

Seminar “Ultra Cold Molecules”

# DECELERATION OF MOLECULES

Universität Hannover

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29th June 2004



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- Why of interest
- Lasercooling ?

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## 4 Summary

# Why is deceleration/cooling of molecules of interest ?

What means cold for experiments

- ▶ air temperature:  $300\text{ K} \equiv 300\text{ m/s}$
- ▶ This limits the observation time

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fundamental studies

- ▶ high precision spectroscopy
- ▶ cold molecule–molecule collisions
- ▶ cold chemistry
- ▶ molecular Bose-Einstein condensate

# Deceleration – is Laser Cooling applicable ?

## Properties

- ▶ Laser cooling - very successful with atoms

# Deceleration – is Laser Cooling applicable ?

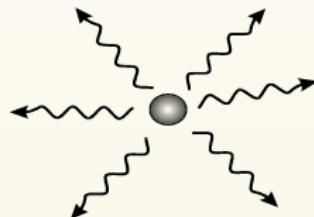
## Properties

- ▶ Laser cooling - very successful with atoms
- ▶ Deceleration by momentum transfer

absorption



emission



directional → total momentum:  
 $\vec{p} = n \cdot \hbar \vec{k}$

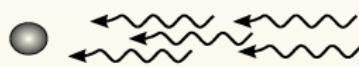
statistically distributed → total  
 momentum:  $\langle \vec{p} \rangle_t = 0$

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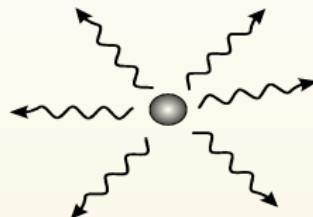
## Properties

- ▶ Laser cooling - very successful with atoms
- ▶ Deceleration by momentum transfer
- ▶ Absorption-Emission Cycle necessary – **two-level atom**

absorption



emission



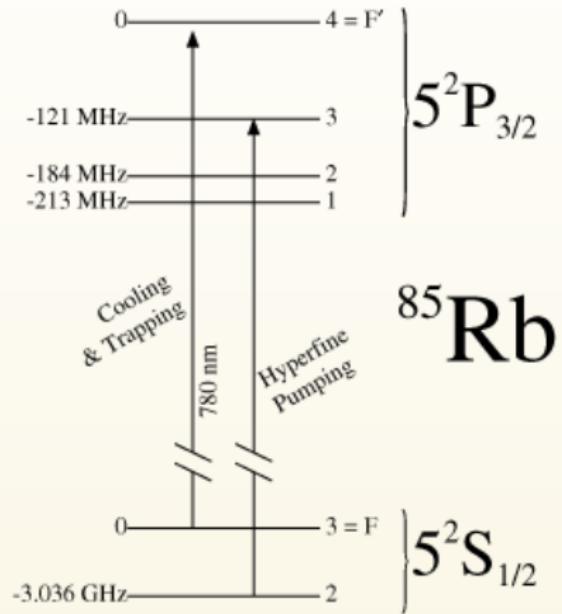
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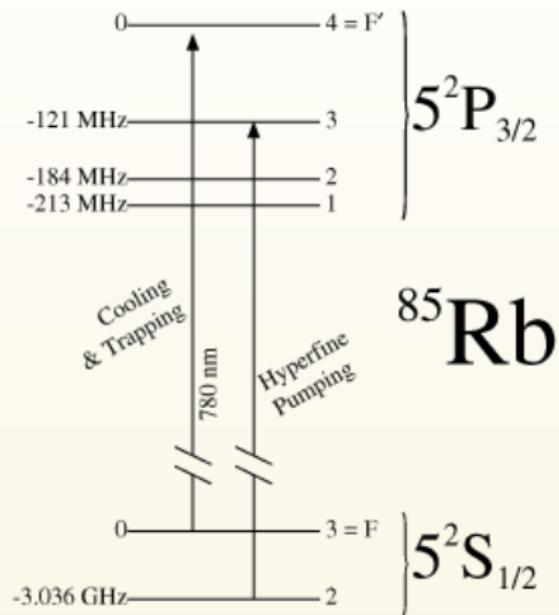
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## Level structure of Rubidium



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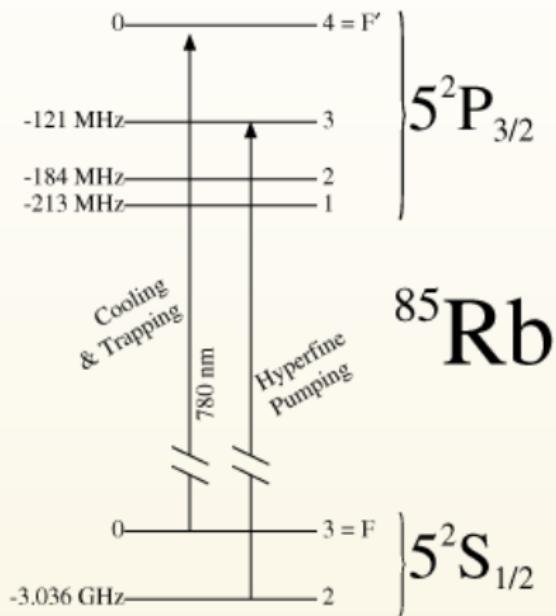


In case of molecules

- ▶ complex energy levels
- ▶ molecules distributed over vibrational states after spontaneous emission

# Problems with Laser cooling

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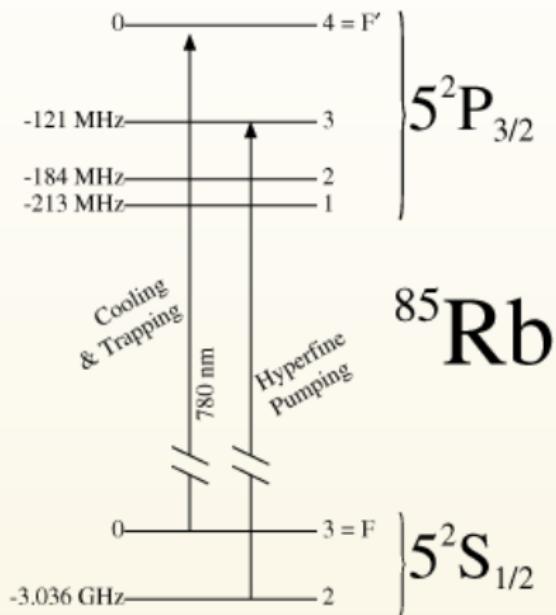


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- ▶ how many repumper necessary ?

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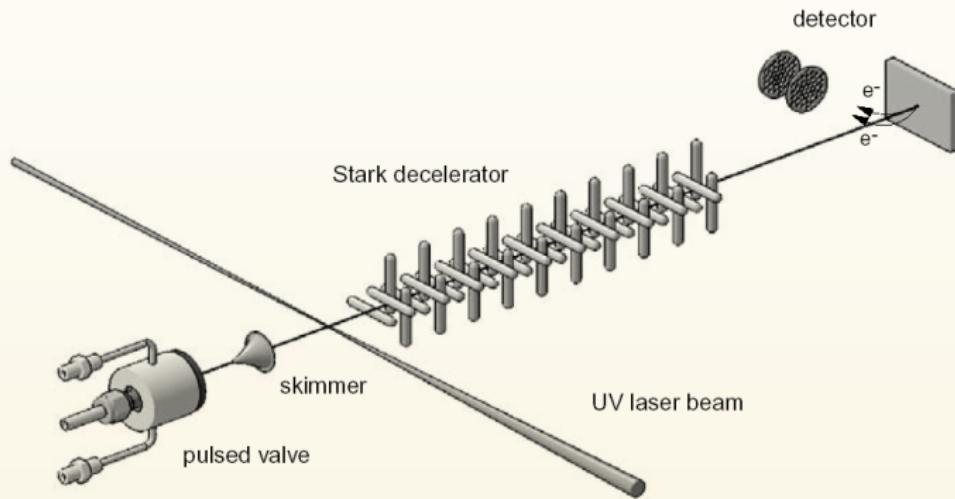


In case of molecules

- ▶ complex energy levels
- ▶ molecules distributed over vibrational states after spontaneous emission
- ▶ how many repumper necessary ?
- ▶ **very difficult to find a closed two-level system in molecules**

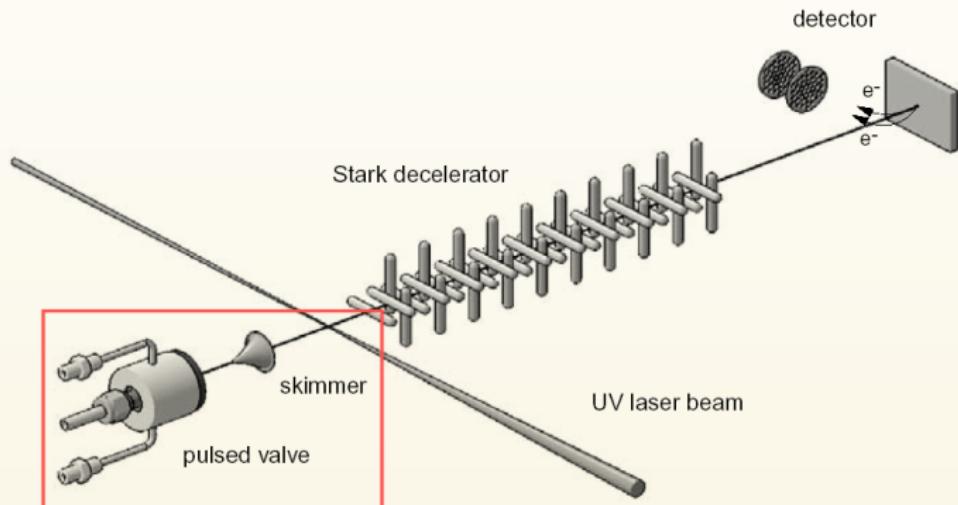
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1. generation by supersonic pulsed valve
2. passes through a skimmer
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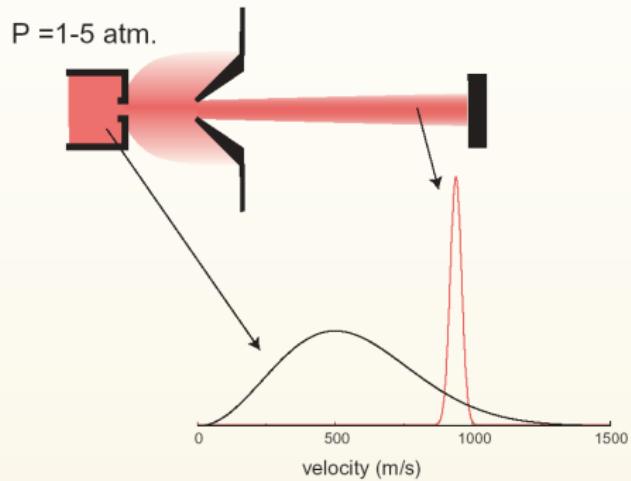


# Pulsed valve

Adiabatic cooling in a supersonic pulsed gas expansion:

## Principle

- ▶ cooled gas
- ▶ gas expansion
- ▶ high pressure into vacuum
- ▶ multiple collisions



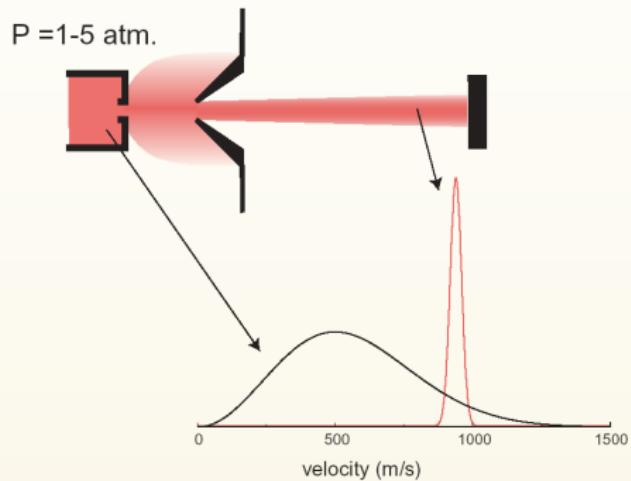
pulsed gas expansion

# Pulsed valve

Adiabatic cooling in a supersonic pulsed gas expansion:

## Principle

- ▶ cooled gas
- ▶ gas expansion
- ▶ high pressure into vacuum
- ▶ multiple collisions
- ▶ fast molecules slowed down
- ▶ high average velocity
- ▶ narrow distribution

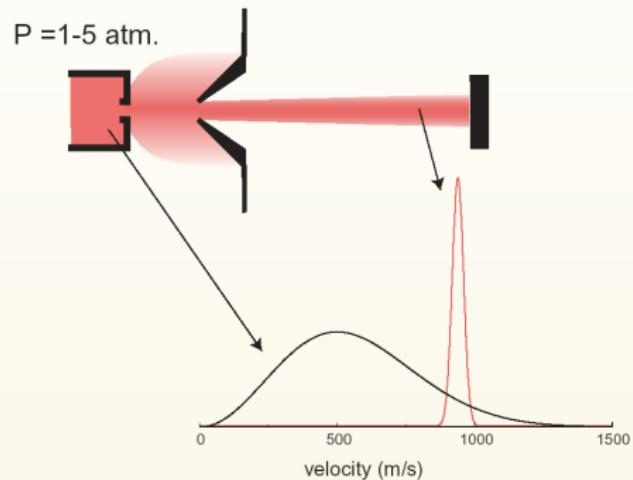


pulsed gas expansion

# Pulsed valve

## Properties

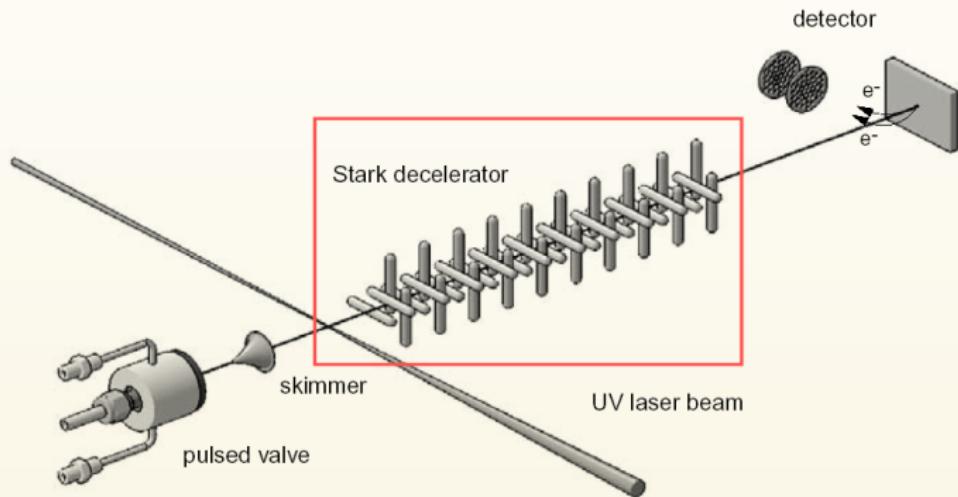
- ▶ vibrational temp.: < 50 K
- ▶ rotational temp.: < 5 K
- ▶ translational temp.: < 1 K
- ▶ density:  $< 10^{12} \text{ m}^{-3}$
- ▶ CO - Experiment:
- ▶ absolute velocity: 275 m/s
- ▶ velocity width: 0.5 K



pulsed gas expansion

# The experiment

1. generation by supersonic pulsed valve
2. passes through a skimmer
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4. Time of flight measurements (various methods)



## Deceleration Principle

- ▶ momentum transfer is not possible (Lasercooling) **X**

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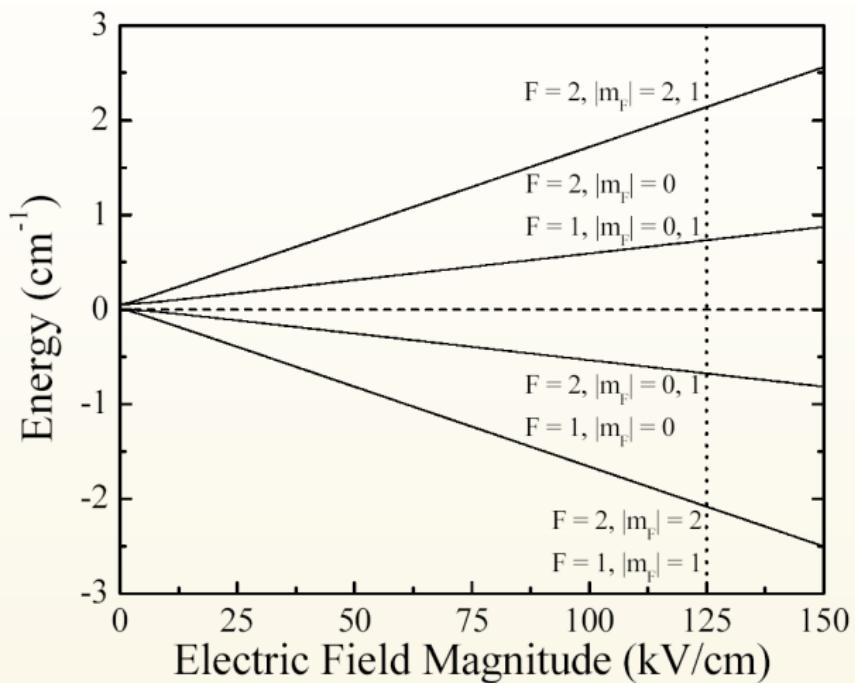
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- ▶ polar molecules → electric dipole moment
- ▶ high electric field
- ▶ **Stark effect** – energy gain in polar molecule by electric field

# Stark effect on polar molecules



Stark Shift for ground state OH molecules in high electric fields

J.R. Bochonski, University of Colorado, Boulder

## Stark effect on polar molecules

- ▶ polar molecules → intrinsic separation of charge – dipole  $\vec{d}_e$
- ▶ dipole alignes with an external electric field  $\vec{\mathcal{E}}$
- ▶ Potential energy:  $\mathcal{H} = -\vec{d}_e \cdot \vec{\mathcal{E}}$ .

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spatial varying electric field

$$v_f^2 = \frac{2\Delta E_{\text{pot}}}{M} + v_i^2$$

$v_i, v_f$  : initial and final velocity,  $M$  : mass.

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gain in potential energy compensated by loss in kinetic energy  
→ **Deceleration of molecules**

# Force on molecules

Force in spatial varying electric field

$$\vec{F} = \nabla(\vec{d}_e \vec{\mathcal{E}})$$

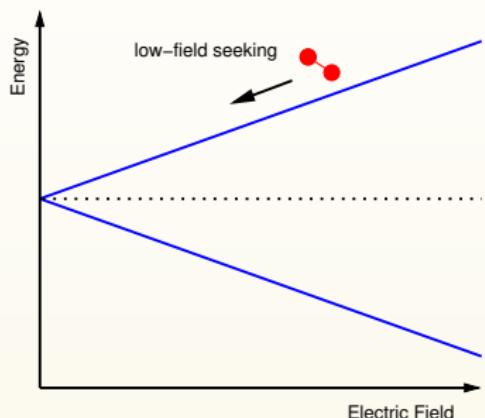
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low-field seeking states

- ▶ Stark energy shift *increases* with increasing electric field
- ▶ molecules are moving towards the *lowest* electric field



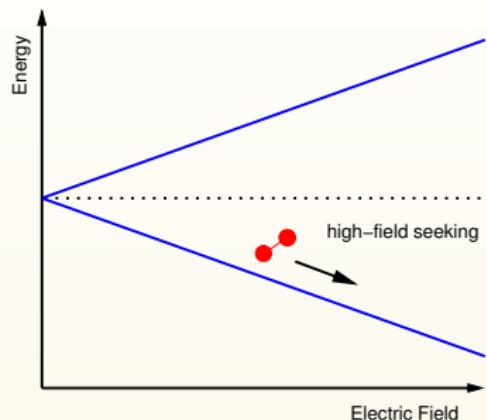
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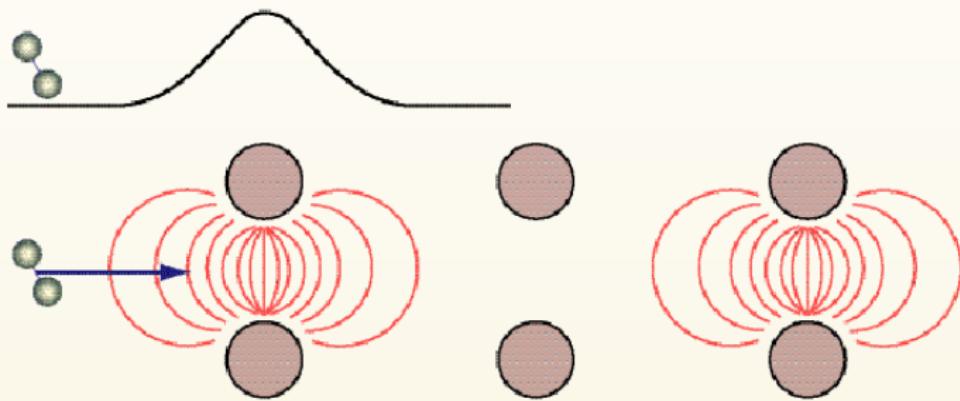
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high-field seeking states

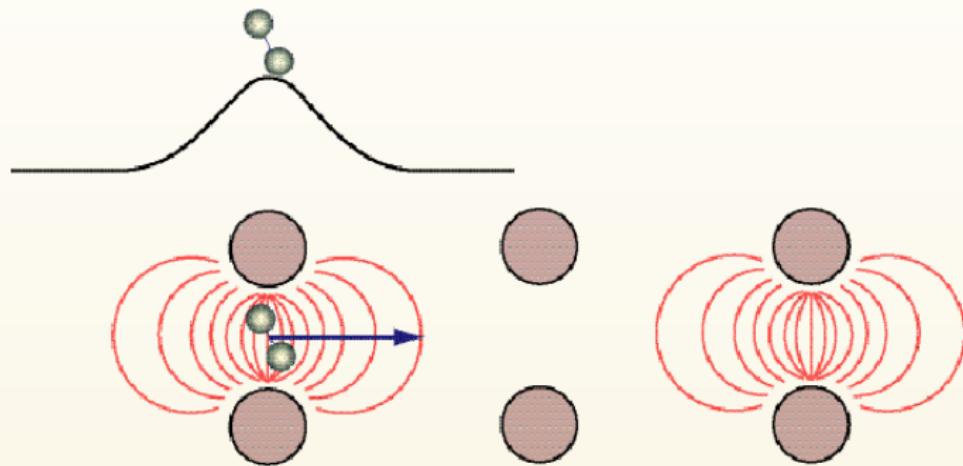
- ▶ Stark energy shift *decreases* with increasing electric field
- ▶ molecules are moving towards the *highest* electric field



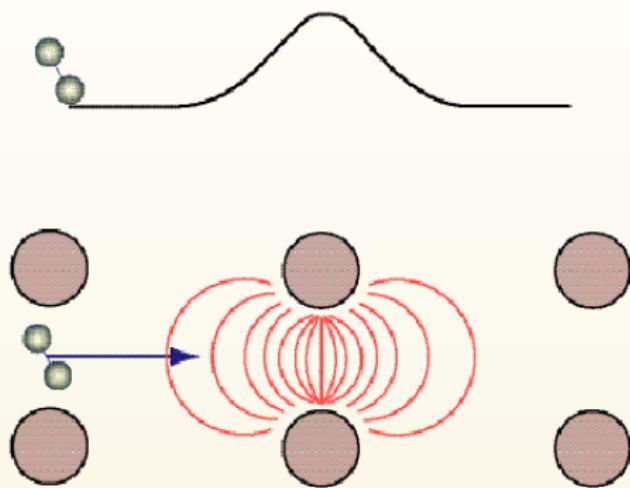
## Deceleration principle - Animation



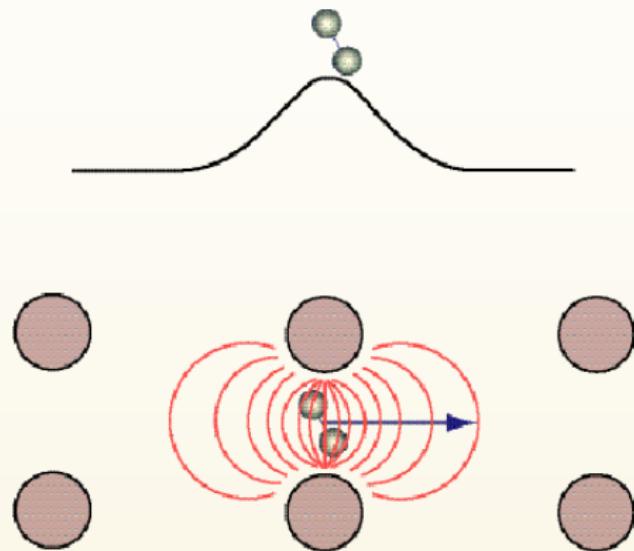
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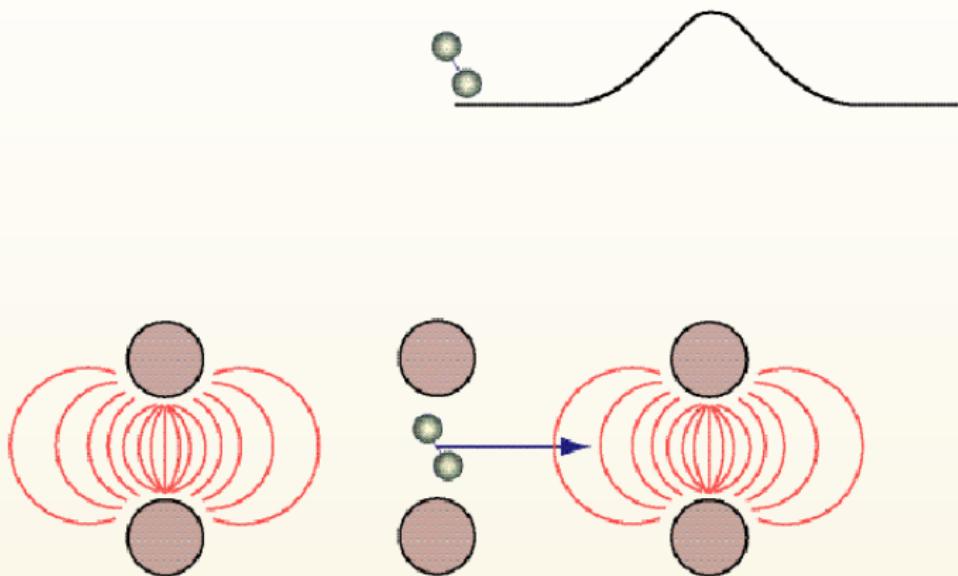
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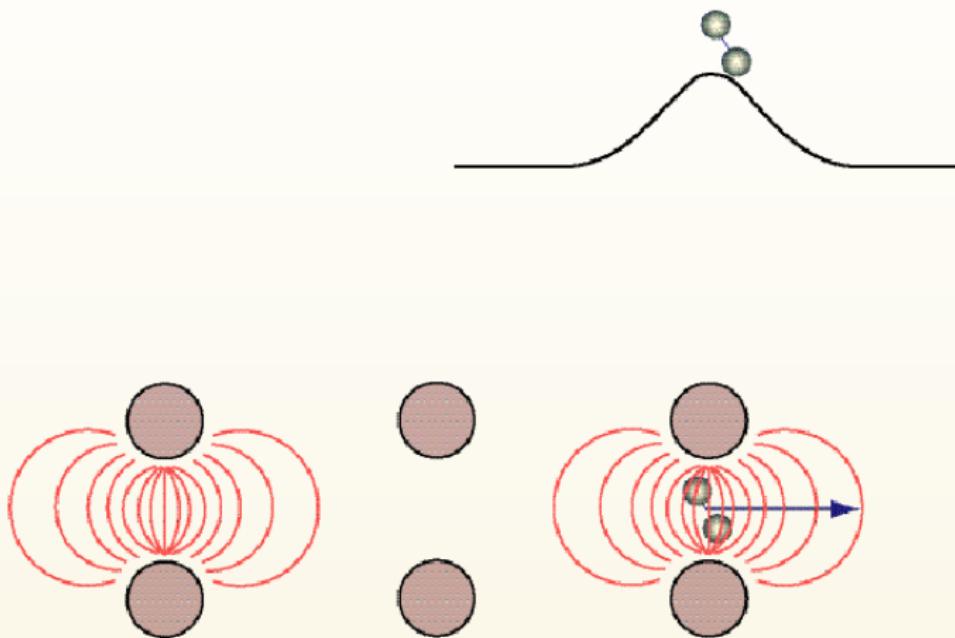
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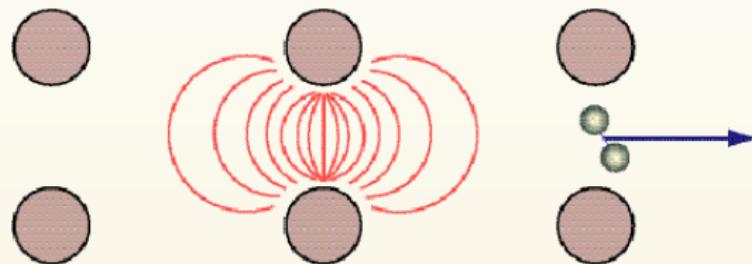
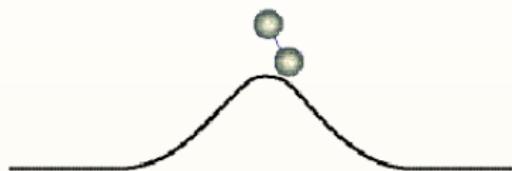
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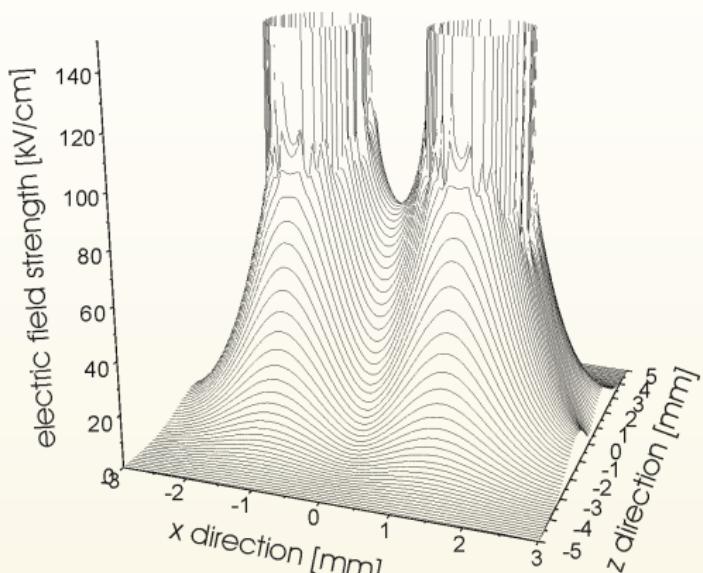


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# Deceleration Properties : Focussing

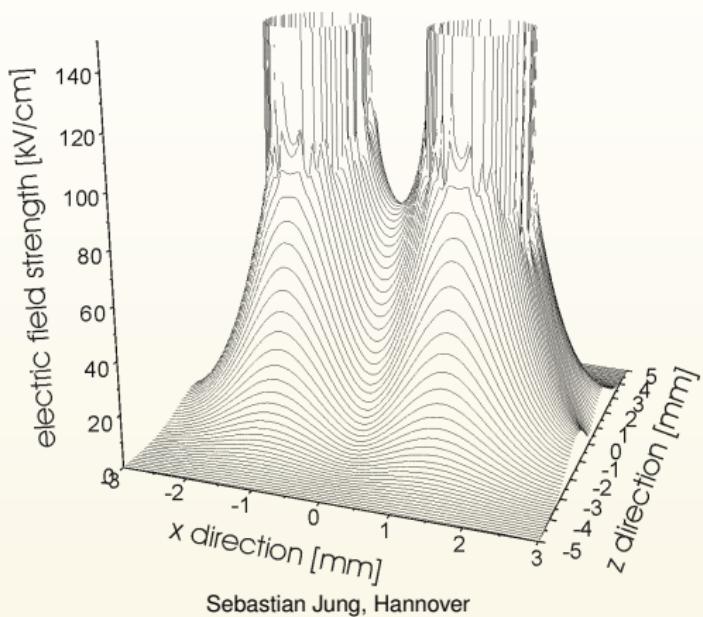
- ▶ minimum electric field on the molecular beam axis



Sebastian Jung, Hannover

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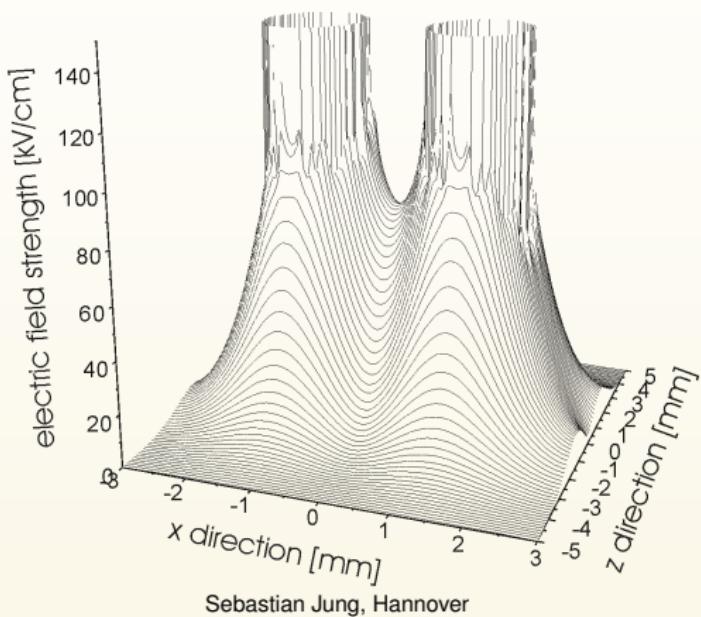
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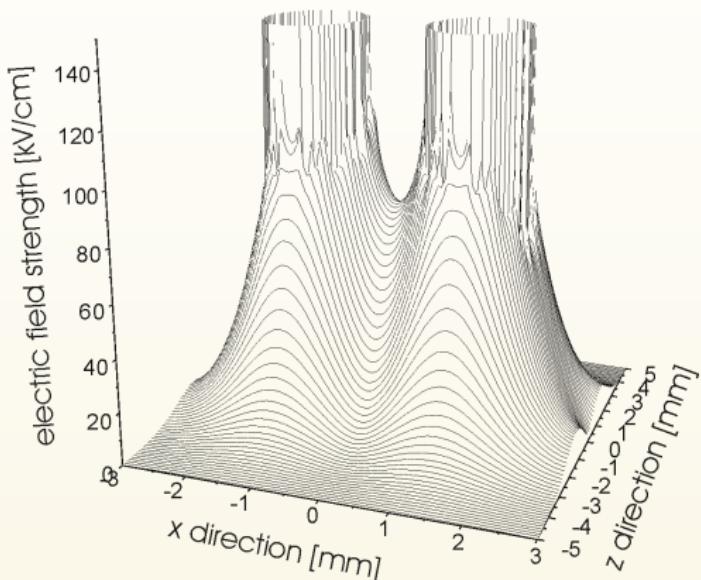
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- ▶ no focussing in the plane parallel to the electrodes



Sebastian Jung, Hannover

# Deceleration Properties : Focussing

- ▶ minimum electric field on the molecular beam axis
- ▶ low-field seeking states experience a focusing force
- ▶ no focussing in the plane parallel to the electrodes
- ▶ alternately horizontally and vertically positioned pairs



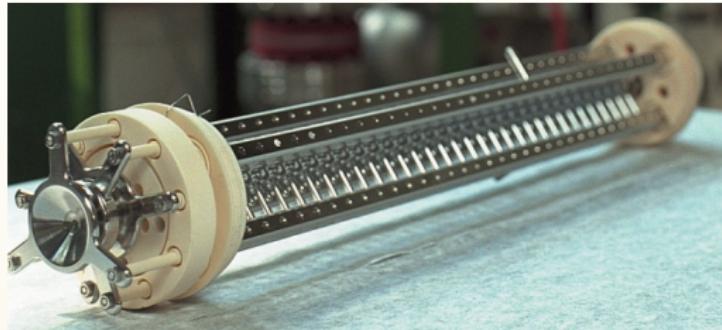
Sebastian Jung, Hannover

# The Stark decelerator



## The Stark decelerator

Experiment from Meijer



- ▶ 63 equidistant electric field stages
- ▶ length of 35 cm
- ▶ maximum voltages of plus and minus 10 kV
- ▶ maximum electric fields of 125 kV/cm

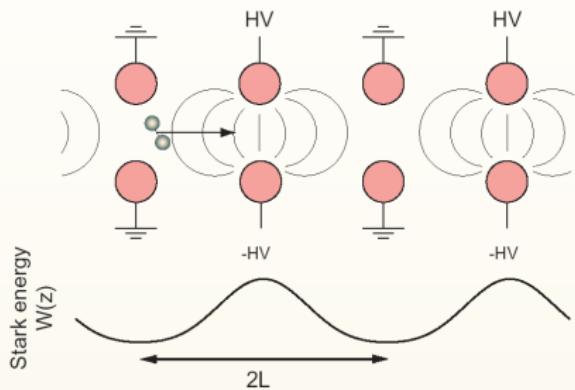
# Deceleration Properties – Phase

Definition of phase:

relative position of a molecules  
with its timing sequence

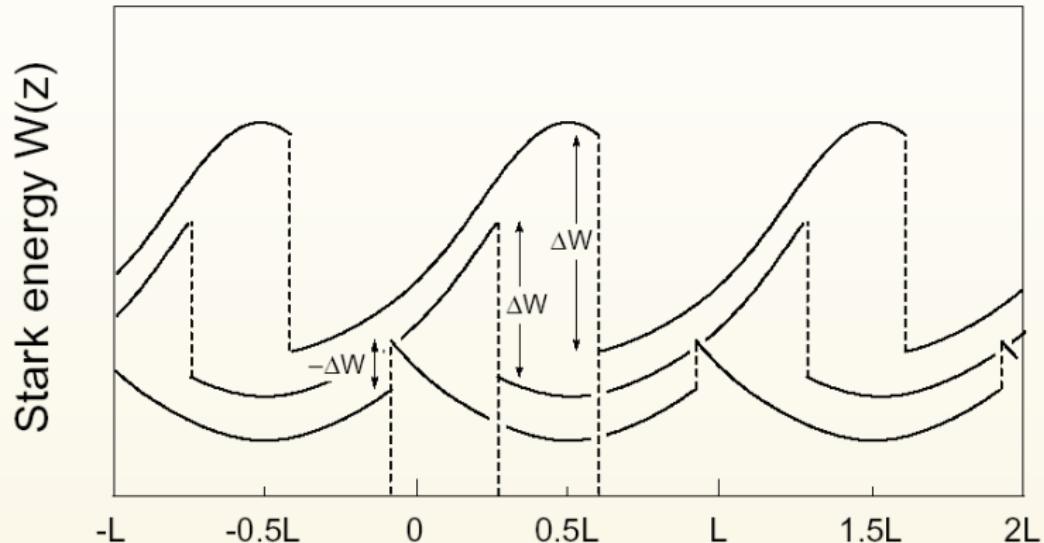
## deceleration requirements

- ▶ the bunch of molecules must be kept together
- ▶ molecules must always have the same phase
- ▶ switching intervals  $\Delta T$  must be gradually increased



# Deceleration Properties – Phase

molecules with wrong phase



Potential energy for some molecules having the same velocity but different phase.

## Deceleration Properties – Phase

oscillation of phase and velocity

What happens to molecules with a slightly different phase or velocity ?

Take:  $\varphi > \varphi_0$ ,  $v = v_0$ .



Molecules will oscillate with both phase and velocity around the equilibrium values.

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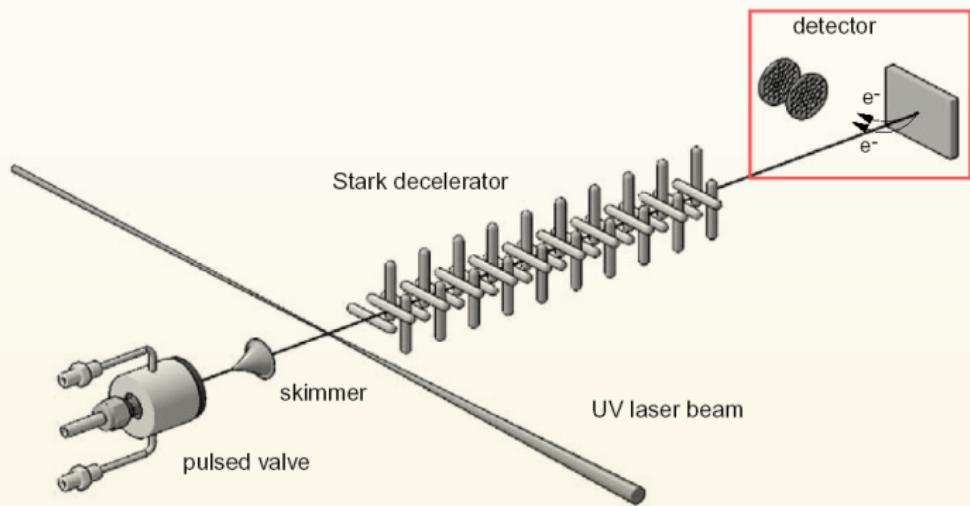
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# The experiment

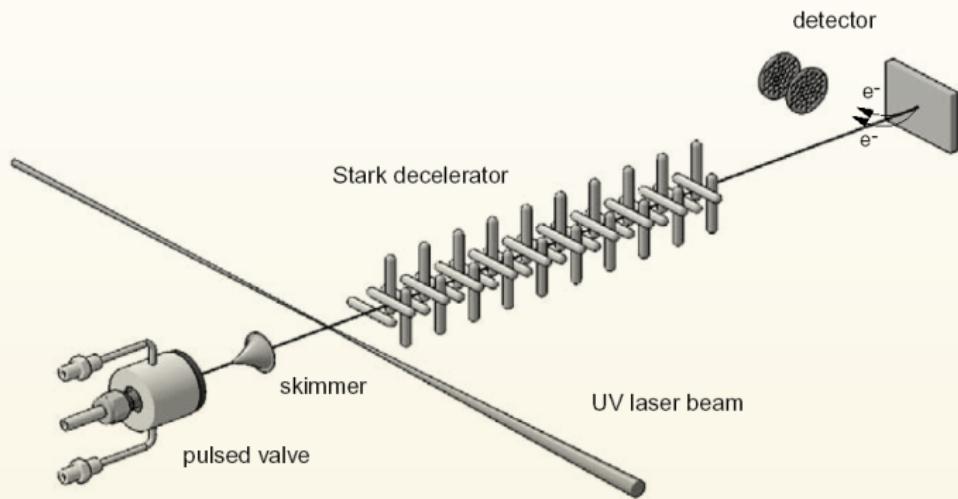
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# Time of flight (TOF)

## Measurement

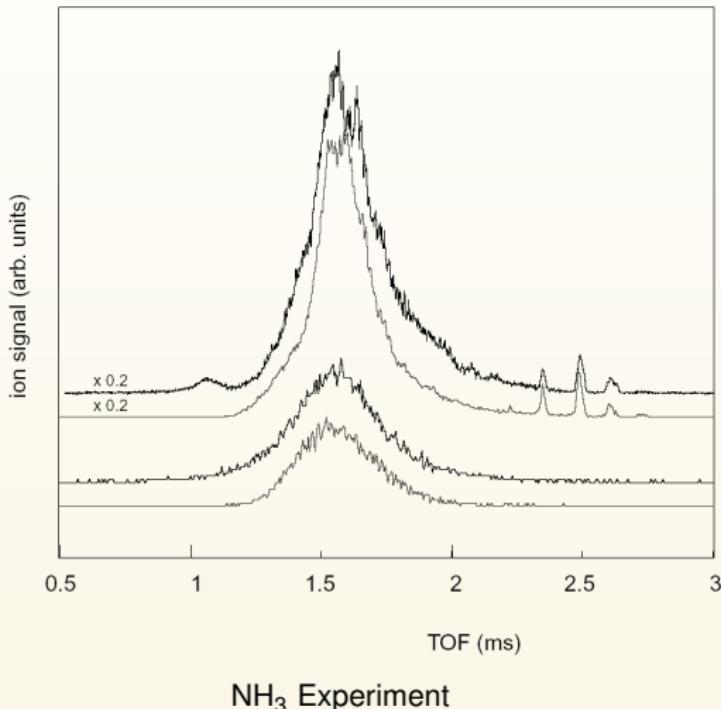
- ▶ molecules impinge on a flat gold surface
- ▶ electron detected as a function of time since laser preparation



# Time of flight (TOF)

## Results

- ▶ original beam:  
lower curve
- ▶ decelerated beam:  
upper curve
- ▶ additional peaks from  
faster and slower  
bunches
- ▶ Simulation:  
gray curves



## TOF results from CO-Experiment

- ▶ timings sequence set for a center velocity of 225 m/s
- ▶ velocity distribution of 4 m/s centered around this central velocity is captured
- ▶ molecules outside the interval are not affected
- ▶ only a subset of molecules – on the order of 1% – is decelerated

# Applicable Molecules

requirements

- ▶ sufficient large positive Stark shift ( $\sim 1 \text{ cm}^{-1}$ )
- ▶ in experimentally feasible electric fields ( $\sim 200 \text{ kV/cm}$ )
- ▶ sufficient low initial kinetic energy
- ▶ sufficient low mass/Stark energy

## Applicable Molecules

demonstrated candidates

- ▶ CO 225 m/s – 98 m/s
  - ▶ NH<sub>3</sub> (ND<sub>3</sub>) (Ammonia) 271.5 m/s – 91.8 (12.0) m/s
  - ▶ OH (diatomic hydroxyl radical) range: 550 m/s – 0 m/s
  - ▶ YbF

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1. deceleration acceleration comparable to laser cooling
  2. molecules can be brought to stillstand
  3. velocity can be chosen precisely (OH)

# Limitations of this cooling technique

molecules

- ▶ polar molecules
- ▶ low mass/Stark energy

*induced polarization  
more deceleration stages*

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## experimental

- ▶ decelerator selects absolute velocities *inherit property*

# What else can be done further... .

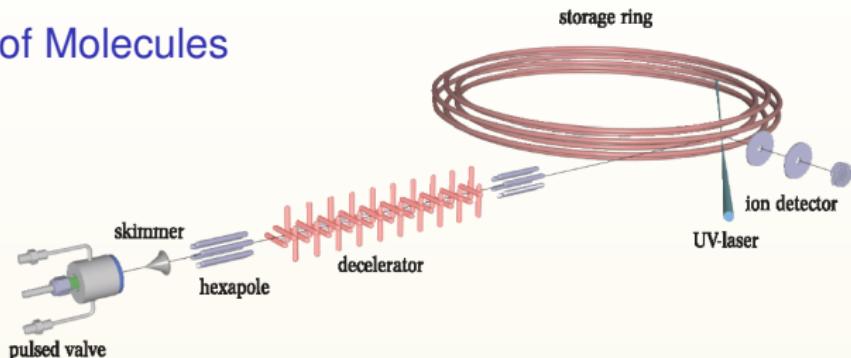
Better and Larger Decelerator



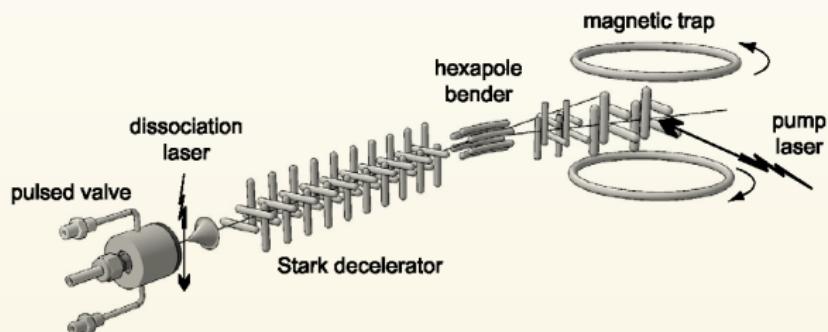
Gerard Meijer, FHI Berlin

# What else can be done further... .

## Trapping of Molecules



Gerard Meijer, Rijnhuizen



S.Y.T. van de Meerakker, Gerard Meijer, Rijnhuizen

# Summary

what have we discussed

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  - ▶ supersonic pulsed valve expansion
  - ▶ Stark effect on polar molecules
  - ▶ The Stark Decelerator and its properties
  - ▶ Results

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  - ▶ Results
4. Problems and prospects

# Literature

-  **Hendrik L. Bethlem.**  
Deceleration and Trapping of Polar Molecules using Time-varying Electric Fields.
-  **Hendrik L. Bethlem, Gerard Meijer.**  
Deceleration and trapping of ammonia using time-varying electric fields.  
*Physical Review A*, 65, 2002.
-  **Gerard Meijer.**  
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*Physik Journal*, 1(5):41–46, 2002.
-  **Gerard Meijer Hendrick L Bethlem, Giel Berden.**  
Decelerating neutral dipolar molecules.  
*Physical Review Letters*, 83(8):1558–1561, Aug 1999.
-  **J.R. Bochonski, E.R. Hudson, H.J. Lewandoski, Jun Ye.**  
Cold free radical molecules in the laboratory frame.