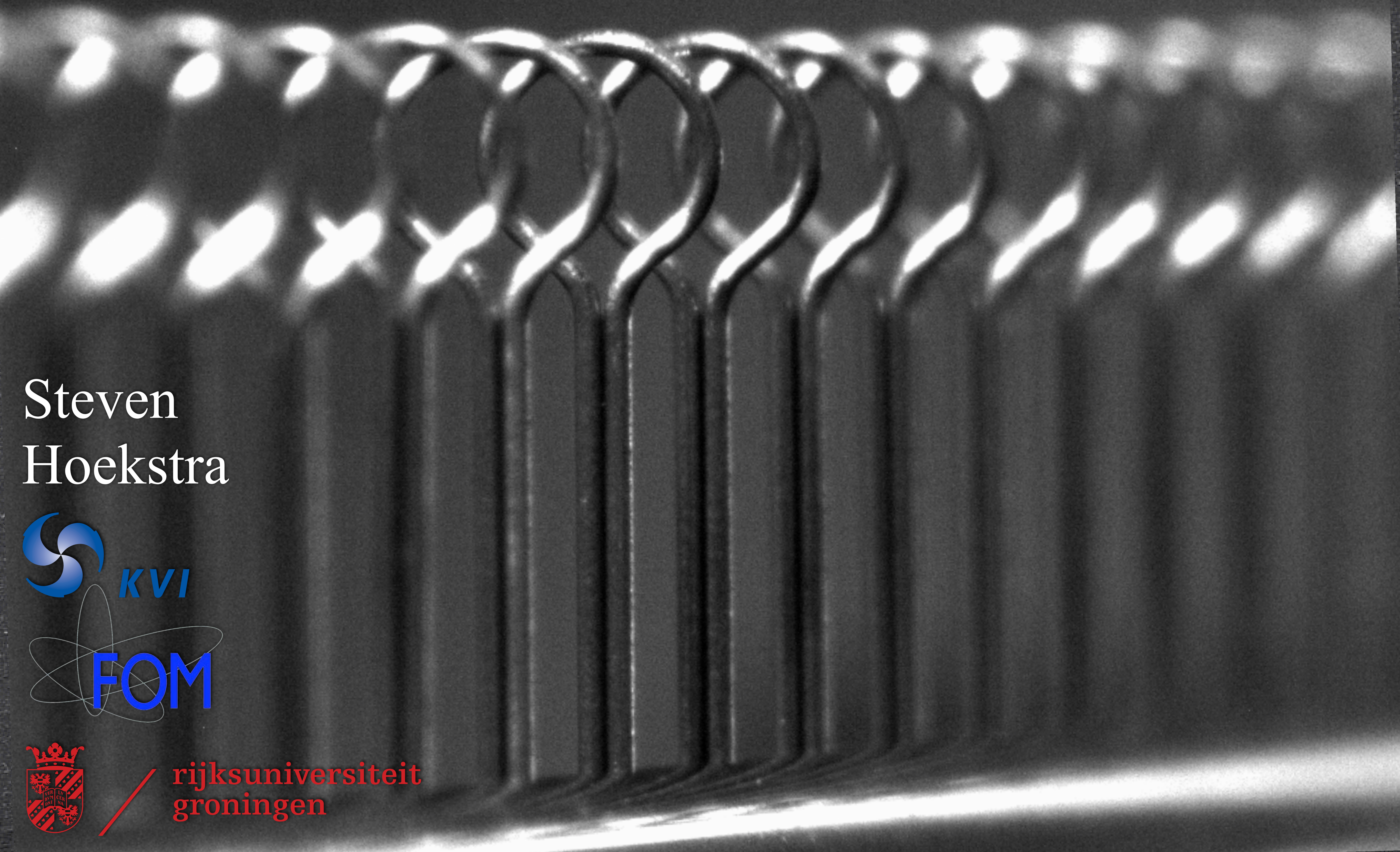
Deceleration and trapping of heavy diatomic molecules for precision tests of fundamental symmetries



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- Introduction: why we do this
- Stark deceleration, and its limitations
- Our approach: ring deceleration + lasercooling of heavy diatomics
- Outlook

Our main motivation:

Selected molecules offer unique sensitivity to probe new physics:

by precision measurements, Standard Model predictions and alternative theories can be tested

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- electric dipole moment of the electron
  because of huge internal fields in polar molecules
  (YbF, PbF, PbO, ThO, WC, HfF^{+})
- time-variation of the constants
  because of high sensitivity of tunneling to mass (NH_3)
  or close-lying states with different shifts (CO)
- (nuclear-spin dependent) parity violation
  because of close-lying rotational and vibrational states with
  opposite parity (BaF, SrF, RaF)

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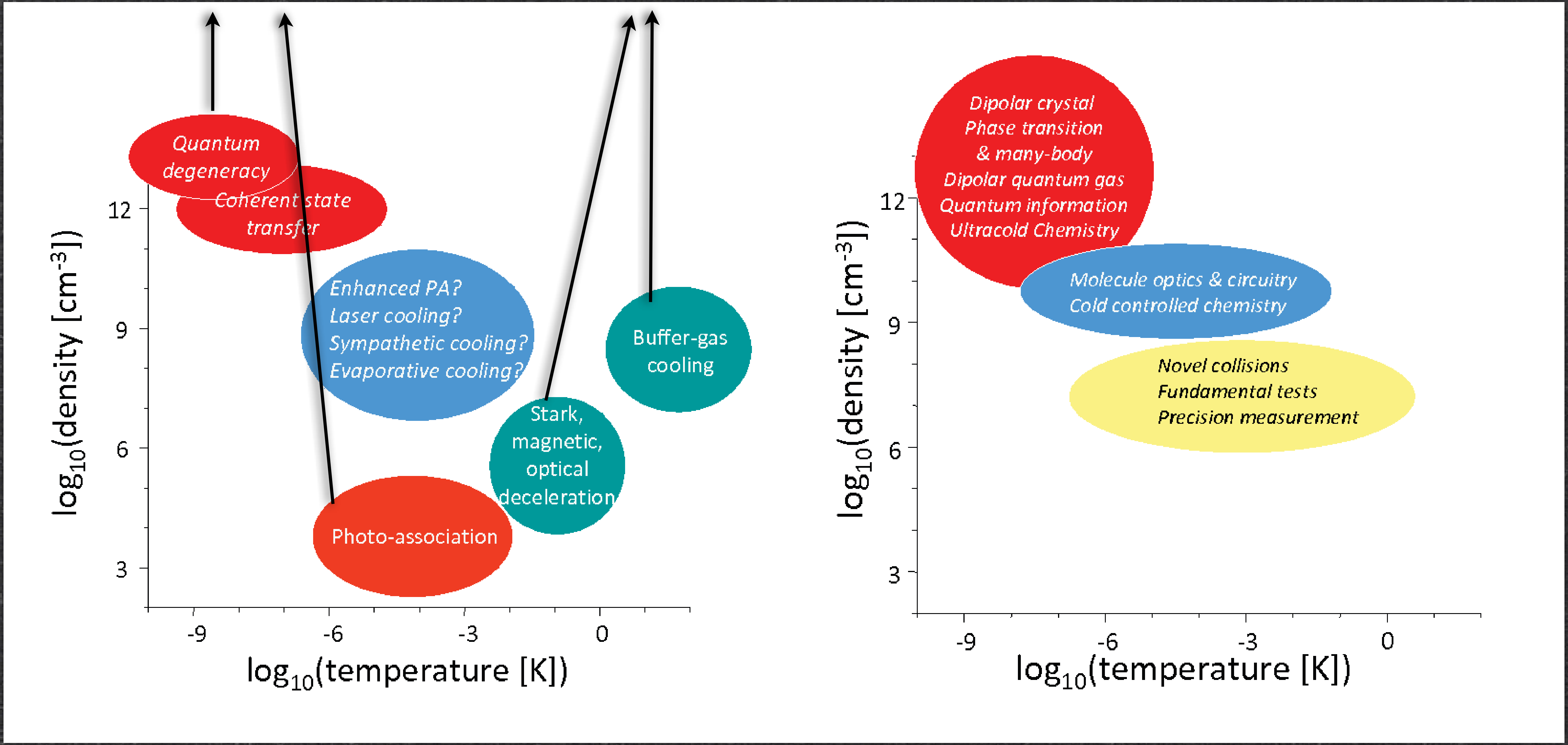
Cold molecules offer increased sensitivity and precision:

- at low temperatures, fewer states are populated
- precision of measurements ultimately limited by interaction time
  - → trapped molecules / fountains / slow beams

The ultimate experiment is done by precision spectroscopy on trapped ultracold molecules

Techniques

Indirect   Direct



Carr, Demille, Krems, Ye: special issue on cold molecules, New Journal of Physics **11** 055049 (2009)

Stark Deceleration

- Can be used to decelerate neutral molecules
- First succesfully demonstrated in 1999:

VOLUME 83, NUMBER 8 PHYSICAL REVIEW LETTERS 23 AUGUST 1999

Decelerating Neutral Dipolar Molecules

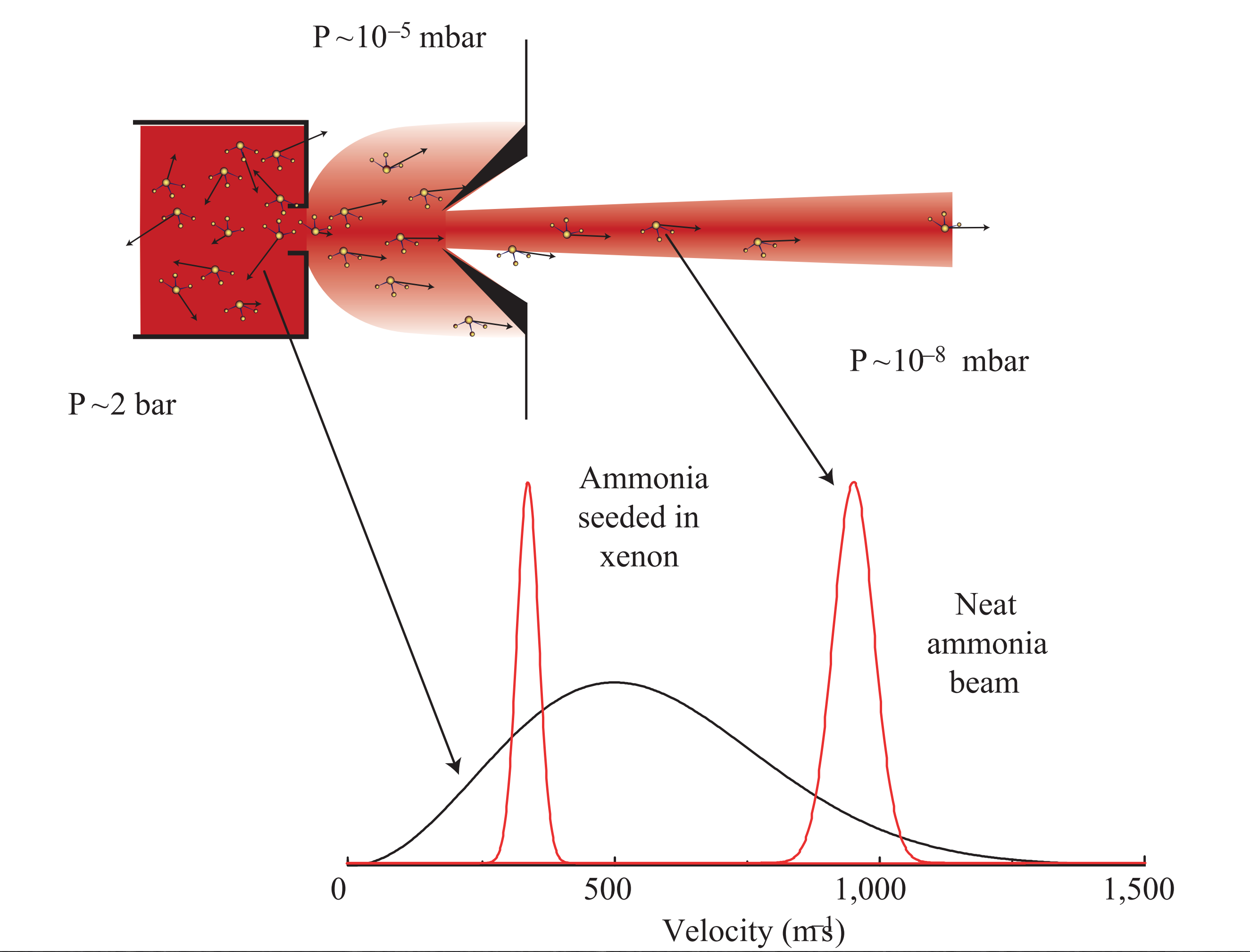
Hendrick L. Bethlem, Giel Berden, and Gerard Meijer
Department of Molecular and Laser Physics, University of Nijmegen,
Toernooiveld 1, NL-6525 ED Nijmegen, The Netherlands
(Received 19 February 1999; revised manuscript received 28 May 1999)

It is experimentally demonstrated that a beam of neutral dipolar molecules can be efficiently decelerated with a time-varying electric field. A pulsed beam of neutral metastable CO molecules is slowed down from 225 m/s ($E_{\mathrm{kin}} = 59\ \mathrm{cm}^{-1}$) to 98 m/s ($E_{\mathrm{kin}} = 11\ \mathrm{cm}^{-1}$) upon passage through an array of 63 synchronously pulsed electric field stages.

PACS numbers: 33.80.Ps, 33.55.Be

- Based on interaction of electric dipole with electric fields
- Favorable molecules: light with large dipole moment
  OH, CO, NH_3, NH, H_2CO, H_2O

Starting with a pulsed molecular beam:



Cooling of internal degrees of freedom
in a (pulsed) supersonic expansion
High initial phase-space density

But: high velocity in the lab frame,
typically in the 250 – 3000 m/s range

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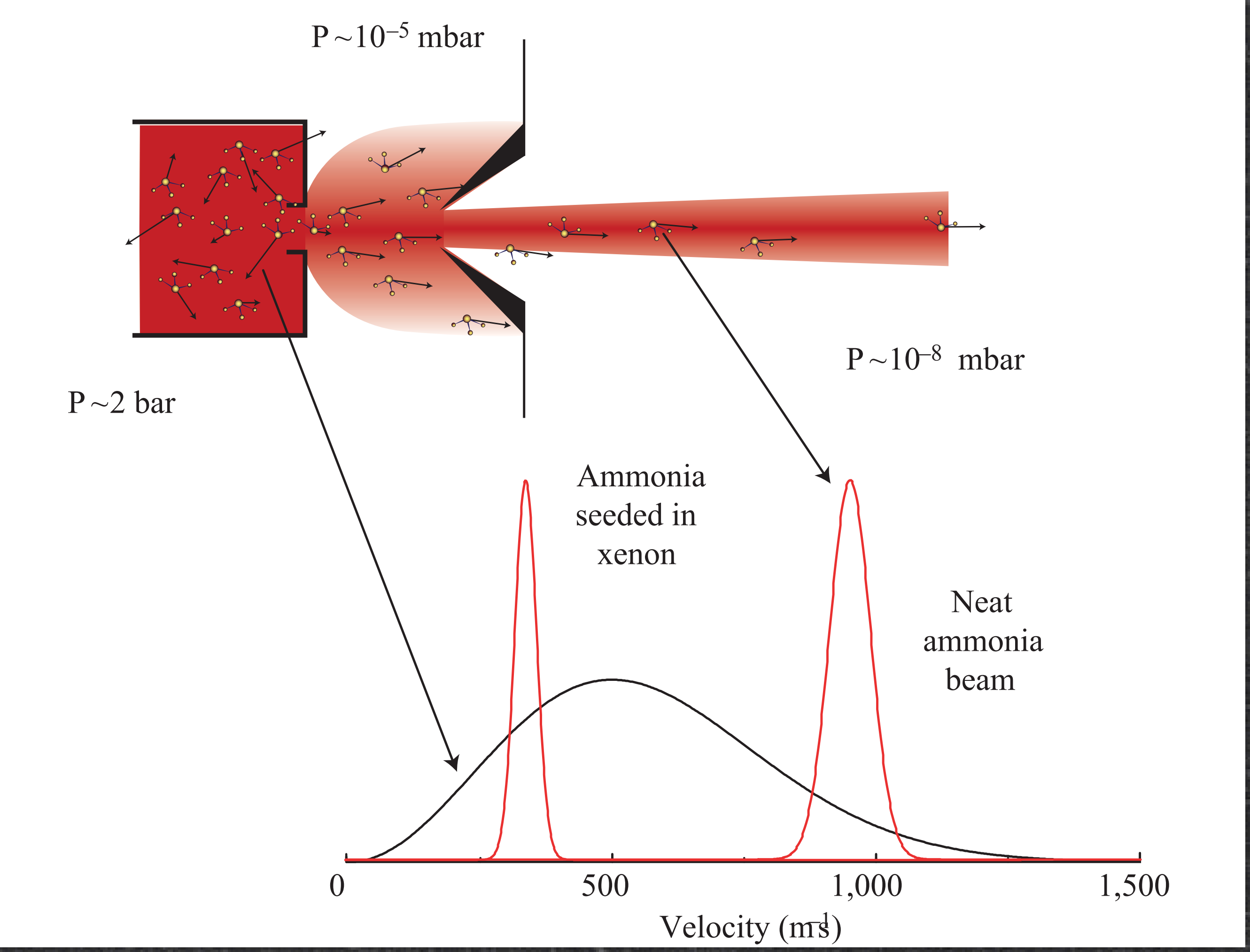

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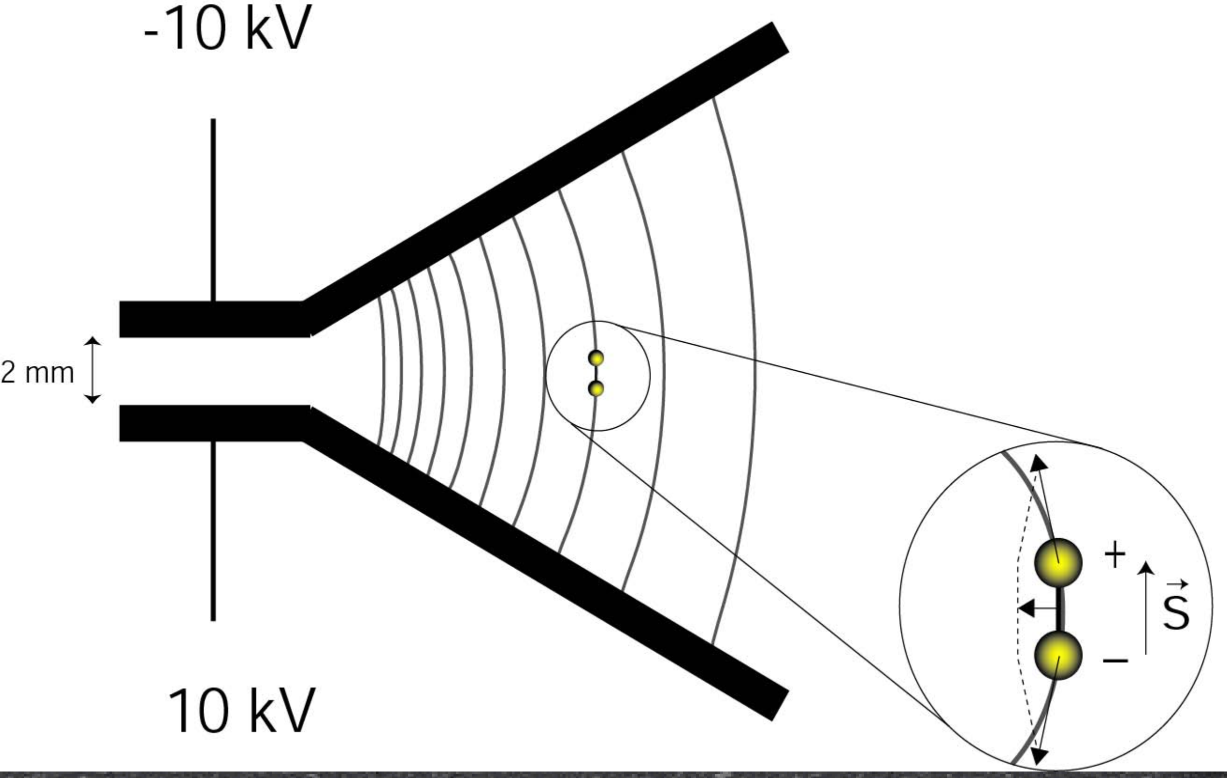
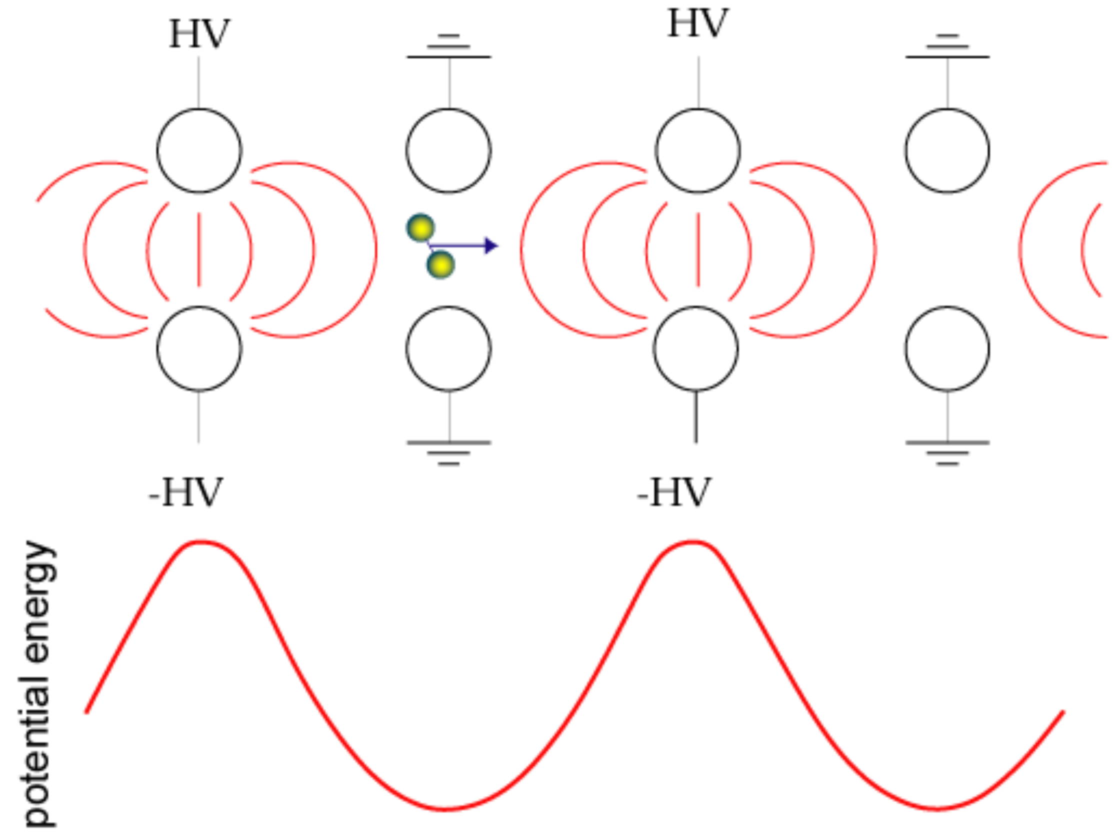


$$U_{pot} = W_{Stark}$$

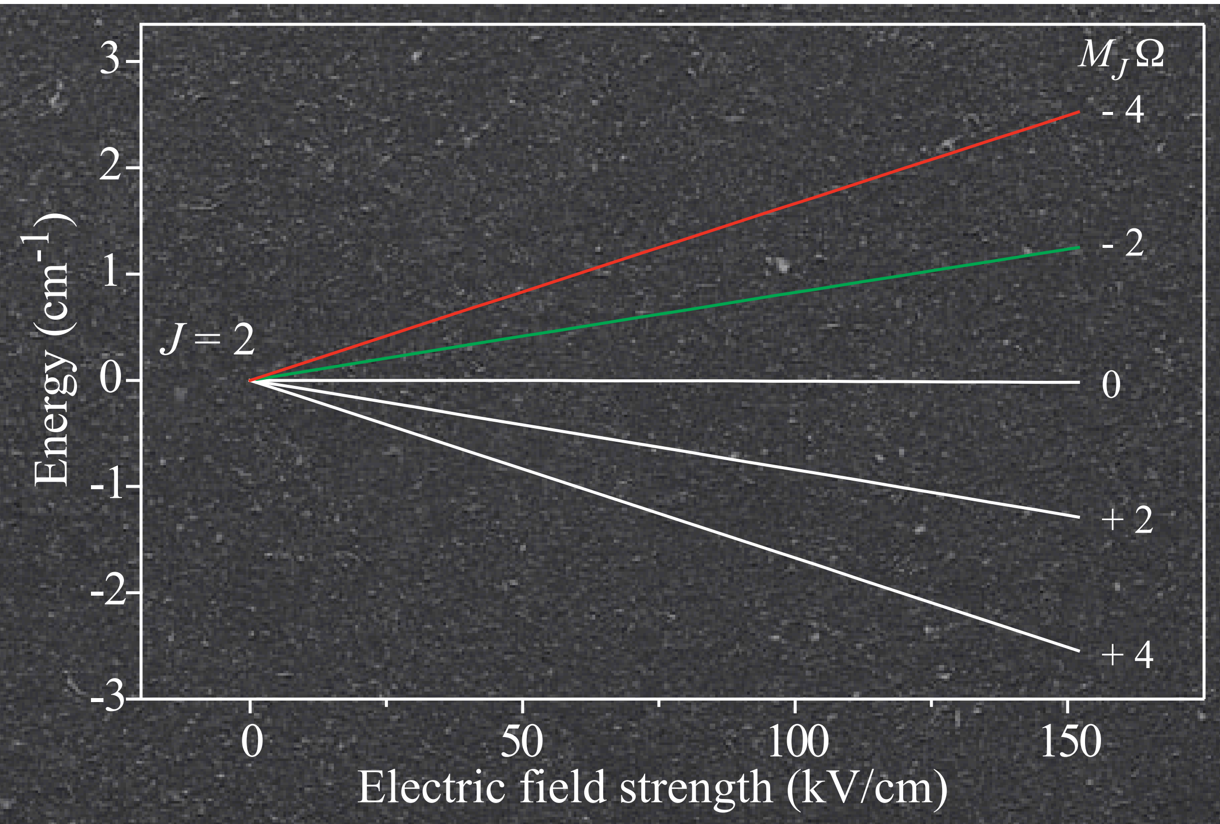
$$W_{Stark} = -\vec{\mu} \cdot \vec{E}$$

$$\vec{F}_{Stark} = -\vec{\nabla} W_{Stark}$$

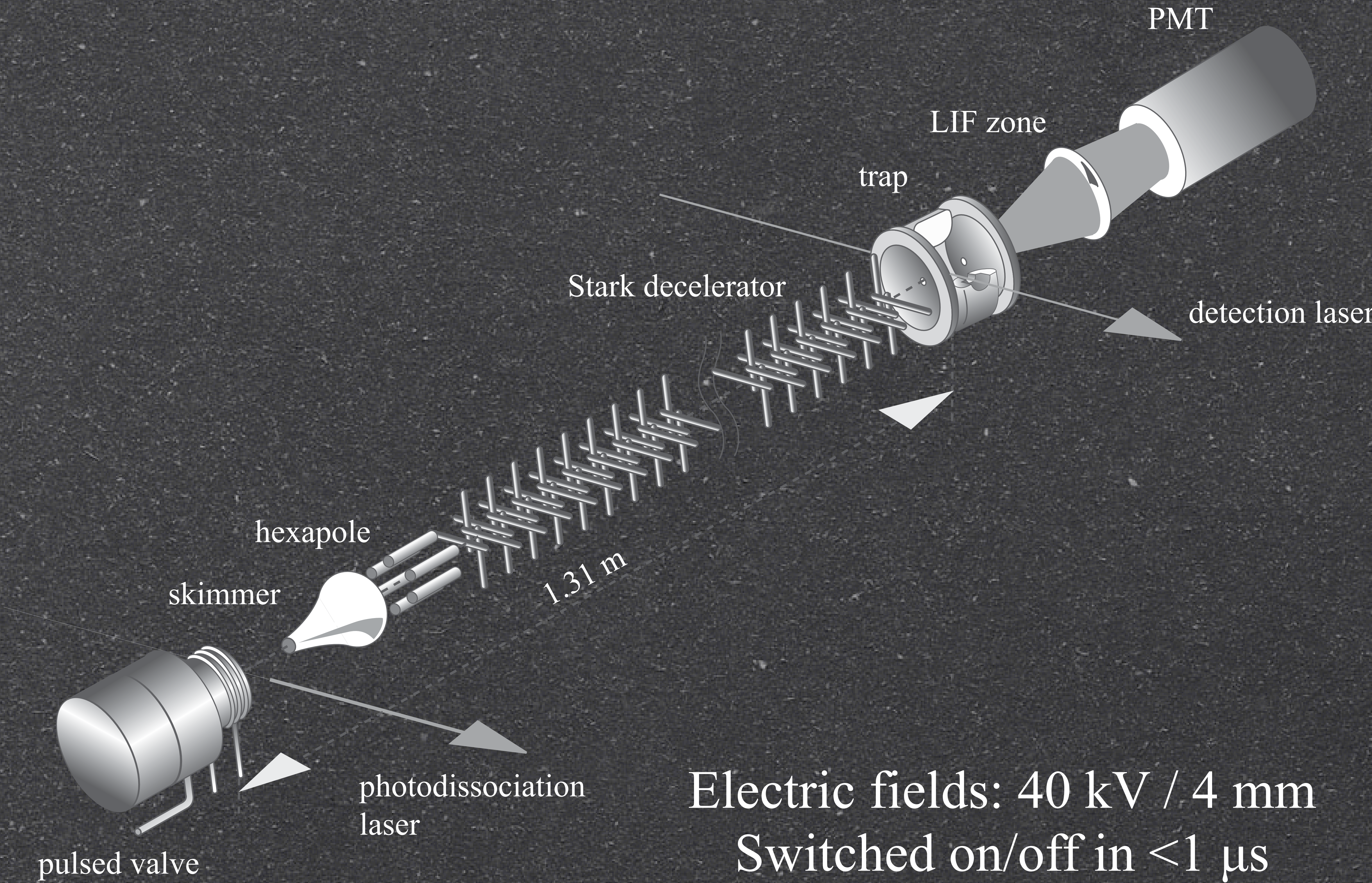
Stark decelerator: principle of operation



Molecules in low-field seeking states gain Stark energy at the expense of kinetic energy



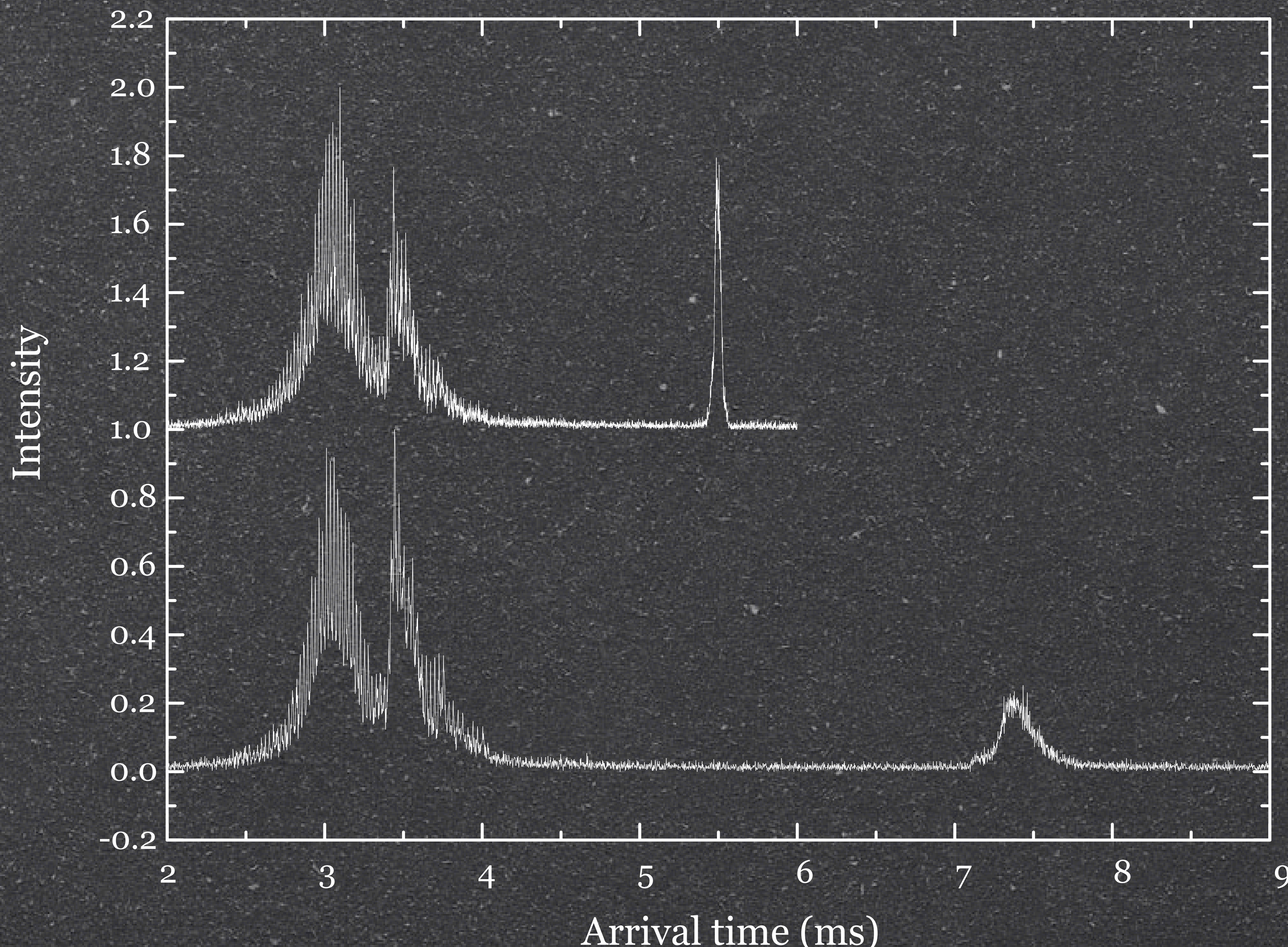
Stark decelerator: schematic overview



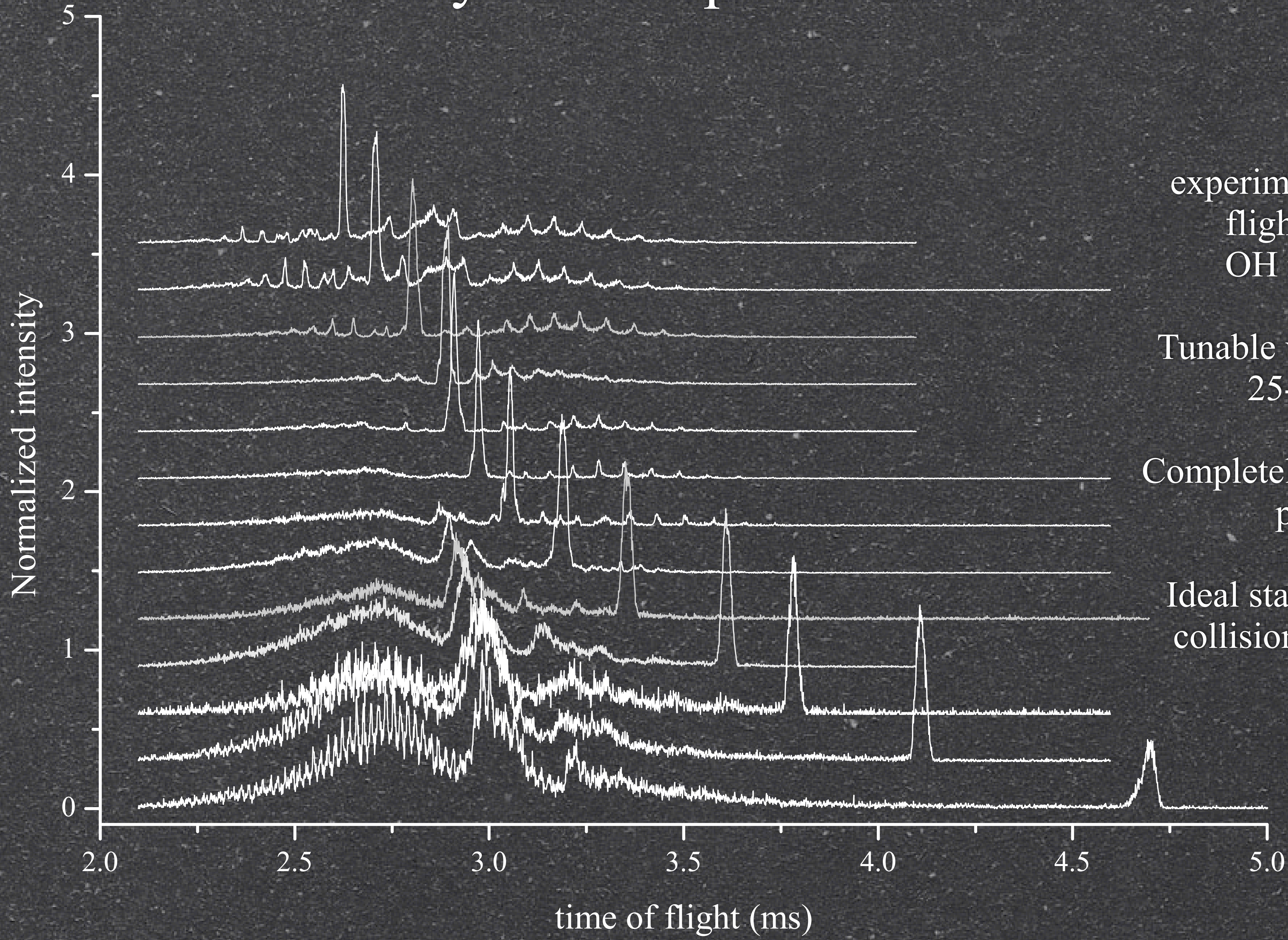
Electric fields: 40 kV / 4 mm
Switched on/off in <1 μs
Number of deceleration stages: ~100

Example measurements: deceleration of OH molecules

Arrival time spectra, 100 m/s and 30 m/s deceleration
Measured with CW laser, F=2 component only



Velocity tunable packets of molecules



experimental time-of-flight profiles: OH molecules

Tunable velocity range: 25-650 m/s

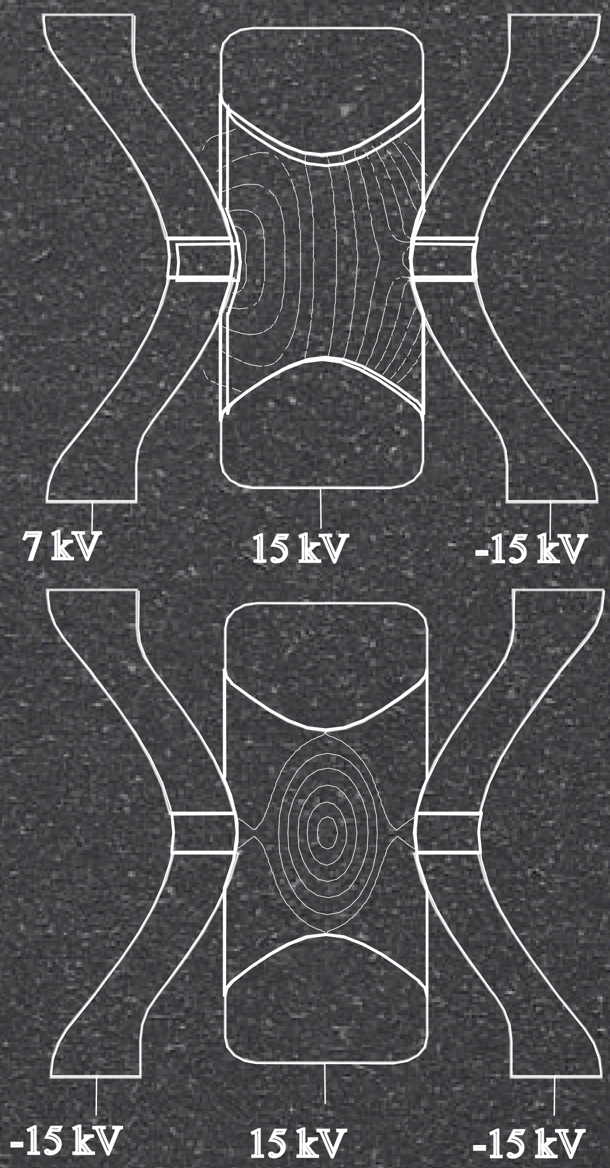
Completely state-selected packets

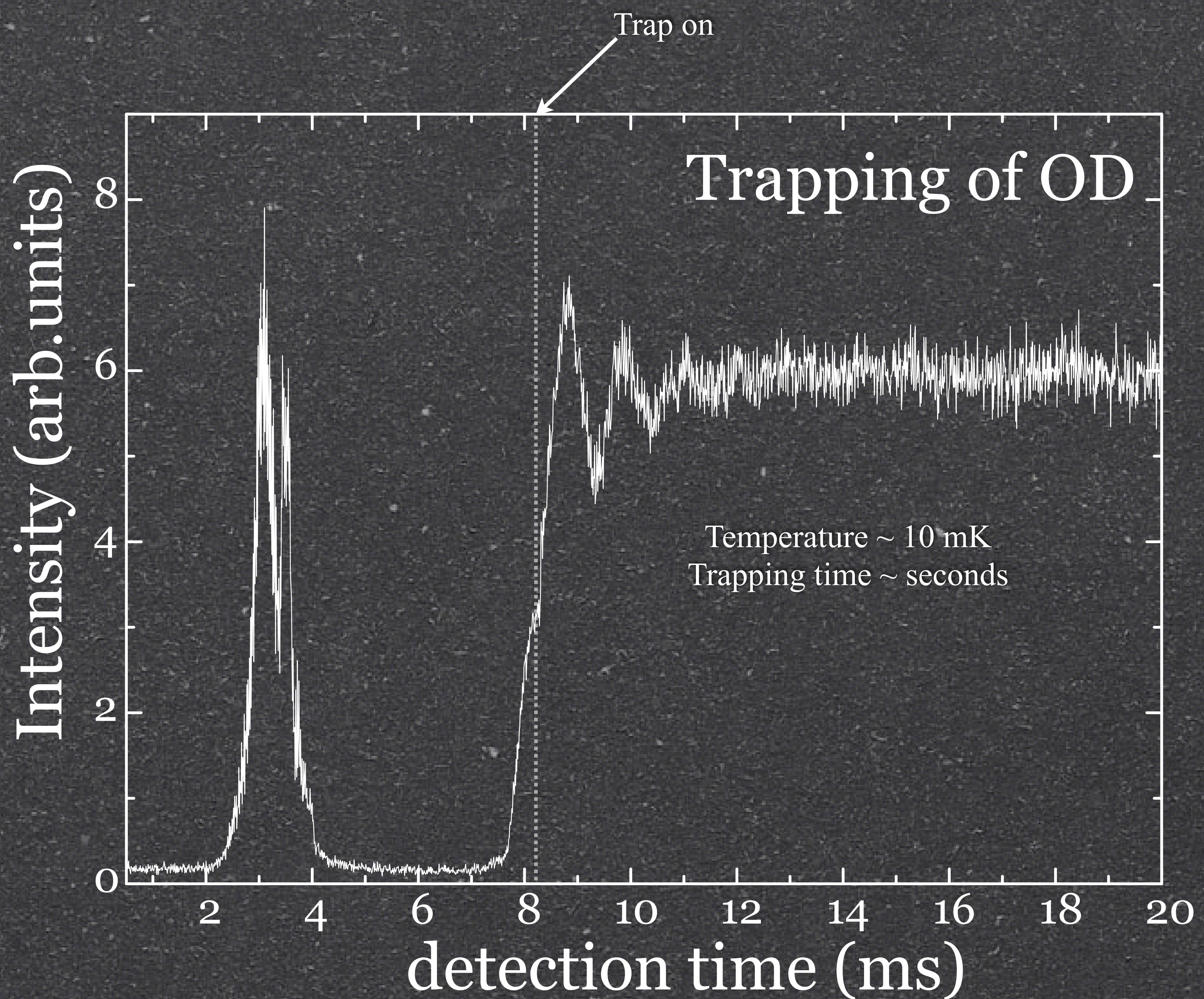
Ideal starting point for collision experiments

Joop J. Gilijamse, Steven Hoekstra, Sebastiaan Y. T. van de Meerakker, Gerrit C. Groenenboom, and Gerard Meijer

Science **313** 1617-1620 (2006)

Example measurements: electric trapping





S. Hoekstra et al, PRL **98**, 133001 (2007)

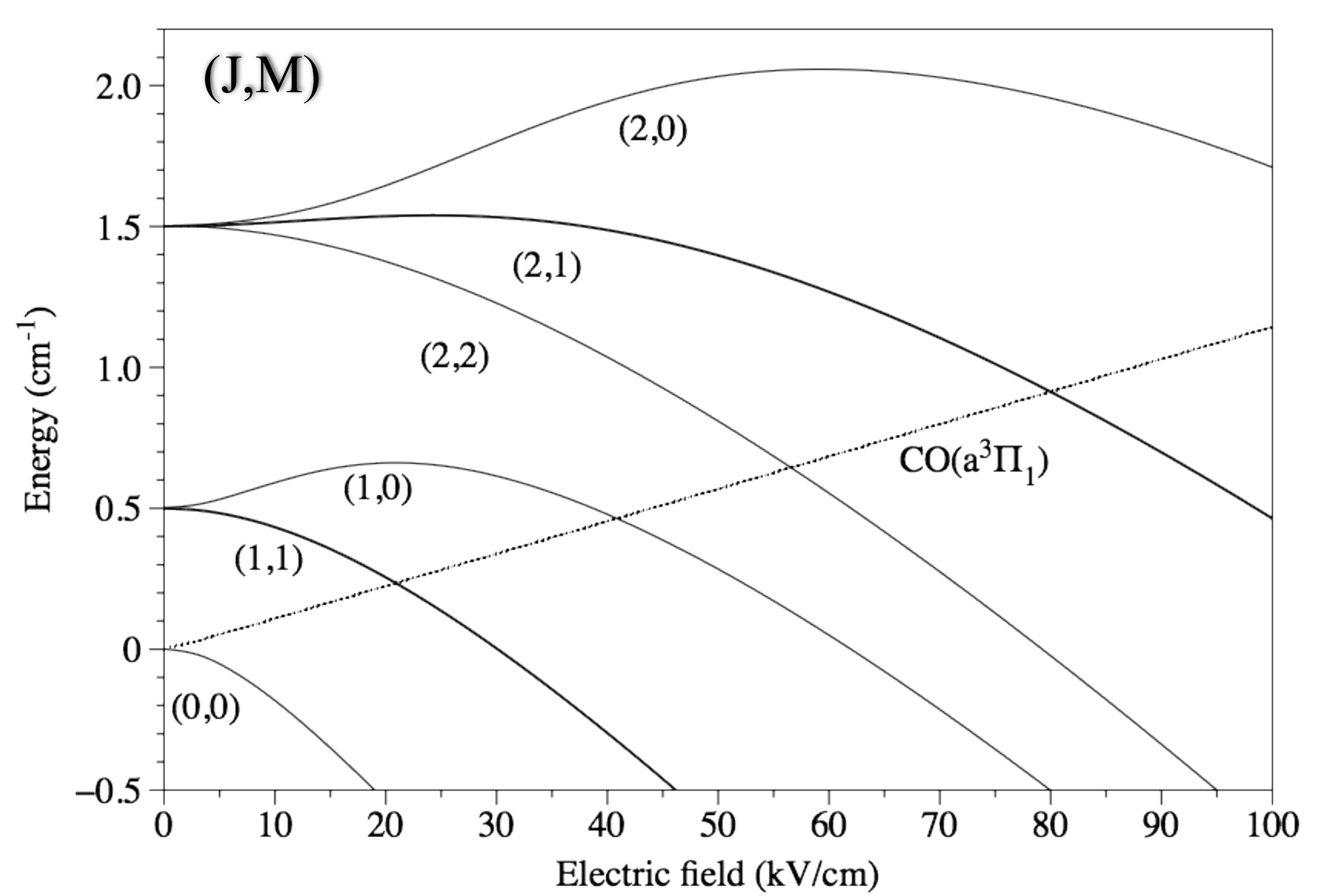
Towards larger and heavier molecules

- High-Z enhancements for many fundamental physics tests

The challenges:

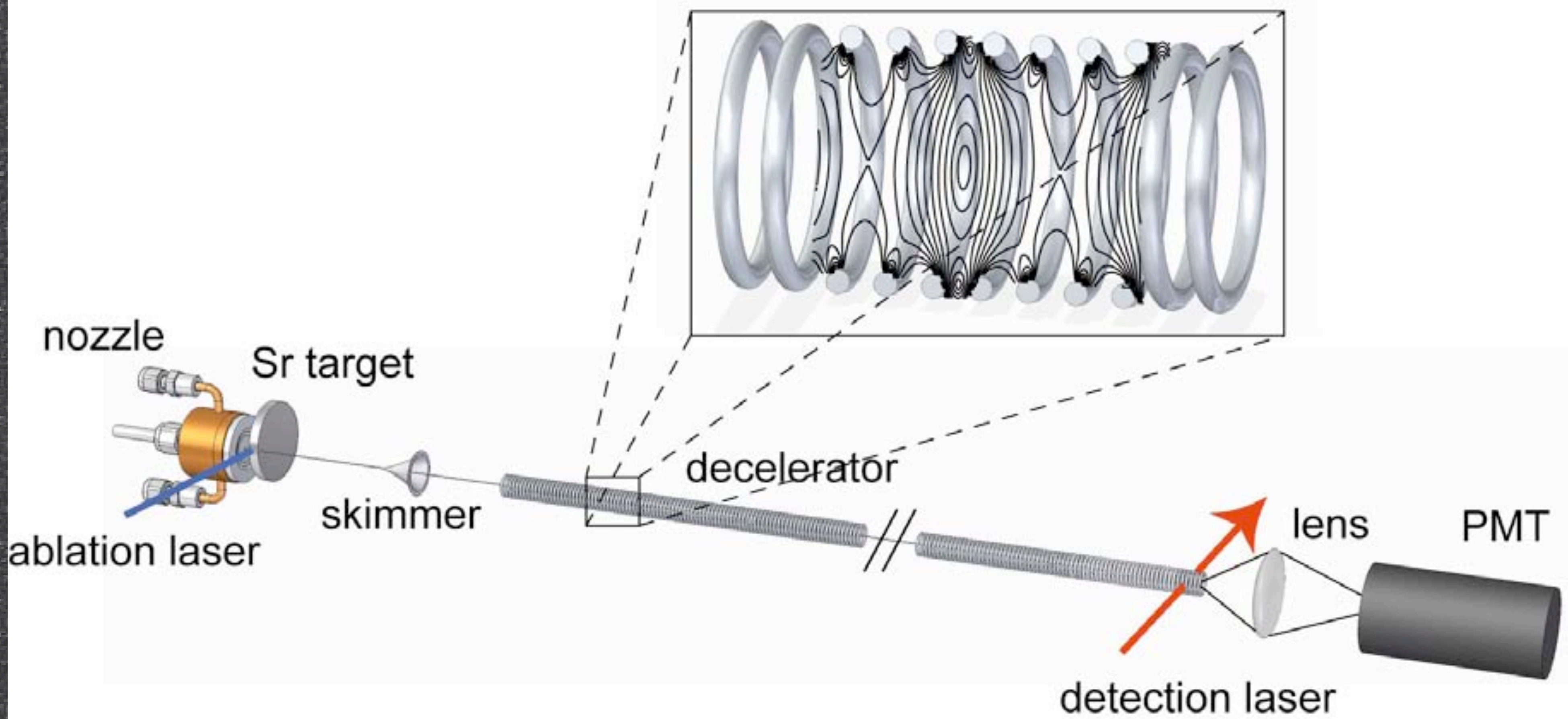
Larger mass requires a longer decelerator - but long decelerators suffer from instabilities...

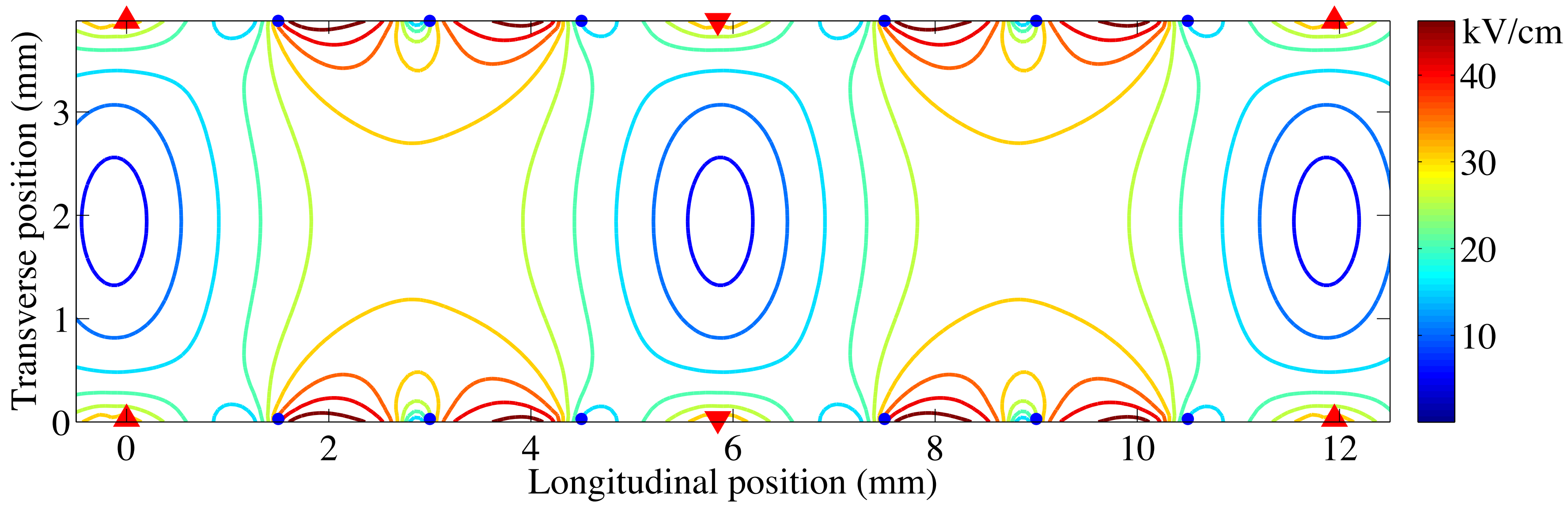
Stark curves of heavy molecules are unfavorable: high-field seeking!



Stark curves of SrF

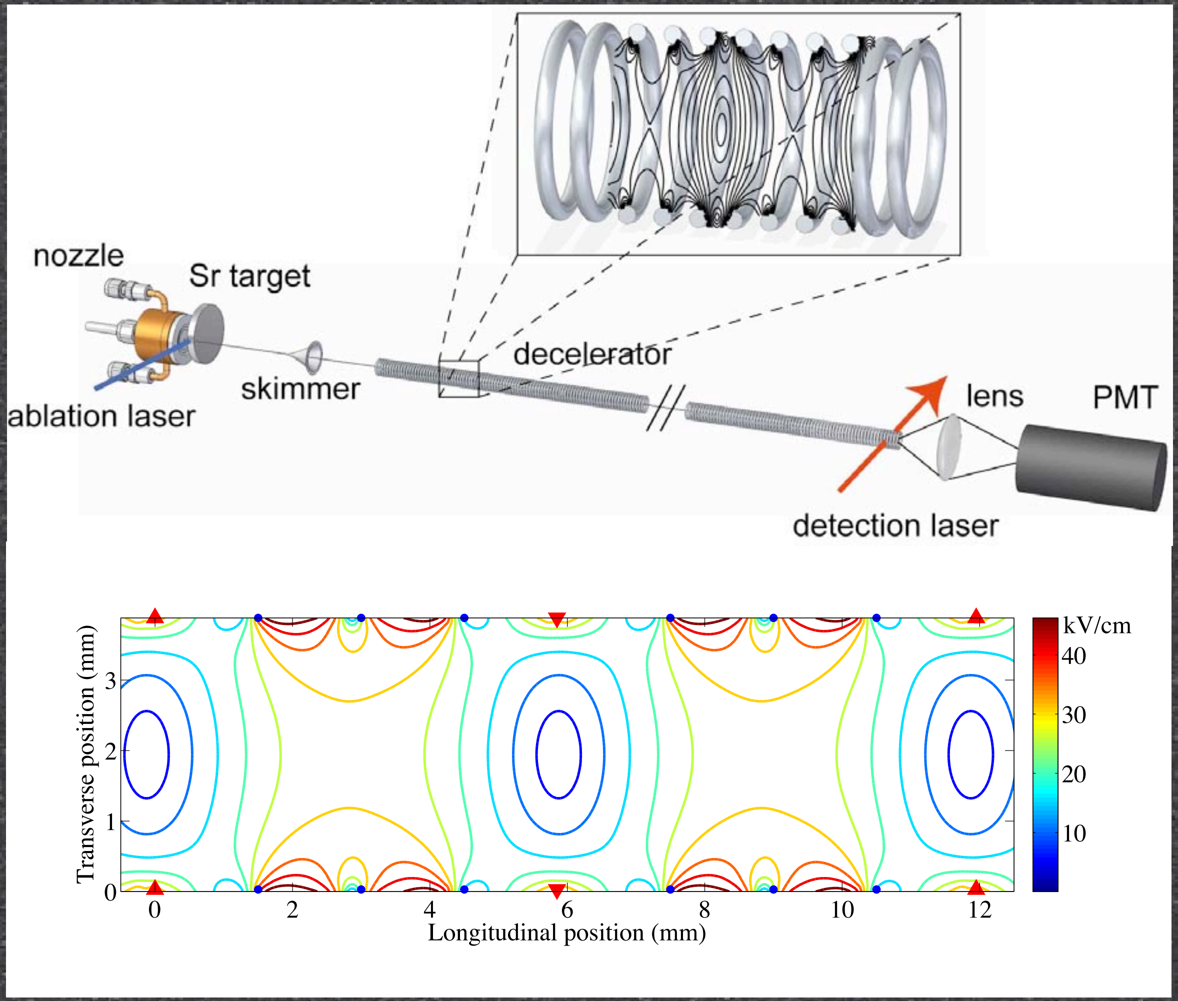
Ring decelerator: molecular conveyer belt





First realization of ring decelerator (CO deceleration):
Osterwalder, PRA **81** 51401 (2010)

Ring decelerator: molecular conveyer belt



First realization of ring decelerator (CO deceleration):
Osterwalder, PRA **81** 51401 (2010)

Advantages of a ring decelerator:

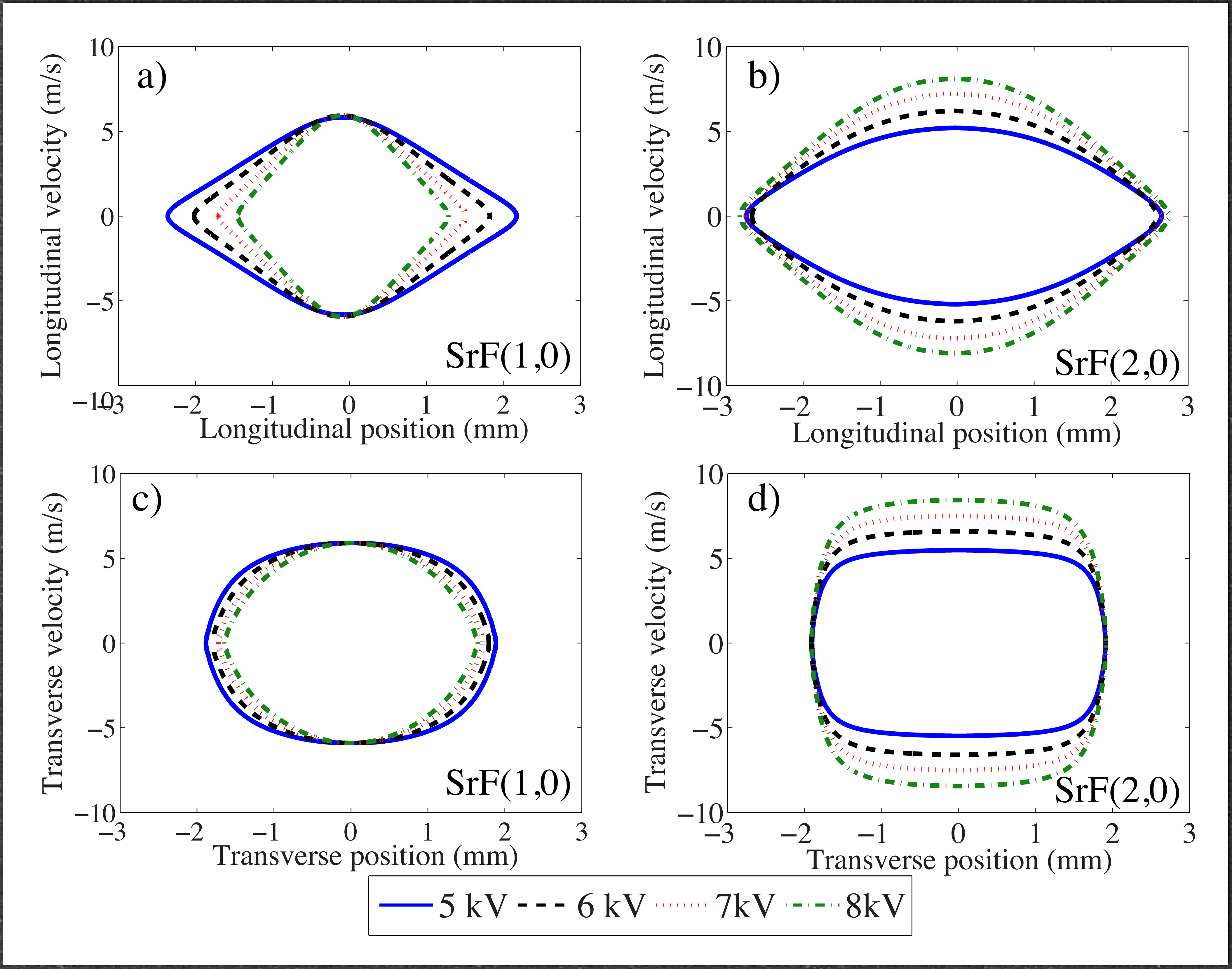
- Molecules remain in low electric fields, so low-field seeking part of Stark curve can be used.

- Inherently stable -> no limit to the length

Challenges:

- Electronics

Numerical calculations: acceptance



Deceleration and trapping of heavy diatomic molecules using a ring decelerator
J. van den Berg, S. Hoekman, E. Prinsen, S.Hoekstra, arXiv:1104.4328 (2011)

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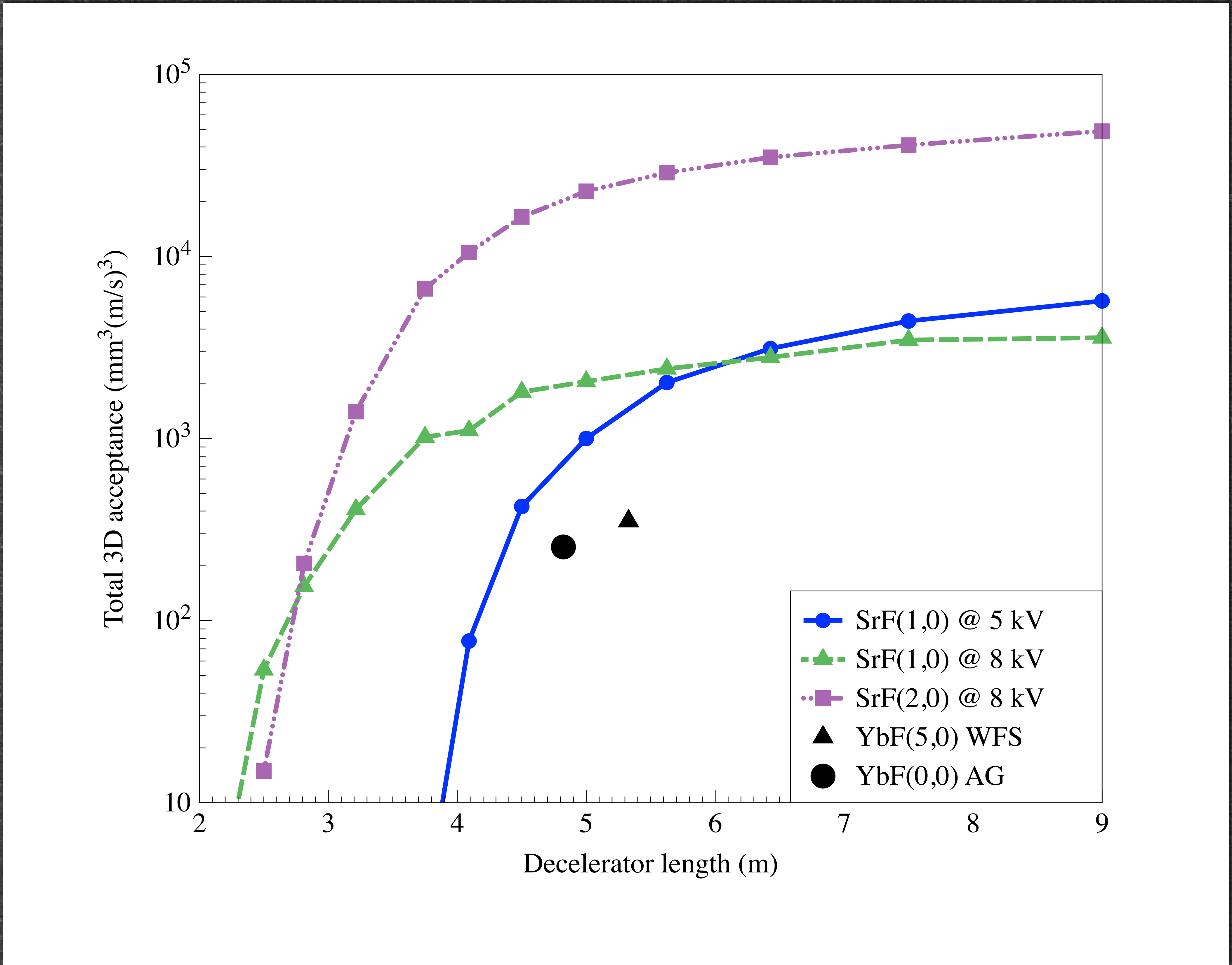

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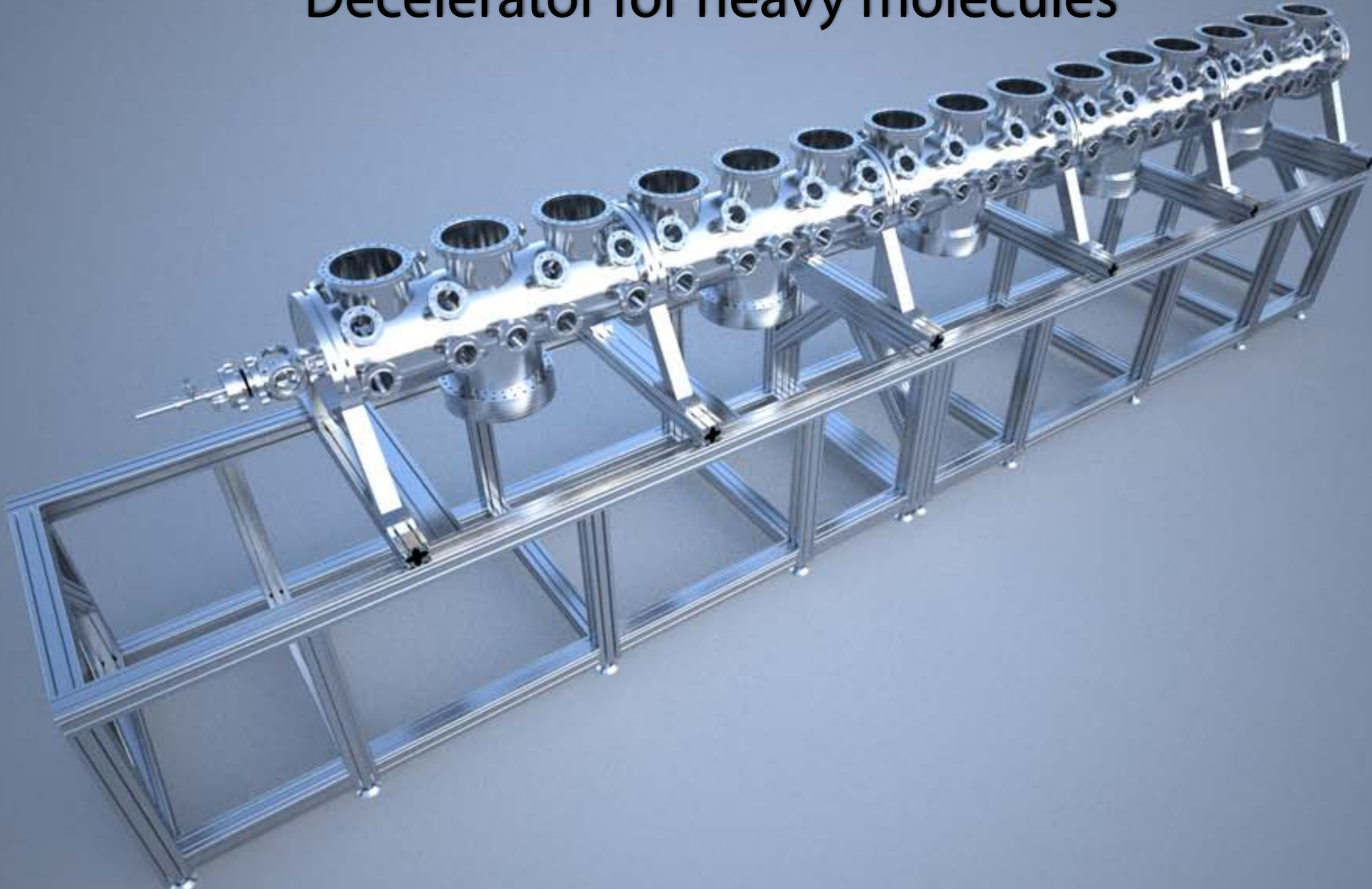
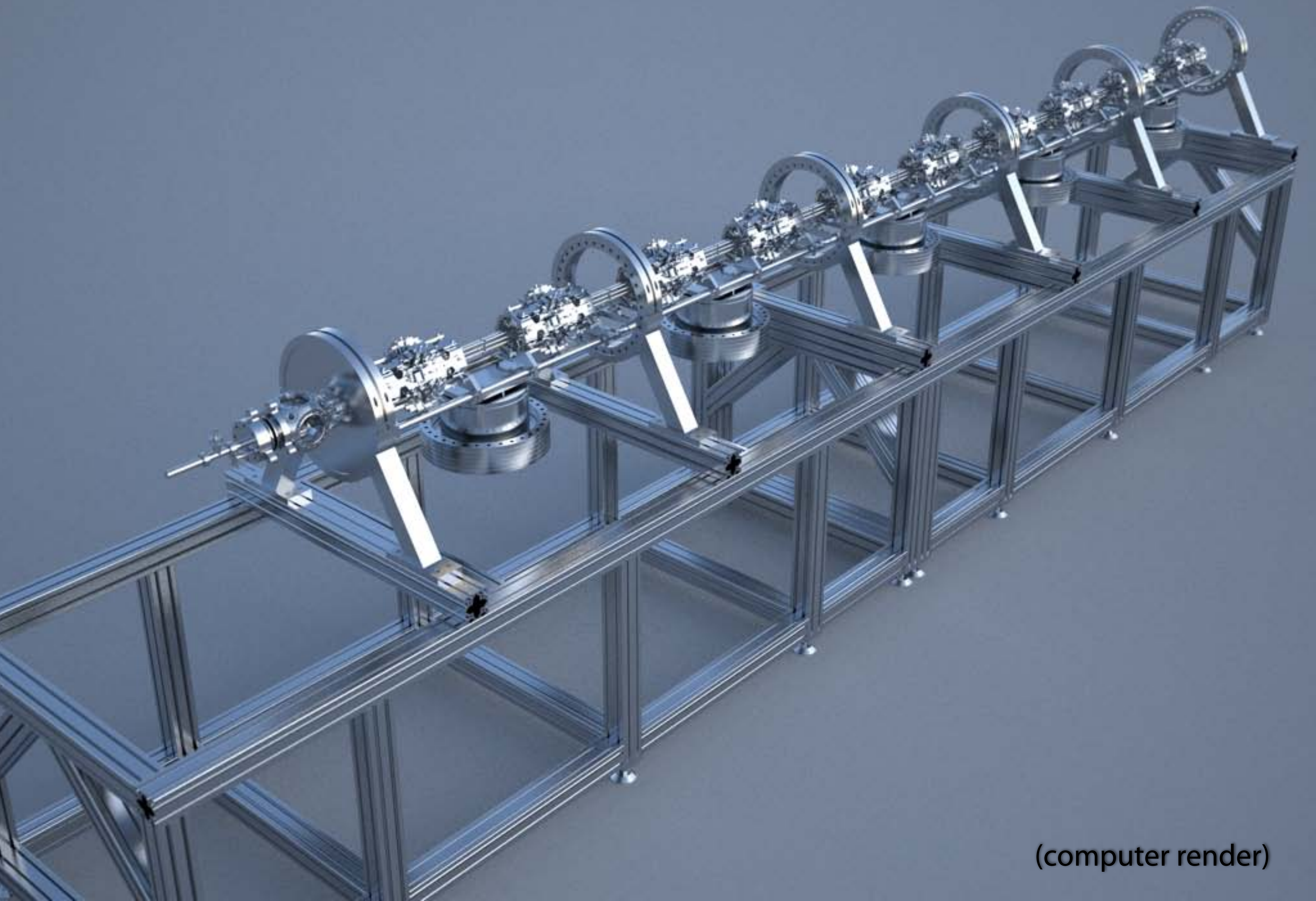
Decelerator for heavy molecules



(computer render)

Decelerator for heavy molecules



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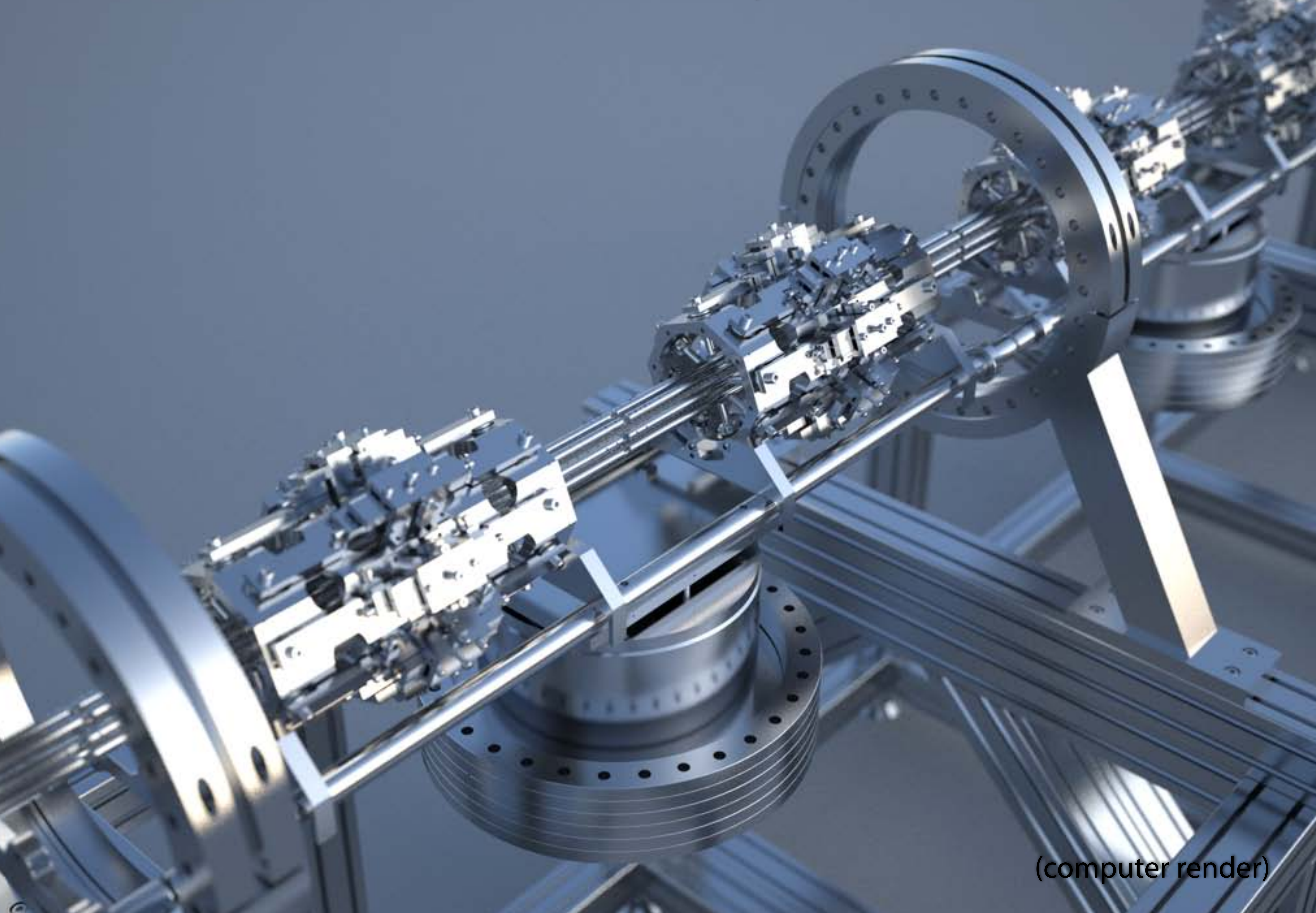

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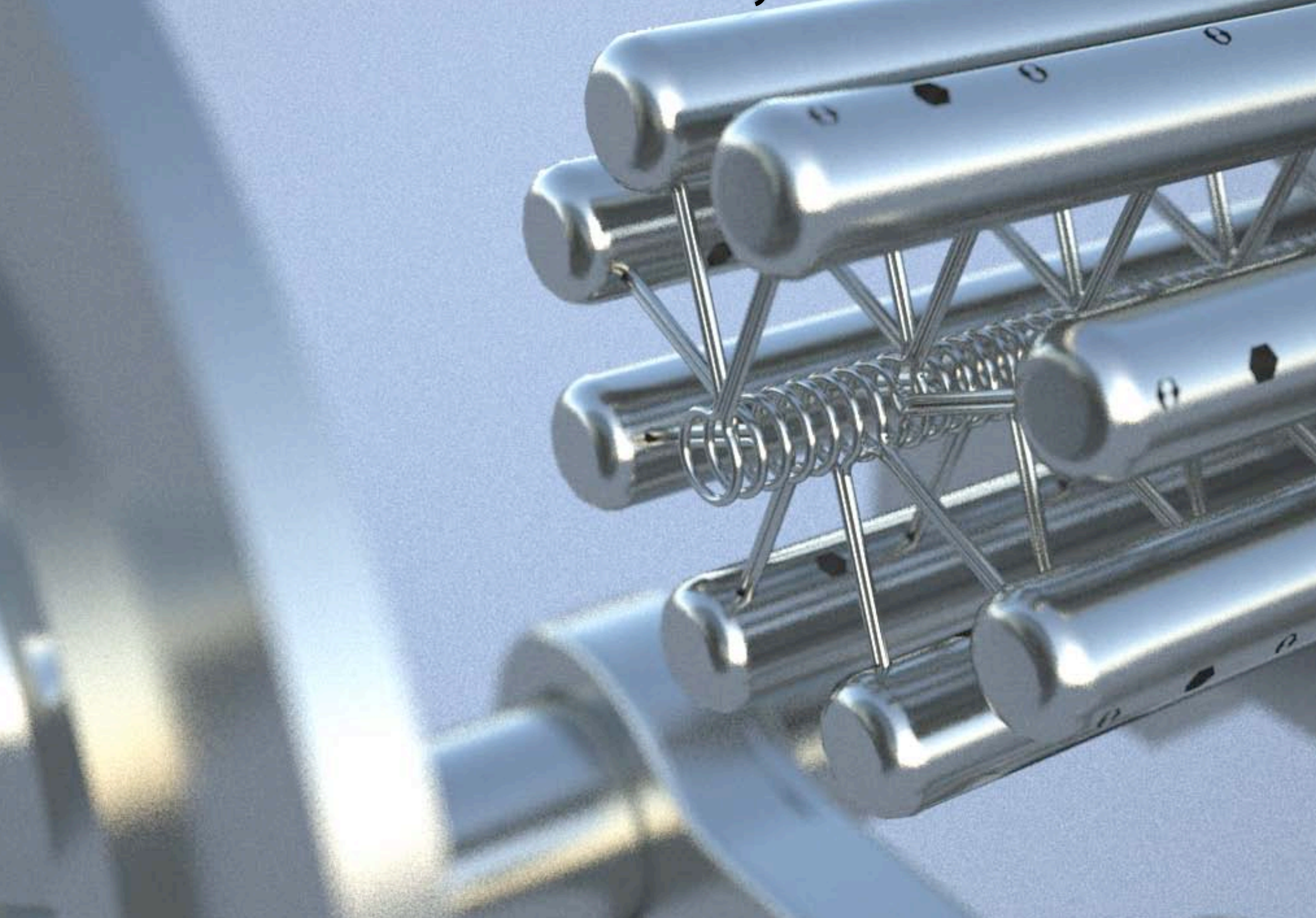

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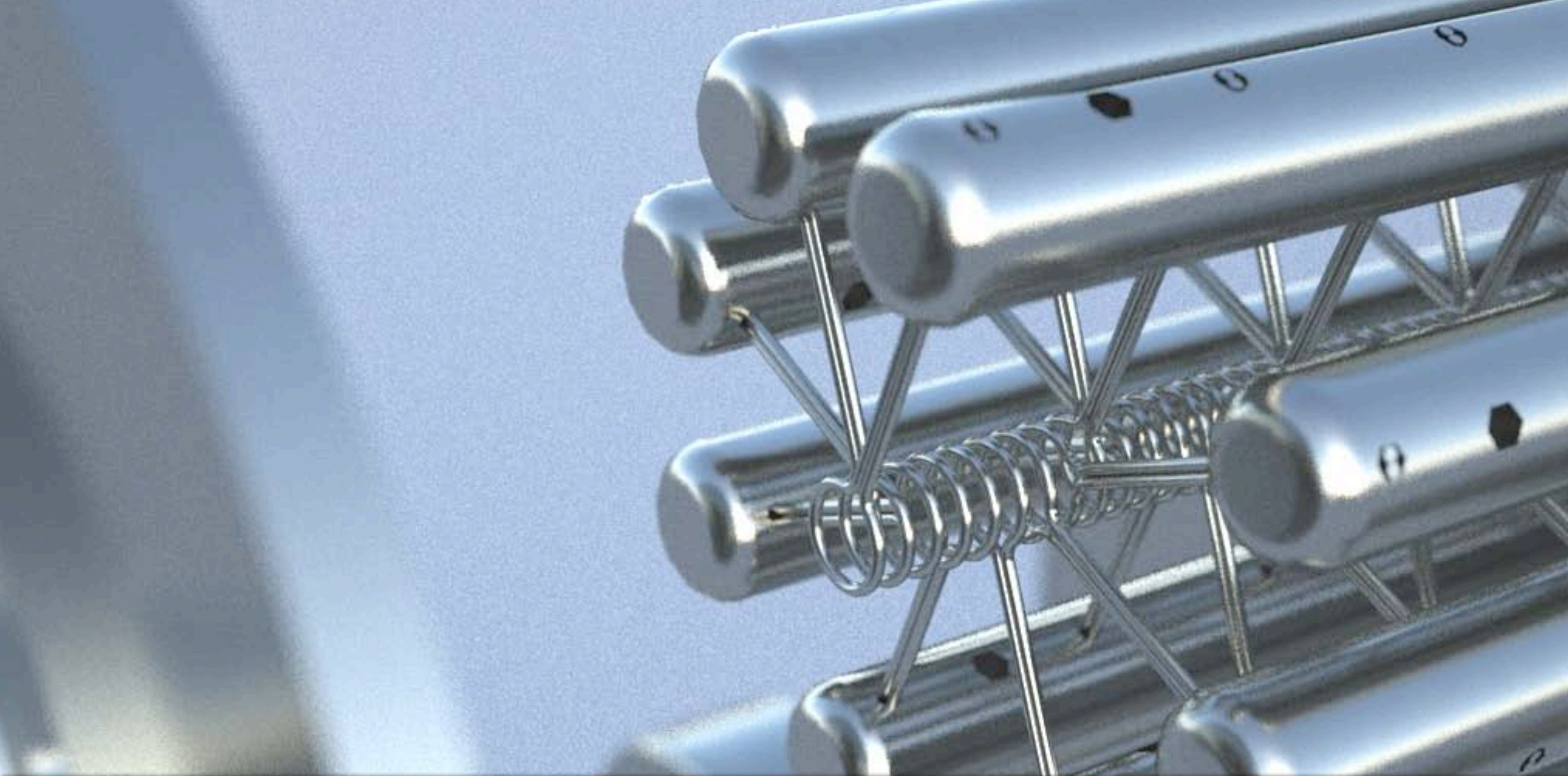


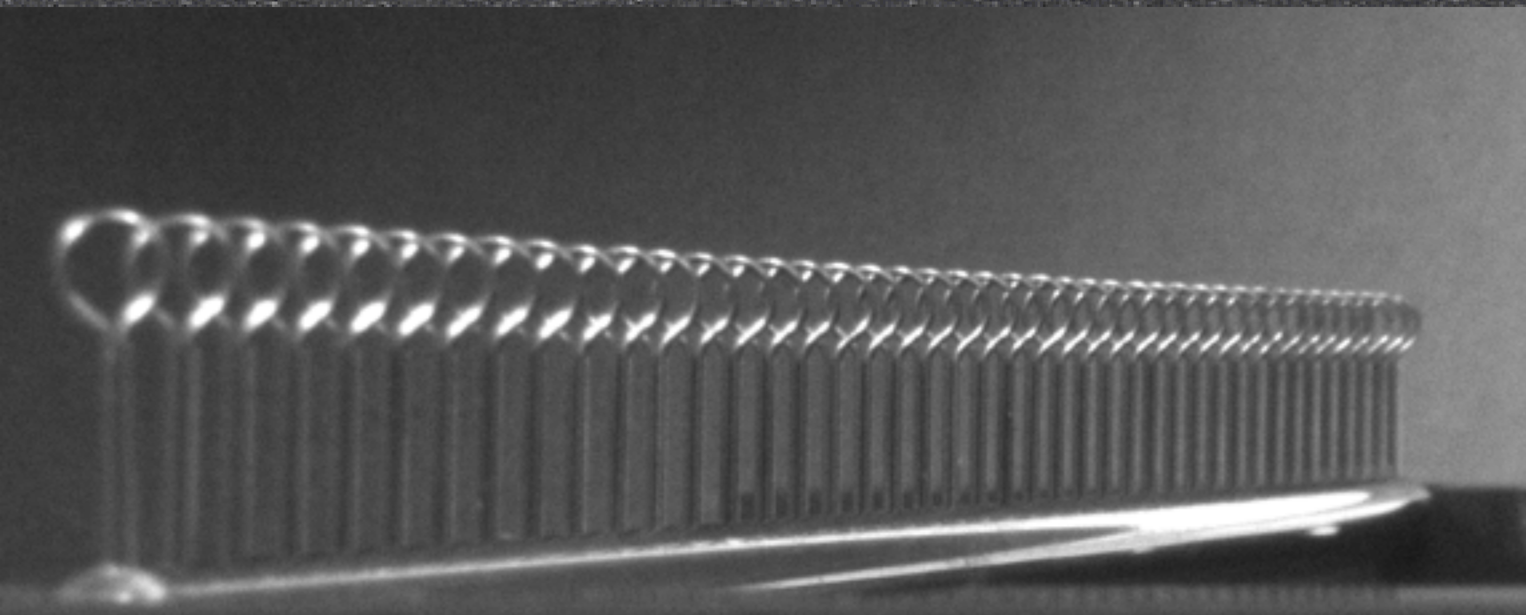
Distance between ring-electrodes: 0.9 mm

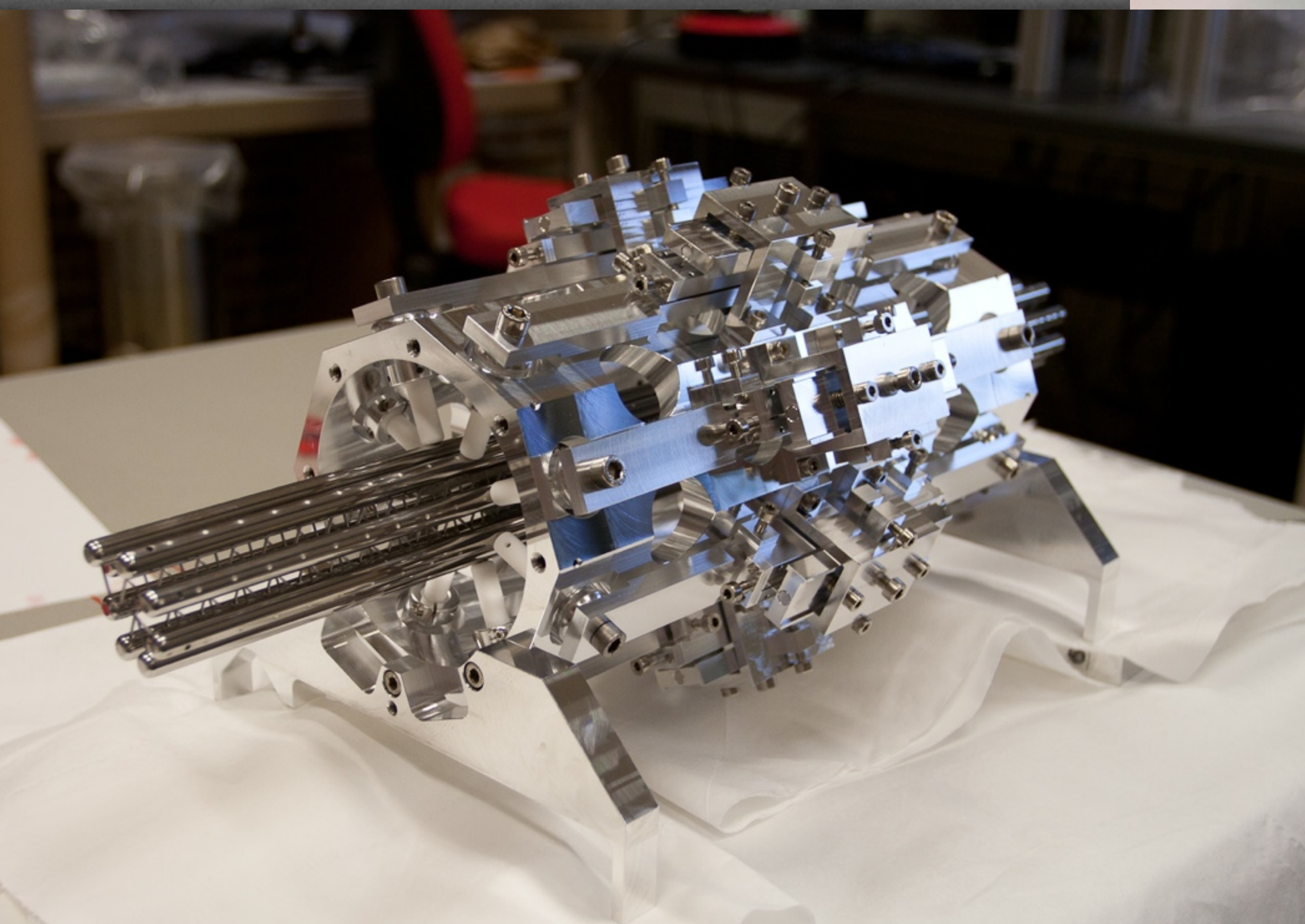
8 Sets of electrodes, Phase-shifted sine waves (30 kHz - DC)

Voltage applied: ±5 kV

Total length: ~ 5 meter, ~3500 electrodes

Now building @ KVI:





Not limited to SrF

Table 1 Ring-deceleration of other alkaline-earth monohalides

Molecule	Mass (amu)	Dipole moment (Debye)	Rotational constant (cm^{-1})	Relative length
CaF(1,0)	59	3.07	0.37	0.38
SrF(1,0)	106	3.49	0.25	1
BaF(1,0)	156	3.17	0.21	1.75
YbF(1,0)	192	3.91	0.24	1.89

At the KVI we can also produce radioactive species (RaF, RaO)

Many of these molecules are also promising lasercooling candidates

Lasercooled RaF as a promising candidate to measure molecular parity violation
T. Isaev, S. Hoekstra, R. Berger
Phys. Rev. A **82** 52521 (2010)

Conclusions

- We are setting up a unique new experiment to decelerate and trap heavy diatomics molecules
- The goal is to perform precision spectroscopy on ultracold and trapped heavy diatomic molecules
- The ring decelerator is a general device, not limited to SrF
- First trapping experiments (NH_3) planned this summer, first deceleration of SrF in 2012

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Corine Meinema

Imko Smid

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Eric Prinsen

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