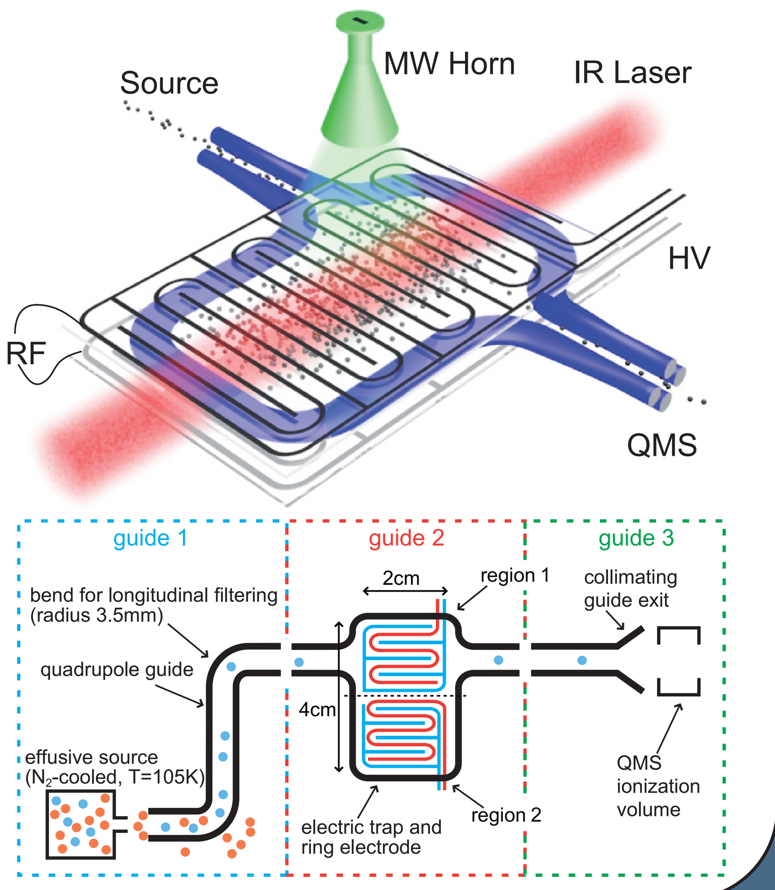
Sisyphus Cooling of Polyatomic Molecules

M. Zeppenfeld, B.G.U. Englert, R. Glöckner, A. Prehn, and G. Rempe.
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
http://www.mpq.mpg.de/qdynamics

The Experiment

Motivation

- Production of molecule ensembles at ultracold temperatures
- Laser cooling of polyatomic molecules impossible
- Alternative approach: opto-electrical cooling



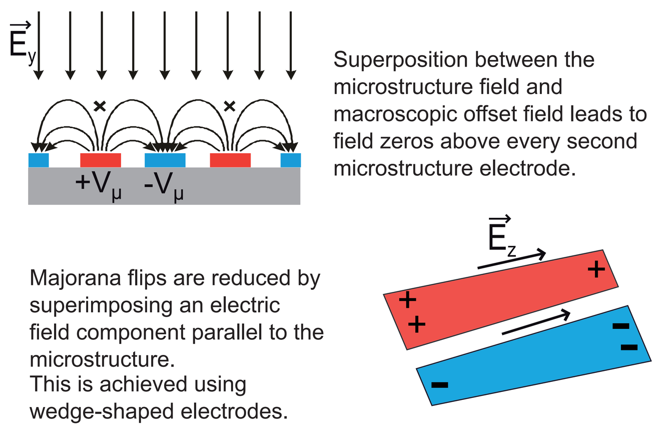
Setup

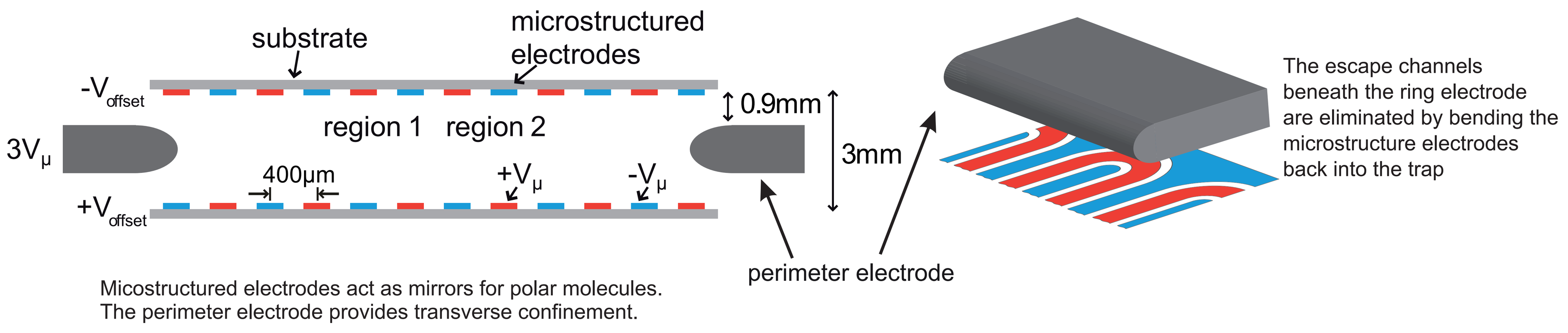
- Microstructured electric trap to store molecules
- Molecule source: bent quadrupole guide (~1K)
- Molecule detection: quadrupole mass spectrometer
- IR laser light: frequency-comb-locked OPO
- Microwaves at 150GHz: amplified multiplier chain

Novel DC Electric Trap

- Trapping of molecules up to 60s with =12s
- Box-like trap potential between microstructured capacitor plates
- Tunable homogeneous electric fields:
  - Selective addressing of molecular transitions
  - Suppression of trap losses via non-adiabatic transitions
- Subdivision into two independent trap regions: additional control of the molecular motion
- Connection to a continuous source of molecules

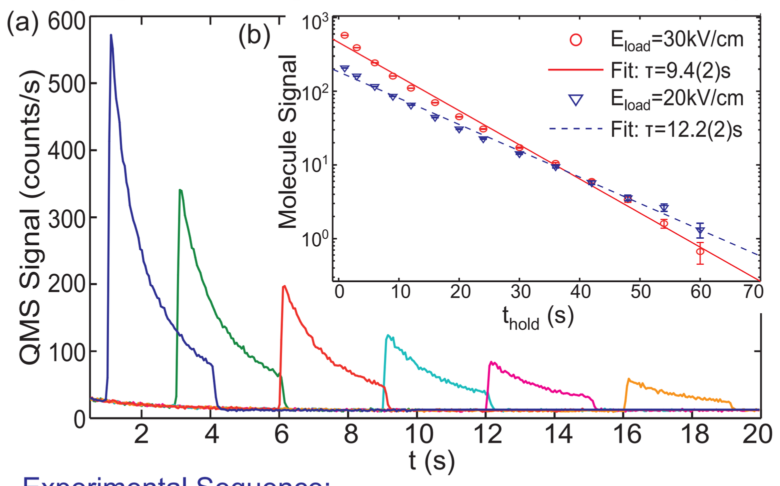
Eliminating Trap Losses:





Trap Results

Measurement of record lifetimes (=12s) by varying the holding time for molecules in the trap:

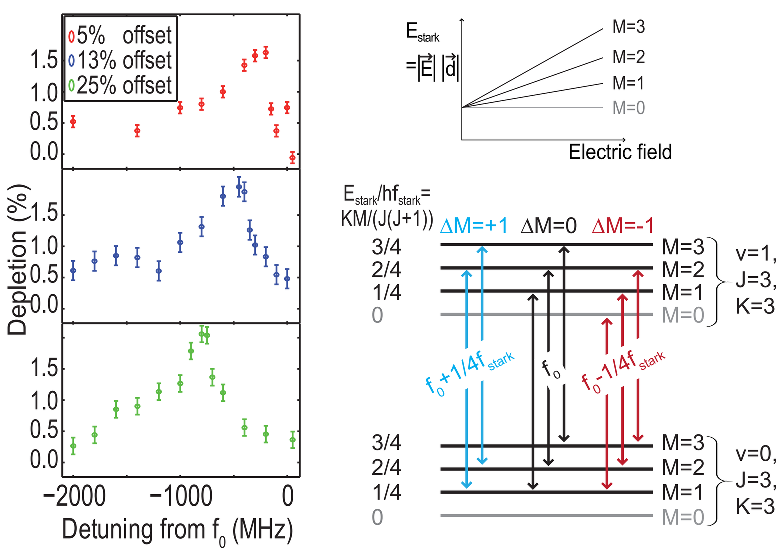


Experimental Sequence:

- Continuous loading at reduced trap and guiding fields
- Measure for two loading fields to analyze velocity dependence
- Trapping for 1 to 60s with E_{hold}=60kV/cm; guide 1 and 3 at high negative voltages thereby electrically closing the two outlets of the trap
- Unloading at guiding configuration

IR Stark Depletion Spectroscopy

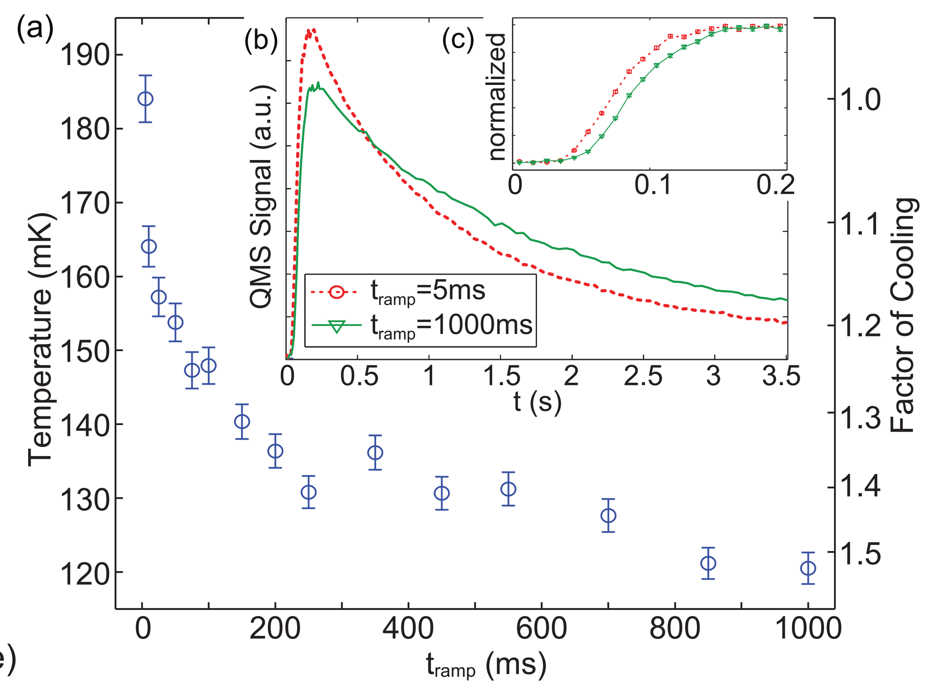
Depletion spectroscopy of |3,3 |3,3 transition at different plate offset fields:



- Narrow spectral feature, ~500MHz linewidth
- Linewidth is two orders of magnitude smaller than trap depth (30GHz)

Adiabatic Cooling

- Make use of the individually controllable trap regions
- Adiabatic expansion from one to both trap regions by ramping of electric fields
- Conservation of phase-space density: expected temperature reduction by factor 1.59
- Experimental analysis of time scale of adiabaticity by varying the ramping time



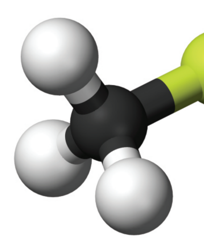
(a) Molecule temperature and cooling factor versus the ramping time.
(b) Typical TOF signal; molecules with t_{ramp}=1000ms arrive later and decay slower than molecules with t_{ramp}=5ns.
(c) Close-up of the normalized rising edge signal.

Results:

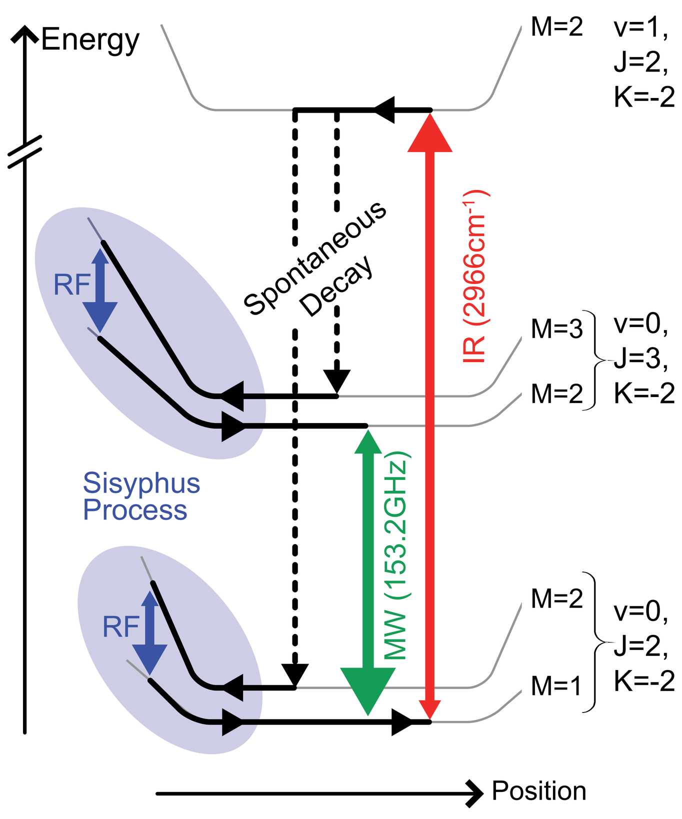
- Measured temperatures:
  T_{max}= 184 ± 3 mK (5ms ramping time)
  T_{min}= 121 ± 2 mK (1000ms ramping time)
- Cooling factor:
  F = T_{max}/T_{min} = 1.53 ± 0.03
  thermodynamic maximum: 1.59

Fluoromethane - CH_3F

- Large rotational constants; relatively few internal states are populated at liquid nitrogen temperatures
- C-H vibrational strech mode (decay rate 15Hz) is addressable with OPO
- Extremely low background at QMS for mass 34
- Dipole moment of 1.85 Debye



Opto-Electrical Cooling



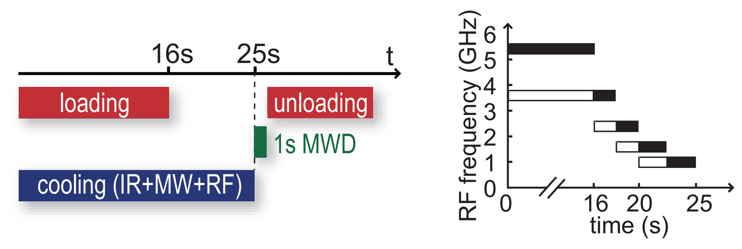
Scheme:

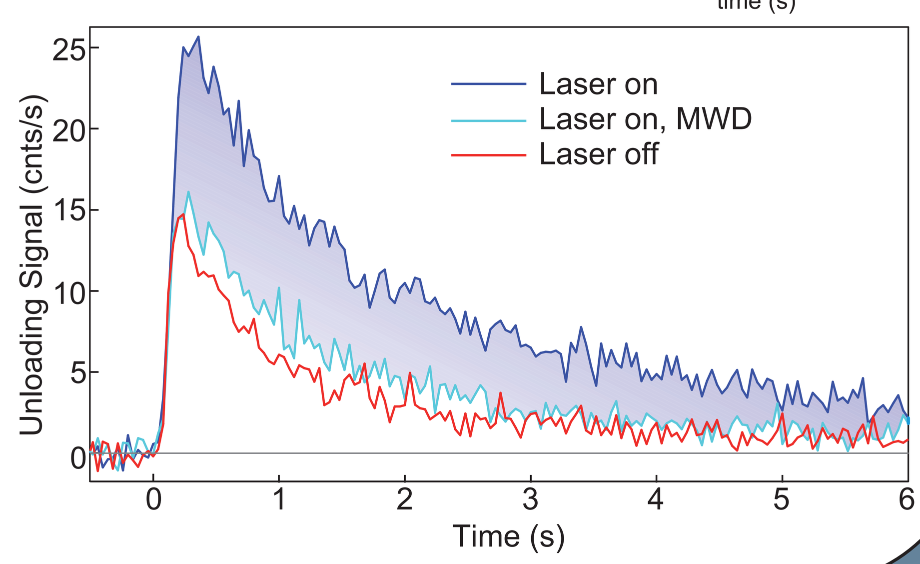
- Sisyphus type cooling
- Use of DC electric field to remove kinetic energy
- Spontaneous decay provides for "one way direction": a dissipative process
- ~12 cycles for one order-of-magnitude temperature reduction
- Use vibrational decay: only a few levels involved due to rotational and vibrational selection rules
- Simulations show cooling below 1mK

suitable for all sufficiently long trappable polar molecules

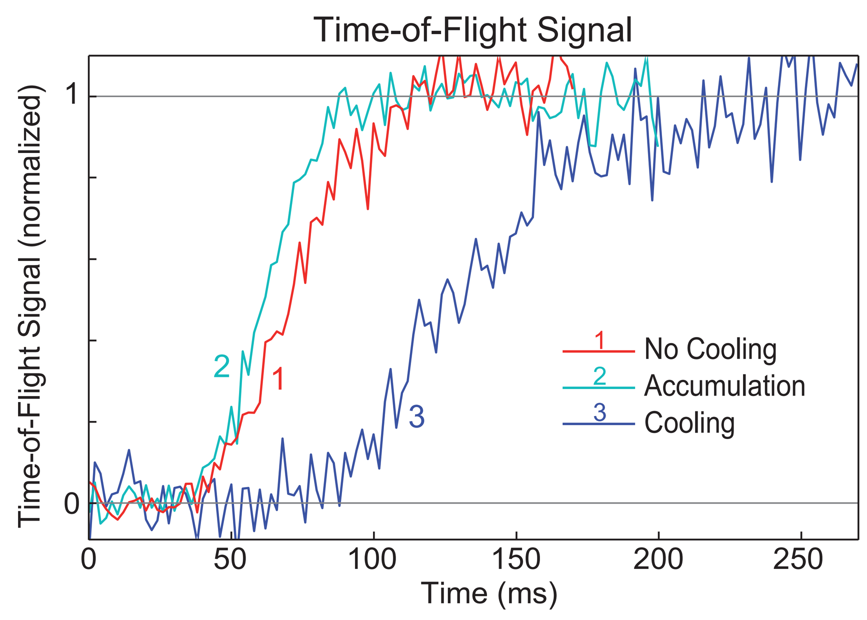
Experimental Realization:

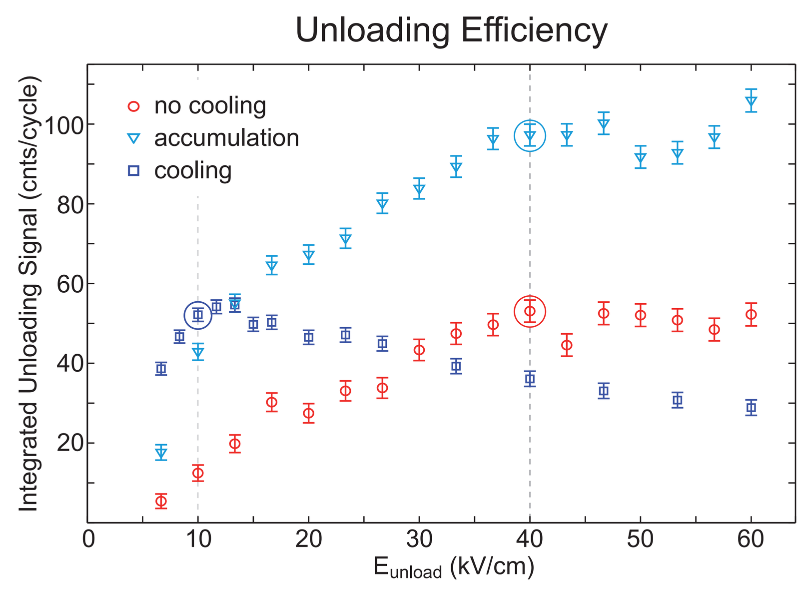
- Accumulation (IR + MW): population increase in states |2,2,2 and |3,2,3
- Cooling (IR+MW+RF): reduction of kinetic energy via RF fields
- RF frequency is sequentially ramped down according to the decreasing energy of the molecules
- State-discriminating detection:
  - microwave depletion (MWD) pulse destroys all molecules in rotational states J=2 and J=3
  - cooling signal = difference in unloading signal with and without MWD



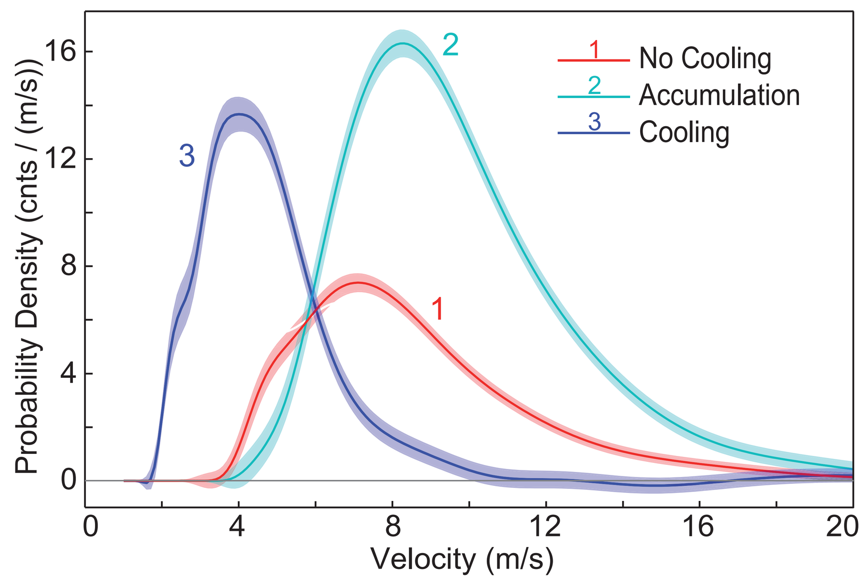


Cooling Results for CH_3F





Velocity Distributions Determined From Time-of-Flight Signal:

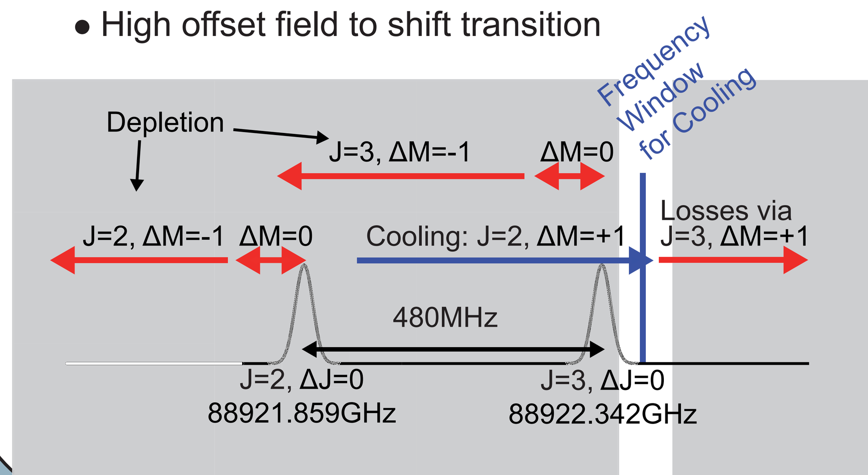


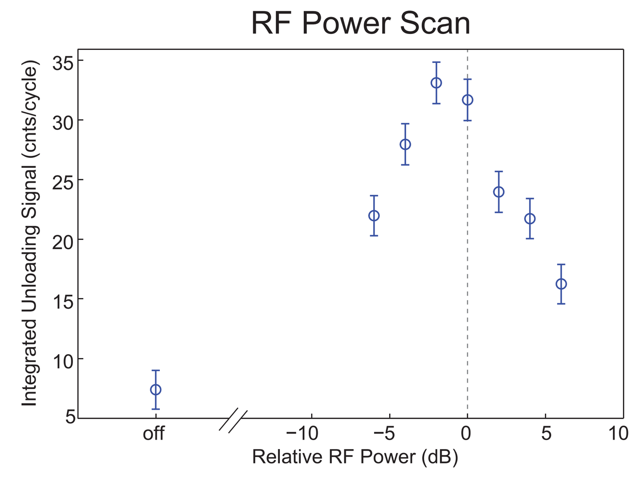
- Phase-space density increased by a factor of 6.9, temperature reduced by a factor of 4.6
- Sisyphus cooling with a spontaneous decay rate of only 15Hz
- Starting from a warm source with hundreds of rotational states populated, our experiment generates a near-state-selected ensemble of cold molecules

	RF	MW +IR	E_{unload} (kV/cm)	⟨v_z⟩ (m/s)	T (mK)	N (cnts)	N / ⟨v_z⟩^{3} (s^3/m^3)
No Cooling	-	-	40	8.1	268	44.9	0.085
Accumulation	-	x	40	9.3	358	98.6	0.121
Cooling	x	x	10	4.3	77	48.2	0.587

Experimental Parameters

- IR frequency for cooling:
  - Transition in Q-branch   avoid losses via J=3
  - High offset field to shift transition
- RF power: strong enough for rapid cooling but weak enough to avoid losses via depletion





Future Prospects

- Combination with buffer-gas cooling and internal state cooling
- Higher microwave frequencies to address K=3: double particle number due to spin statistics
- Different molecule species with stronger vibrational decay
- State-selective detection via REMPI spectroscopy
- Investigate new physics

[1] M. Zeppenfeld *et al.*, arXiv:1208.0046[physics.atom-ph] (2012).
[2] B.G.U. Englert *et al.*, Phys. Rev. Lett. **107** 263003 (2011).
[3] M. Zeppenfeld *et al.*, Phys. Rev. A **80**, 041401(R) (2009).
[4] T. Junglen *et al.*, Euro. Phys. J. D **31**, 365 (2004).