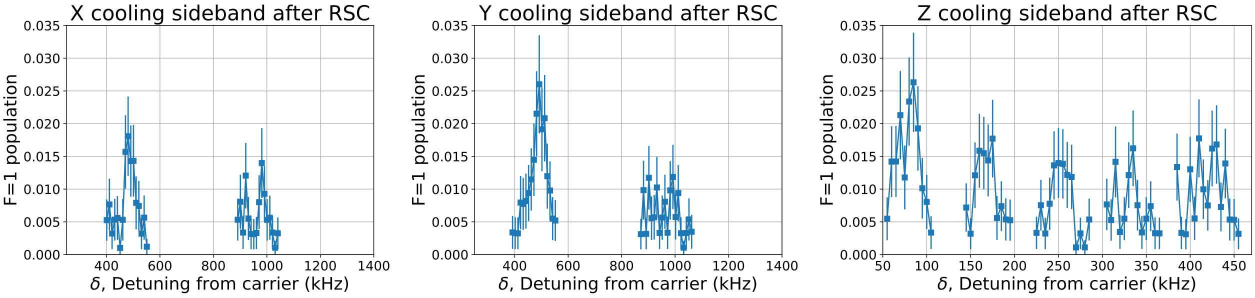
1.2.6. Group 6

This group is repeated 30 times.

Axis	Δn	δ' (MHz)	δ'_0 (MHz)	Duration (μs)	Ω_0 (kHz)	Power ramp
z	-1	18.683	18.605	78.7	$2\pi \times 11$	F2
z	-1	18.683	18.605	135.0	$2\pi \times 11$	F2
z	-1	18.685	18.605	78.7	$2\pi \times 11$	F2
x	-1	19.130	18.649	36.9	$2\pi \times 23$	F1
y	-1	19.130	18.648	24.0	$2\pi \times 35$	F1
z	-1	18.685	18.605	78.7	$2\pi \times 11$	F2
z	-1	18.685	18.605	135.0	$2\pi \times 11$	F2
z	-1	18.685	18.605	78.7	$2\pi \times 11$	F2
x	-1	19.130	18.649	70.0	$2\pi \times 23$	F1
y	-1	19.130	18.648	46.0	$2\pi \times 35$	F1

2. ZOOMING INTO THE COOLING SIDEBANDS

The height of the cooling sidebands decreases to about 2% after the Raman sideband cooling, making them very hard to see on when plotting on the same scale as the heating sideband as well as the spectra before cooling. A zoom-in of the spectra after cooling is included here so that they can be seen more clearly. Only the cooling orders ($\Delta n = -1, -2$ for radial X and Y axes and $\Delta n = -1, \ldots, -5$ for axial Z axis) are shown.



[1] D. A. Steck, Tech. Rep. (2010), URL http://steck.us/alkalidata.

[2] M. Kasevich and S. Chu, Phys. Rev. Lett. **69**, 1741 (1992).