Frequency Comb Cooling of $^{87}$Rb atoms

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Motivation

- laser cooling is an important tool for fundamental physics, quantum measurement and technology
- due to limitations of the present continuous wave (CW) lasers, cooling is currently limited to atomic/molecular species with simple level structure and transitions in the visible/near infrared range
- our approach: use radiation pressure force of a frequency comb (FC) to cool atoms below Doppler limit
- equidistant comb modes of a FC could allow for cooling of rotational and vibrational degrees of freedom in molecules with complex level structure
- FC lasers provide high peak powers needed for efficient conversion to vacuum ultraviolet (VUV) frequencies, needed for laser cooling of e.g. hydrogen, aluminium, deuterium, antihydrogen

Experiment

- FC generated by Er fiber mode-locked laser
- spectrum is centered around 780 nm, width 10 nm
- maximum total beam power 65 mW
- beam interacts with a cold cloud of $^{87}$Rb atoms trapped in a magneto-optical trap (MOT)
- MOT properties: temperature T=60-300 µK, atom number N=10^11
- after MOT preparation stage (typically 500 ms), cooling beams are turned off and the FC beam turned on to interact with the atomic cloud
- two types of measurements: center-of-mass displacement due to single beam, and time-of-flight (TOF) measurements to determine cooling temperature of the cloud after interacting with a pair of counter-propagating beams

Atom-light interaction

- three FC modes interacting with the D$_2$ line of $^{87}$Rb atoms via three one-photon optical dipole transitions
- power per comb mode is 500 nW, repetition frequency f$_{rep}$=80.5 MHz
- atom dynamics governed by optical Bloch equations (OBEs) with full hyperfine level structure included in the model
- semiclassical force calculations: only near resonant comb modes contribute
- single beam force $F$:
  \[ F = \frac{\hbar}{\kappa} (\Omega_{\gamma} g_{\gamma} + \Delta \delta_{\gamma} \rho_{\gamma}) + \frac{\hbar}{\kappa} \Delta \delta_{\gamma} \rho_{\gamma} \]
  \( \Omega \) - Rabi frequency of n-th mode
  \( g_{\gamma} \) - coupling coefficient of i-th mode
  \( \rho_{\gamma} \) - optical coherence

Results – Radiation pressure force

- measurements of single beam radiation pressure force after 1 ms irradiation by a comb with total power P=18 mW
- two peaks separated by 25.5 MHz, signature of FC mode interaction with different atomic transitions
- estimated acceleration for δ=0 is 110 m/s$^2$, resulting in scattering rate of 18.6 kHz, comparable to two-photon values

Results – Comb cooling

- beam configuration: LIN $\perp$ LIN
- squeezing of the cloud along the beam axis in TOF, sign of 1D laser cooling
- strongest cooling for detuning δ=3 MHz from the F=2→F'=3 transition
- strongest heating for δ=2 MHz
- |δ|>3: no cooling or heating due to small interaction with the cloud
- lowest temperature: $T_{x,min} = (108 \pm 7) \mu K$, below Doppler limit of $T_D = 140 \mu K$
- similar results obtained in LIN $\parallel$ LIN and δ $\perp \sigma$ configurations
- observation of sub-Doppler FC cooling via a one-photon transition, no detrimental effects due to blue-detuned comb modes

Influence of initial temperature on minimal temperature

- lower initial temperature $T_0$ → lower minimal temperature
- higher initial temperature → higher efficiency of cooling,
  \( \Delta T = T_0 - T_{x,min} \) cooling efficiency approaches zero for $T_0 = 60 \mu K$

Transient behavior of FC laser cooling

- transient behavior for $T_0$=120 µK and δ=3 MHz
- steady state reached for cooling time of 3 ms
- steady state $T$=55 µK

REFERENCES