Electrons monoénergétiques à partir de la ionisation d'atomes (froids)

Daniel Comparat

Laboratoire Aimé Cotton, CNRS, Université Paris-Sud, ENS Paris Sac

Raphaël Hahn
Colin Lopez
Zeudi Mazzotta
Elias Moufarej
Yan Picard

How to do it ?

- Photoionization of a gas
  - 1974
- Photoionization of a laser cooled gas
  - 2005
- Excitation of Rydberg atoms + field ionization
  - Our work

How to do it ?

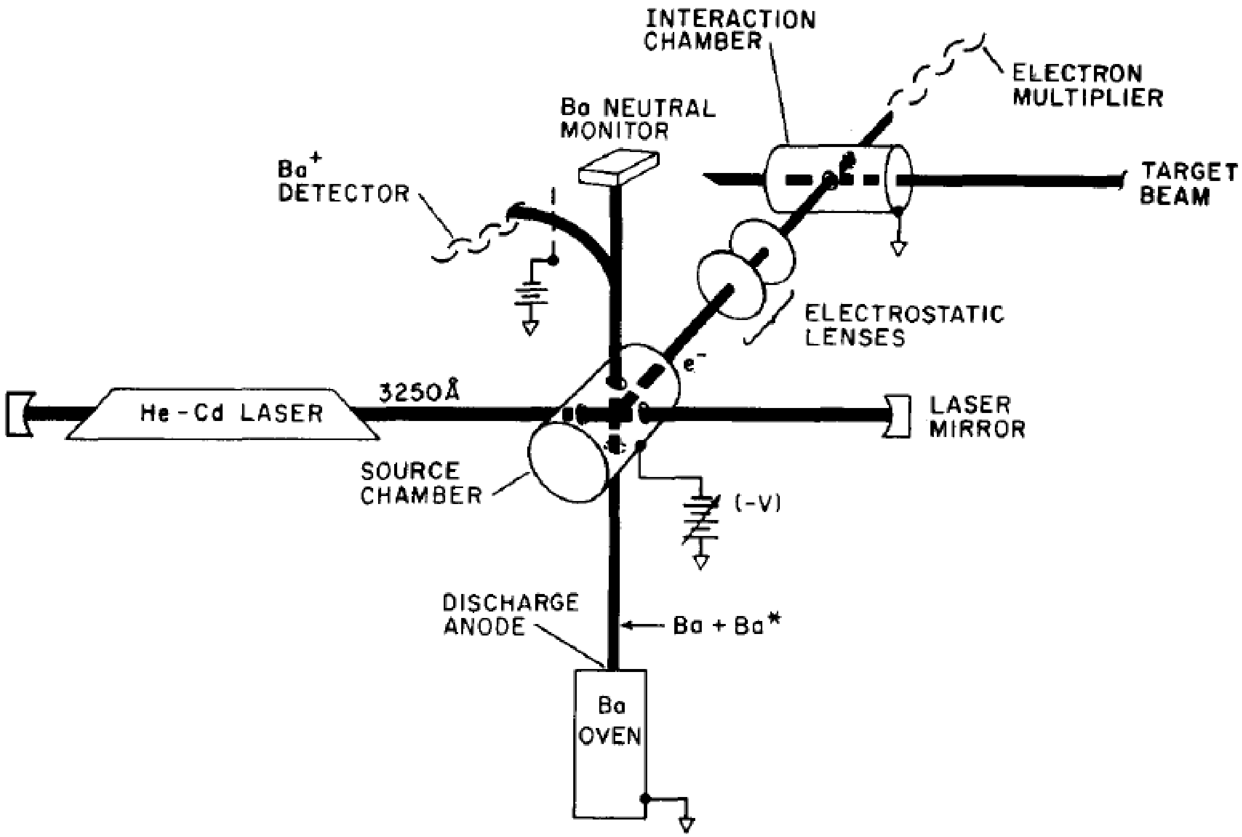
- Photoionization of a gas
  - 1974
- Photoionization of a laser cooled gas
  - 2005
- Excitation of Rydberg atoms + field ionization
  - Our work

A photoionization source of monoenergetic electrons*

A. C. Gallagher† and G. York

Joint Institute for Laboratory Astrophysics, National Bureau of Standards and University of Colorado, Boulder, Colorado 80302

Review of Scientific Instruments **45**, 662 (1974)

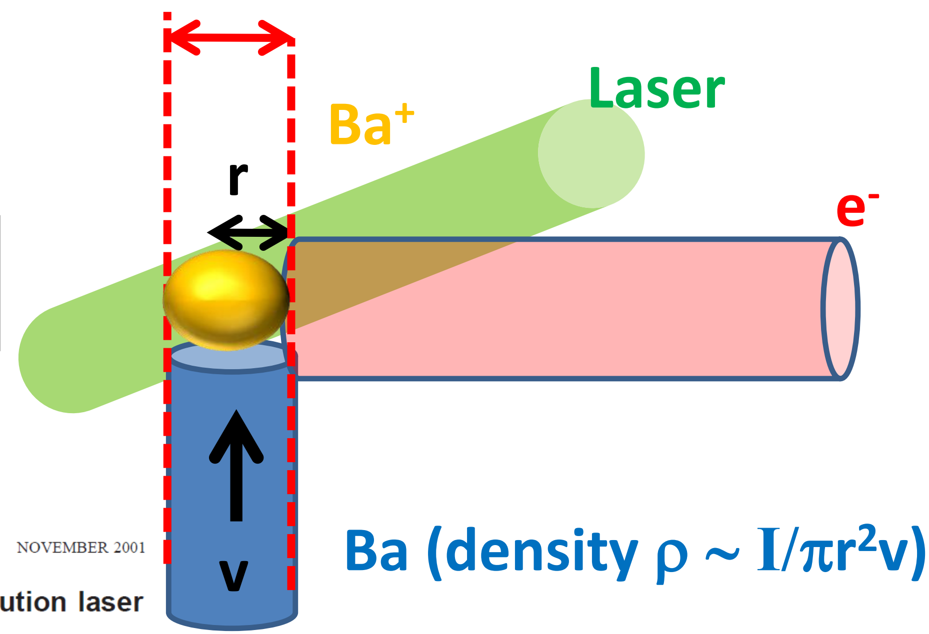


A photoionization source of monoenergetic electrons is described and design criteria for such sources are discussed. The present design produces a beam of $\simeq 10^{-12}$–10^{-13} A by photoionization of a metastable ($^1D_2$) barium beam inside the cavity of a He–Cd laser operating at 3250 Å. The photoelectrons are produced with 17 meV kinetic energy and a calculated energy spread of <1 meV. Energy analysis is provided by measuring the width of the 11.08 eV argon resonance. The observed width of this resonance has, to date, been limited to ~ 6 meV, but tests are reported which indicate that this width is largely due to Doppler spreading in the target atomic beam and potential gradients across the collision volume.

$$E(r) = \Delta V/r = (4\rho\pi r^3/3)/(4\pi r^2 \varepsilon_0)$$

$$\Delta V\ (\text{meV}) \sim I/(6\pi v \varepsilon_0)$$

$$\boxed{\Delta V\ (\text{meV}) \sim 10\ I(\text{nA})}$$



REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 72, NUMBER 11 NOVEMBER 2001

Energy broadening due to photoion space charge in a high resolution laser photoelectron source

J. Bömmels, E. Leber, A. Gopalan, J. M. Weber, S. Barsotti, M.-W. Ruf, and H. Hotop[a)]

A novel electron scattering apparatus combining a laser photoelectron source and a triply differentially pumped supersonic beam target: characterization and results for the $He^-(1s\,2s^2)$ resonance

Eur. Phys. J. D **22**, 17–29 (2003)

A. Gopalan[1], J. Bömmels[1], S. Götte[1], A. Landwehr[1], K. Franz[1], M.-W. Ruf[1], H. Hotop[1,a], and K. Bartschat[2,b]

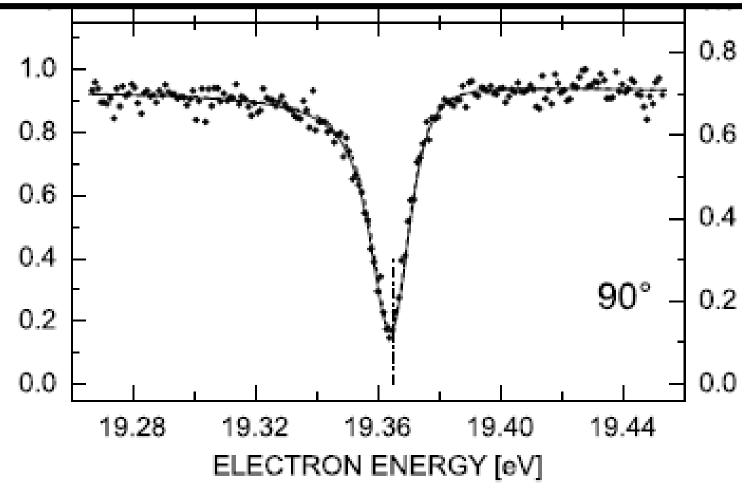
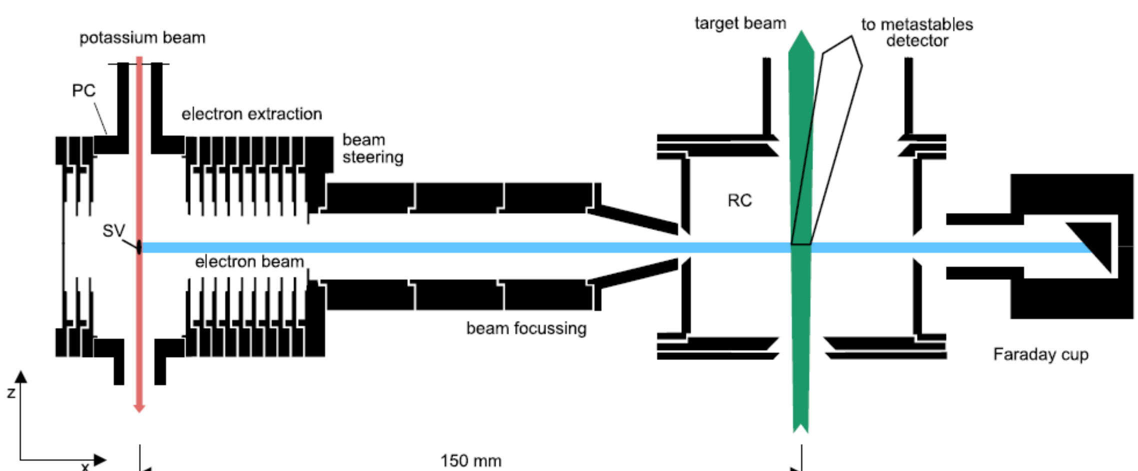


Fig. 11. Resonance profiles for the $He^-(1s\ 2s^2\ {}^2S_{1/2})$ reso-

~ 1 meV resolution

10 Kelvin

A. Gopalan *et al.*: A novel electron scattering apparatus: results for the $He^-(1s\ 2s^2)$ resonance



Attachment of Electrons to Molecules at meV Resolution*

Aust. J. Phys., 1992, **45**, 263–91

D. Klar, M.-W. Ruf and H. Hotop

TOPICAL REVIEW

J. Phys. B: At. Mol. Opt. Phys. 28 (1995) 1645–1672.

Electron–molecule collisions at very low electron energies

F B Dunning

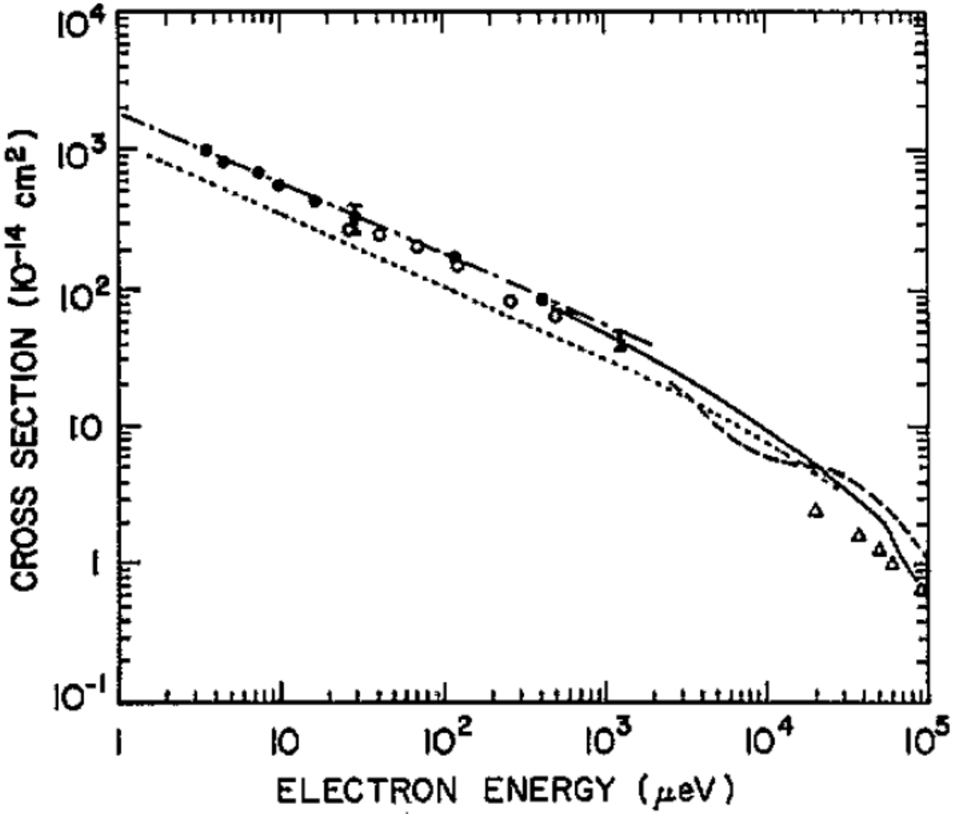
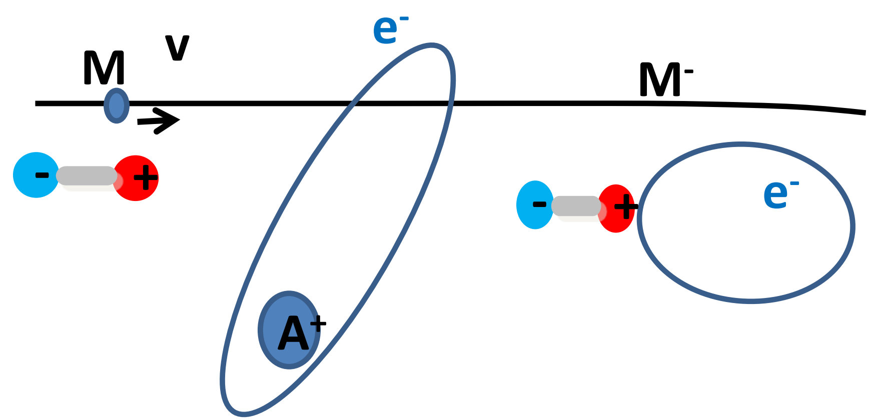


Figure 3. Cross sections for electron attachment to CCl_4. ●, $\bar{\sigma}_e$-K(np); — · —, $\sigma_e(v)$-K(np) (Frey *et al* 1994b); ○, $\bar{\sigma}_e$-K(np) (Ling *et al* 1992); ——, free electrons (Hotop 1994); – – –, free electrons (Orient *et al* 1989); △, free electrons (Christodoulides and Christophorou (1971); -----, theory (Klots 1976).



Electron in Rydberg atoms

~ 1-10 μeV resolution

How to do it ?

- Photoionization of a gas

  Low energy 10eV, 1nA, <1meV resolution

  - Require lots of laser power (cavity)
  - problem with ionic space charge **ΔV (meV) ~ 10 I(nA)**
  - Doppler spreading

- Photoionization of a laser cooled gas
  - 2005: ultra cold source ?

- Excitation of Rydberg atoms + field ionization
  - Our work

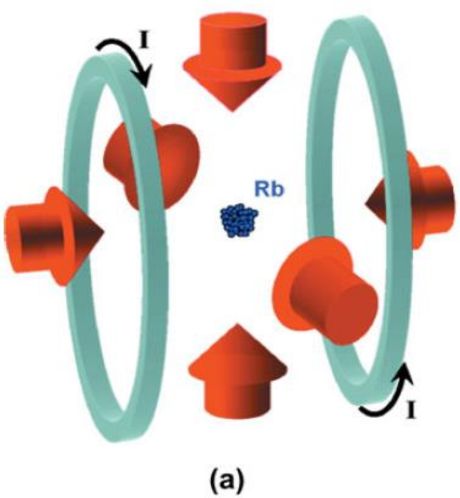
From cold atoms !

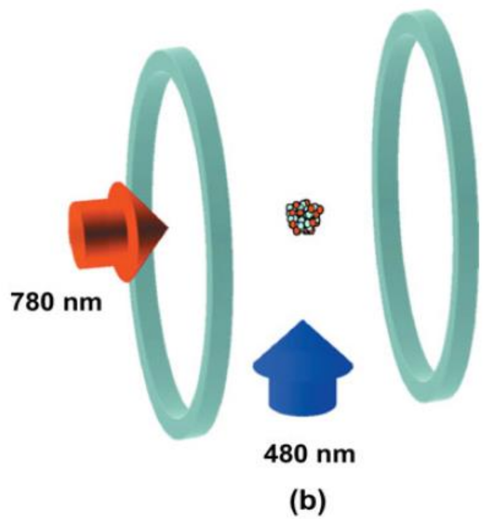
Idea: Phys. Rev. Lett. **95**, 164801 (2005)
Exp: Phys. Plasmas 14 093101 (2007)

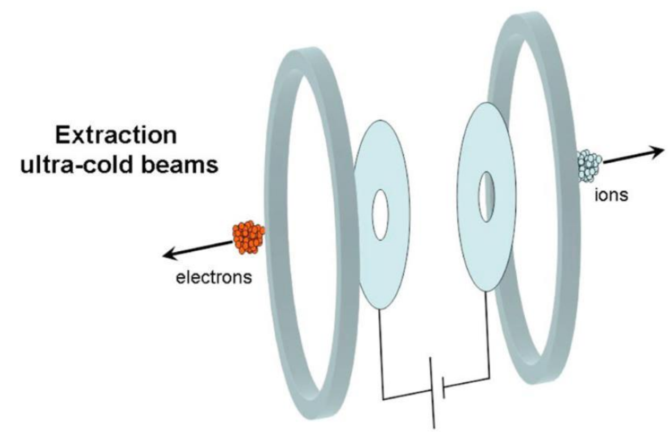
cold atoms

Photoionization

Acceleration





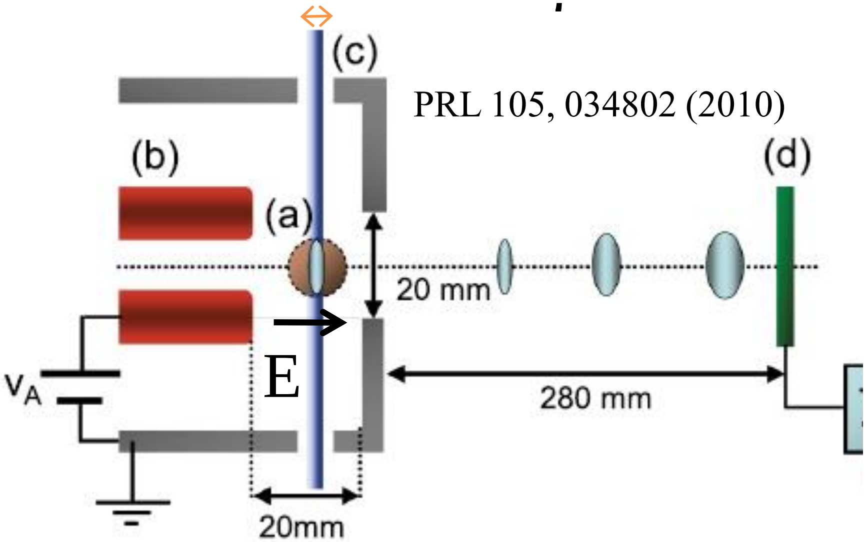


Microsc. Microanal. 15, 282–289, 2009

In 3D MOT (ions): low energy dispersion

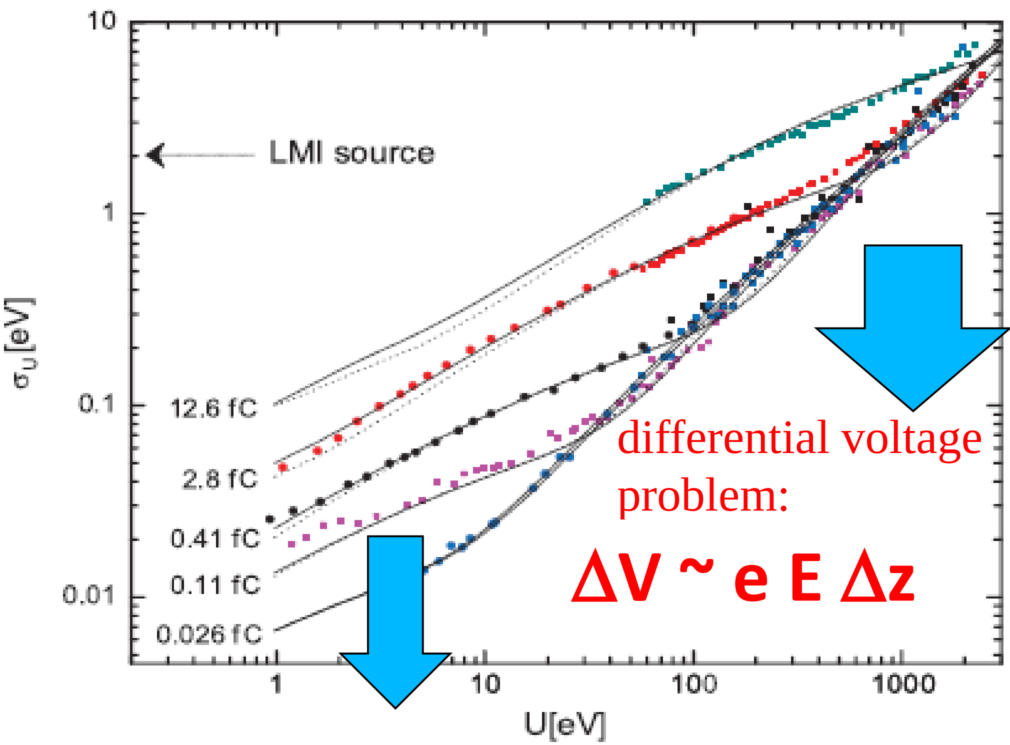
ΔU < 0.02 eV
Ion Beam Energy as low as 1 eV

Δz ~ 30µm



10 µK, 10^8 atomes in 1 mm^3

Rb 3D MOT: ion pulses



Coulomb explosion

High E (> 1keV) to avoid coulomb explosion

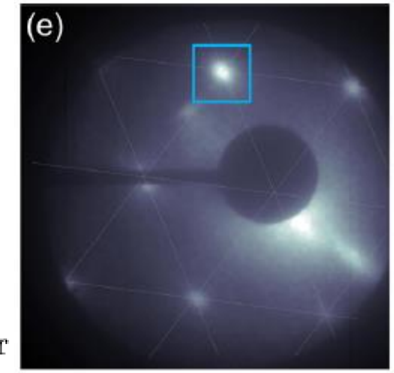
Low E (< 1keV) to avoid differential voltage problem

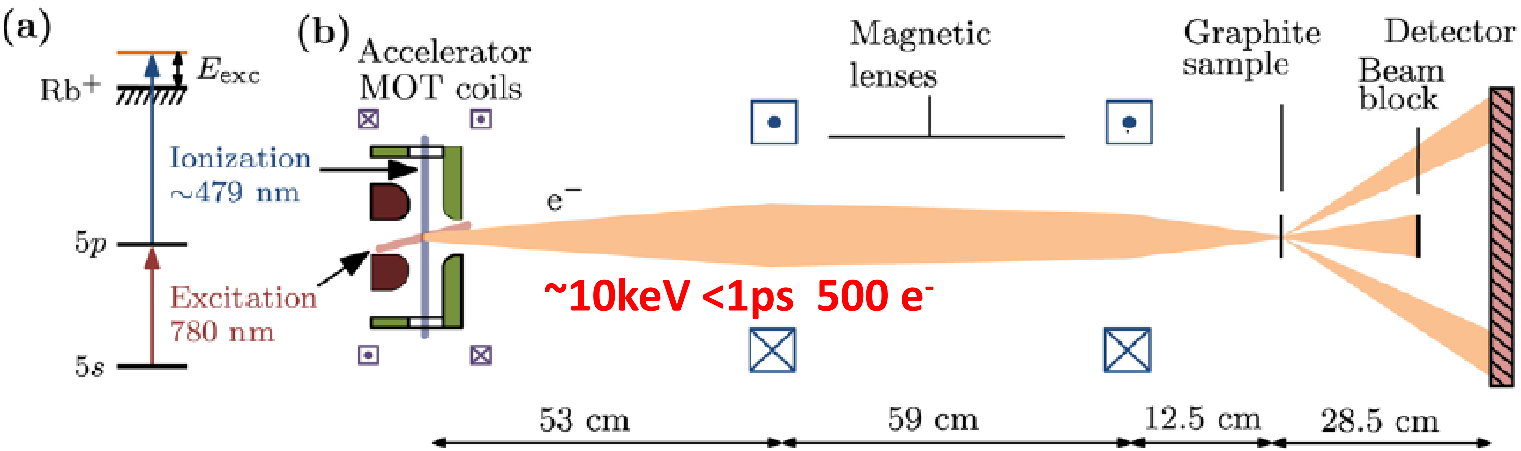
1keV on 10µm → ΔV ~ 10meV

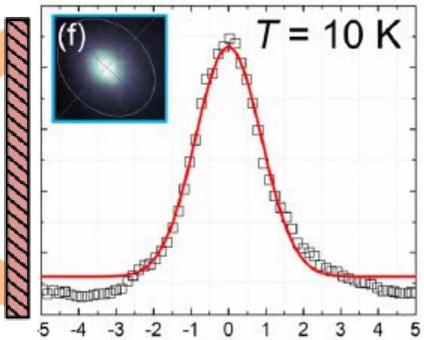
STRUCTURAL DYNAMICS 1, 034302 (2014)

Ultrafast electron diffraction using an ultracold source

M. W. van Mourik,[1] W. J. Engelen,[1] E. J. D. Vredenbregt,[1,2] and O. J. Luiten[1,2]

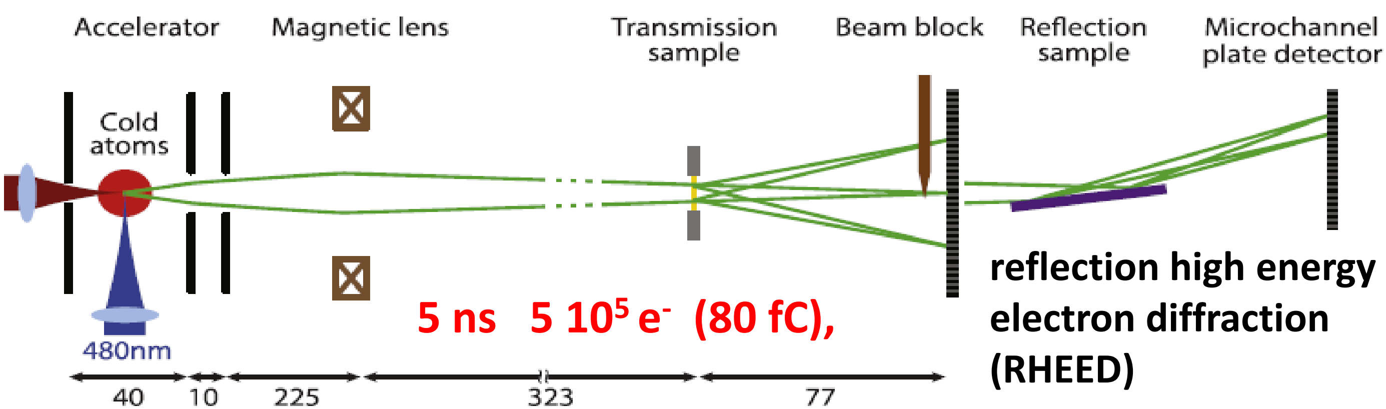




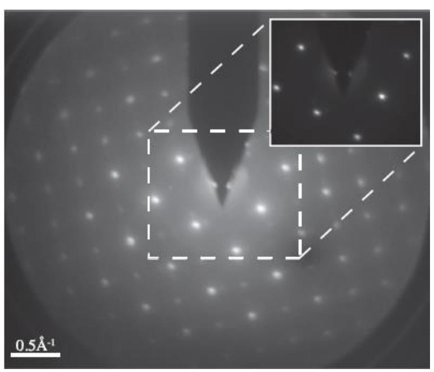


Single-shot electron diffraction using a cold atom electron source

Rory W Speirs[1], Corey T Putkunz[1], Andrew J McCulloch[1], Keith A Nugent[2], Benjamin M Sparkes[1] and Robert E Scholten[1]



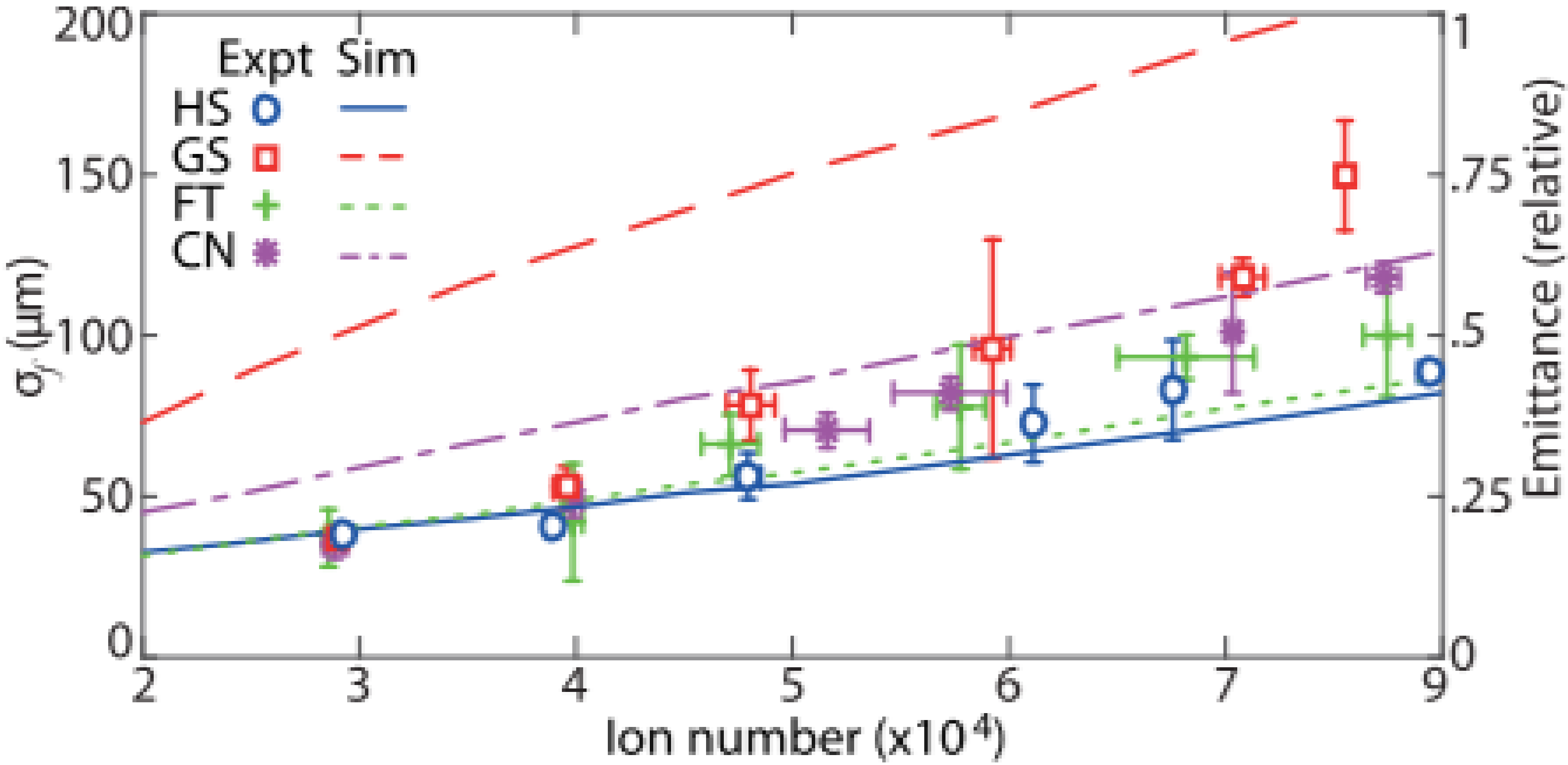
reflection high energy electron diffraction (RHEED)



Suppression of Emittance Growth Using a Shaped Cold Atom Electron and Ion Source

D. J. Thompson,[1] D. Murphy,[1] R. W. Speirs,[1] R. M. W. van Bijnen,[2] A. J. McCulloch,[1] R. E. Scholten,[1,*] and B. M. Sparkes[1]
[1]*School of Physics, The University of Melbourne, Victoria 3010, Australia*
[2]*Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

(Received 20 May 2016; published 3 November 2016)



For accelerators ?

J. Phys. B: At. Mol. Opt. Phys. 47 (2014) 234009 (8pp)
doi:10.1088/0953-4075/47/23/234009

An ultracold electron source as an injector for a compact SASE-FEL

S B van der Geer, E J D Vredenbregt, O J Luiten and M J de Loos

Department of Applied Physics, Eindhoven University of Technology, P O Box 513, 5600 MB Eindhoven, The Netherlands

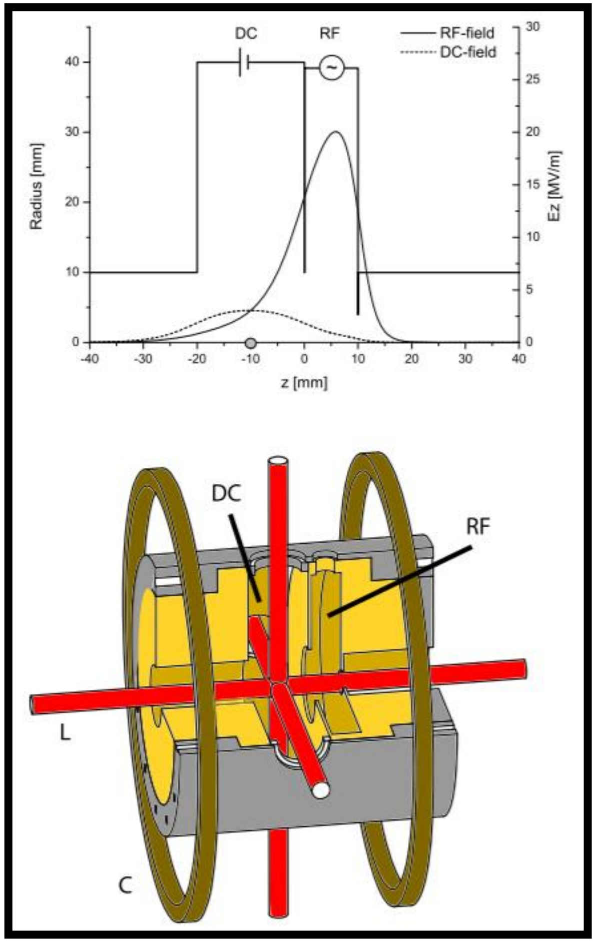
MOPFI074 Proceedings of IPAC2013, Shanghai, China

ULTRACOLD AND HIGH BRIGHTNESS ELECTRON SOURCE FOR NEXT GENERATION PARTICLE ACCELERATORS

G. Xia, M. Harvey, A. J. Murray, W. Bertsche, R. Appleby, S. Chattopadhyay
School of Physics and Astronomy, University of Manchester, Manchester, United Kindom

Table 1: Comparison between ultracold electron source and conventional electron source

	Ultracold Electron Source	Conventional electron source
Electron temperature [K]	<10	1000-10000
Beam charge (pC)	1000	100-3000
Emittance[mm.mrad]	0.04	~1
Brightness [A/m^2 sr]	10^{16}	10^{12}-10^{13}
Bunch length [ps]	0.1-1	~10
Lifetime [hours]	no age limit	< few hundred

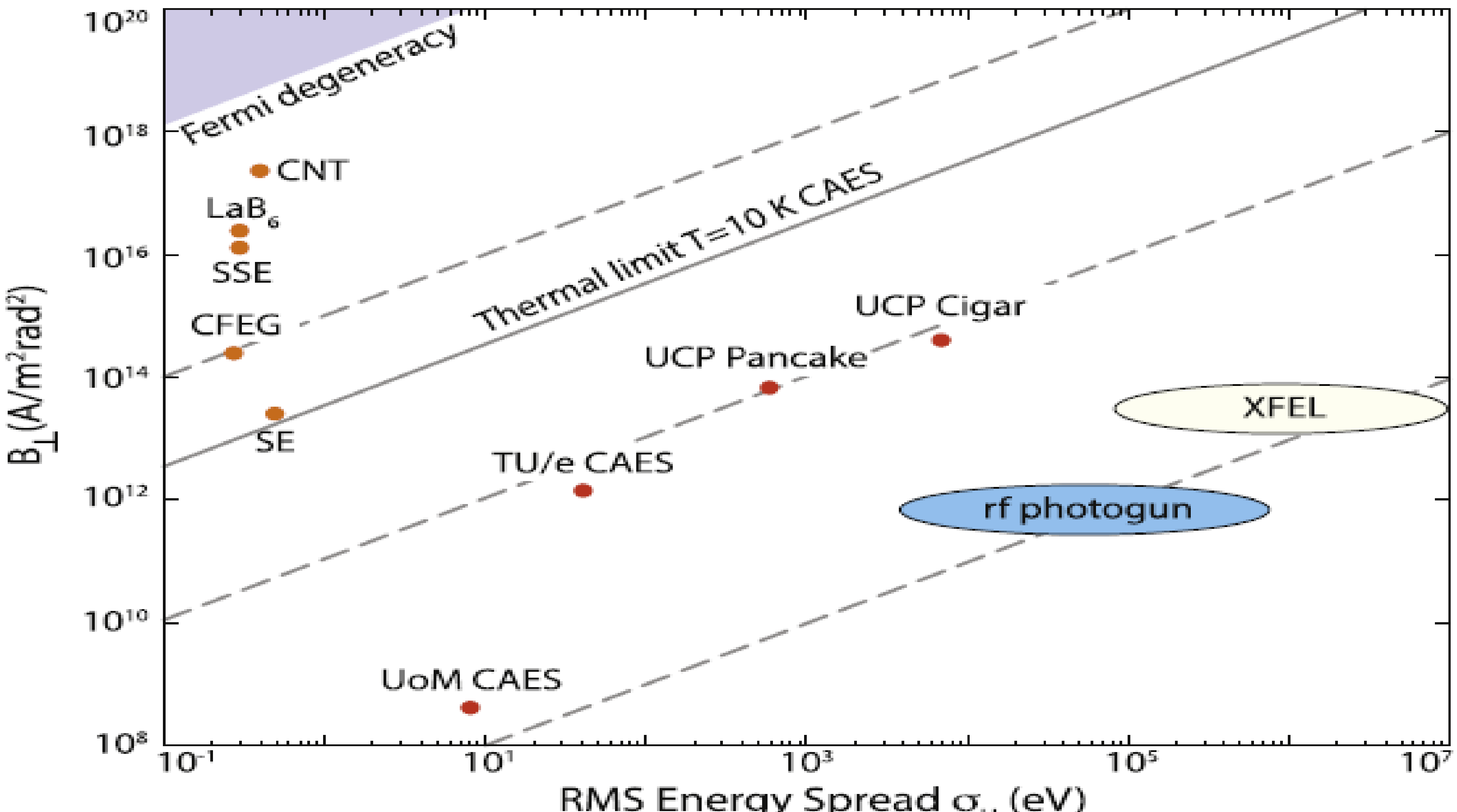


IOP Publishing
Journal of Physics B: Atomic, Molecular and Optical Physics
J. Phys. B: At. Mol. Opt. Phys. **49** (2016) 164004 (17pp)
doi:10.1088/0953-4075/49/16/164004

Cold electron sources using laser-cooled atoms

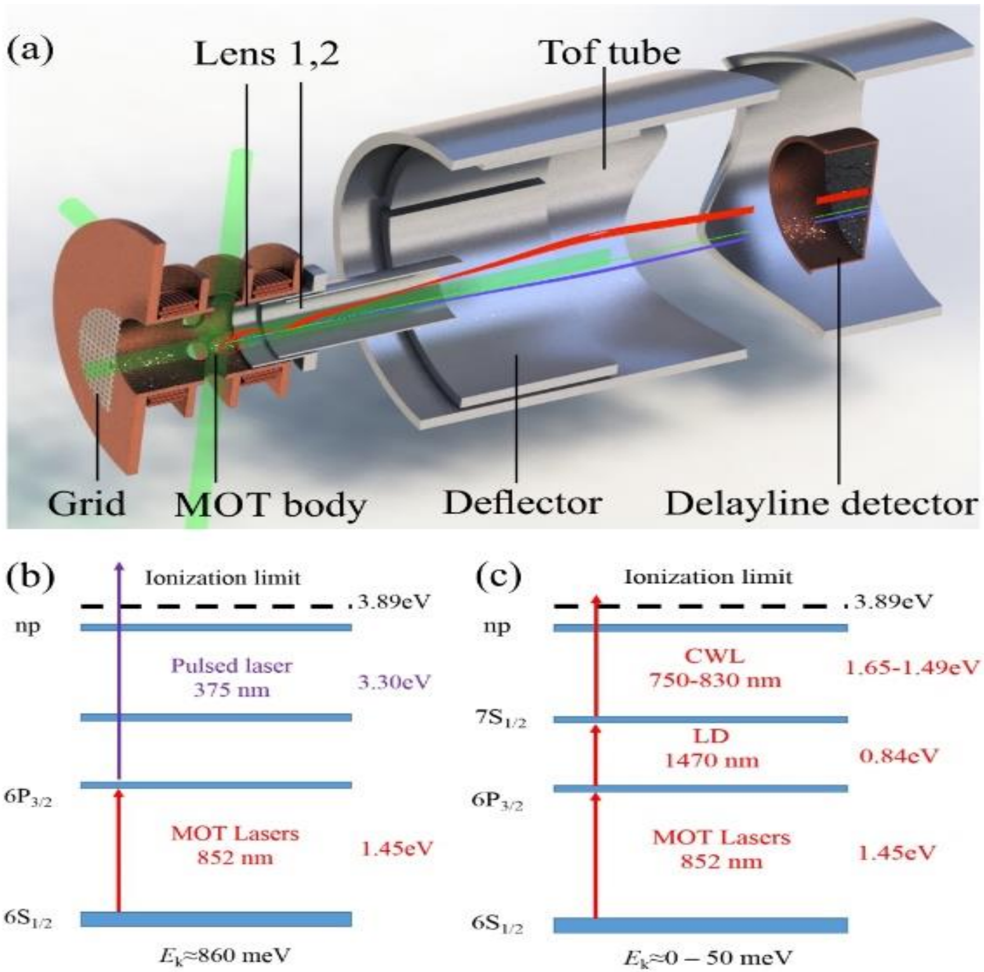
Andrew J McCulloch[1], Ben M Sparkes[1] and Robert E Scholten

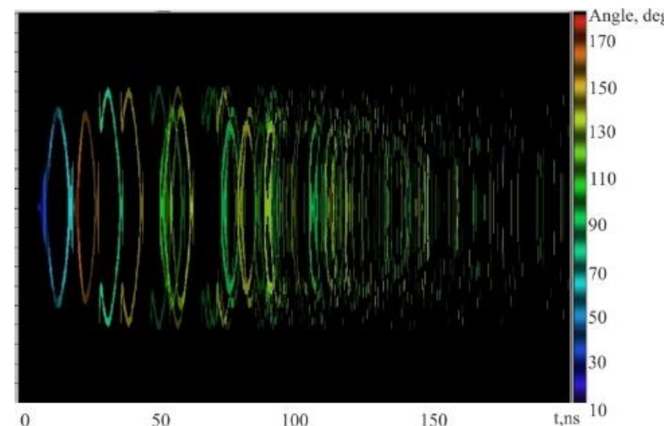
School of Physics, The University of Melbourne, 3010, Australia

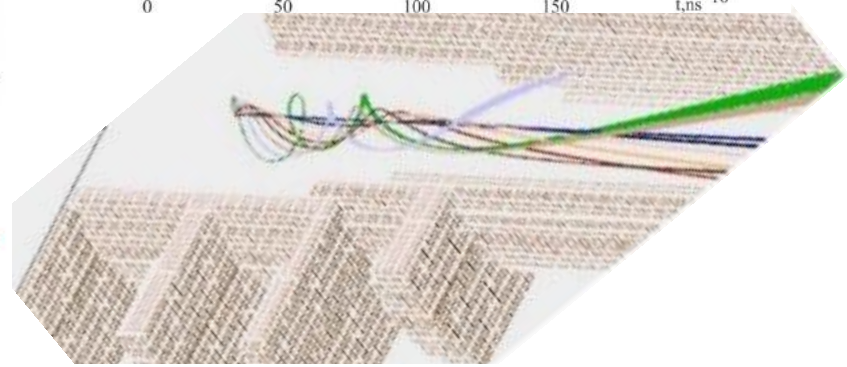


Pulsed Electron Beam by Photoionization of Cold Cs-Atoms in a Magneto-Optical Trap

Olena Fedchenko, Sergii Chernov, Gerd Schönhense → Mainz, Germany
Andrew McCulloch, → Melbourne, Australia
Mélissa Vielle-Grosjean, Daniel Comparat → Orsay, France







Energy ~100eV → width of a few meV, pulses in the 100ps range are more demanding (in progress, B field off)

How to do it ?

- Photoionization of a gas

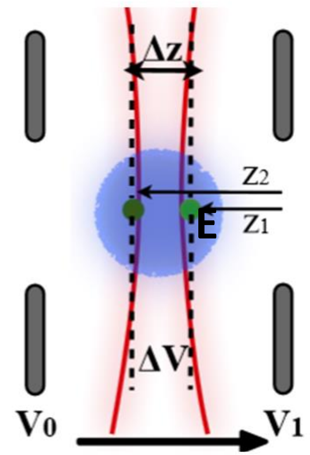
  Low energy 10eV, 1nA, <1meV resolution

  - Require lots of laser power (cavity)
  - problem with ionic space charge **ΔV (meV) ~ 10 I(nA)**
  - Doppler spreading

- Photoionization of a laser cooled gas

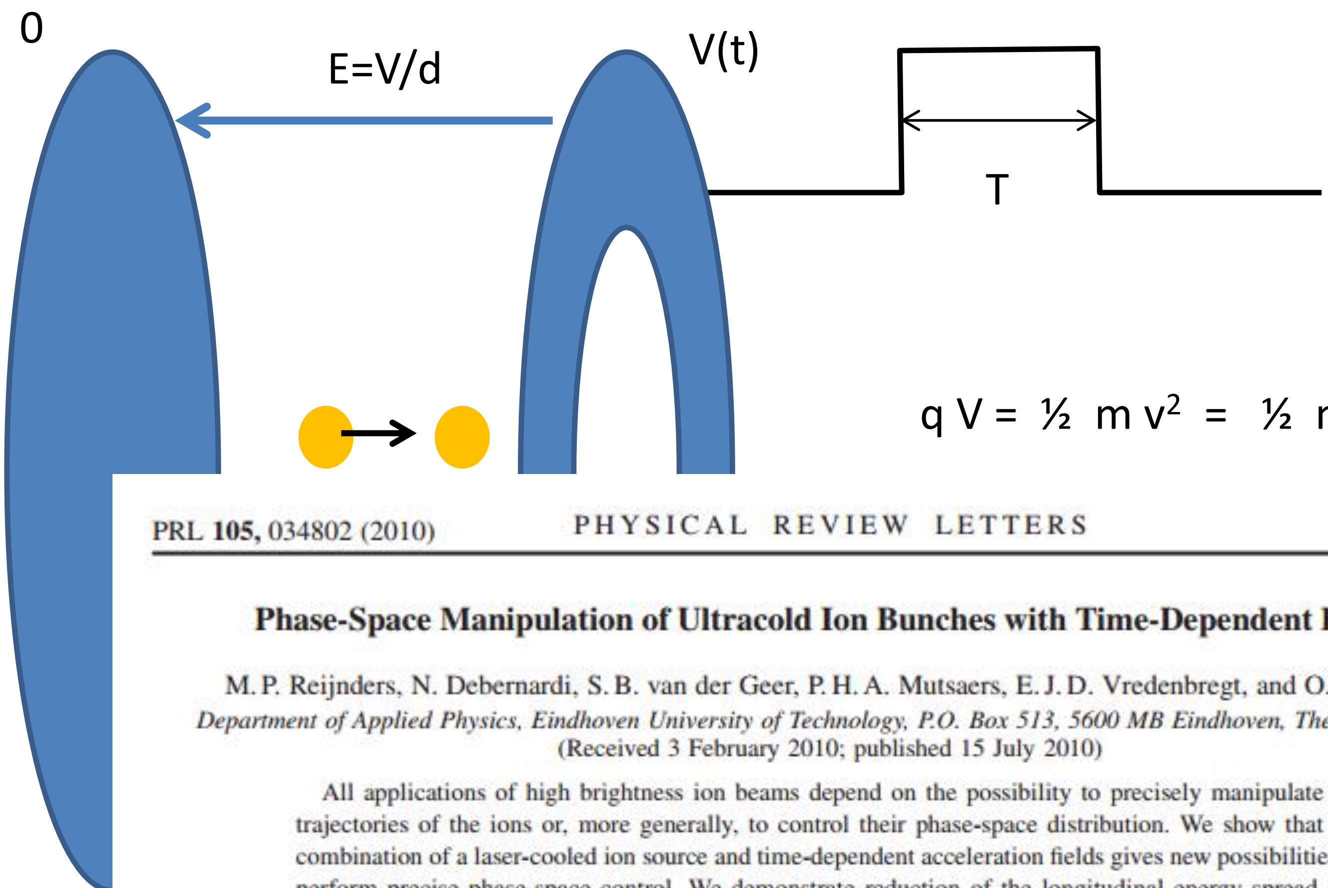
  1ps 10keV $10^5 e^-$ ~100meV

  - Not so ultra cold (>10 K) « Yes for ions » (1 mK)
  - Differential voltage problem: **ΔV ~ e E Δz**



- Excitation of Rydberg atoms + field ionization
  - Our work at Orsay

No differential voltage problem → pulsed



$$q\,V = \tfrac{1}{2}\, m\, v^2 = \tfrac{1}{2}\, m\,(q\,E\,T/m)^2$$

cities !

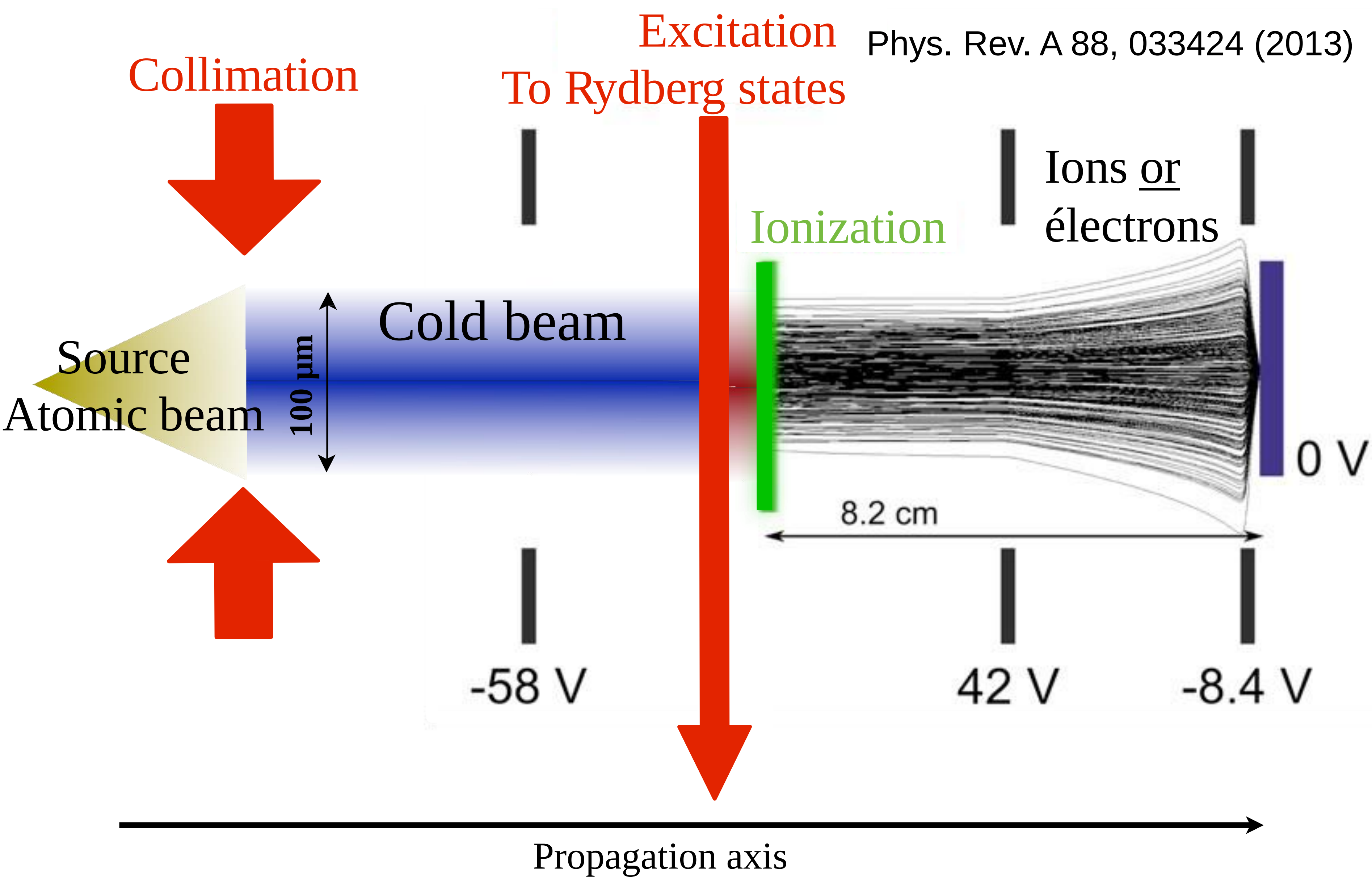
PRL 105, 034802 (2010) PHYSICAL REVIEW LETTERS week ending 16 JULY 2010

Phase-Space Manipulation of Ultracold Ion Bunches with Time-Dependent Fields

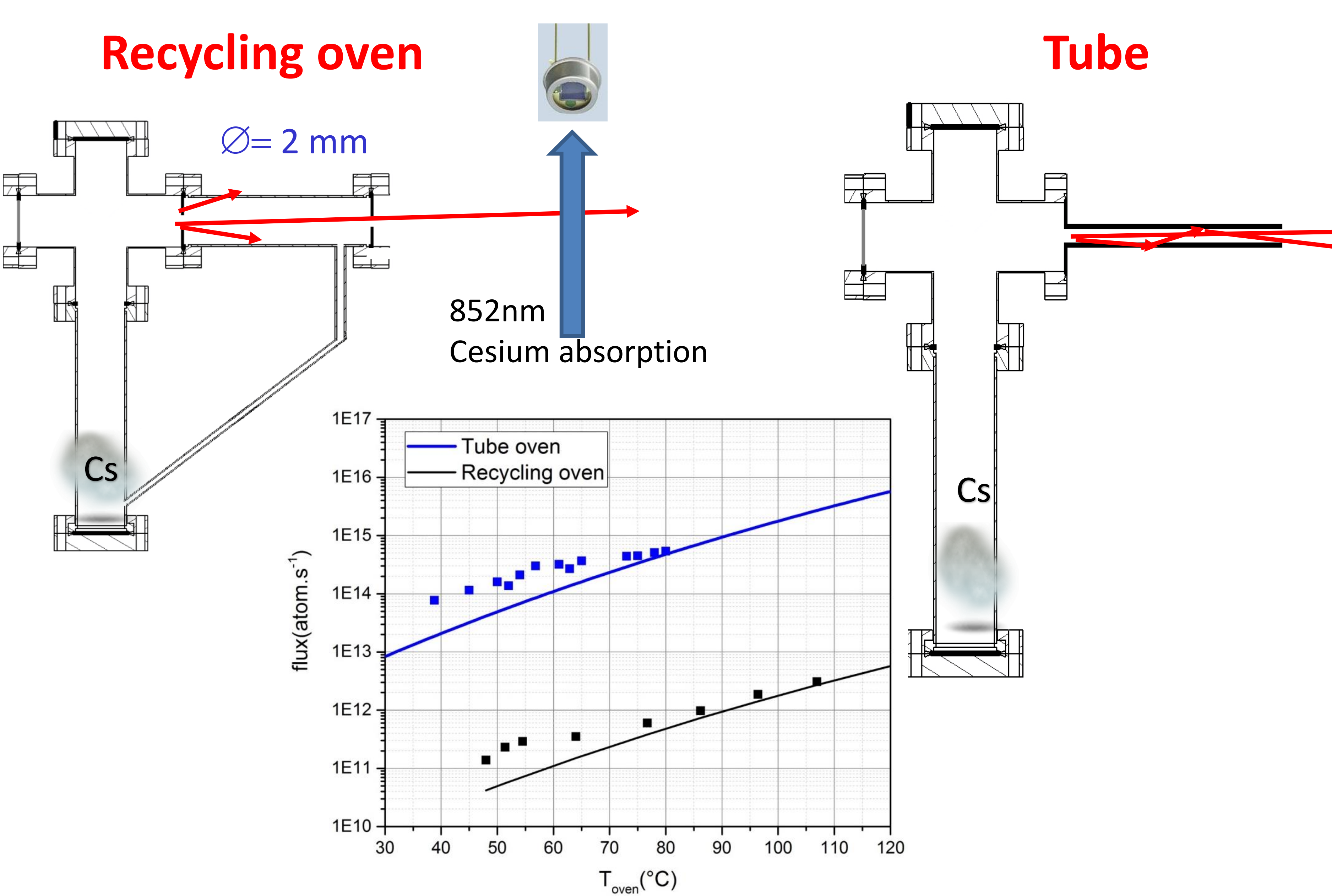
M. P. Reijnders, N. Debernardi, S. B. van der Geer, P. H. A. Mutsaers, E. J. D. Vredenbregt, and O. J. Luiten
Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
(Received 3 February 2010; published 15 July 2010)

All applications of high brightness ion beams depend on the possibility to precisely manipulate the trajectories of the ions or, more generally, to control their phase-space distribution. We show that the combination of a laser-cooled ion source and time-dependent acceleration fields gives new possibilities to perform precise phase-space control. We demonstrate reduction of the longitudinal energy spread and realization of a lens with control over its focal length and sign, as well as the sign of the spherical aberrations. This creates new possibilities to correct for the spherical and chromatic aberrations which are presently limiting the spatial resolution.

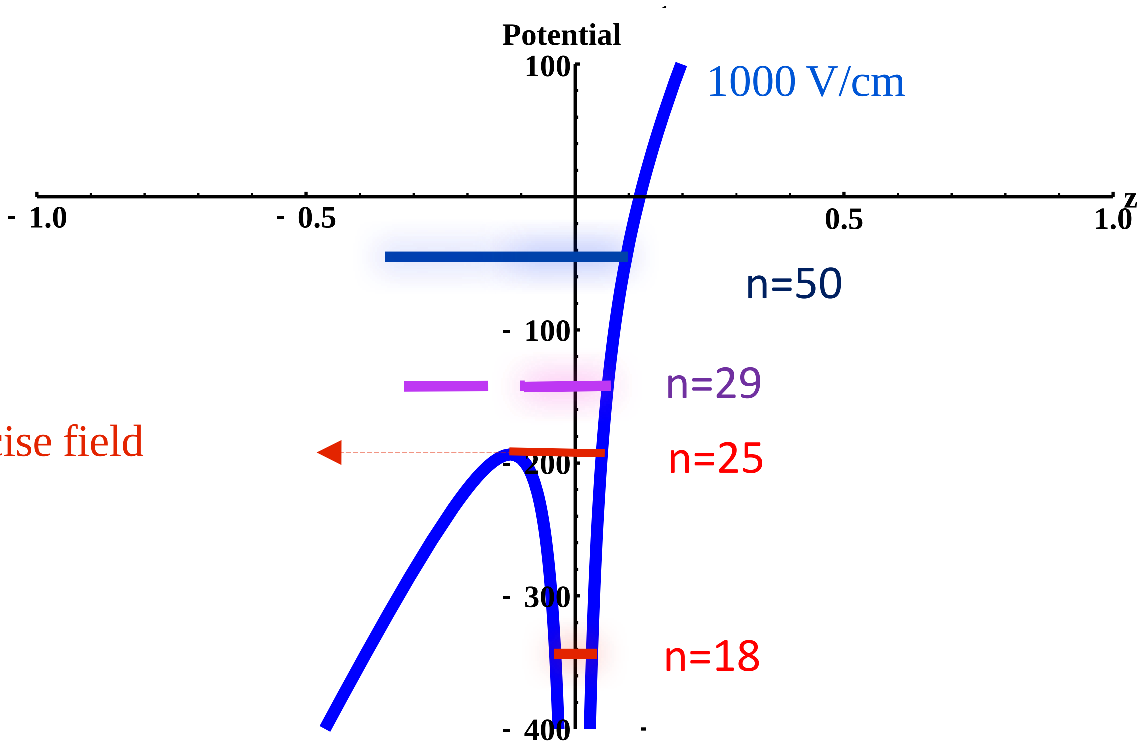
Other solution: Rydberg field ionization



Study of cesium oven



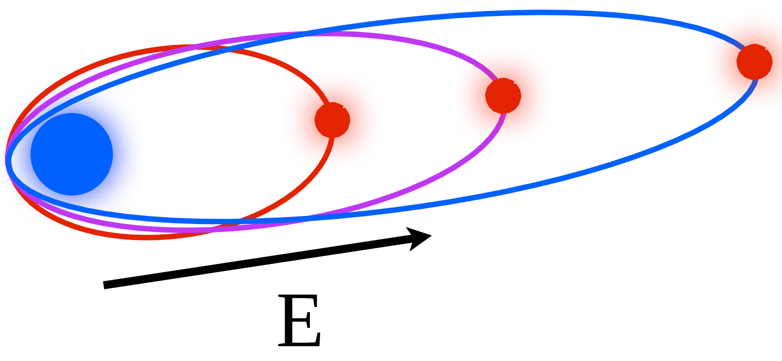
Rydberg states and electric field



Ionisation at a precise field

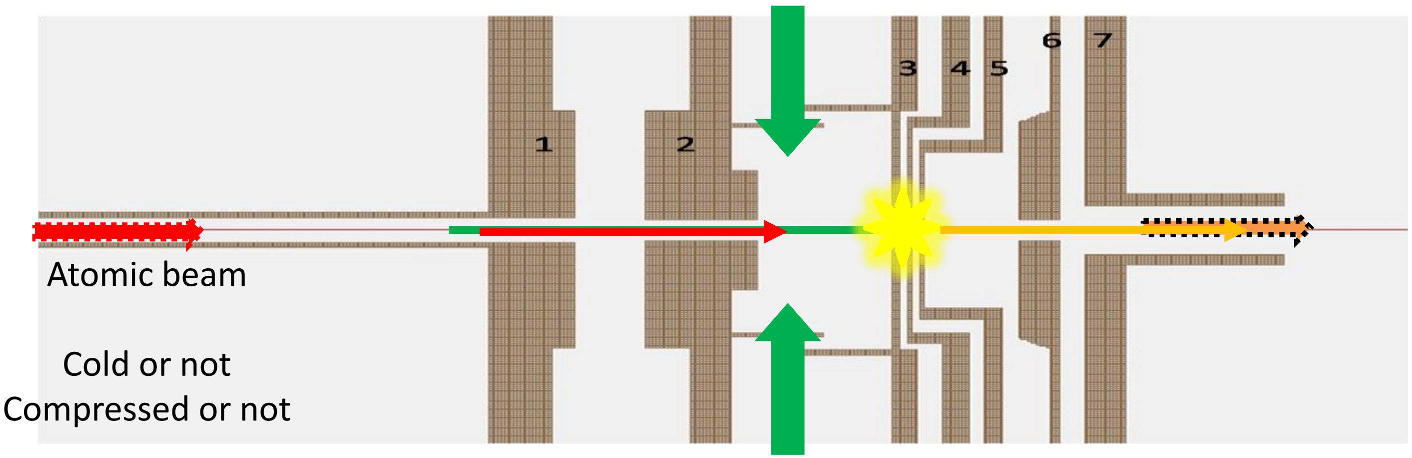
Ionization field:

$$E \sim \frac{3\ \text{V/cm}}{(n/100)^4}$$

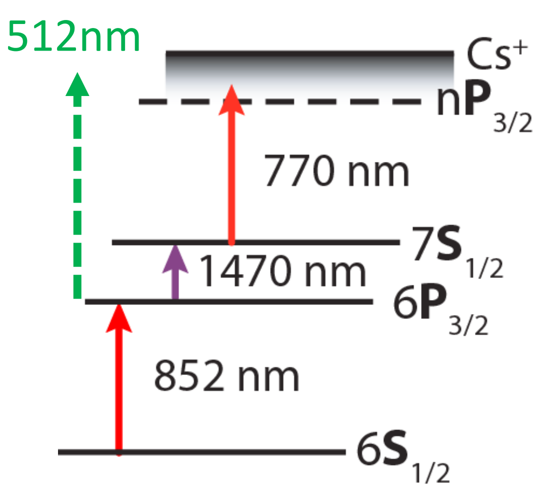


Basic idea

less laser power required

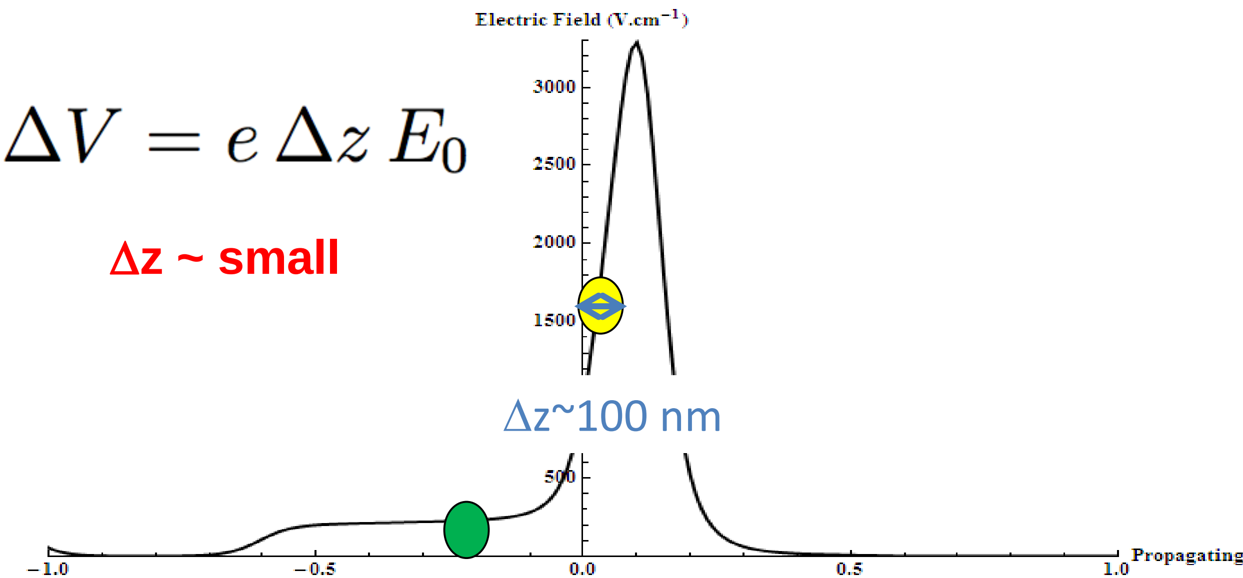


2D Cs MOT



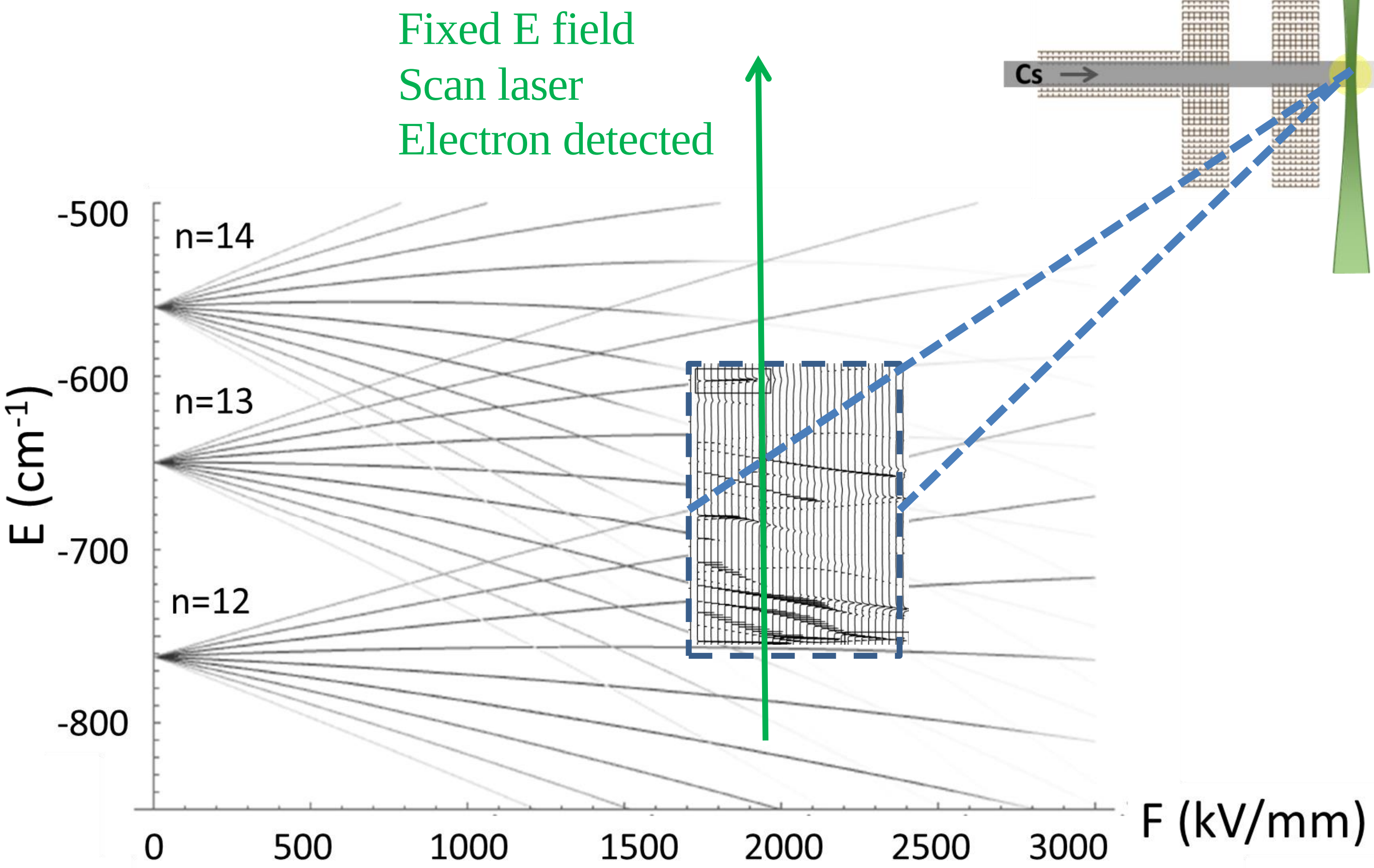
$$\Delta V = e\,\Delta z\,E_0$$

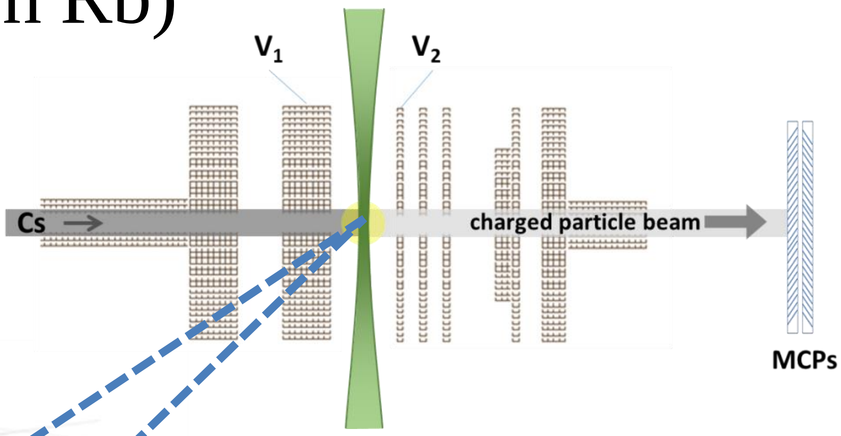
Δz ~ small

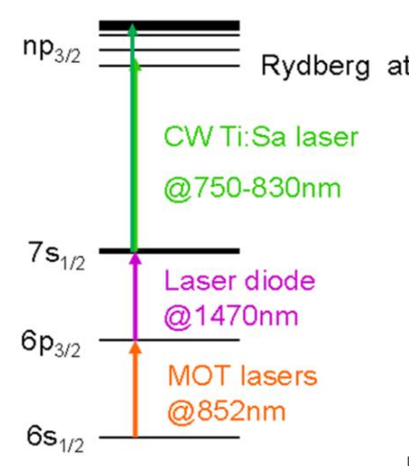


Forced field ionization of Rydberg states for the production of monochromatic beams *PRA accepted*

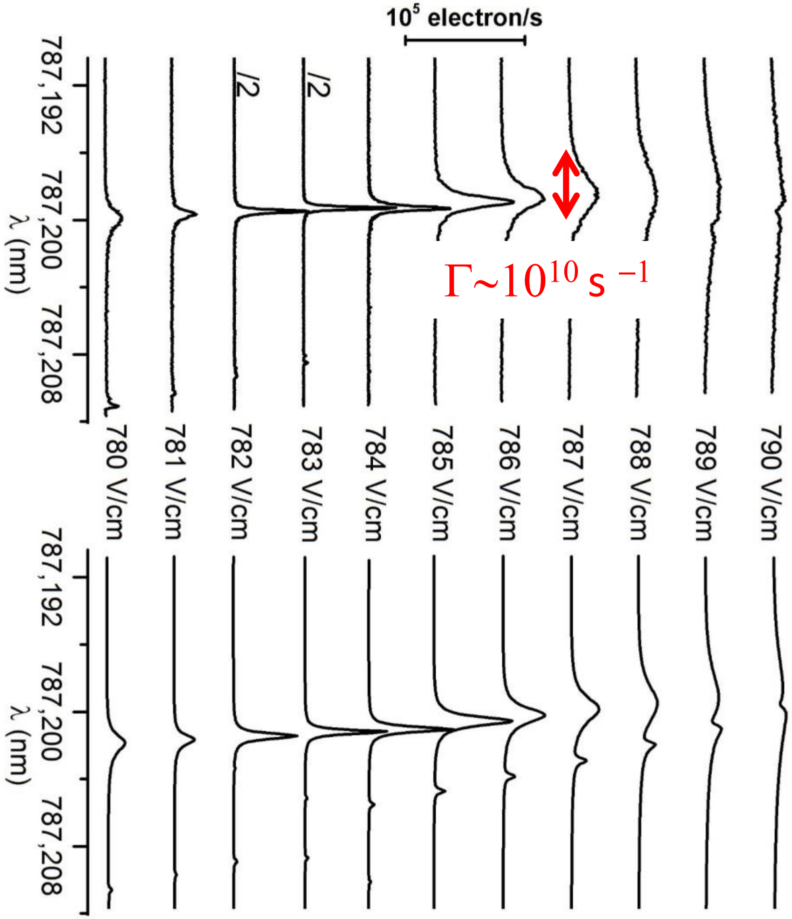
* R. Scholten + A. McCulloch (on Rb)
* Francis Robicheaux (theory)







Ex: Possible useful state



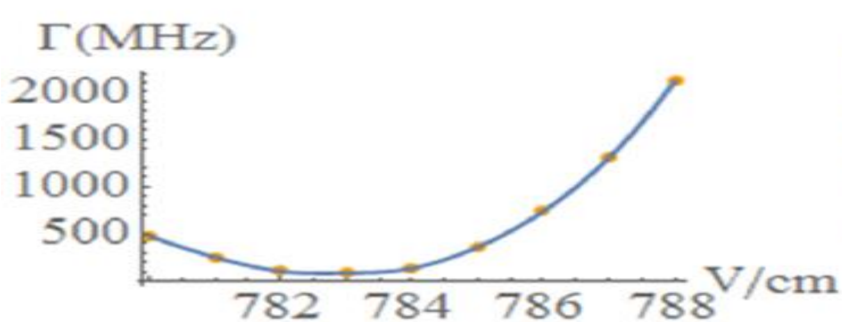
Exp.

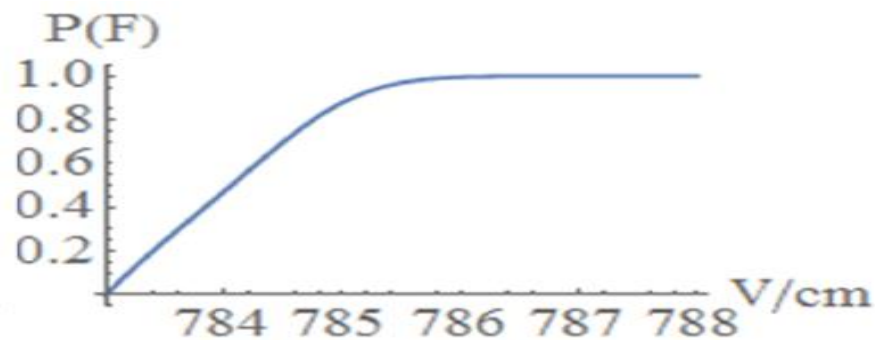
Th.

v ~ 100m/s
E ~ 1000 V/cm
$\Gamma \sim 10^{10}\,\mathrm{s}^{-1}$

ΔV ~ e E Δz ~ e E v/Γ

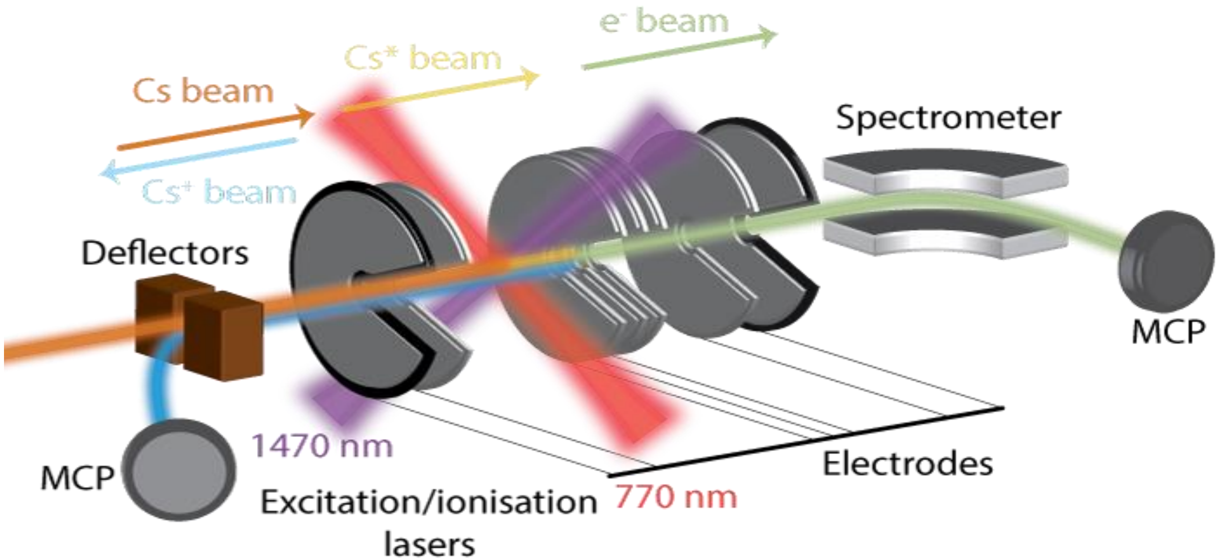
ΔV ~ 1 meV

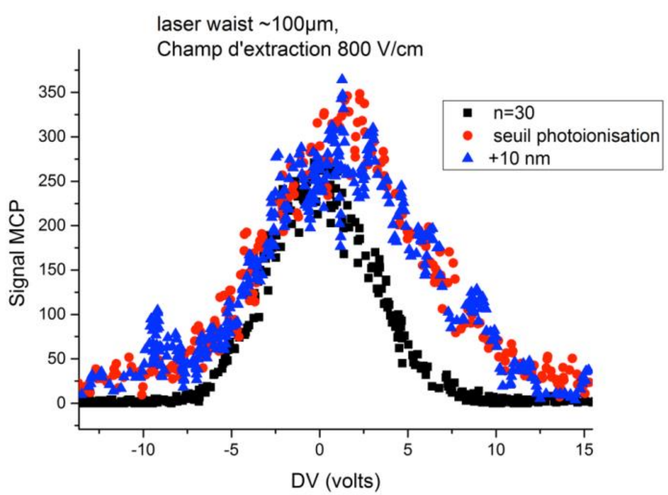




Toward measure of energy dispersion

Cs OVEN





In 2015: Rydberg seems better than photoionization

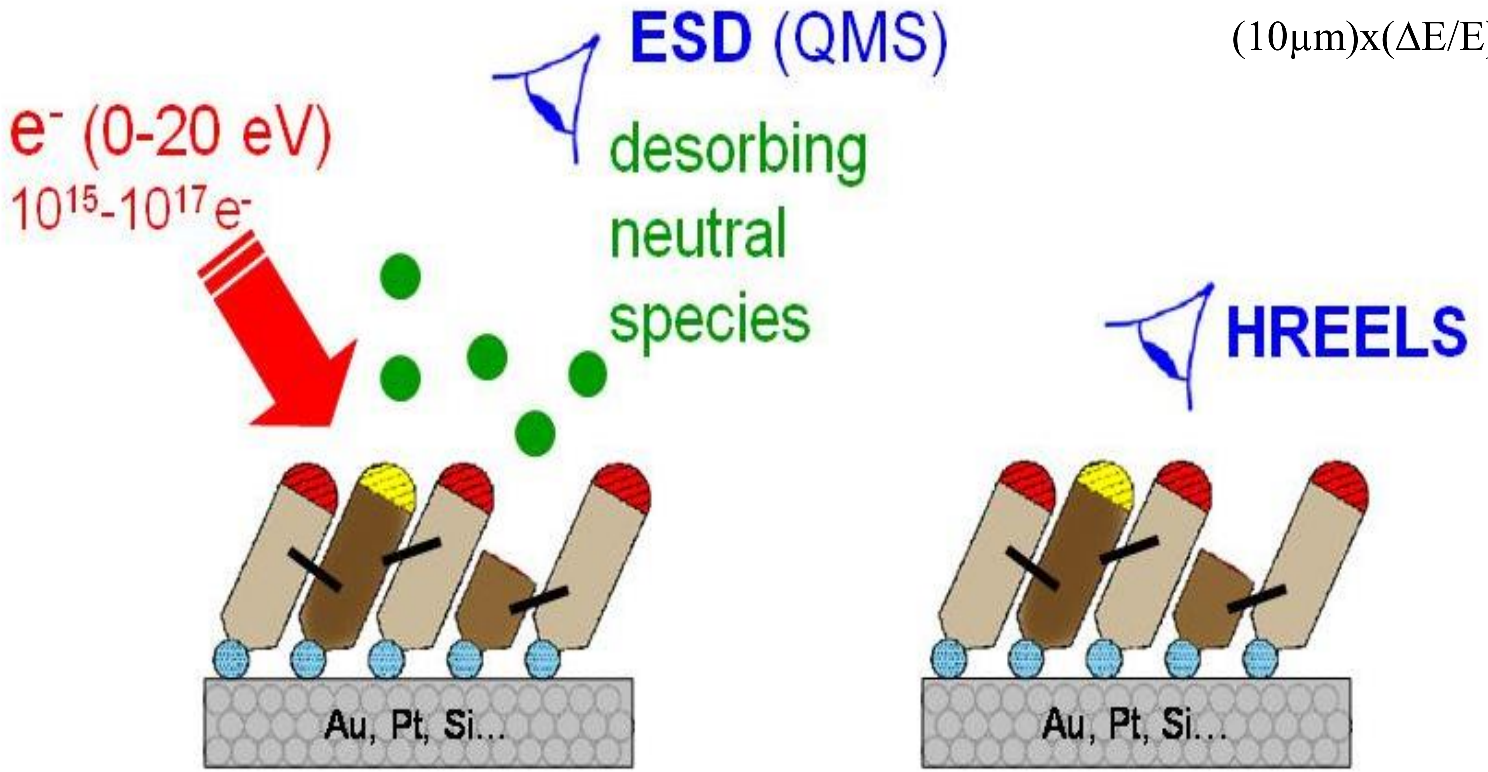
Futur application at ISMO: ANR/DFG

Nanofunctionalisation of molecules on surfaces.

- Current source: **5 µA on (1 mm²) (1 A/m²)**
- New source: **10 pA on (10 nm)² (10^5 A/m²)**

goal → **Better spatial resolution and energy spread**

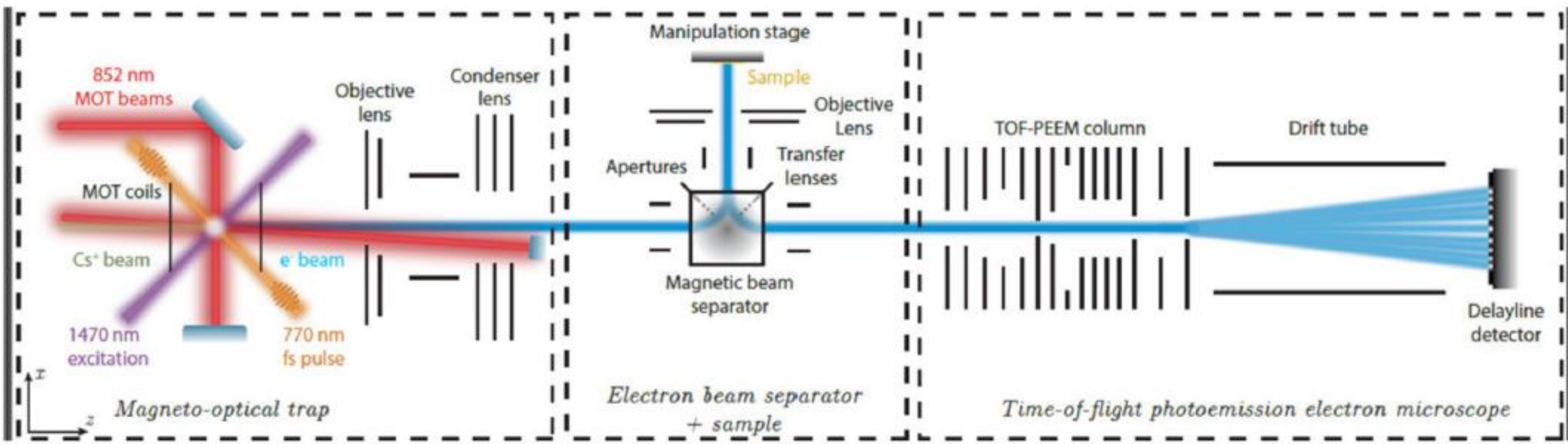
focus limit :
(10µm)x(ΔE/E)



Futur

HREELM :High resolution electron energy loss **microscopy**

ISMO:
Lionel Amiaud, Anne Lafosse



SPCSI:
Nicholas BARRETT, Claire MATHIEU

Univ. of Mainz:
Gerd Schönhense

LAC
Yan Picard, Daniel Comparat

Conclusion

- Photoionization of a gas

  Low energy 10eV, 1nA, <1meV resolution

  - problem with ionic space charge **ΔV (meV) ~ 10 I(nA)**

- Photoionization of a laser cooled gas

  1ps 10keV 10^5e- ~100meV

  - Not so ultra cold (>10 K) !!
  - Differential voltage problem: **ΔV ~ e E Δz**

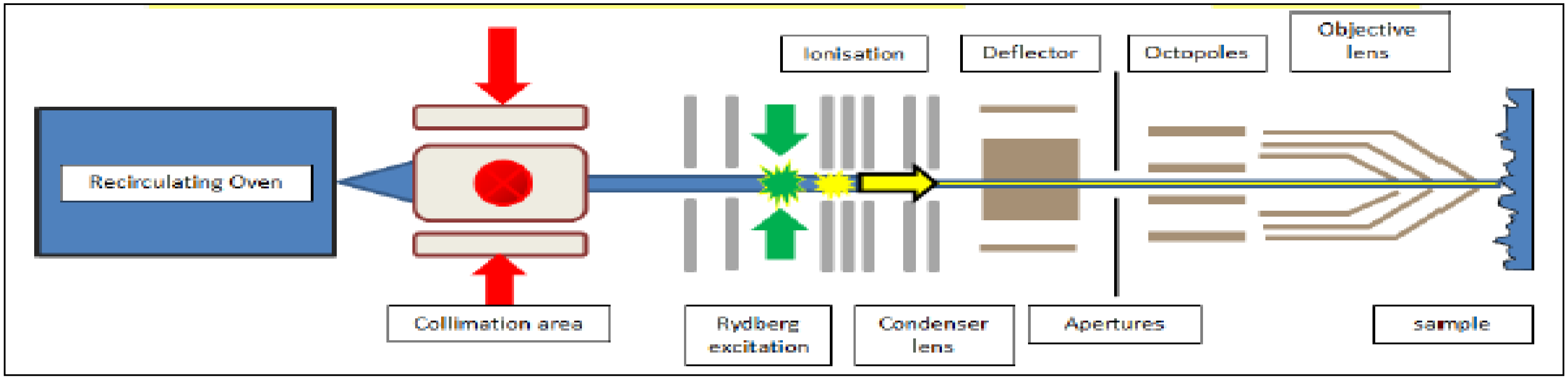
- Excitation of Rydberg atoms + field ionization

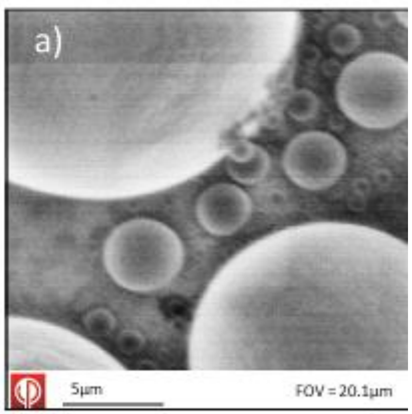
  ~1-10 meV, 1 nA (new oven ?)

  - Require less laser power (10mW no cavity)

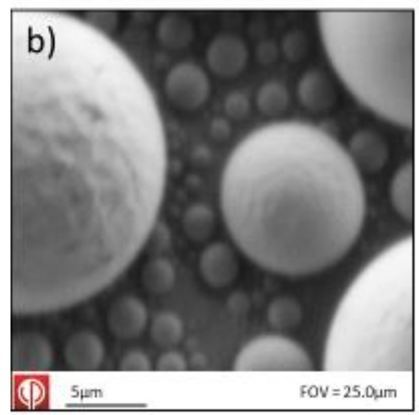
Focused beam→ industrial product ?

ORSAY PHYSICS
TESCAN ORSAY HOLDING





Our cold source Cs^+



State of the art

Focused ion beam Ga^+

Ultramicroscopy164(2016)70–77

Current 130 pA.
Energy 1-5 keV
resolution around 40 nm,
energy spread ~1 eV,

Next step: Industrial lasers (Muquans, AzurLight Systems, LP2N)