Trapping hydrogen and deuterium atoms using electric and magnetic fields

Stephen Hogan

Department of Physics and Astronomy
University College London

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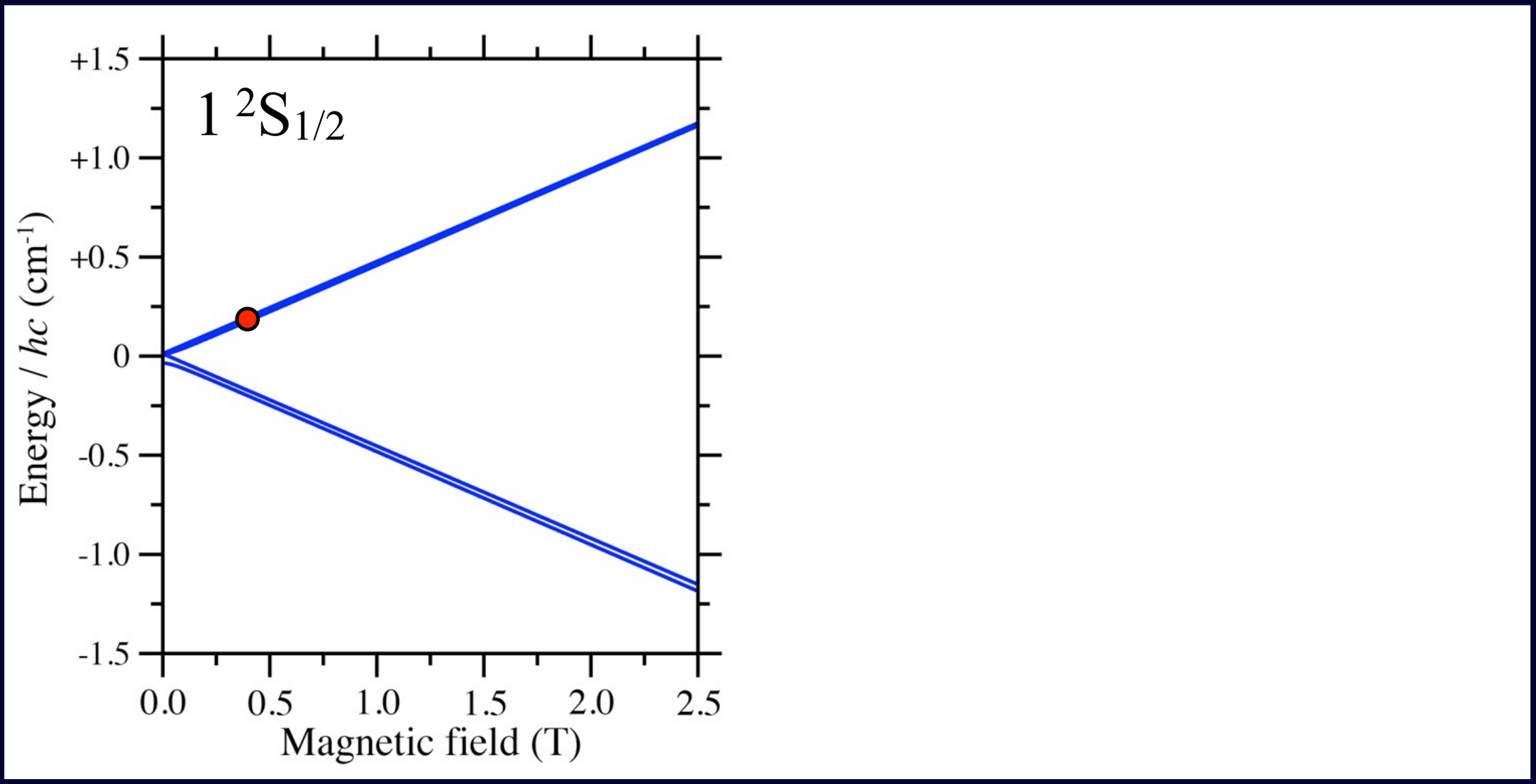
Overview

- Electric and magnetic traps for H and D atoms
- Decelerating and trapping H and D atoms
- Future prospects for:
  - maximising number/number density of trapped atoms
  - experiments with T atoms

Magnetic traps for H and D

- Zeeman effect in H atom



Magnetic traps for H and D

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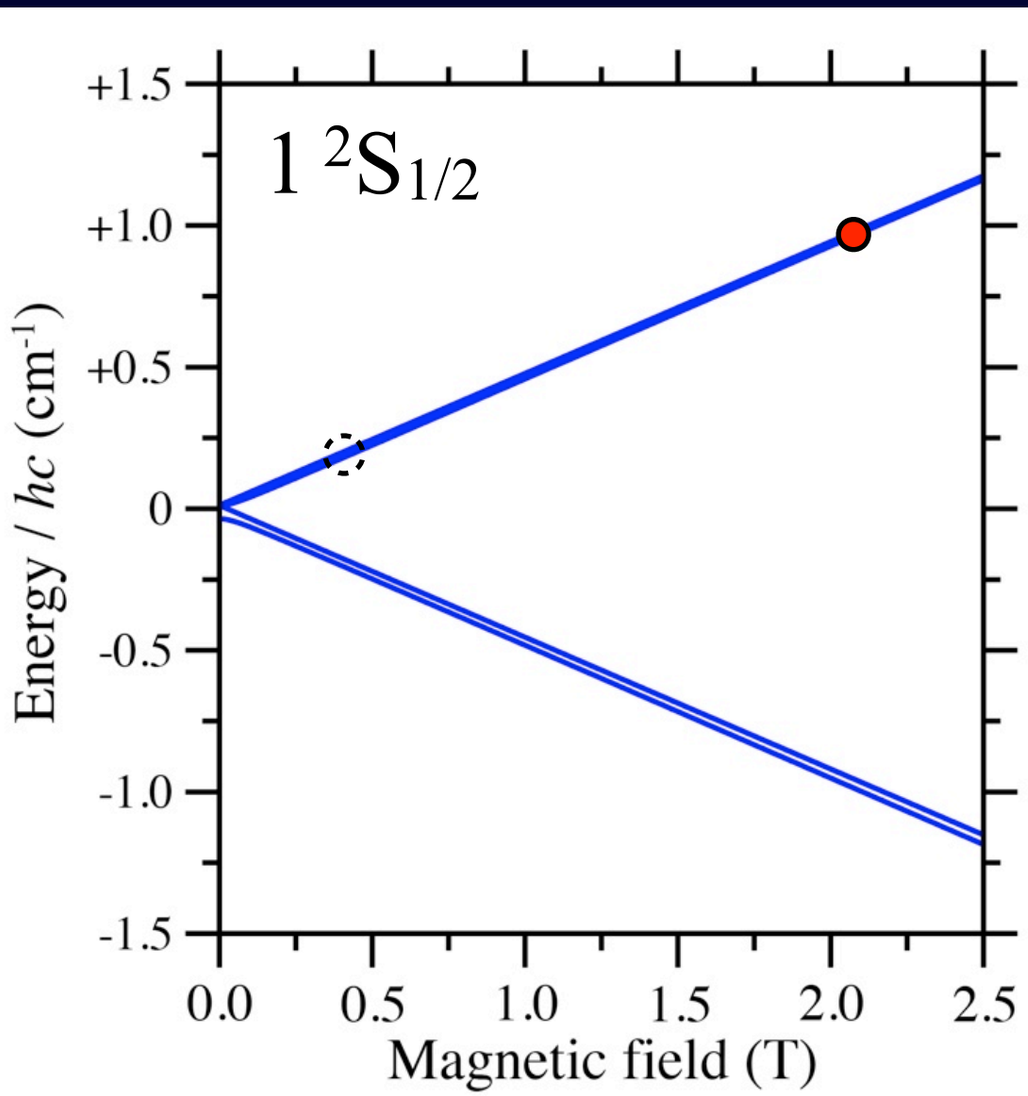
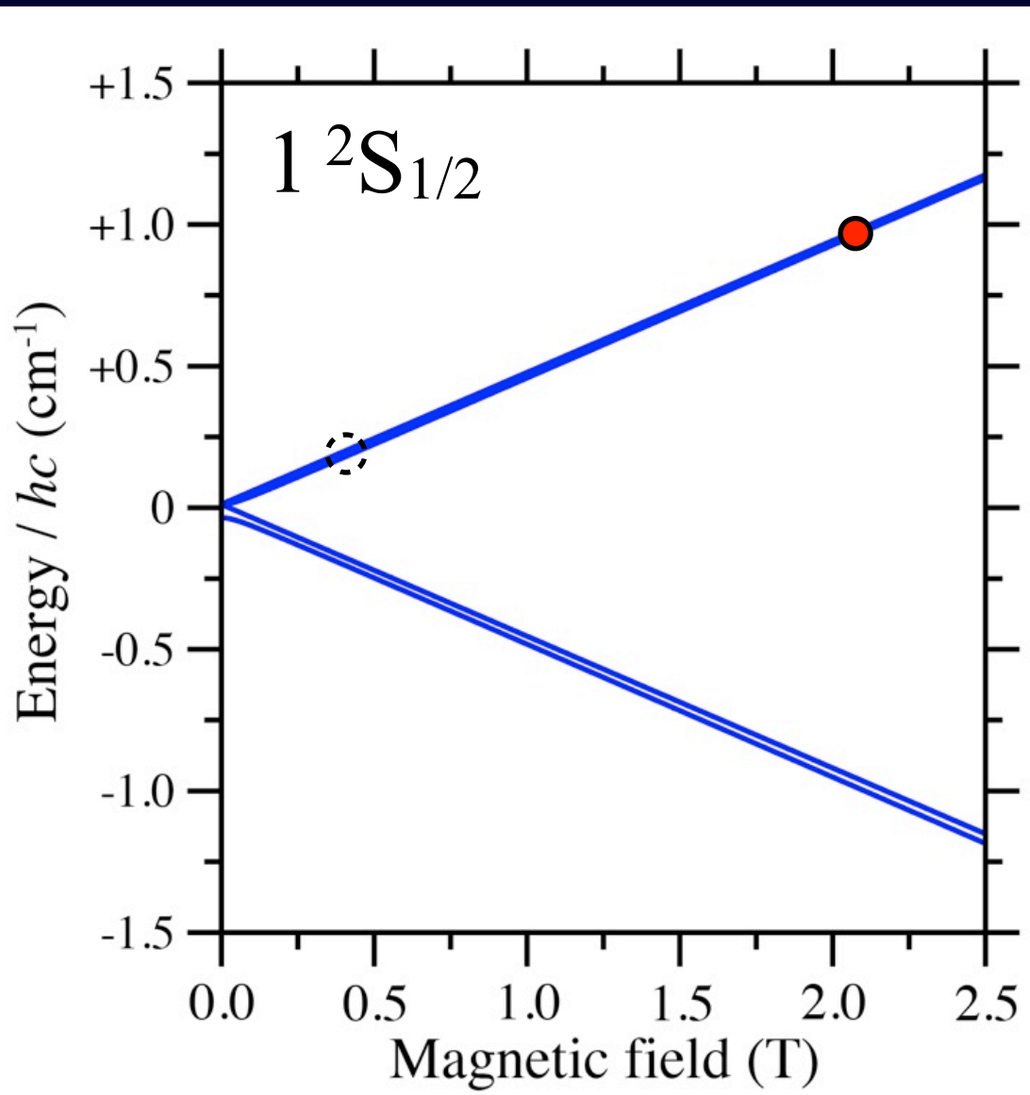


Low-field-seeking sublevels

High-field-seeking sublevels

Magnetic traps for H and D

- Zeeman effect in H atom



Zeeman Energy:

$$W_{\text{Zeeman}} = -\vec{\mu}_{\text{mag}} \cdot \vec{B}$$

$$(\mu_{\text{mag}} = 1\,\mu_{\text{B}})$$

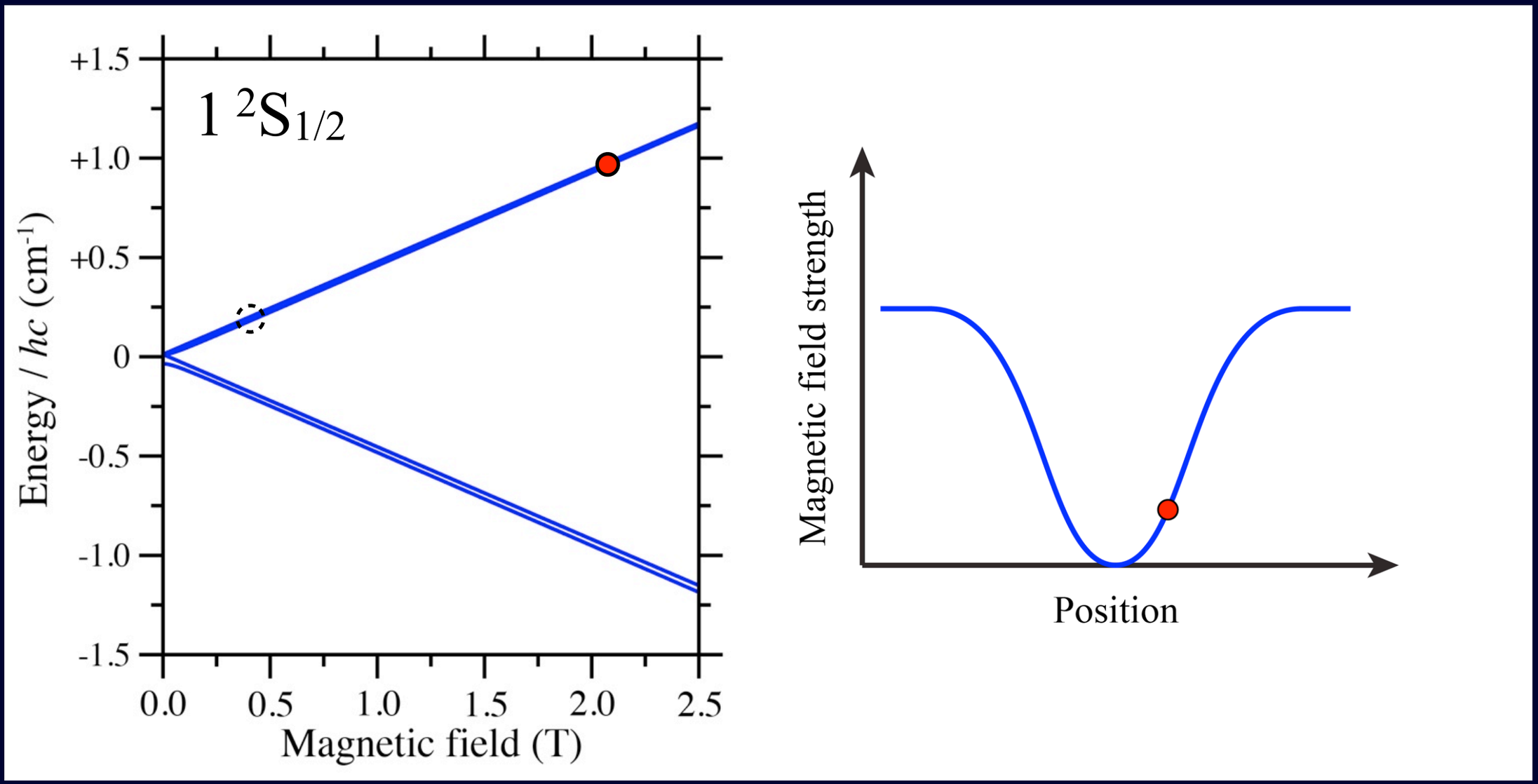
Force:

$$\vec{f} = -\nabla W_{\text{Zeeman}}$$

$\Delta E_{\text{kin}} / e = 0.1$ meV

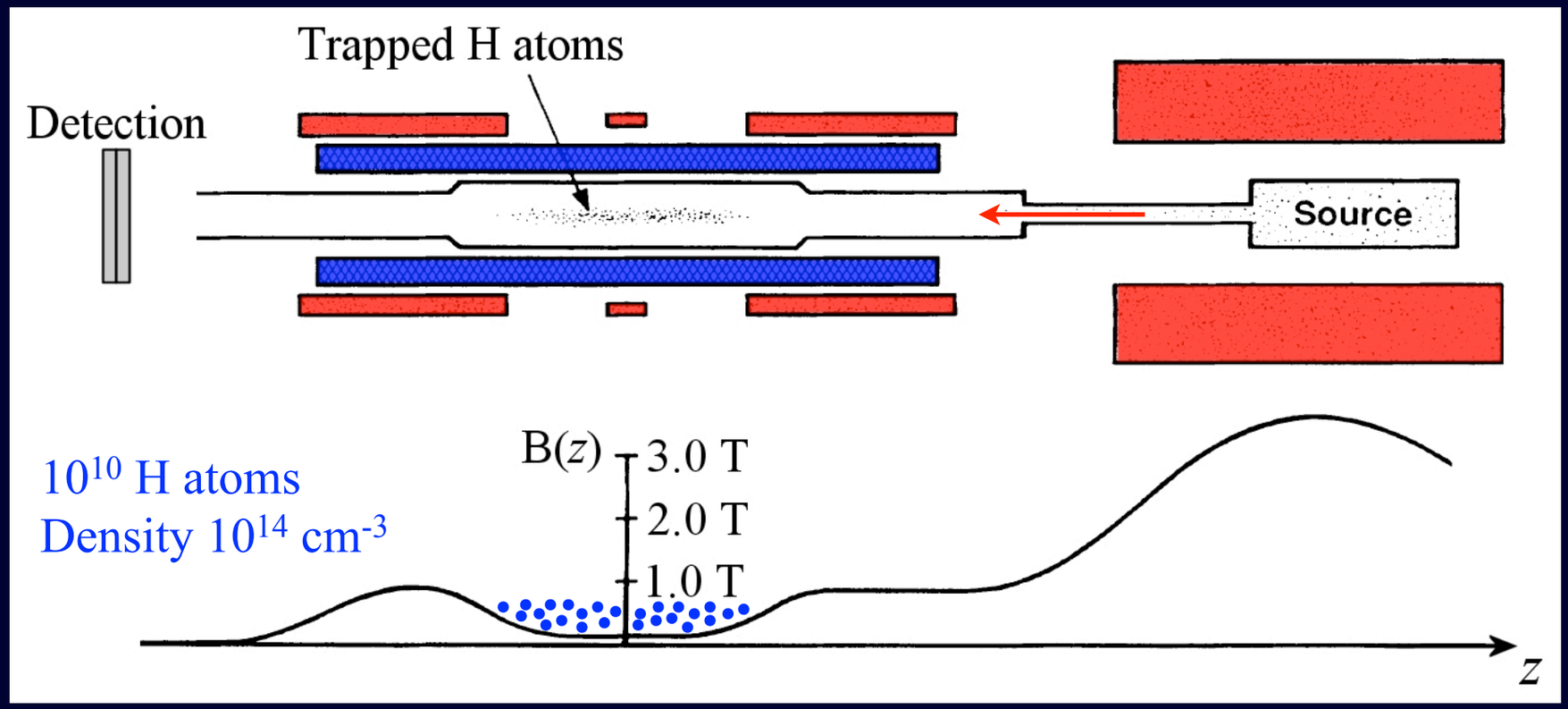
Magnetic traps for H and D

- Zeeman effect in H atom



Magnetic trapping H atoms

1. Production of hot H atoms by microwave discharge of H_2
2. Thermalisation of H atoms by collisions with $^3He/^4He$ film on cell walls



- Kleppner and Greytak (MIT)
- Silvera and Walraven (FOM, Amsterdam)

Hess, Kochanski, Doyle, Masuhara, Kleppner, and Greytak, *Phys. Rev. Lett.* **59**, 672 (1987)

Difficulty trapping D atoms

	Hydrogen	Deuterium
Molecular binding energy	4.52 eV	4.60 eV
Boiling point	20.35 K	23.45 K
Melting point	14.0 K	18.55 K
^{4}He binding energy (E_b/k_B)	1.14(1) K	3.1(2) K
	1.00(2) K	3.97(7) K
	1.11(1) K	2.5(4) K
^{3}He binding energy (E_b/k_B)	0.38(5) eV	?
Recombination cross length	0.20(3) Å	5600 Å [4 T]
	0.25(5) Å	300 Å
		0.55(13) Å [39 G]

Steinberger, PhD Thesis, MIT (2004)

Pulsed supersonic beams

- Seeded supersonic beam

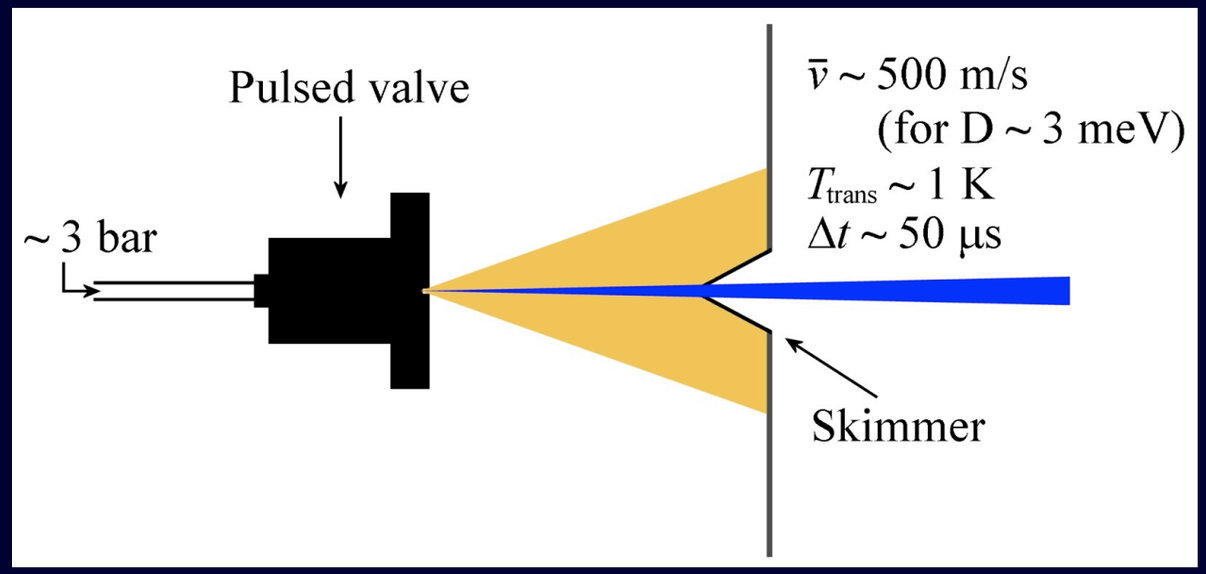
  $Kr : ND_3 \equiv 9 : 1$

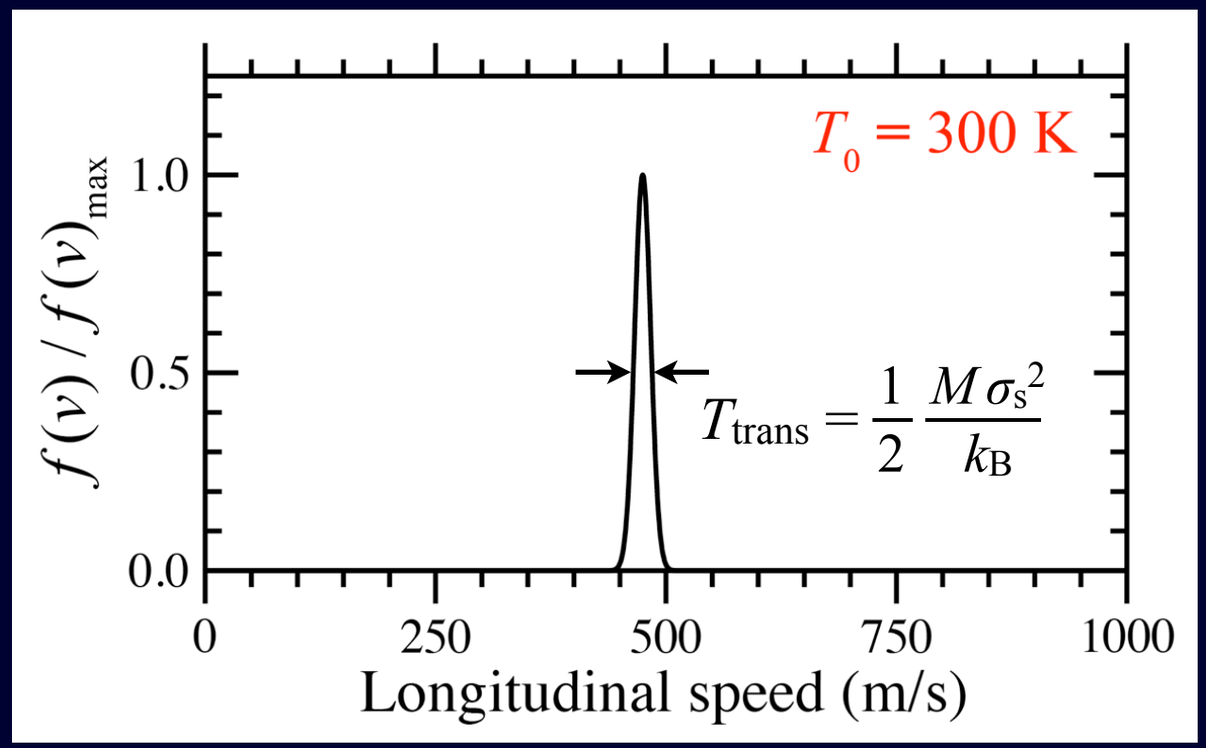
- H or D atom production:

  NH_3 or ND_3 photodissociation

$NH_3 + h\nu \rightarrow NH_2 + H$

$ND_3 + h\nu \rightarrow ND_2 + D$

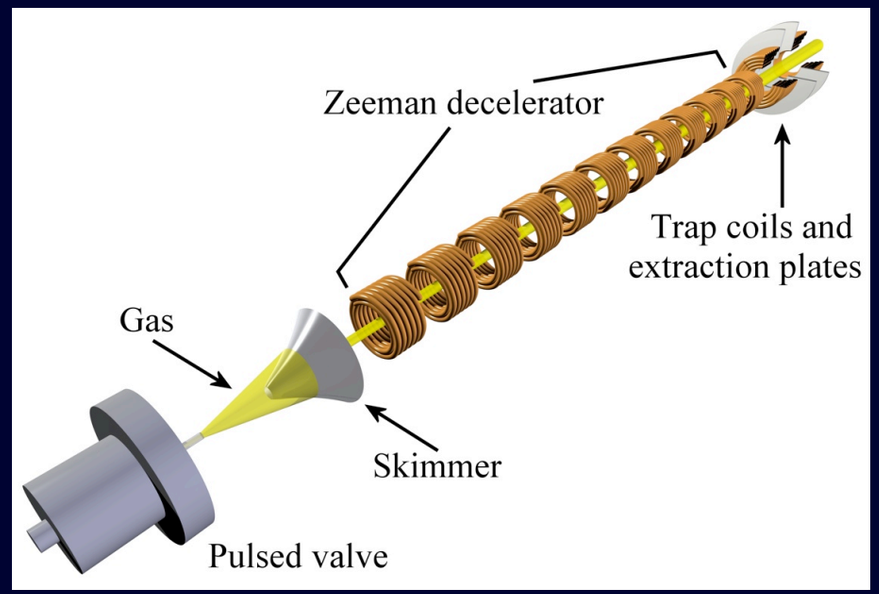




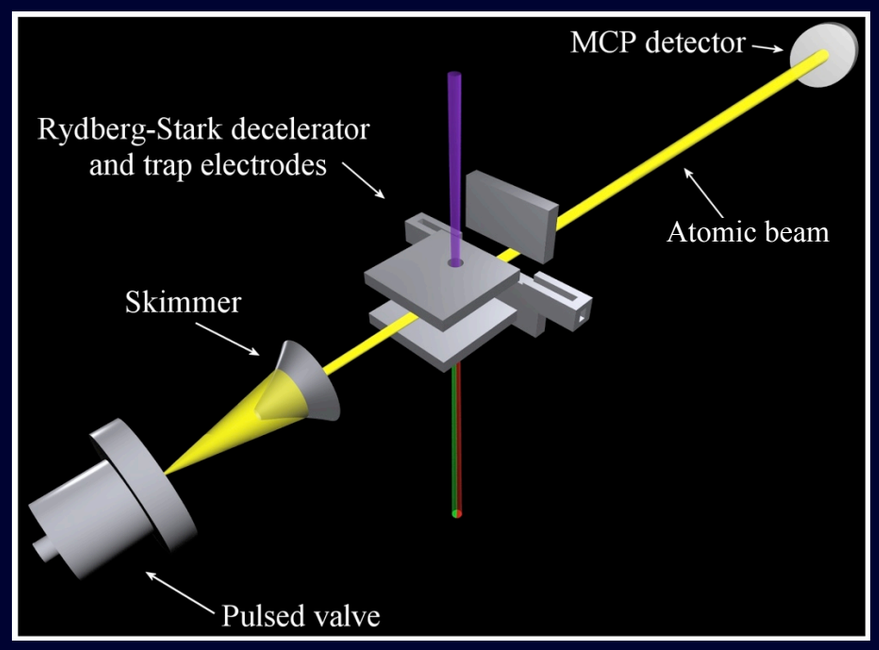
Willitsch, Dyke, and Merkt
Mol. Phys. **102**, 1543 (2004)

Stark and Zeeman deceleration

- Multistage Zeeman deceleration
  ground state H and D atoms



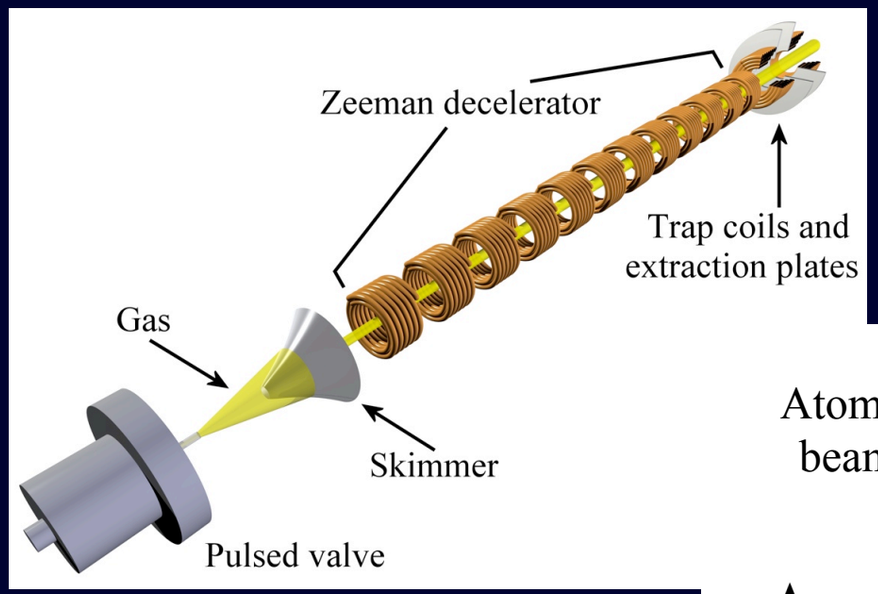
- Rydberg-Stark deceleration
  H and D atoms in Rydberg states

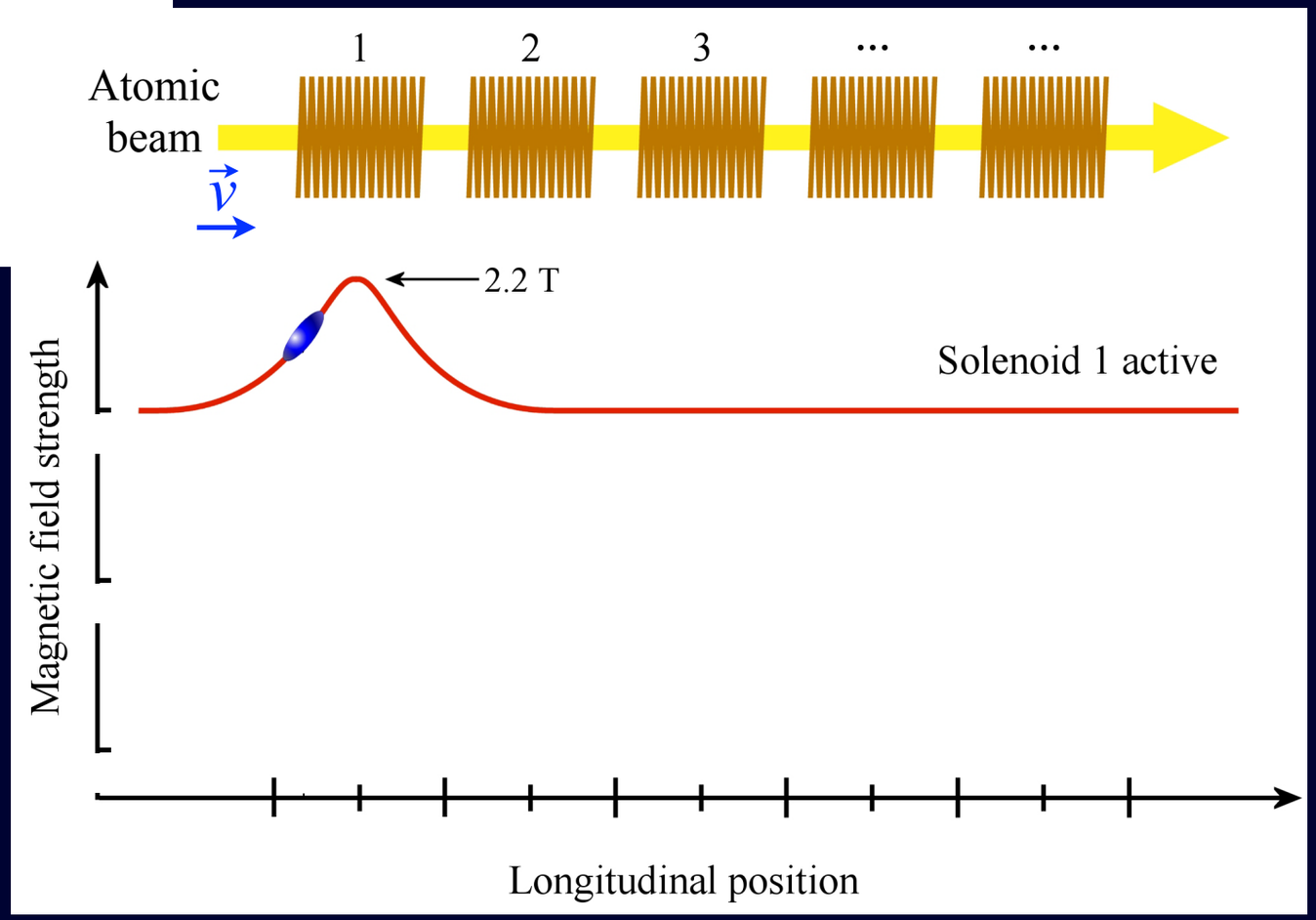


Hogan, Motsch and Merkt
Phys. Chem. Chem. Phys. **13**, 18705 (2011)

Multistage Zeeman deceleration

- Operation principle





Vanhaecke, Meier, Andrist, Meier and Merkt, *Phys. Rev. A* **75**, 031402R (2007)
Hogan, Sprecher, Andrist, Vanhaecke and F. Merkt, *Phys. Rev. A* **76**, 032412 (2007)

Multistage Zeeman deceleration

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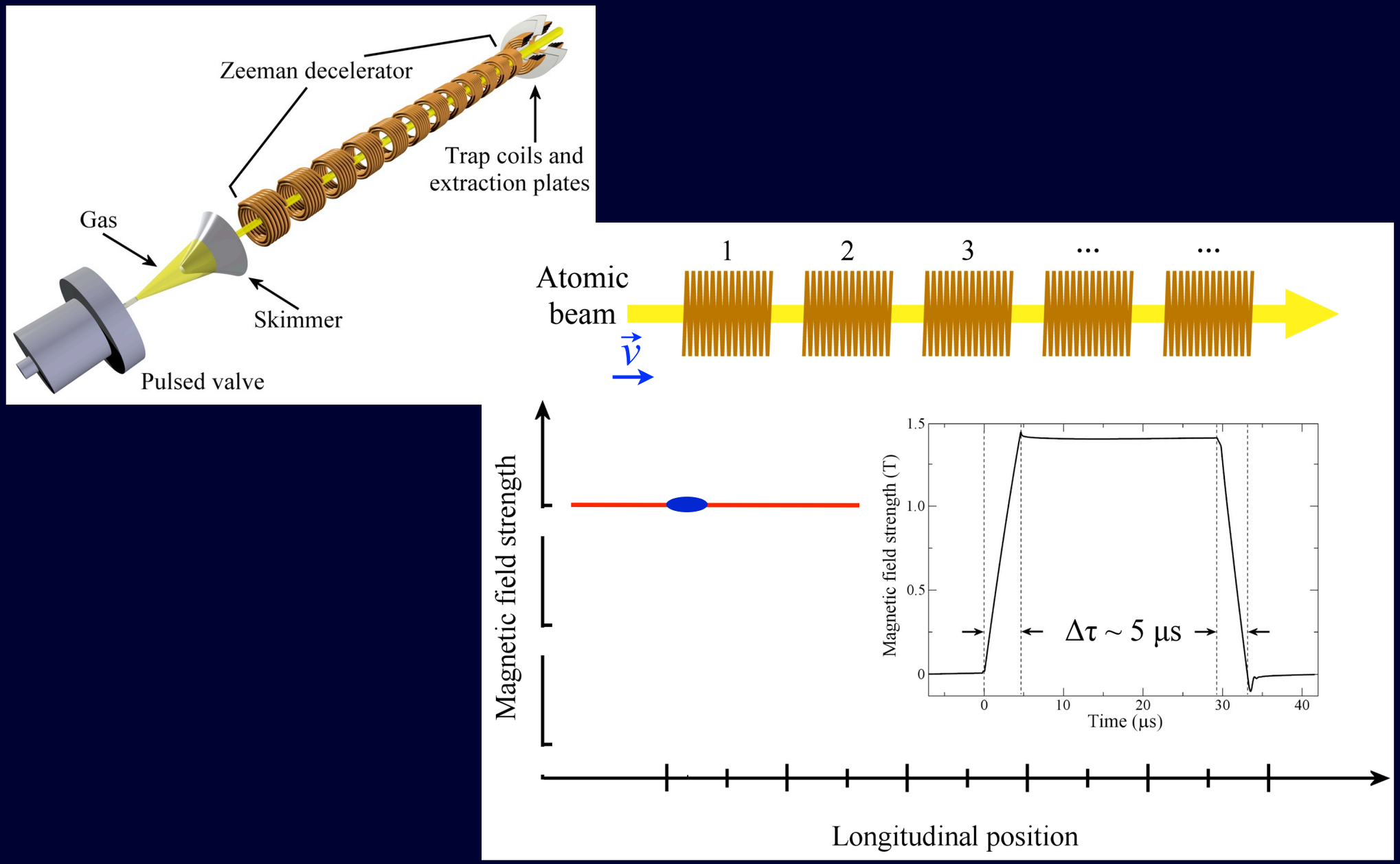

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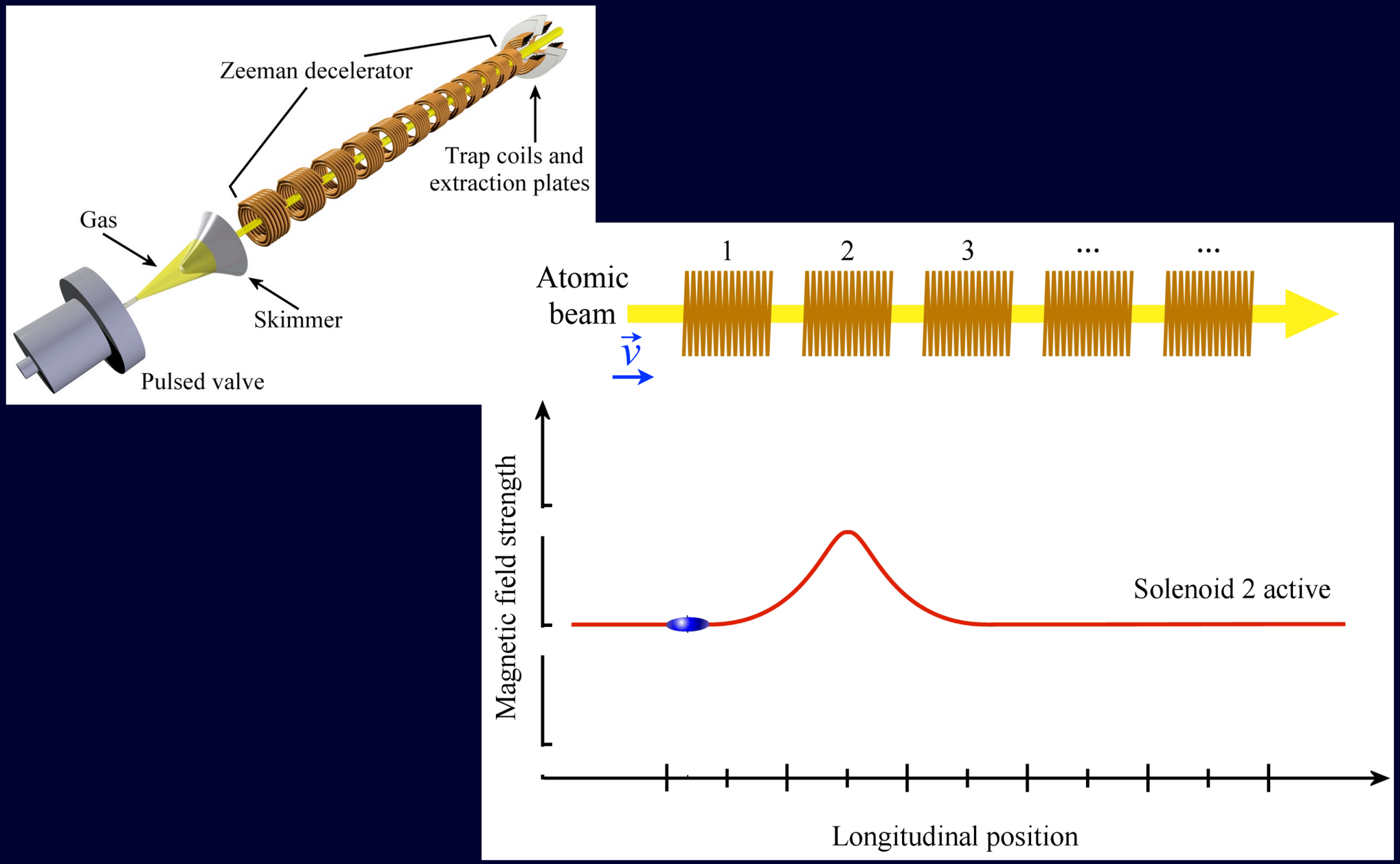

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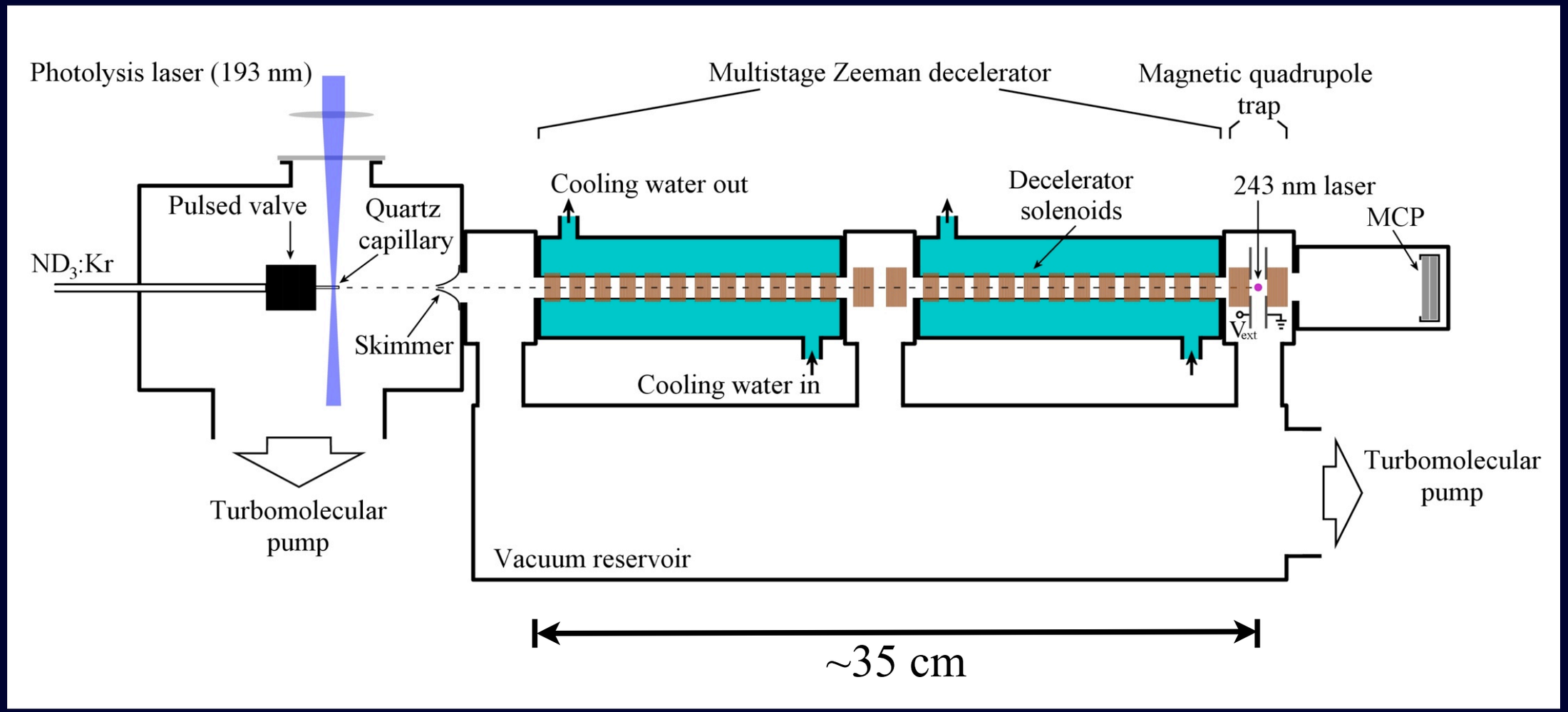
Decelerating deuterium atoms



Hogan et al., *Phys. Rev. Lett.* **101**, 143001 (2008)
Wiederkehr et al., *Phys. Rev. A* **81**, 021402R (2010)

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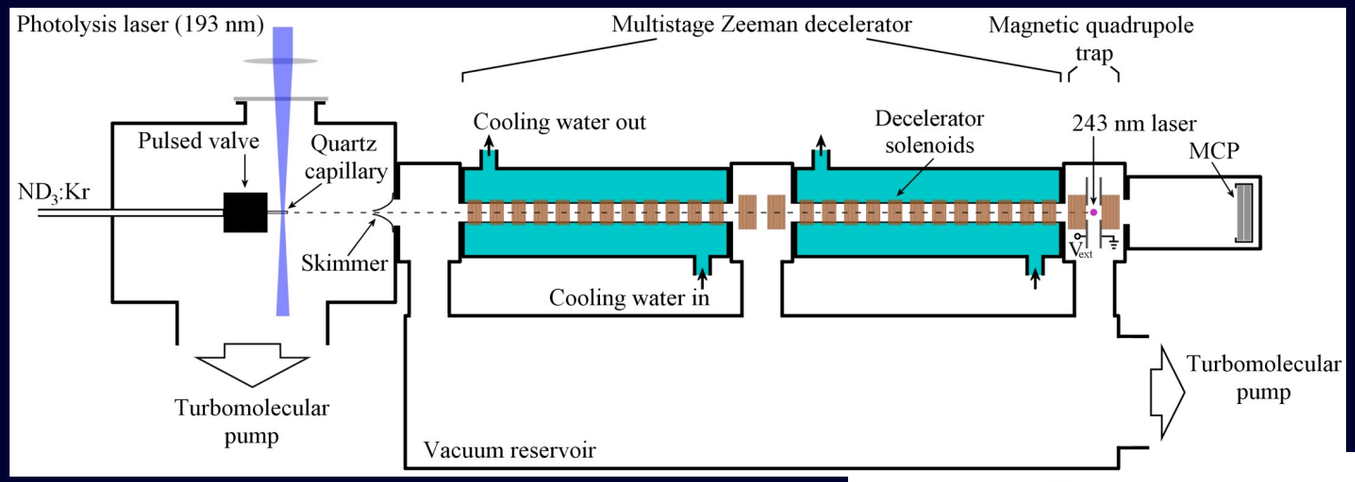

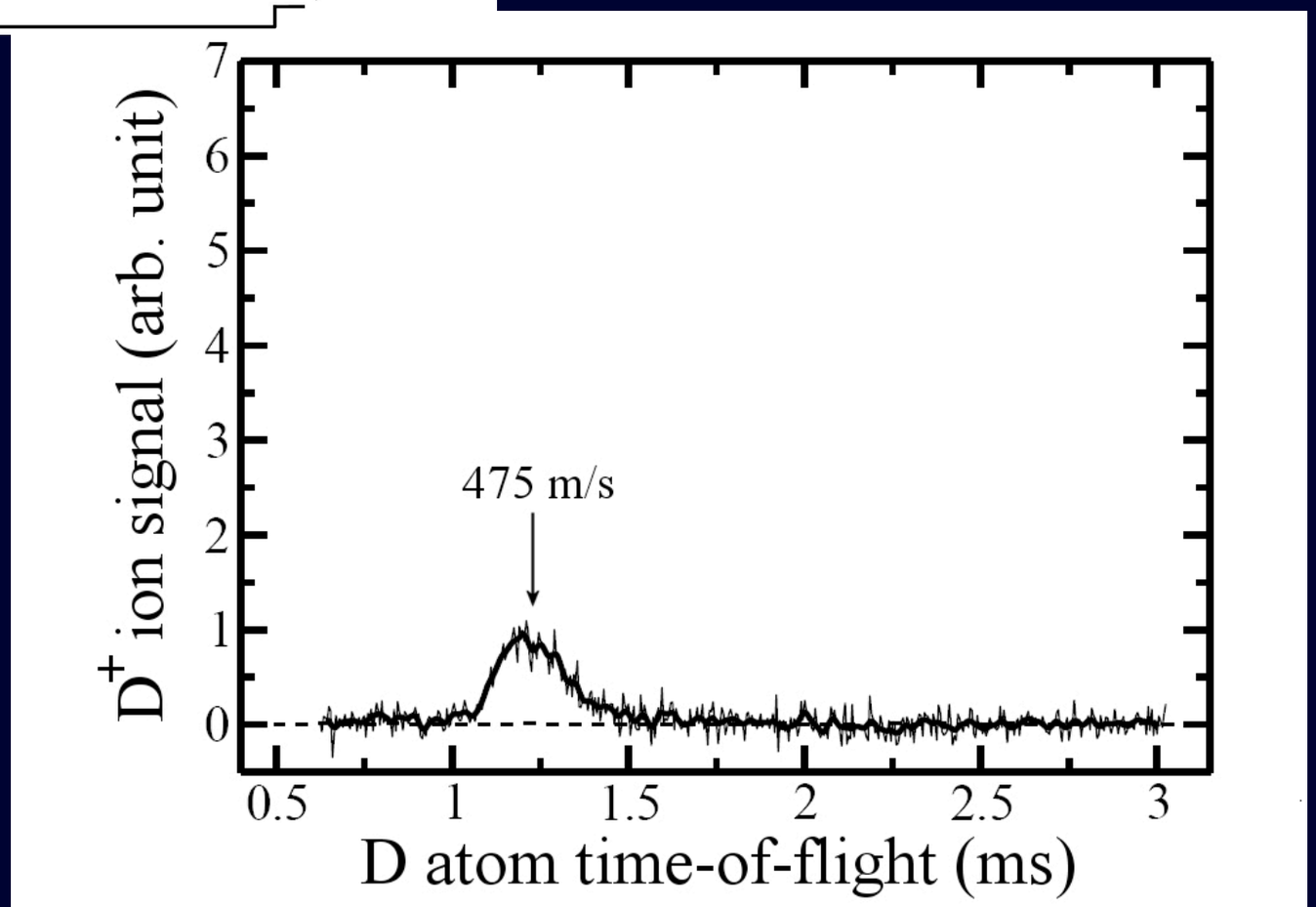

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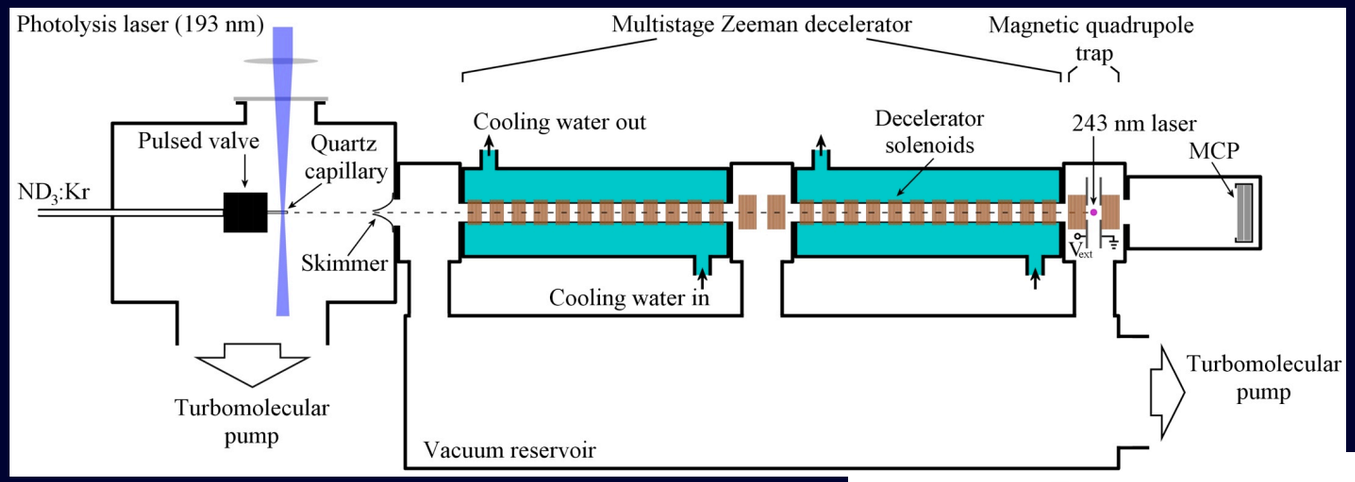

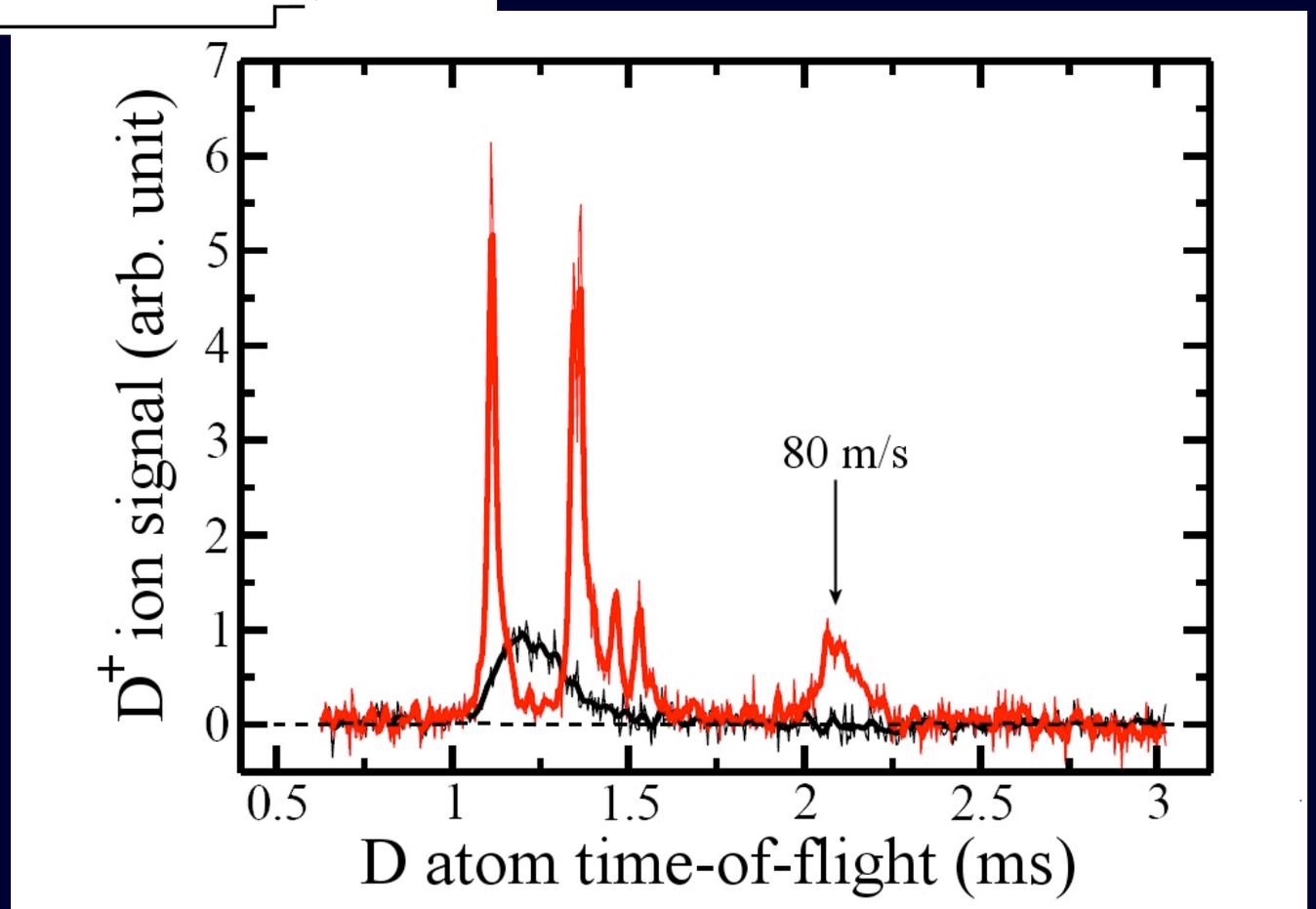

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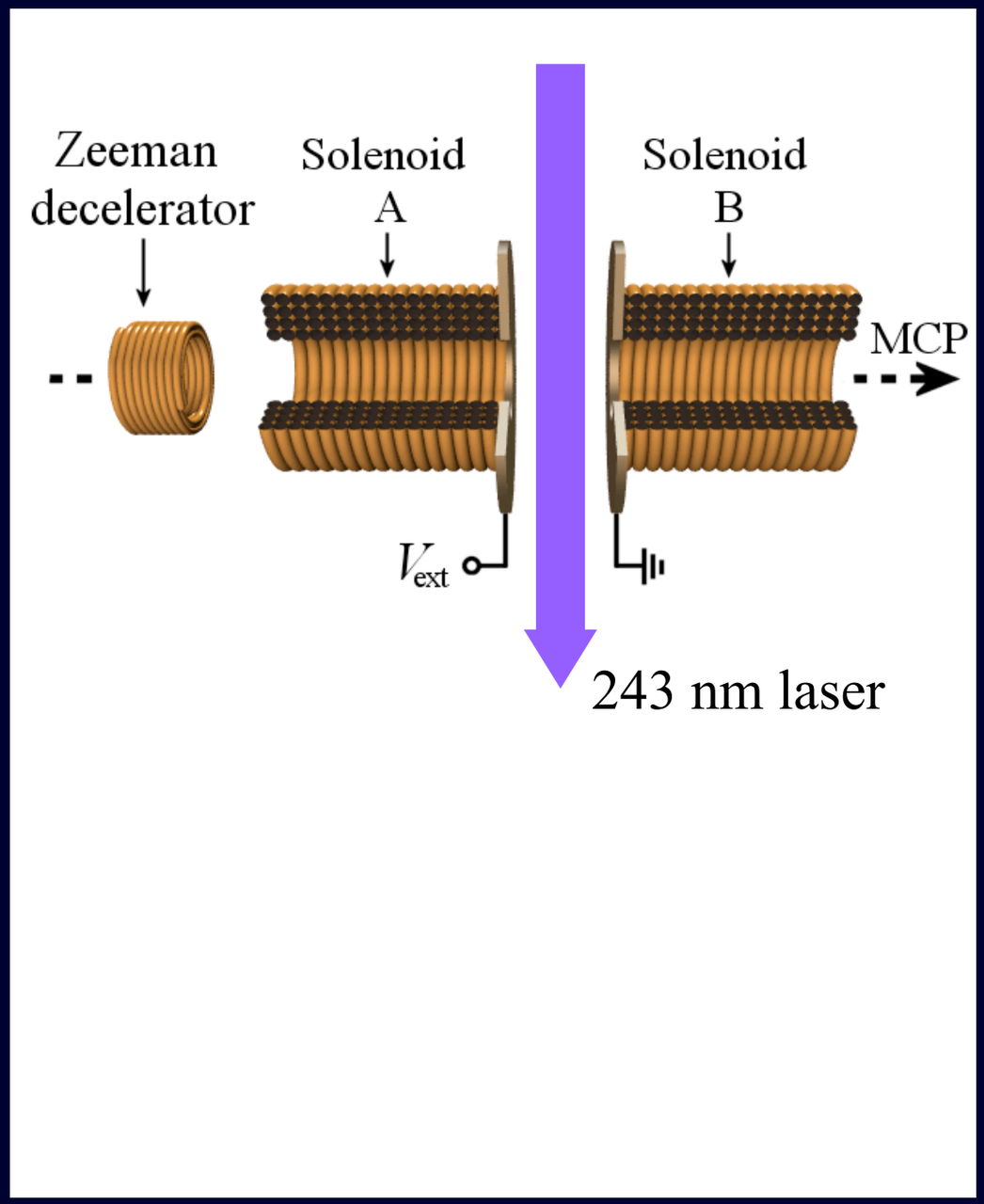
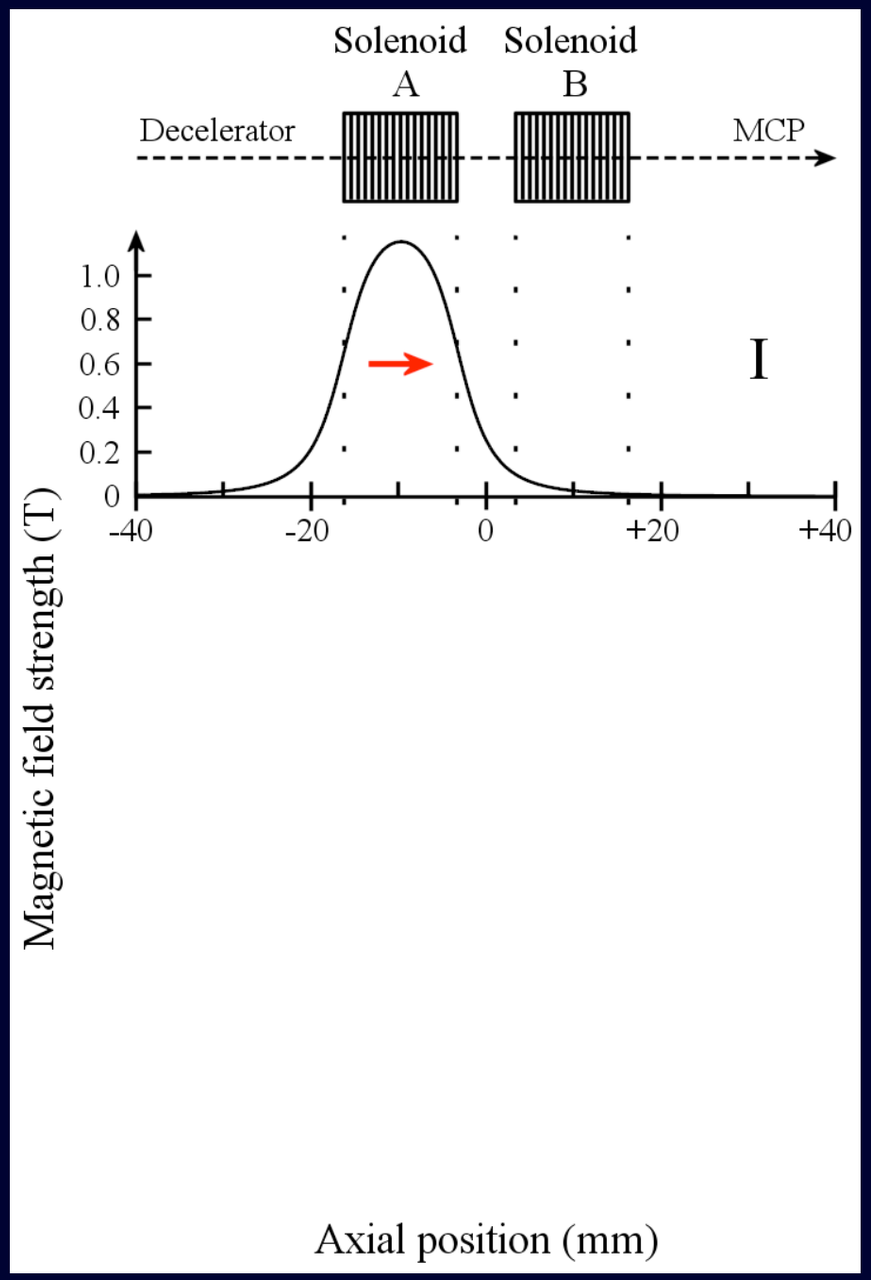
Trap loading





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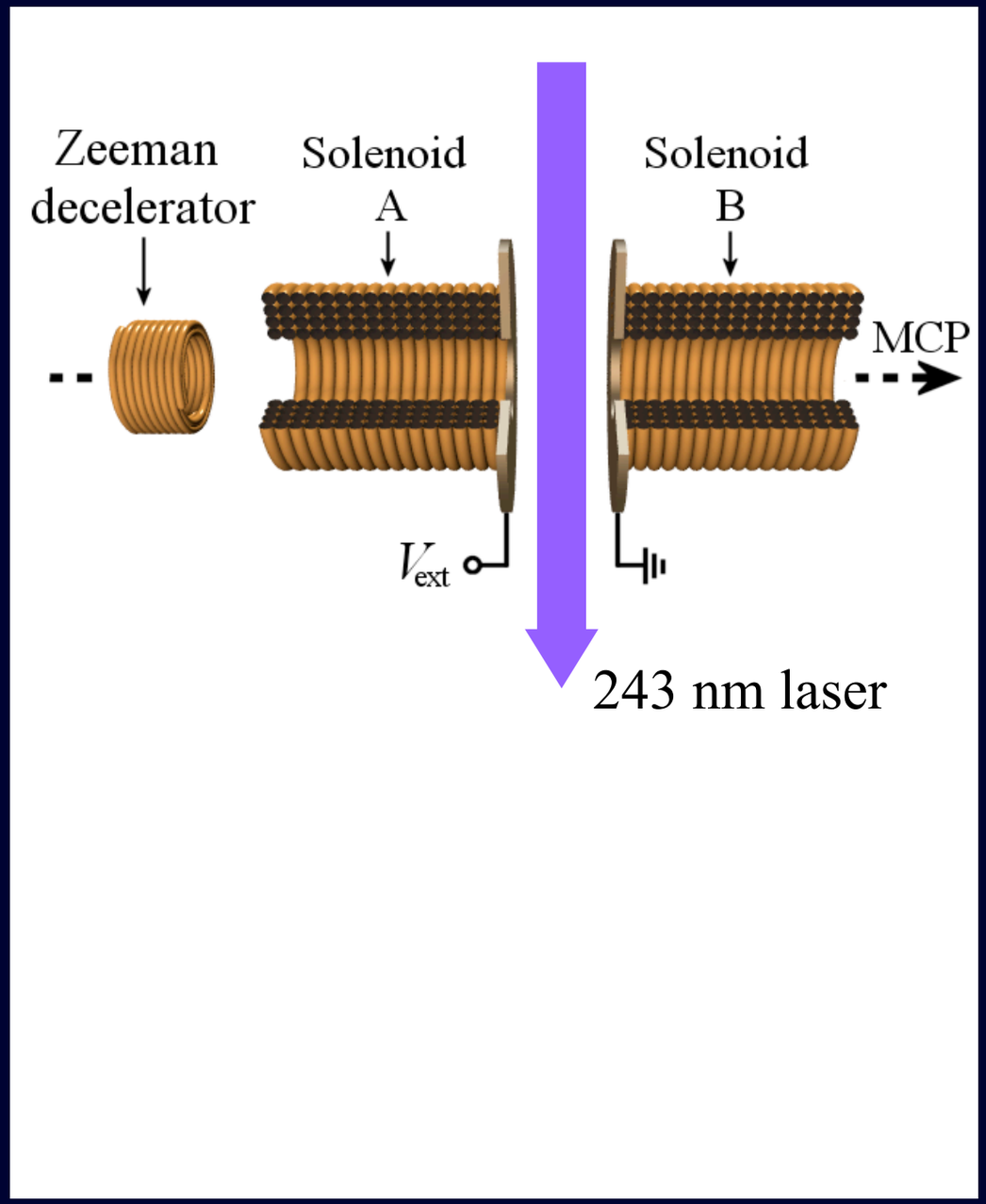

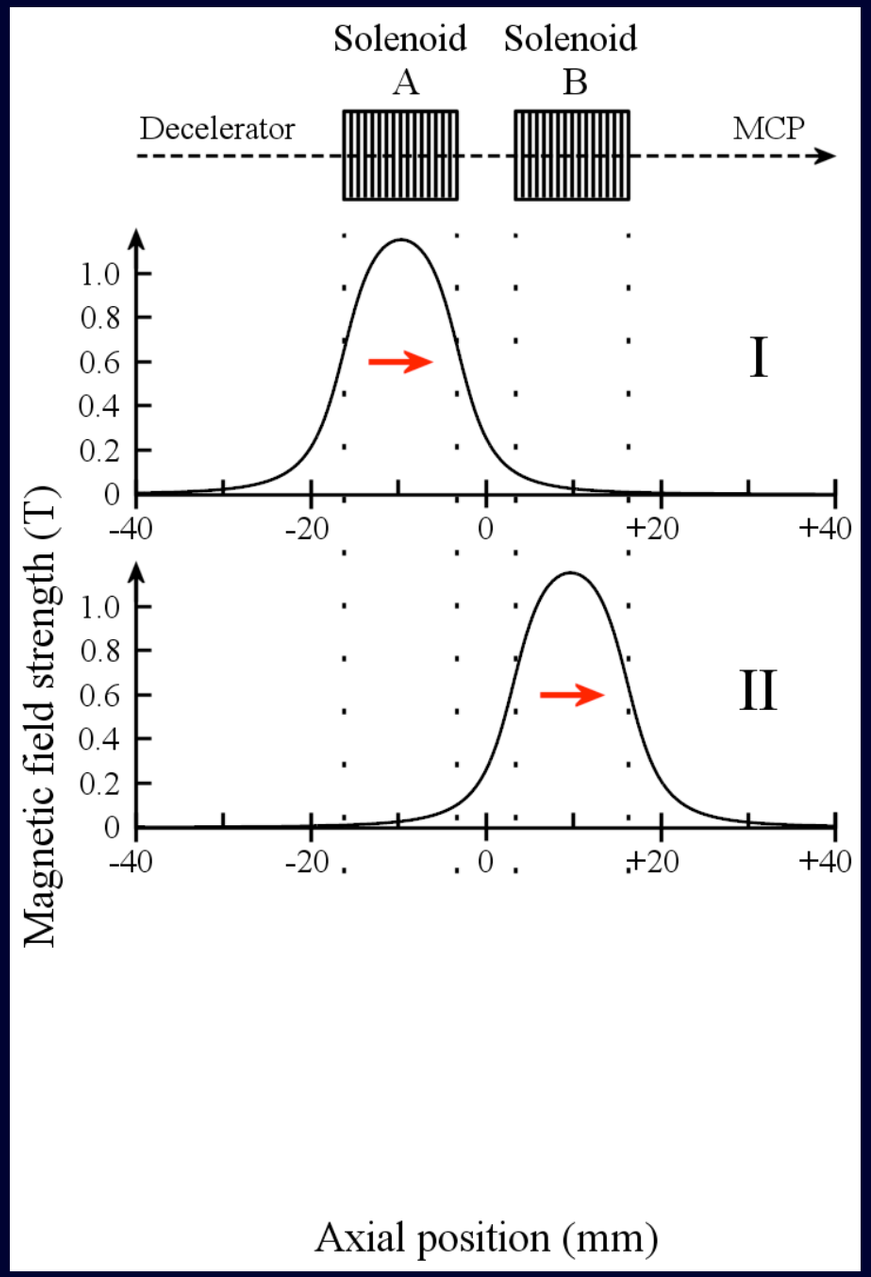

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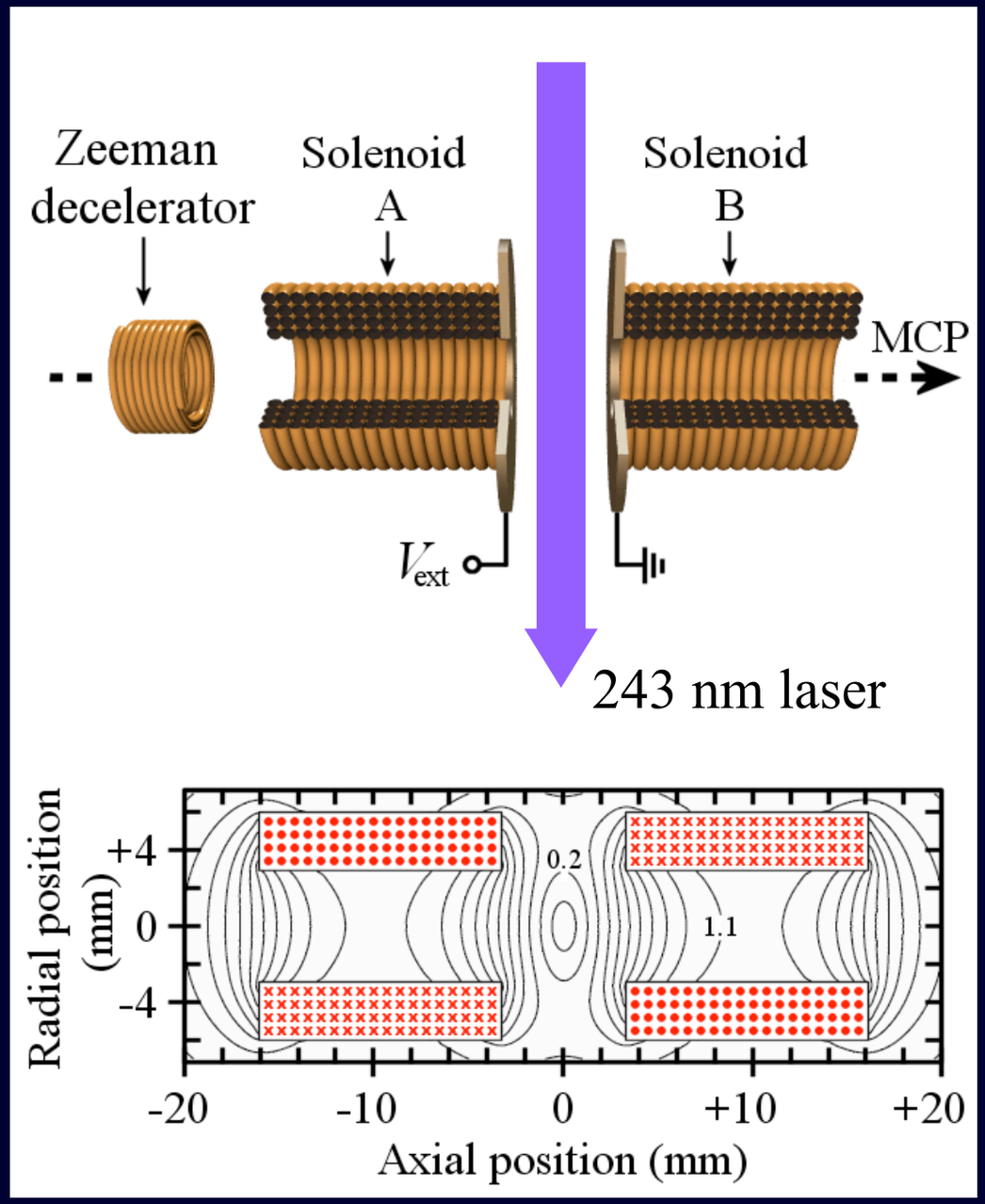

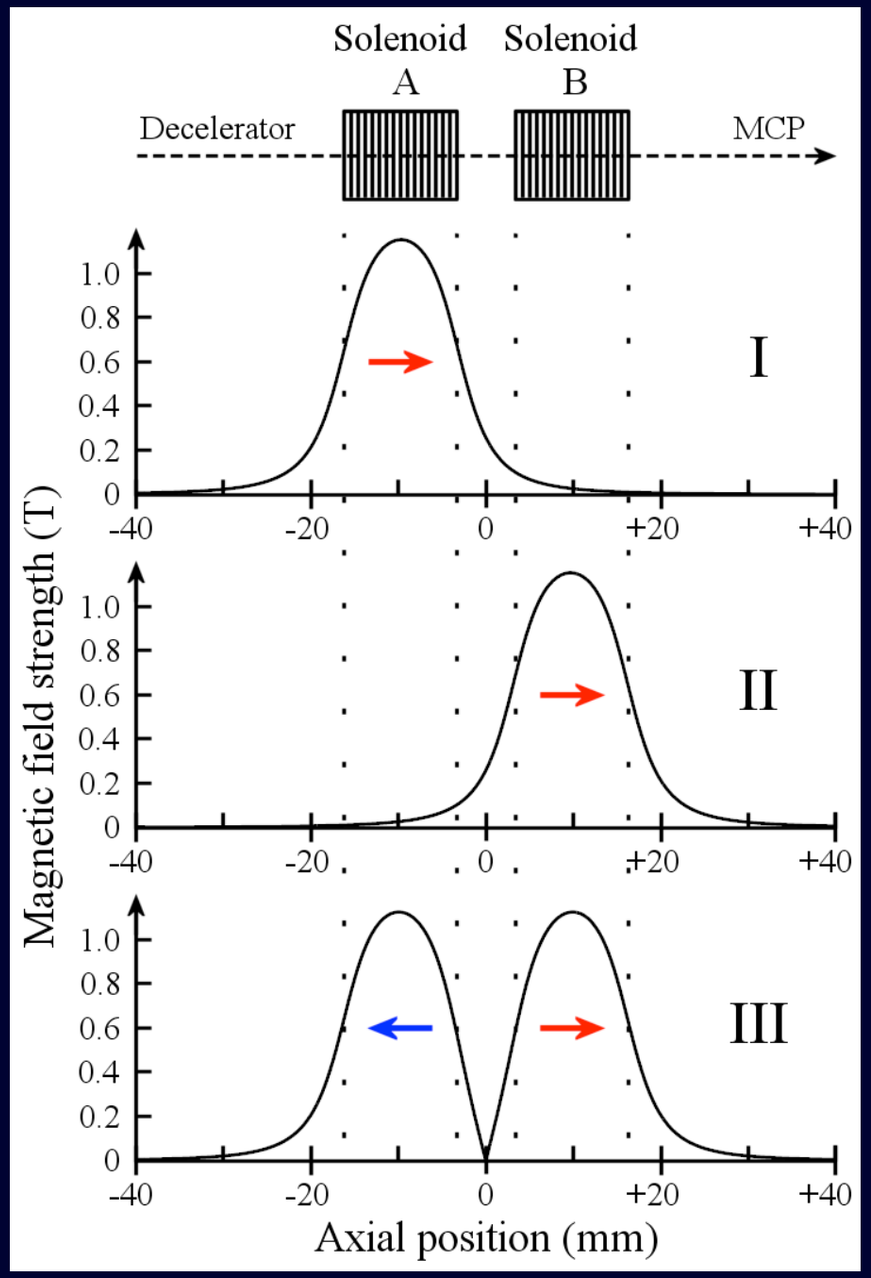

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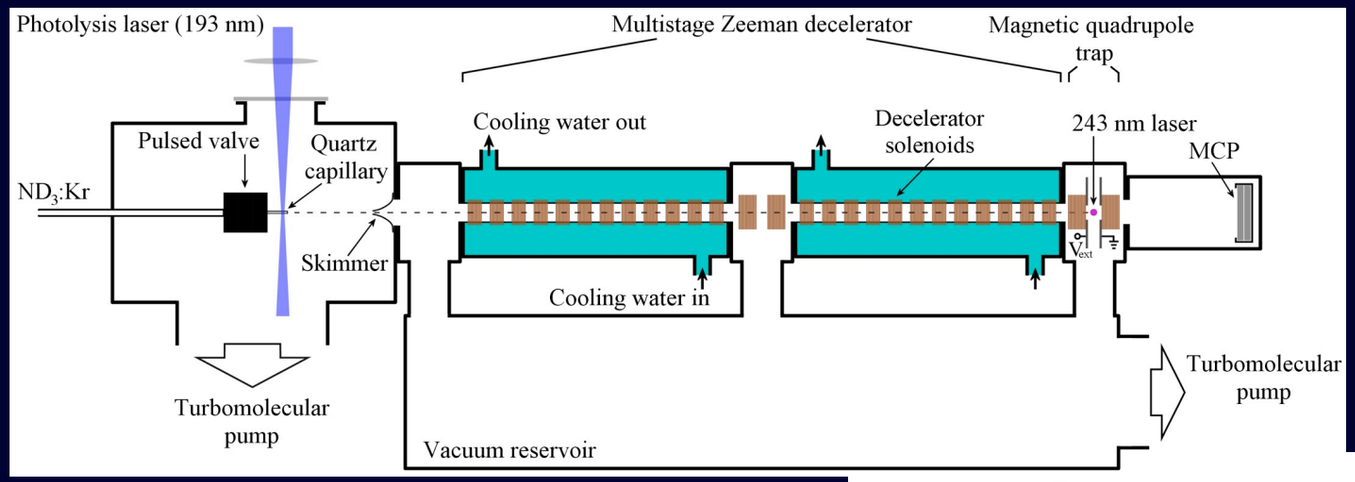
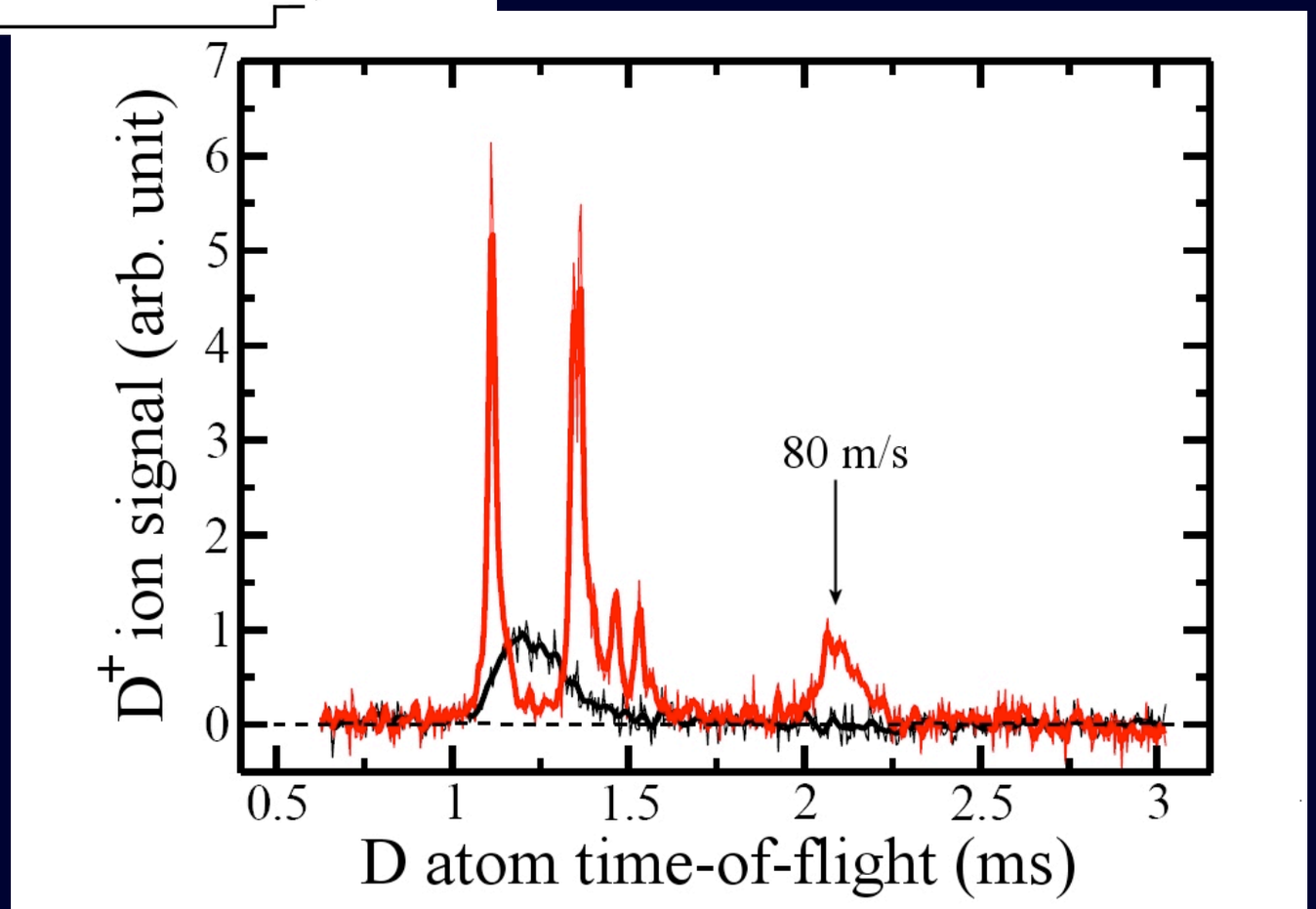
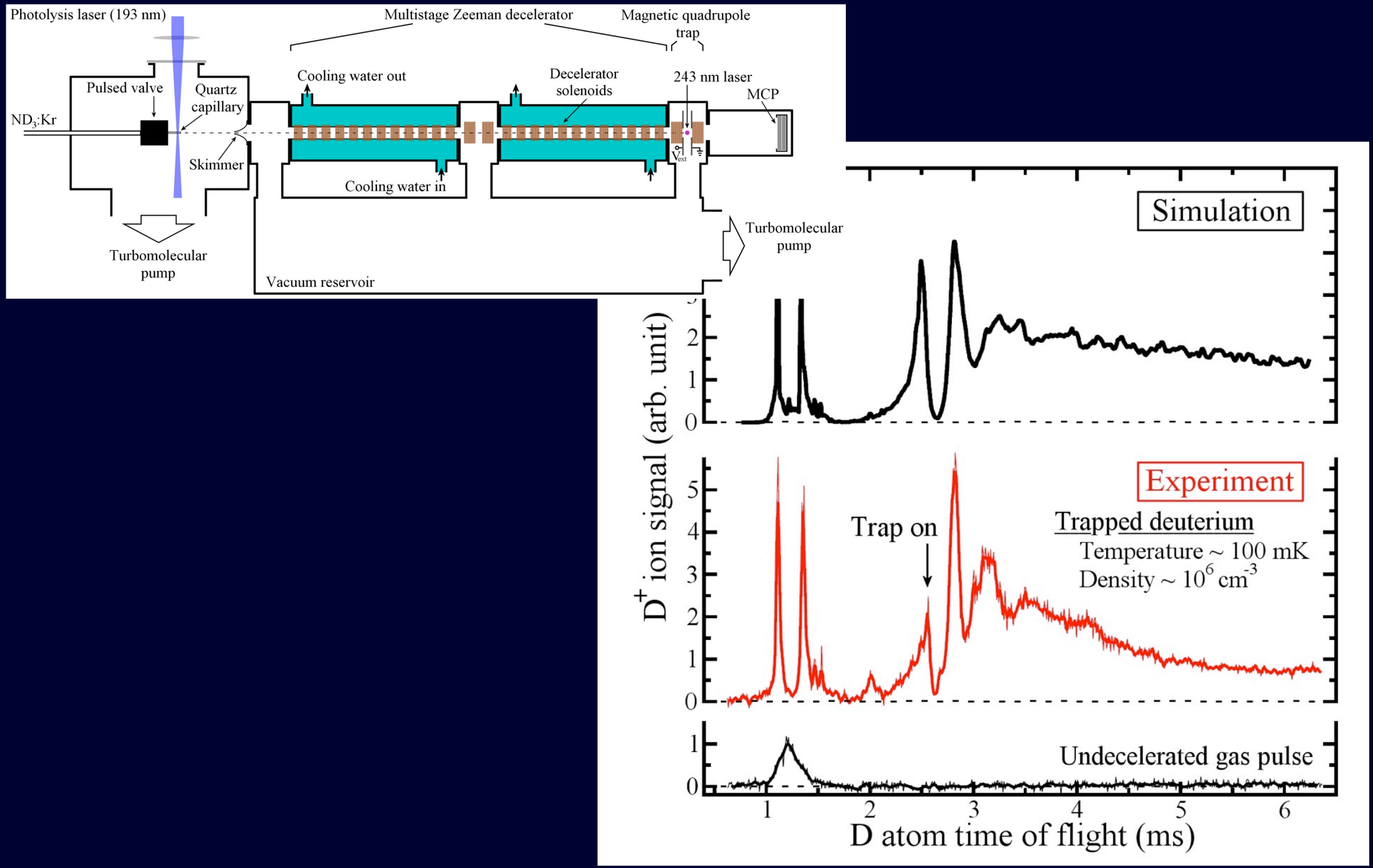




Hogan et al., *Phys. Rev. Lett.* **101**, 143001 (2008)
Wiederkehr et al., *Phys. Rev. A* **81**, 021402R (2010)

Magnetic trapping deuterium atoms



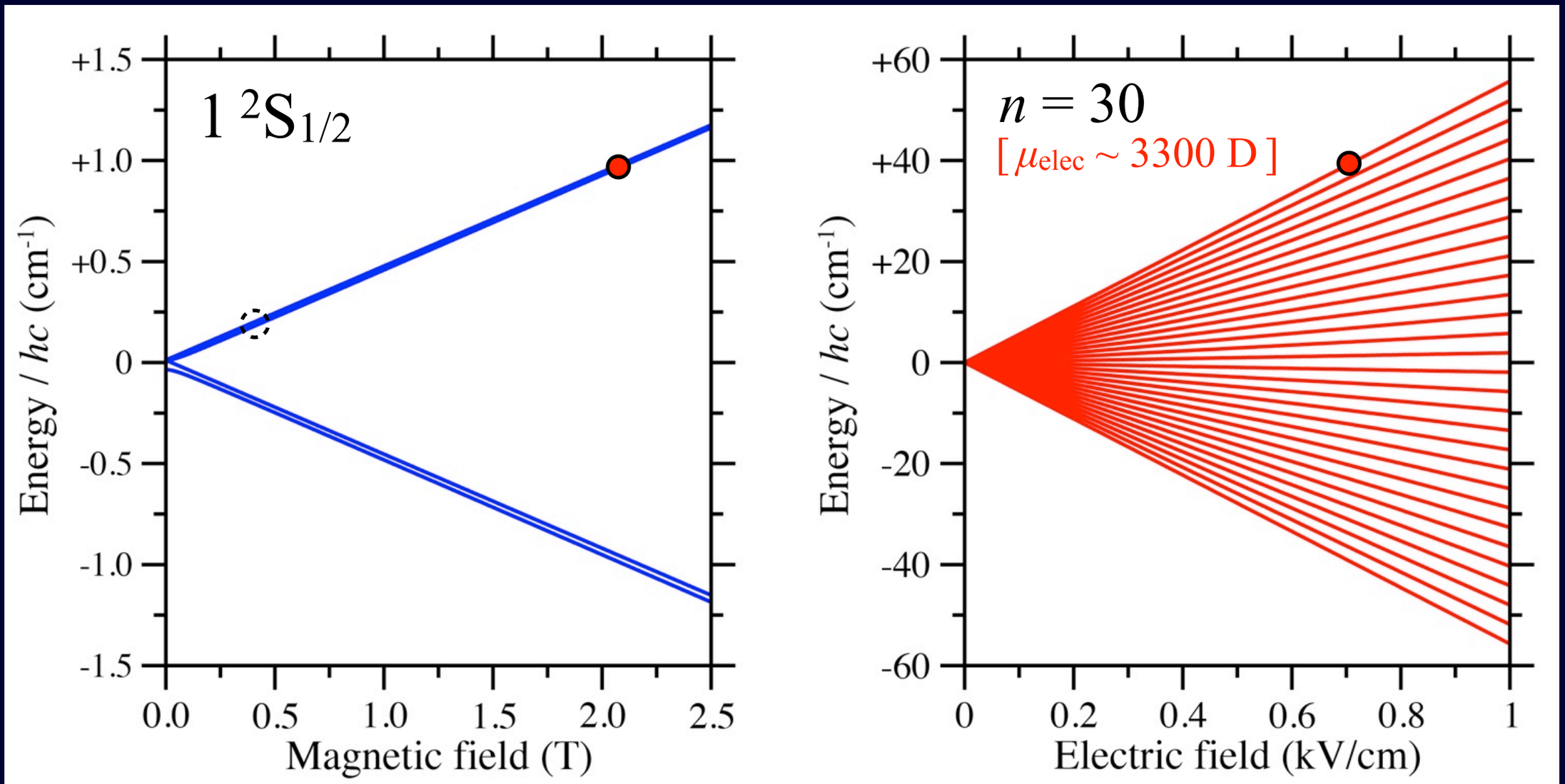
Hogan et al., *Phys. Rev. Lett.* **101**, 143001 (2008)
Wiederkehr et al., *Phys. Rev. A* **81**, 021402R (2010)

Electric traps for H and D

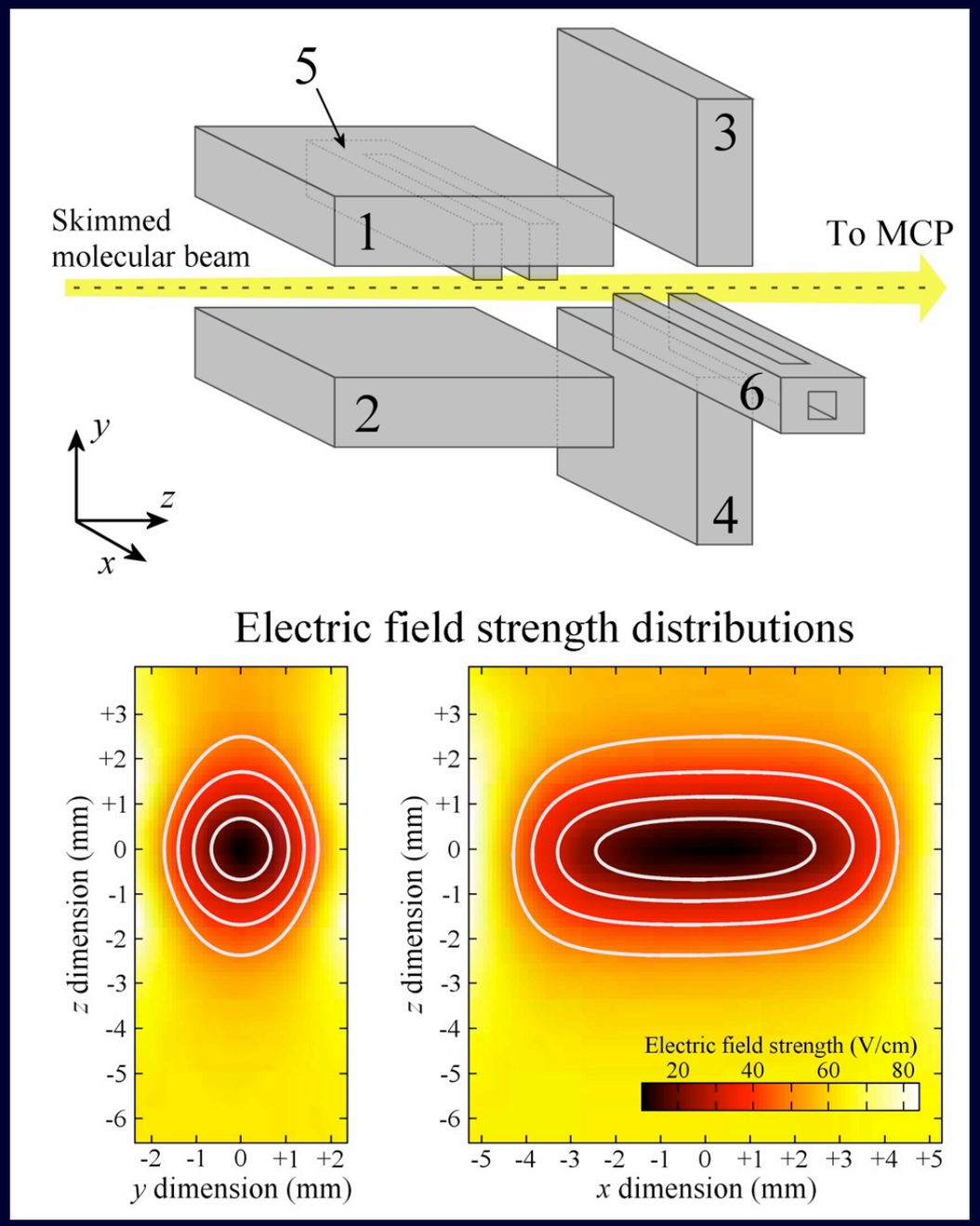
- Stark effect in H atom

Zeeman effect
in ground state

Stark effect
in Rydberg states



Trap loading procedure



- Operating conditions

  $|V_{1,2,3,4}| = 20$ V

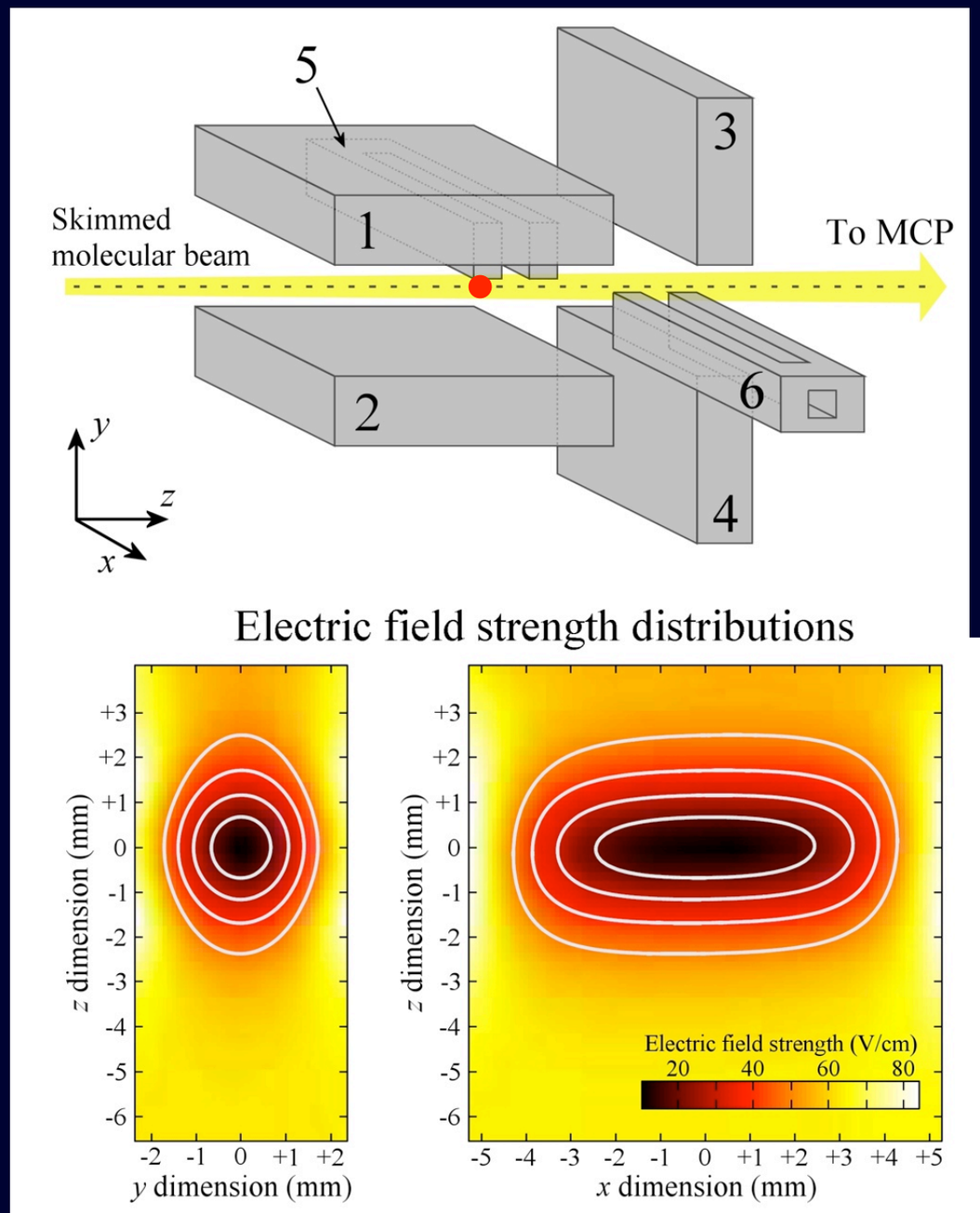
  $F_{\min} = 9$ V/cm

  $F_{\text{saddle}} = 64$ V/cm

  $[T = E/k_B \sim 3$ K, for $n = 30]$

Hogan and Merkt, *Phys. Rev. Lett.* **100**, 043001 (2008)

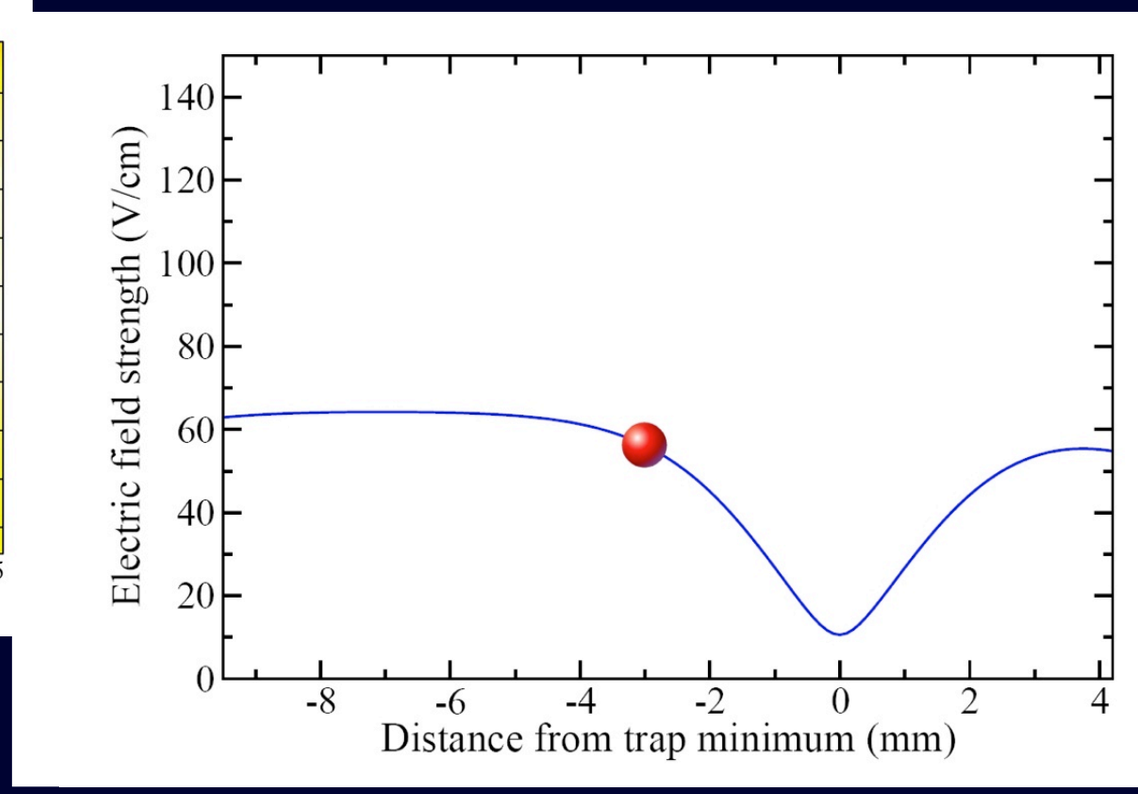
Trap loading procedure



- 1. Photoexcitation

$1\,^2\mathrm{S} \;\rightarrow\; 2\,^2\mathrm{P} \;\rightarrow\; n\,^2\mathrm{S} \,/\, n\,^2\mathrm{D}$

121 nm 365 nm



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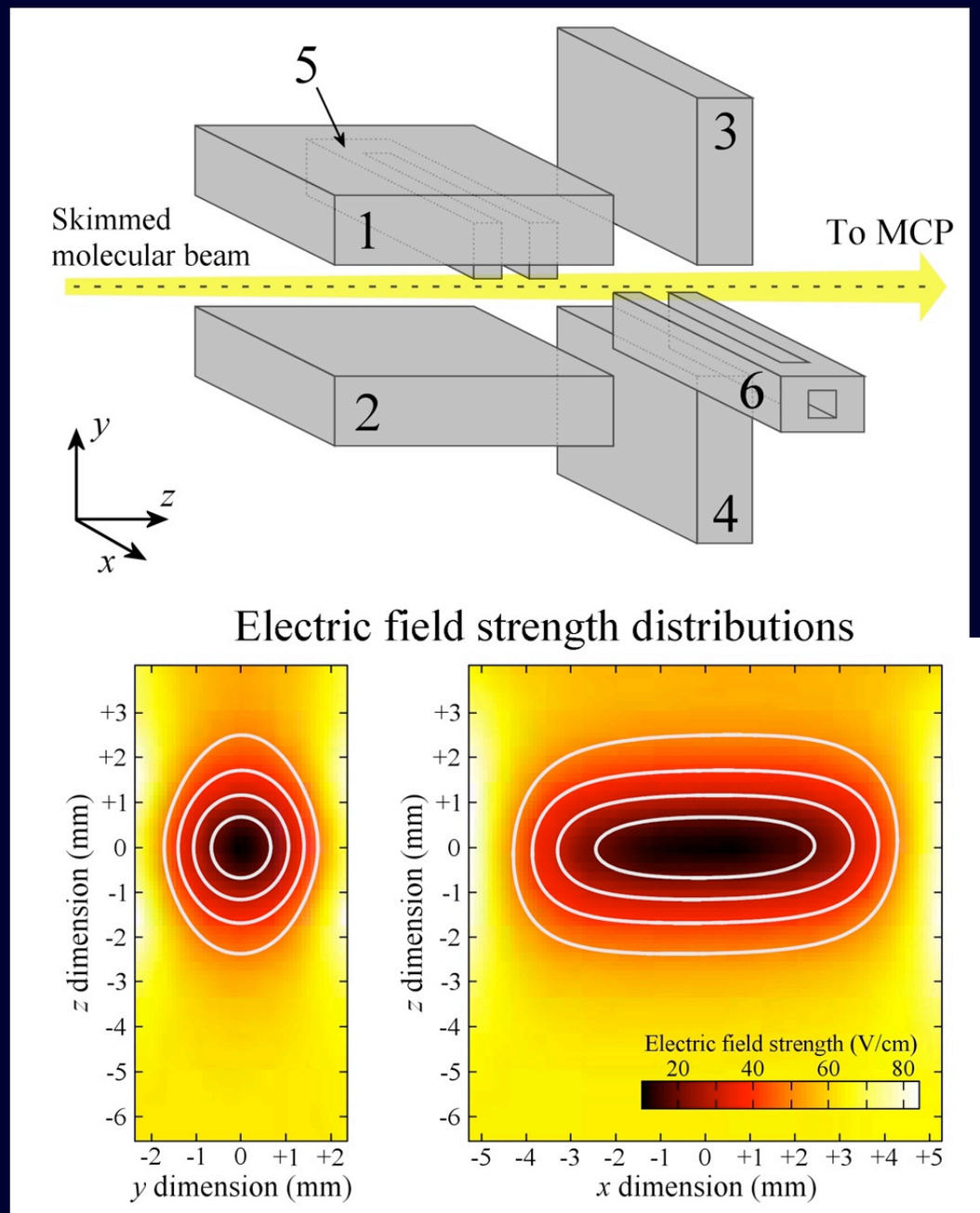
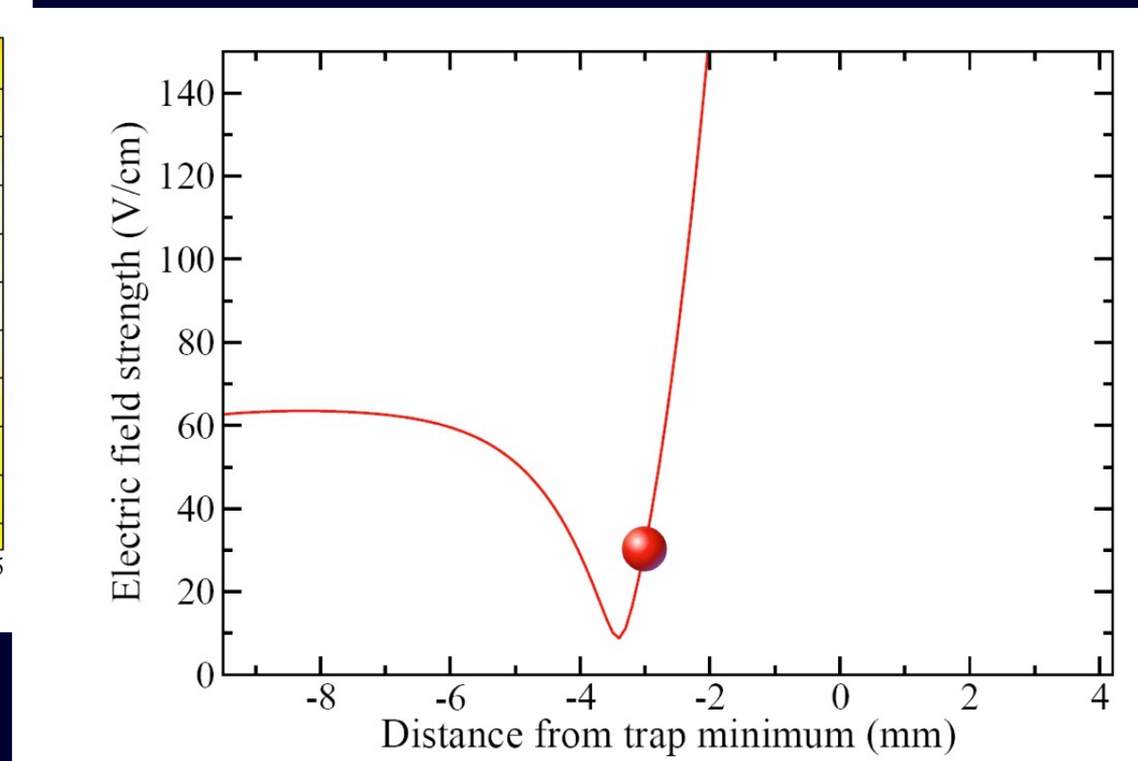


- 1. Photoexcitation
- 2. Deceleration



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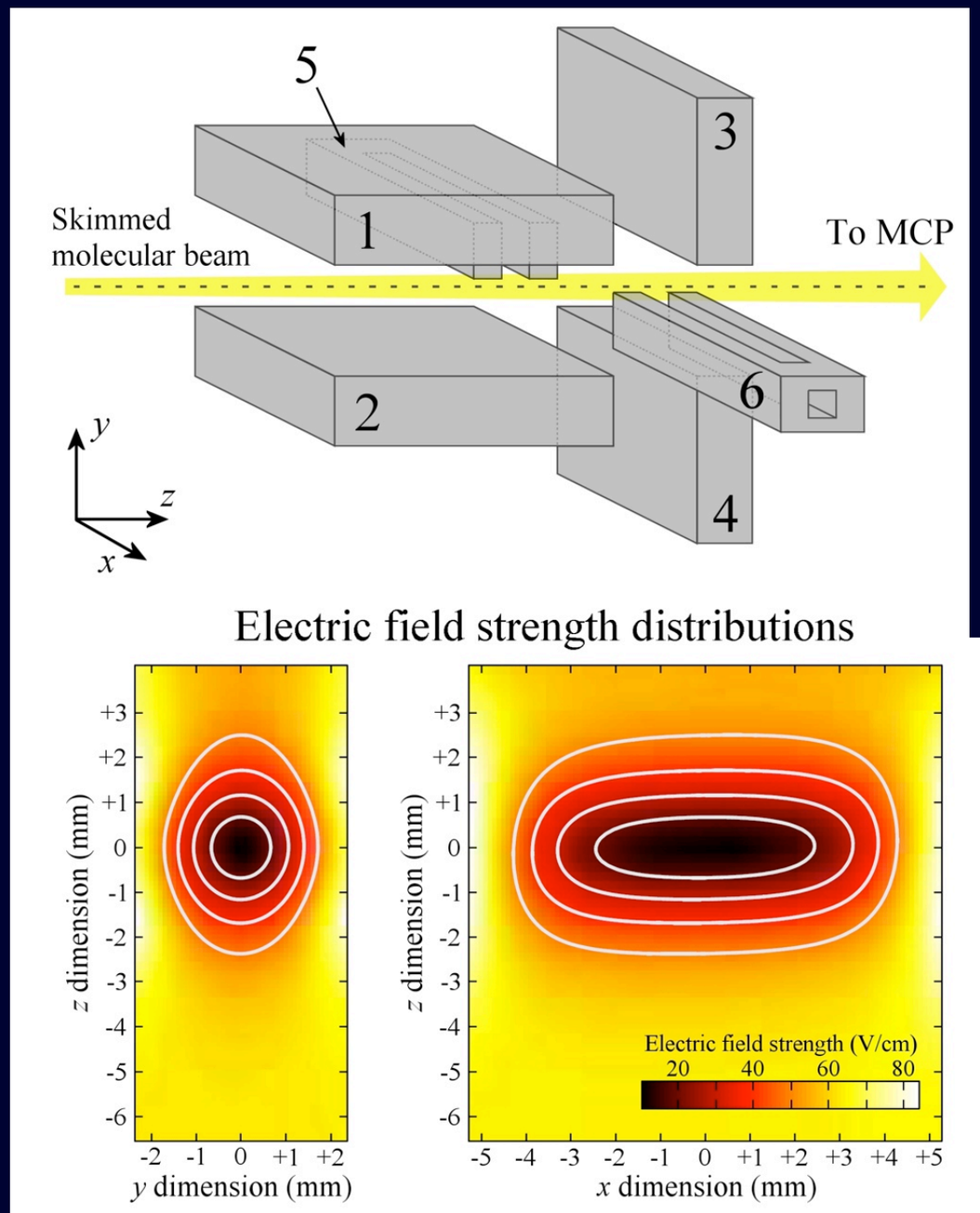

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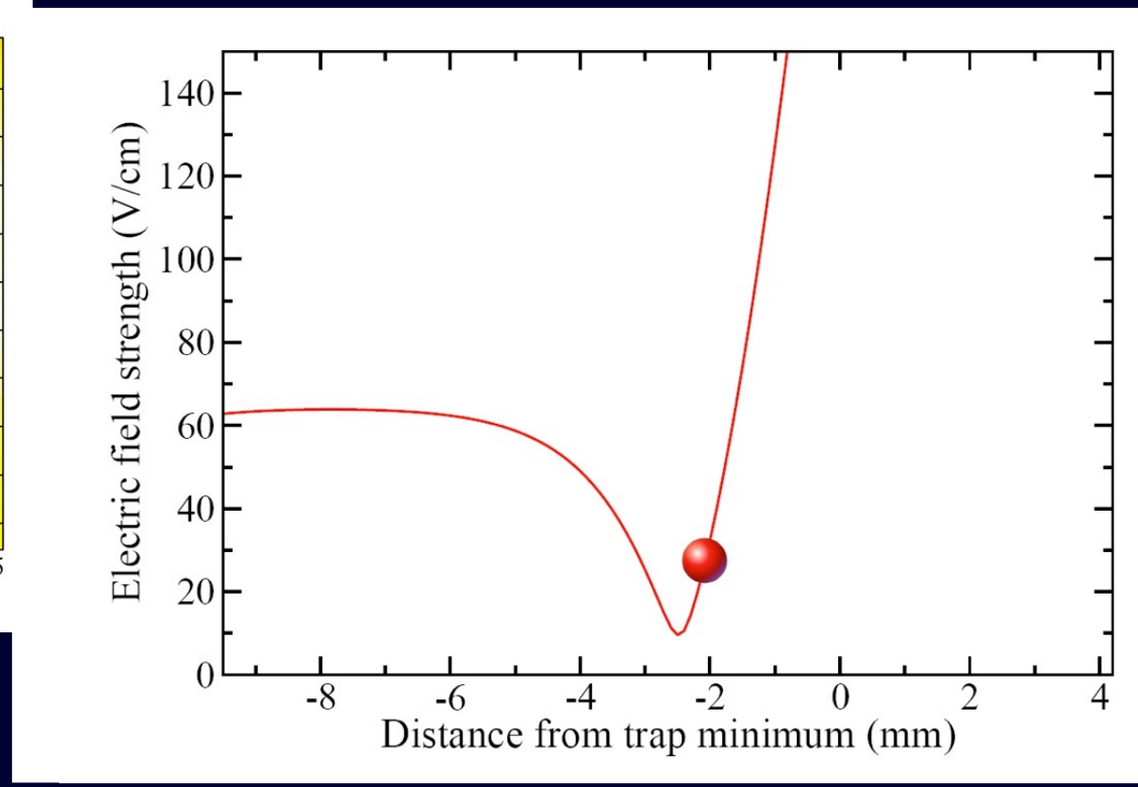

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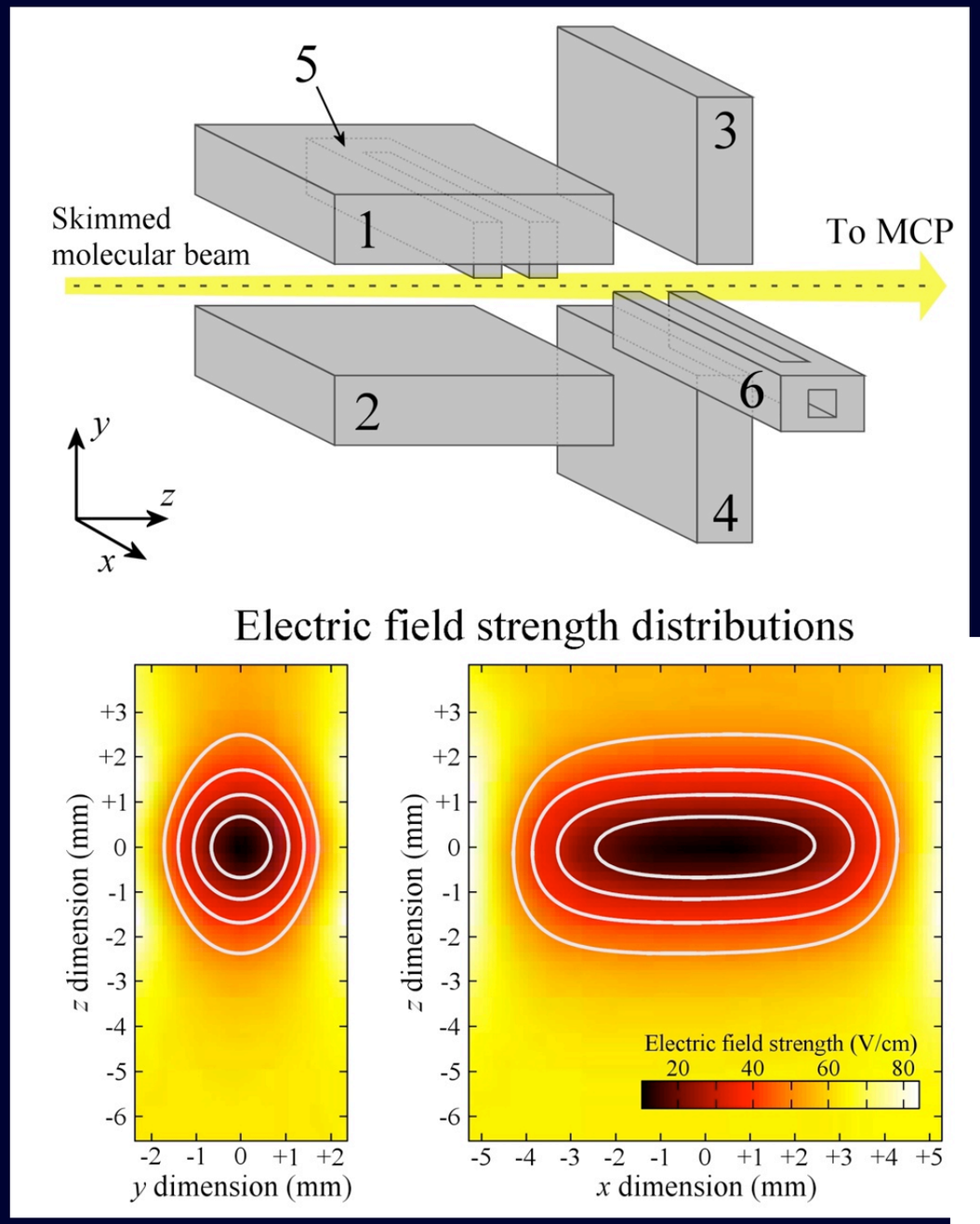

- 1. Photoexcitation
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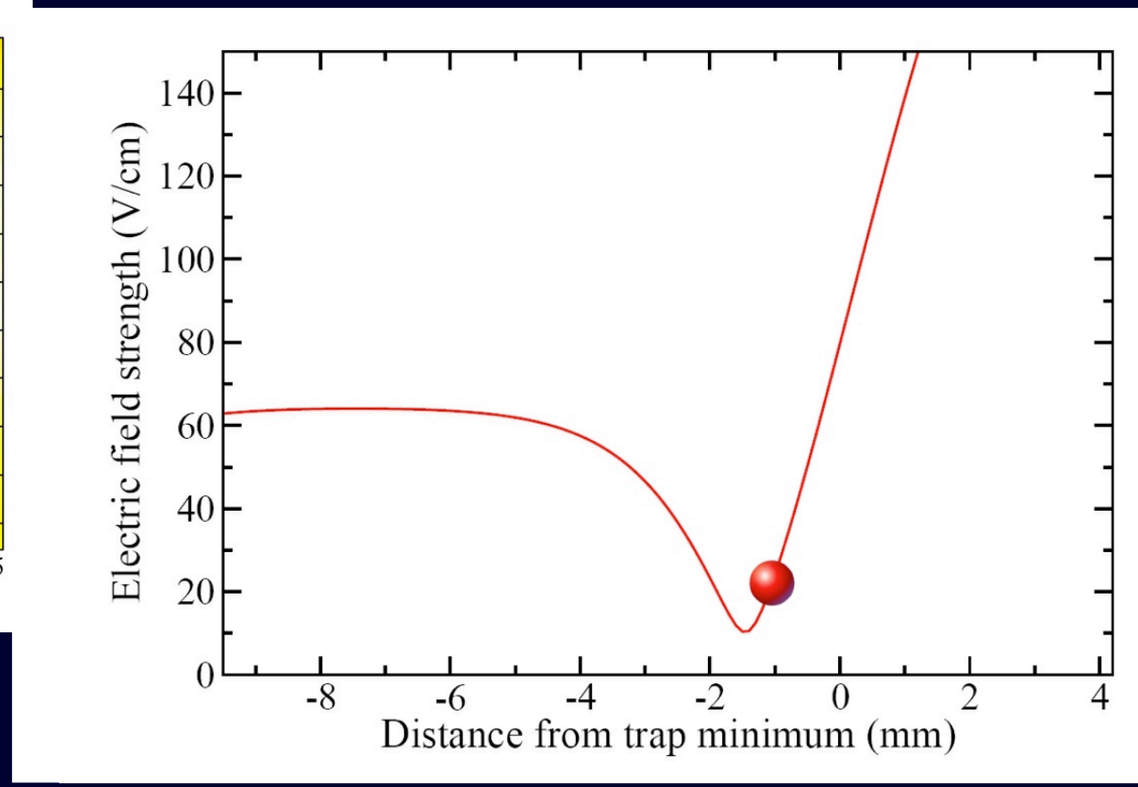

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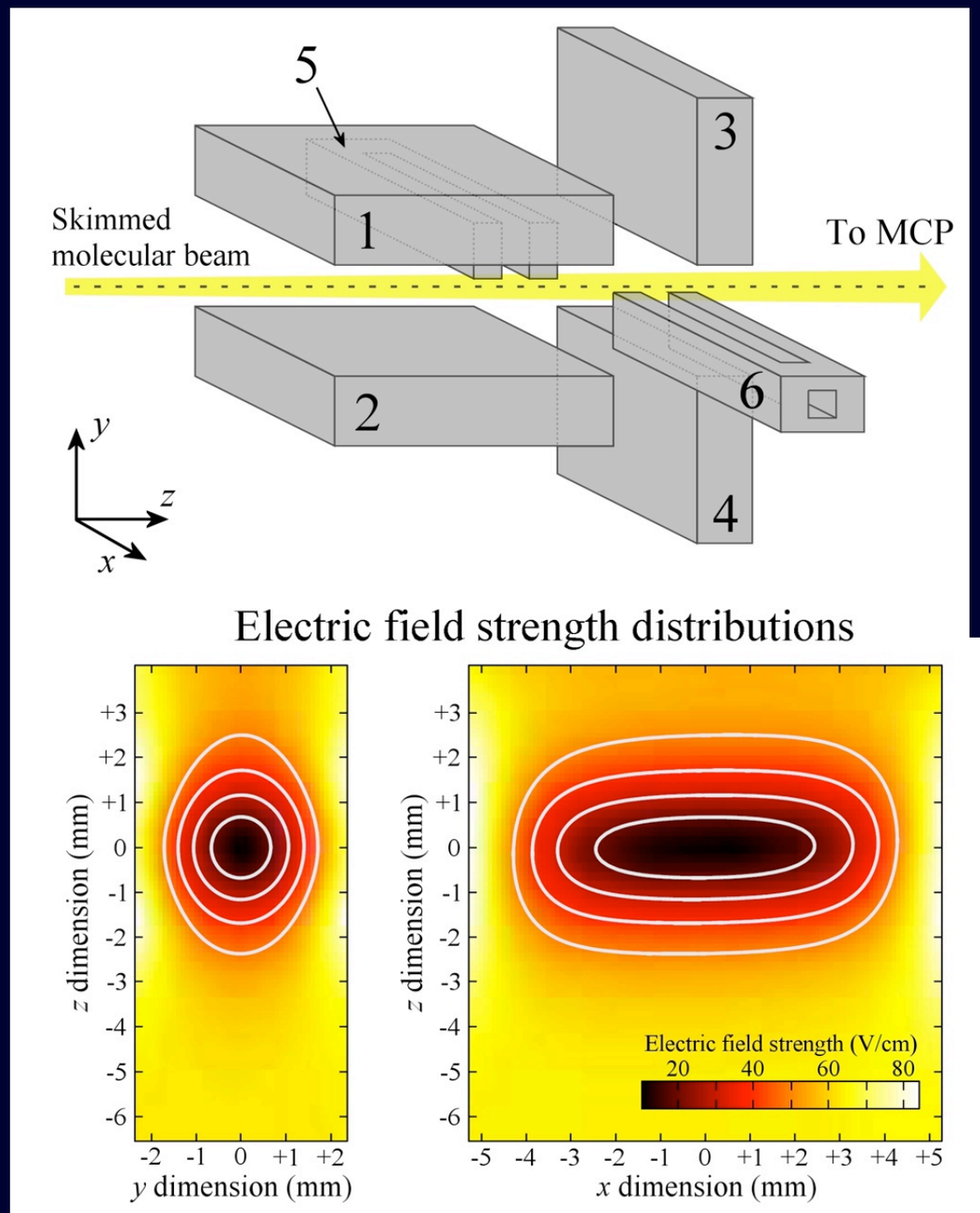
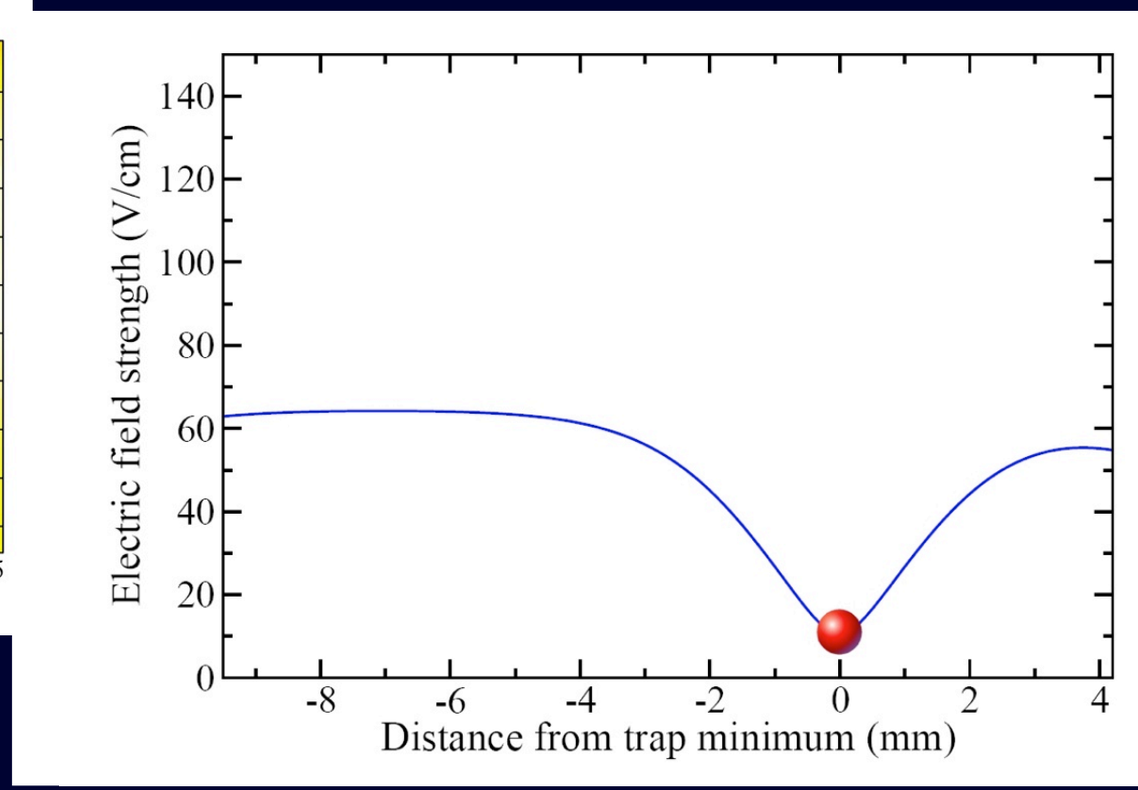
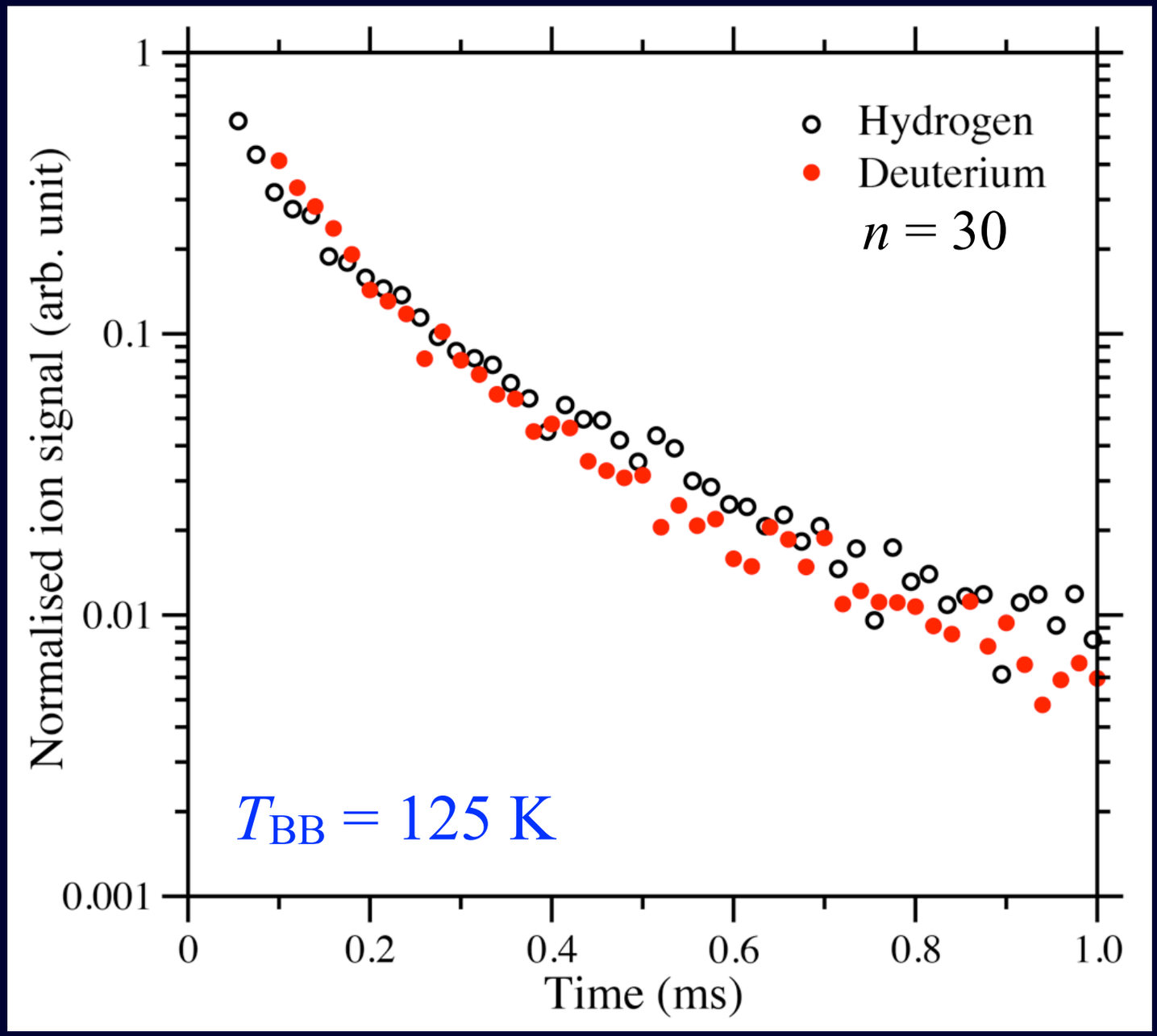


- 1. Photoexcitation
- 2. Deceleration
- 3. Electrostatic trapping



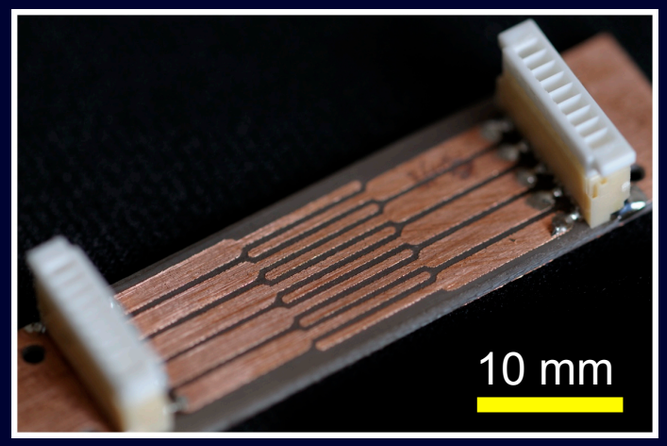
Electrostatic trapping H and D



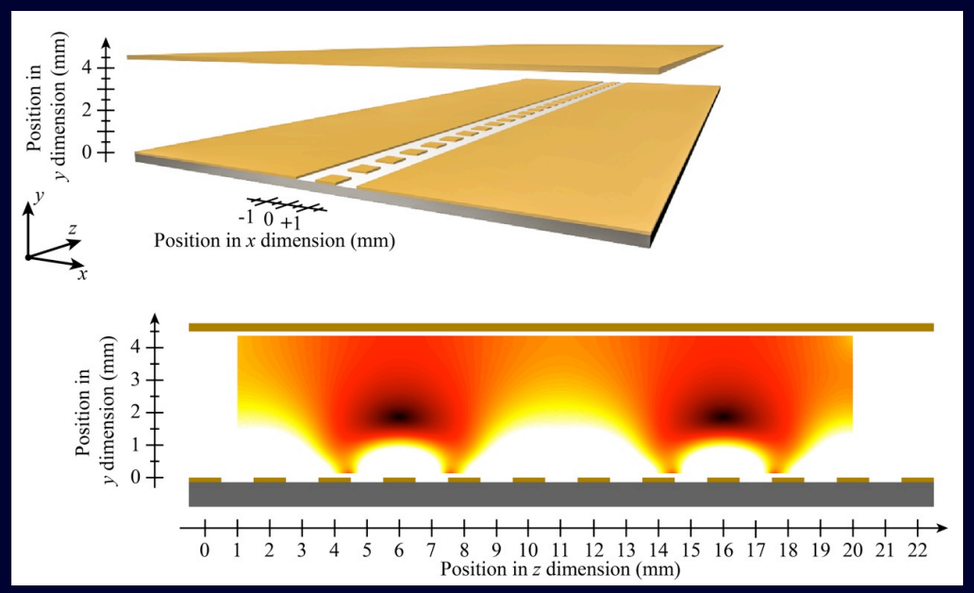
Hogan, Seiler and Merkt, *J. Phys. B* **46**, 045303 (2013)

Chip-based decelerators

- Scalable miniature decelerators



Hogan, Allmendinger, Saßmannshausen, Schmutz and Merkt
Phys. Rev. Lett. **108**, 063008 (2012)



Lancuba and Hogan, *Phys. Rev. A* **90**, 053420 (2014)

Atom number densities

- Multistage Zeeman deceleration and magnetic trapping D atoms

  ~10^5 atoms trapped; $n \cong 10^6$ cm^{-3}

- Rydberg-Stark deceleration and electrostatic trapping D atoms

  ~10^5 atoms trapped; $n \cong 10^7$ cm^{-3}

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- Trapped atom number densities limited by D atom source

  NH_3 / ND_3 photodissociation

$$NH_3 + h\nu \rightarrow NH_2 + H$$
$$ND_3 + h\nu \rightarrow ND_2 + D$$

NH_2 densities of 10^{12} cm^{-3} have been achieved

Willitsch, Dyke, and Merkt, *Mol. Phys.* **102**, 1543 (2004)

Atom number densities

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1. - Optimisation of ND_3 photodissociation
- Dissociation of D_2 in electric discharge or by electron impact

factor of ≥ 10^4 increase in D atom density

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2. Increase phase space acceptance of decelerators to address larger fraction of atoms in beams: *factor of ~10 increase in density*

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factor of ≥ 10^4 increase in D atom density

2. Increase phase space acceptance of decelerators to address larger fraction of atoms in beams: *factor of ~10 increase in density*

3. Load multiple bunches of atoms into magnetic trap:
factor of 10 – 100 increase in density

Prospects for T atom trapping

- Techniques of multistage Zeeman deceleration and Rydberg-Stark can be directly applied to T atoms

- Aim to develop high-density discharge/electron impact dissociation supersonic sources of H and D atoms with technology that can be transferred to T atoms

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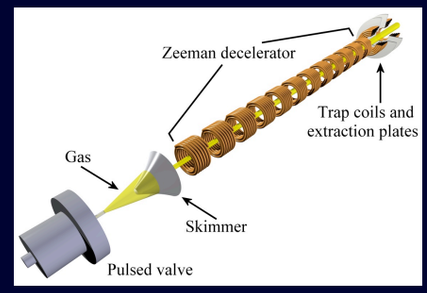
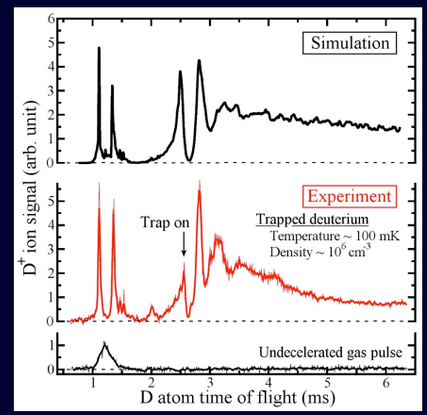
- Magnetic trapping ground state atoms
  - initially following multistage Zeeman deceleration
  - at later stage after decay to ground state following Rydberg-Stark deceleration

Summary

- Multistage Zeeman deceleration
  - Magnetic trapping ground state D atoms





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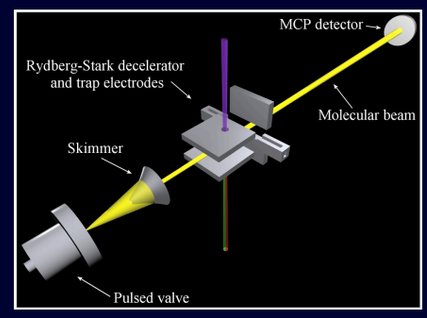
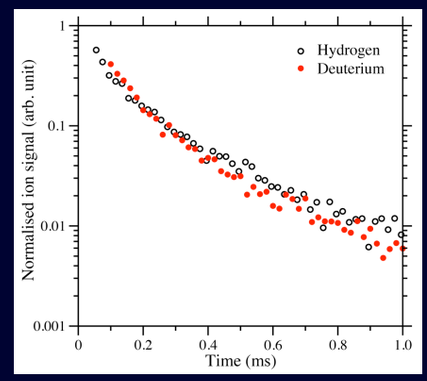
- Rydberg-Stark deceleration
  - Electrostatic trapping D atoms in Rydberg states





Christian Seiler and Frédéric Merkt (ETH Zurich)