Trapped atoms as a source of cold electrons

Edgar Vredenbregt

Coherence and Quantum Technology group

with Wouter Engelen, Daniël Bakker, Bas van der Geer, Rick van Bijnen, Nicola Debernardi, Jom Luiten and many others

Department of Applied Physics

TU/e Technische Universiteit Eindhoven University of Technology

Where innovation starts

Big thanks to ...

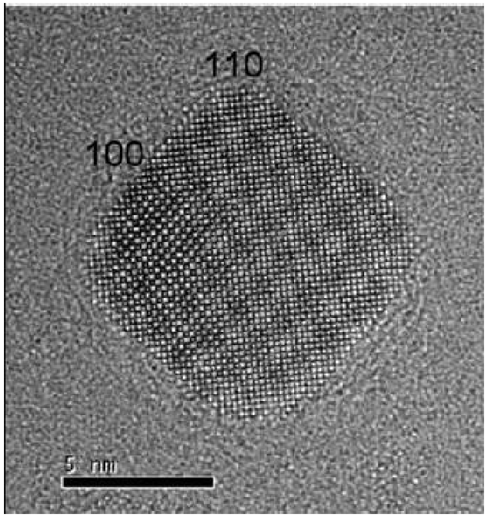
Daniel Comparat and the Orsay team

- for organizing this
- coming up with the idea
- venue, finances
- scientific program
- in France (Nimes)

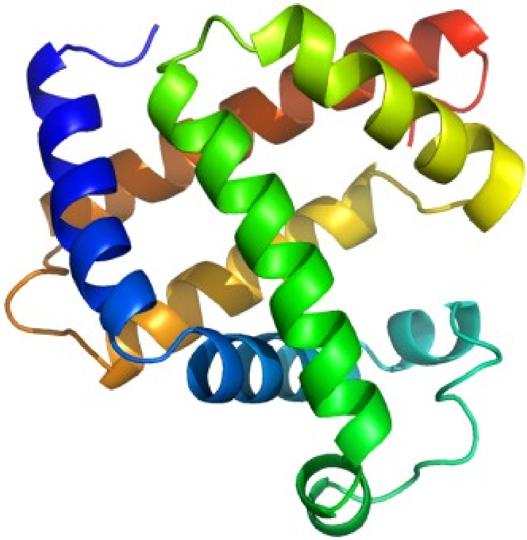
Structural dynamics...

resolve atomic **length** *and* **time** scales:

1 Å @ 100 fs (as)



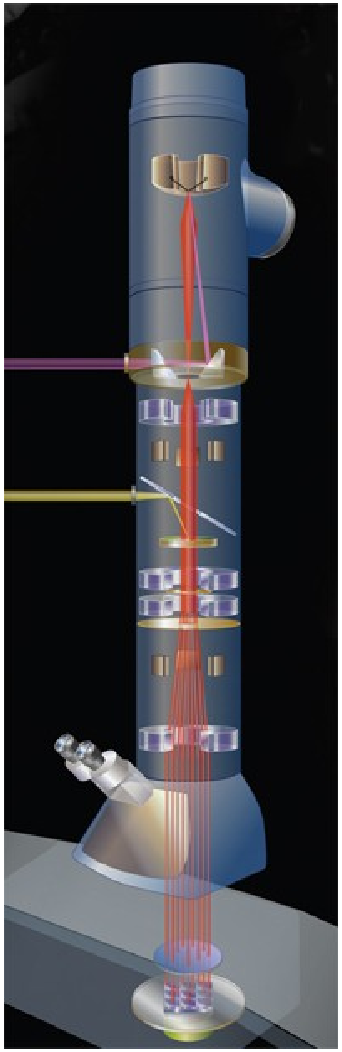
CeO_2 catalyst nanoparticle



Myoglobin

Microscopy developments

Using pulsed lasers &
photo-cathodes



Dynamic Transmission Electron Microscope (DTEM):
nanosecond single-shot images

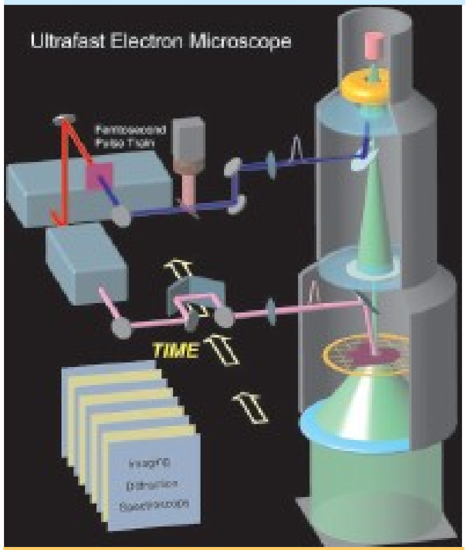
Reed, Browning et al,
Livermore Nat'l Lab

LaGrange et al, APL 89 (2006) 044105

"Four-dimensional ultrafast electron microscopy":
sub-ps multi-shot images &
diffraction patterns

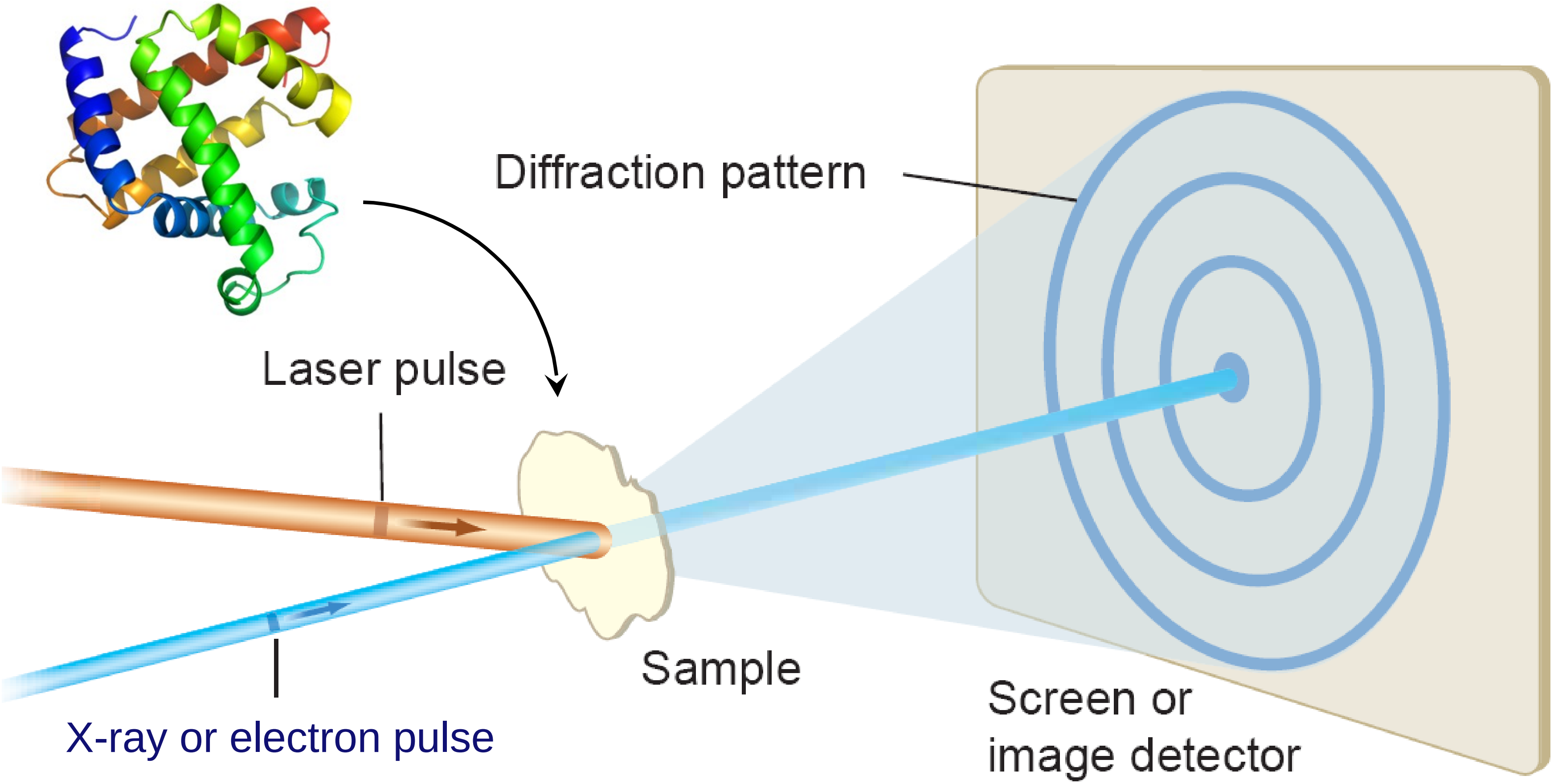
Zewail group, CalTech

Lobastov et al, PNAS 102 (2005) 7069



100fs @ 80MHz
single electrons

Ultrafast electron/X-ray diffraction

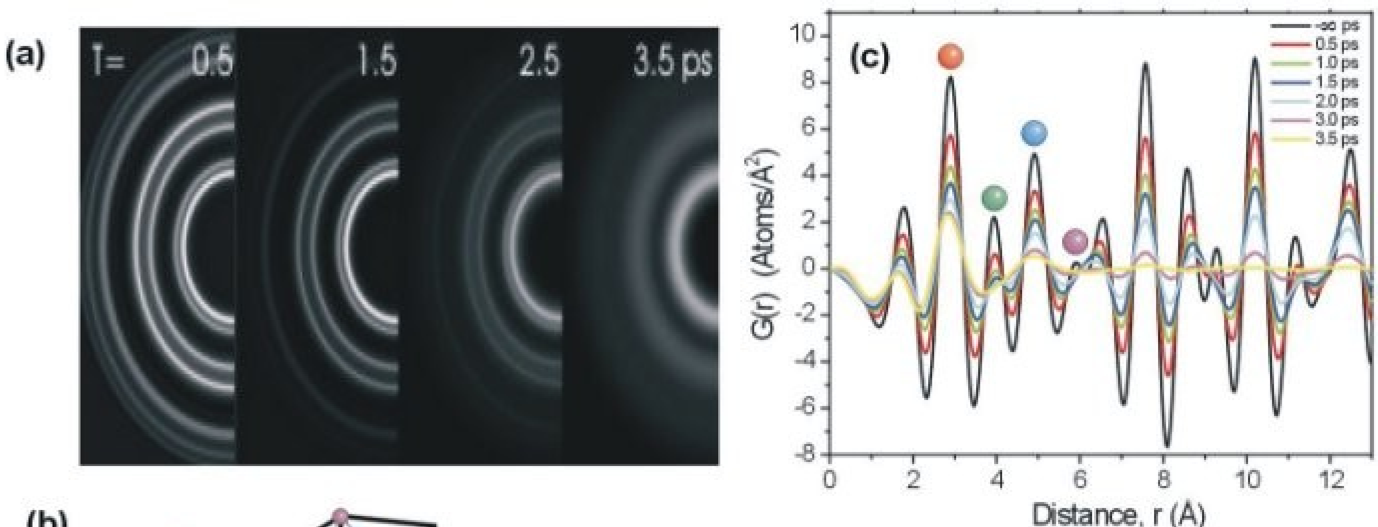


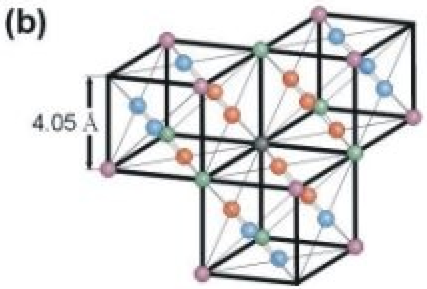
Electrons: Miller group (Toronto, MPSD/CFEL), Zewail group (CalTech), Carbone group (EPFL), Siwick group (McGill), Baum group (LMU/MPQ), …
X-rays: XFEL (LCLS), European XFEL & FLASH @ DESY, SwissFEL@PSI, FERMI@ELETTRA, ...

Diffraction example

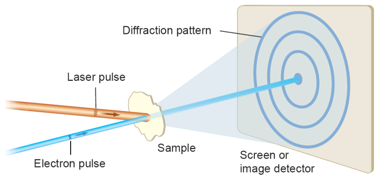
Siwick, Dwyer, Jordan and Miller,

An Atomic-Level View of Melting Using Femtosecond Electron Diffraction





An atomic-level view of melting (a) Diffraction patterns showing the progress of a laser-induced polycrystalline to liquid phase transition in Al. The structural rearrangements take only 3.5 ps (1ps = 10^{-12} s) **(b)** The face centered cubic (FCC) structure of Al. Atoms have been colour-coded such that each colour represents a given distance from the central black atom. **(c)** The time-dependent spectrum of interatomic spacings, G(r,t), at different stages through the phase transition. The correspondence between the peaks in G(r) and the FCC Al lattice are shown for the first four peaks by labeling with the same colour as in (b). Long-range ordering in atomic position is almost entirely preserved for the first 1.5 ps, but decays after this time such that a liquid-like atomic configuration is reached by 3.5 ps.



Science 302 (2003) 1382

Eindhoven ultrafast electron source

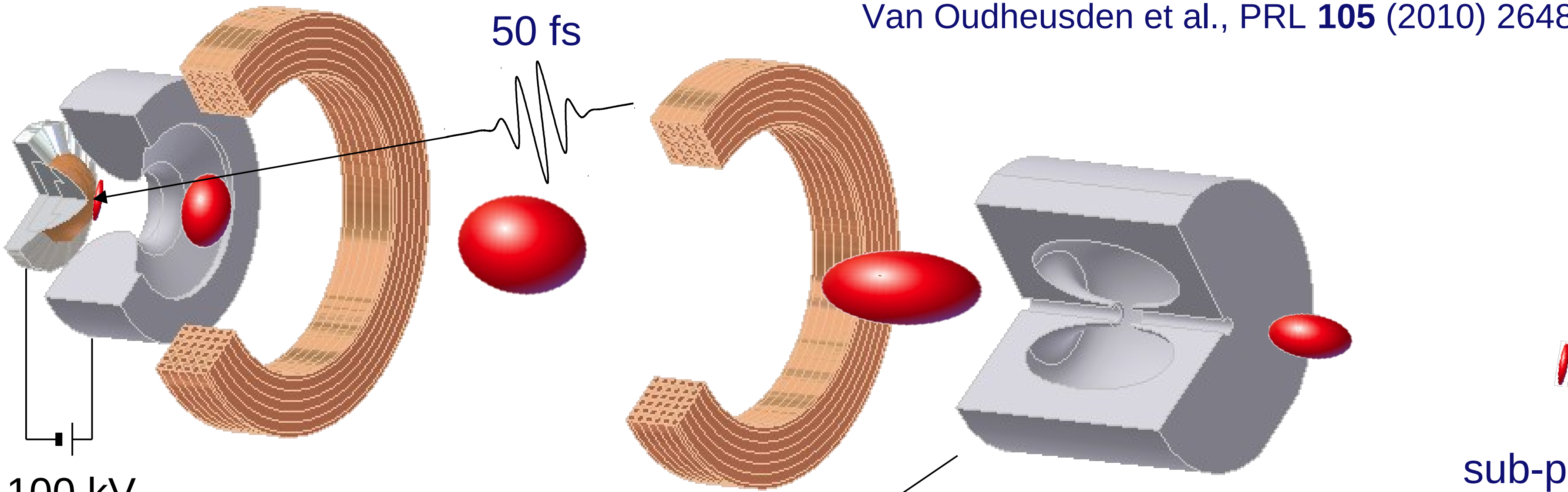
Jom Luiten and coworkers

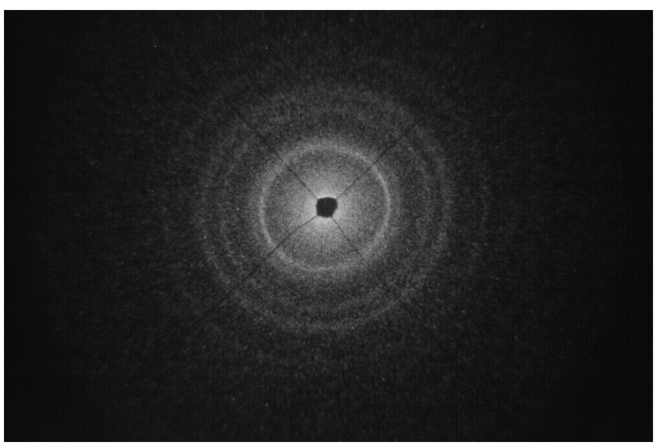
We are taking orders
Only € 99,999.99

Single-shot UED setup

Thijs van Oudheusden, Peter Pasmans, Stefano dal Conte and Jom Luiten

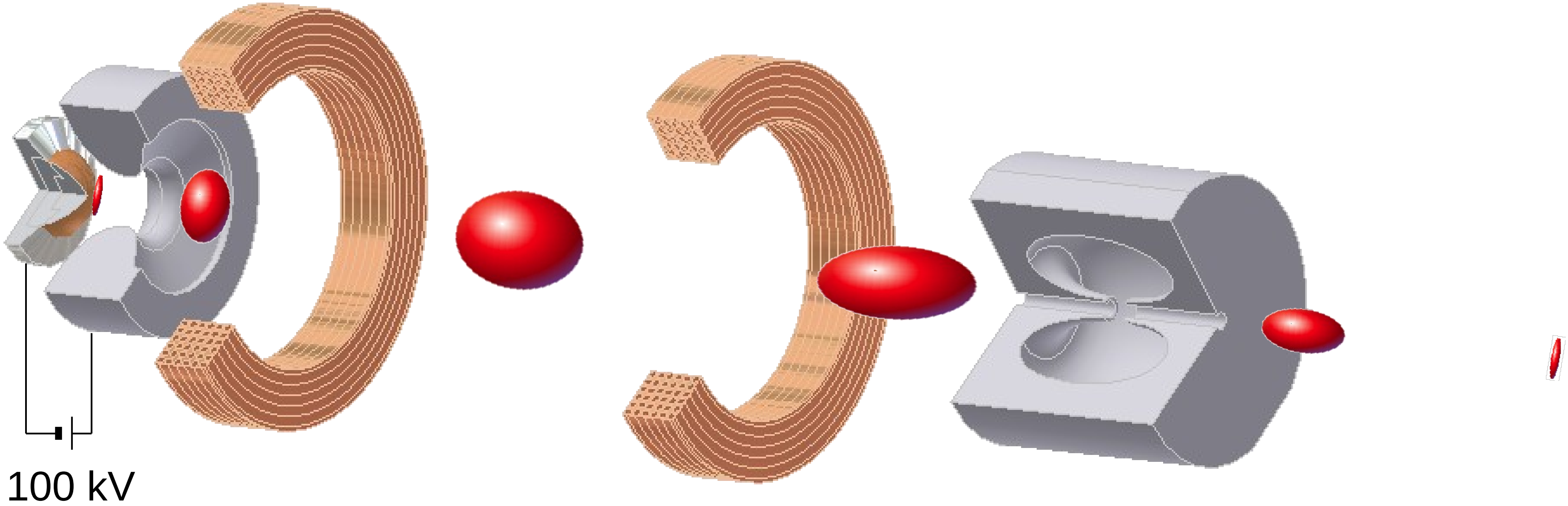
Van Oudheusden et al., JAP **102** (2007) 093501
Van Oudheusden et al., PRL **105** (2010) 264801





SINGLE SHOT
0.1 pC (10^6 e) , 100 keV
polycrystalline Au foil

Single-shot UED summary



- Cu photo-cathode
- Q = 0.1 pC ***single-shot***
- bunch length < 1ps ***ultrafast***
- ***transverse coherence length 3 nm***
  (0.2 mm spot size = typical)

limited to “small” periodicity (*ex:* gold crystals)

what about larger structures?

biomolecules

Increase transverse coherence length

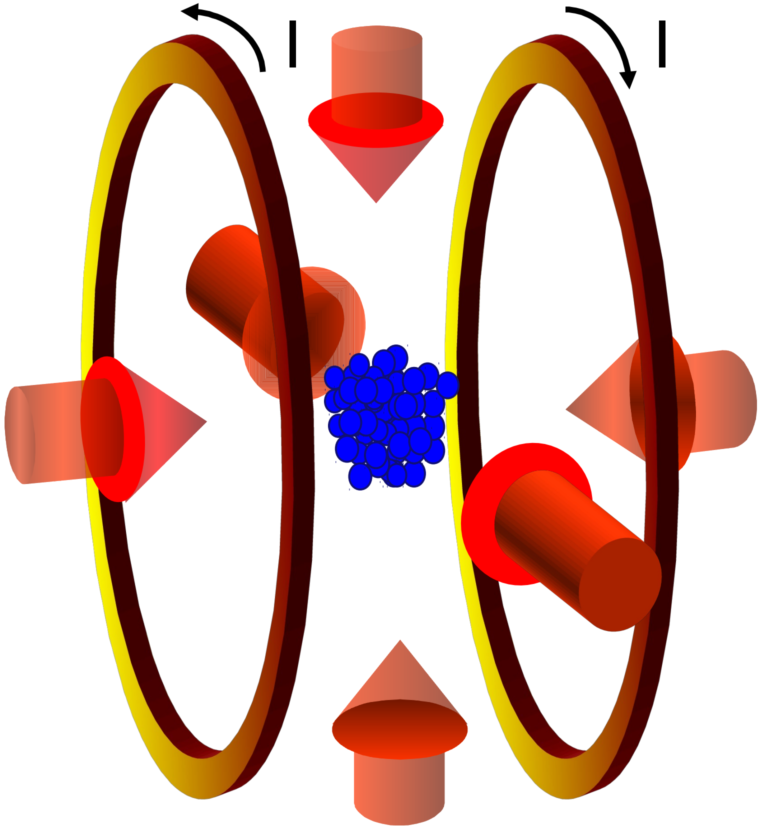
Relative coherence length

$$L_c = \frac{\hbar}{\sqrt{mkT}} \frac{\sigma_{sample}}{\sigma_{source}} \quad \Rightarrow \quad C_\perp = \frac{h}{\sqrt{2\pi mkT}} \frac{1}{\sigma_{src}\sqrt{2\pi}}$$

field or photo-emission source: kT_e = 0.5 eV → T = 5000 K

UltraCold Electron Source ⇒
- 10K → 20x larger L_c
- "single-shot" (1M ***e***)

Magneto-Optical atom Trap (MOT)



Laser cooling & trapping: ***(Nobel 1997)***

6 laser resonant beams +

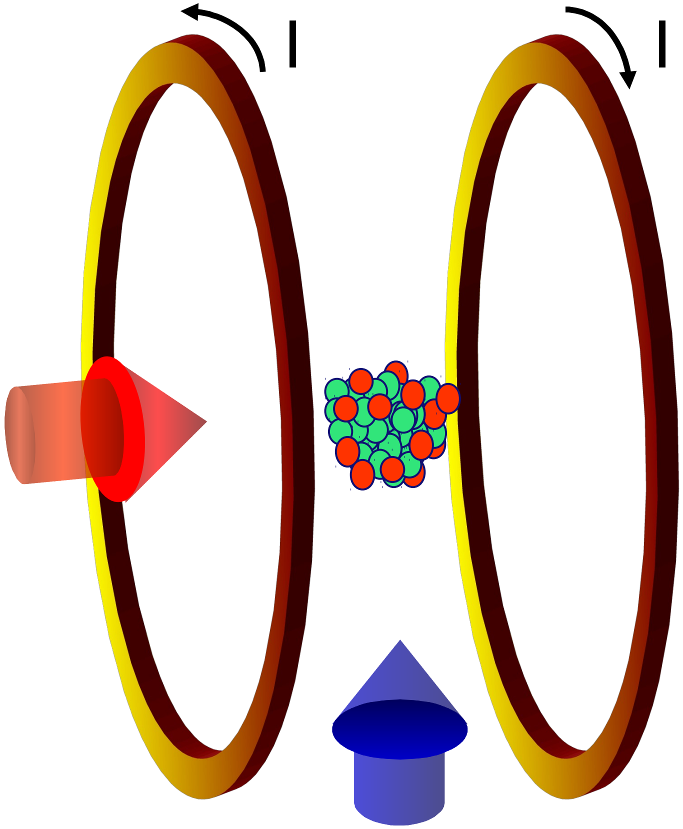
quadrupole magnetic field

N = few 10^8 rubidium atoms

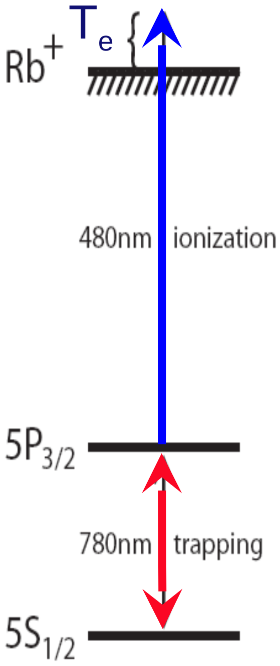
σ = 0.9 mm, n = 10^{10} cm^{-3}

T < 0.001 K

Ultracold Plasma by photo-ionization



Electron temperature



$$kT_e < \frac{h}{\tau}$$

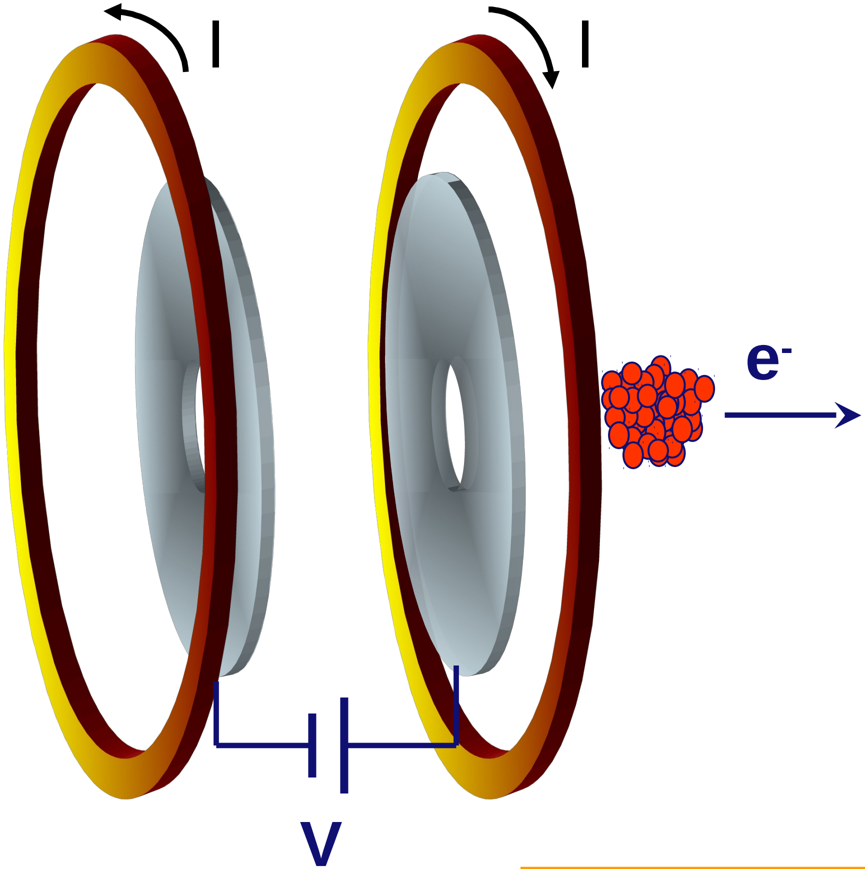
Rolston, Killian, Bergeson, Pillet, Comparat ...

$$\tau = 1\ ps \rightarrow T_e = 10\ K$$

& plasma effects

Ultracold electron source

Ultrafast electron diffraction (TU/e, Scholten)
Low-energy microscopy (Orsay)



UCES

$T_e \approx$ **15 K**
τ < 1 ns (ps)
10^5 e per pulse

Luiten group @ TU/e:

- develop into practical source
- investigate properties: cold!

Photo-electron sources

Not an entirely new idea: low energy-spread electron beams for electron-atom/molecule collisions

1974: *Gallagher and York*, RSI 45, 662
< 1 fA, meV resolution, Ba beam + intra-cavity HeCd-laser

1994: *Klar, Hotop et al*, Meas. Sci. Technol. 5, 1248
1 fA current, < 1 meV energy spread, Ar* beam + CW tuneable dye laser

2010 *Kurokawa et al*, PRA 82, 062707 (2010) Ar gas + synchrotron radiation

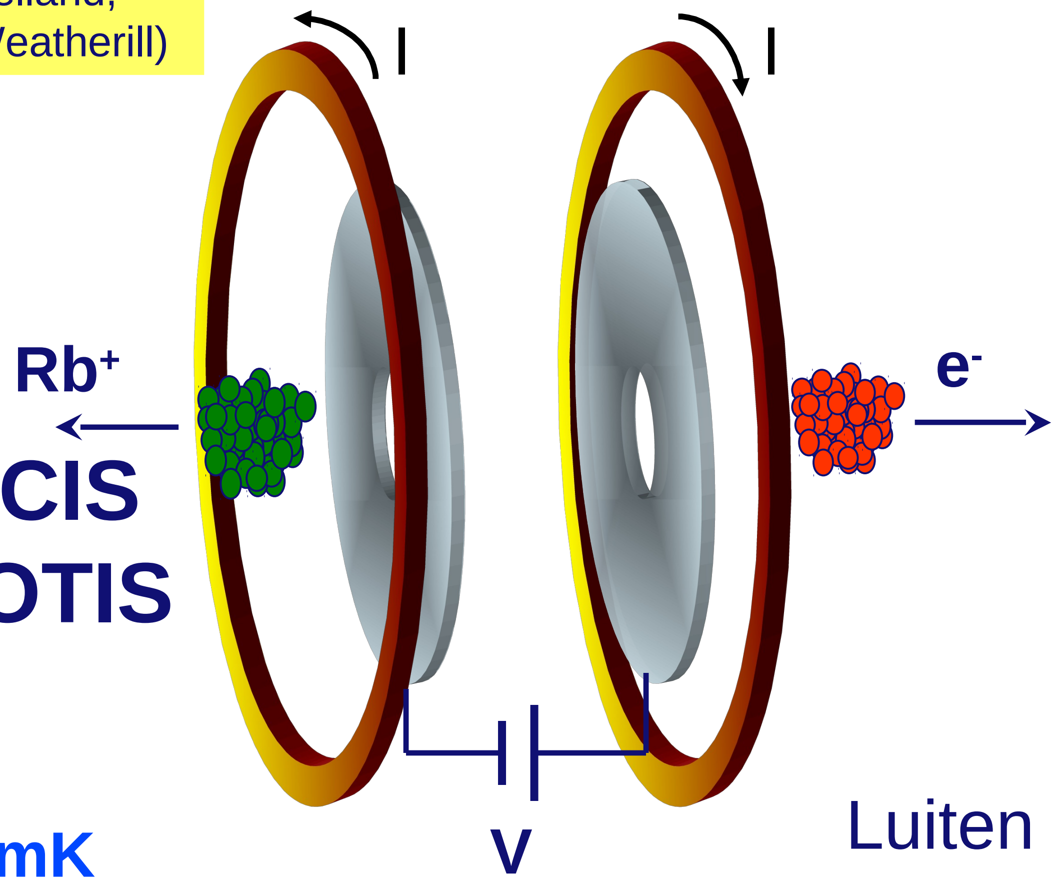
What's new?

- **Applications (structural dynamics)**
- **Ultrafast operation (pulse length, peak current, charge density)**
- **Cold atom techniques → increased control**

  charge shaping: *McCullogh, Scholten et al*, Nat Phys 7 (2011) 785

Ultracold electron AND ion source

Focused ion beams & ion microscopy, ion-on-demand, implantation (McClelland, TU/e, Comparat, Weatherill)



UCES:

$T_e \approx$ **15 K**

UCIS

MOTIS

$T_i \approx$ **1 mK**

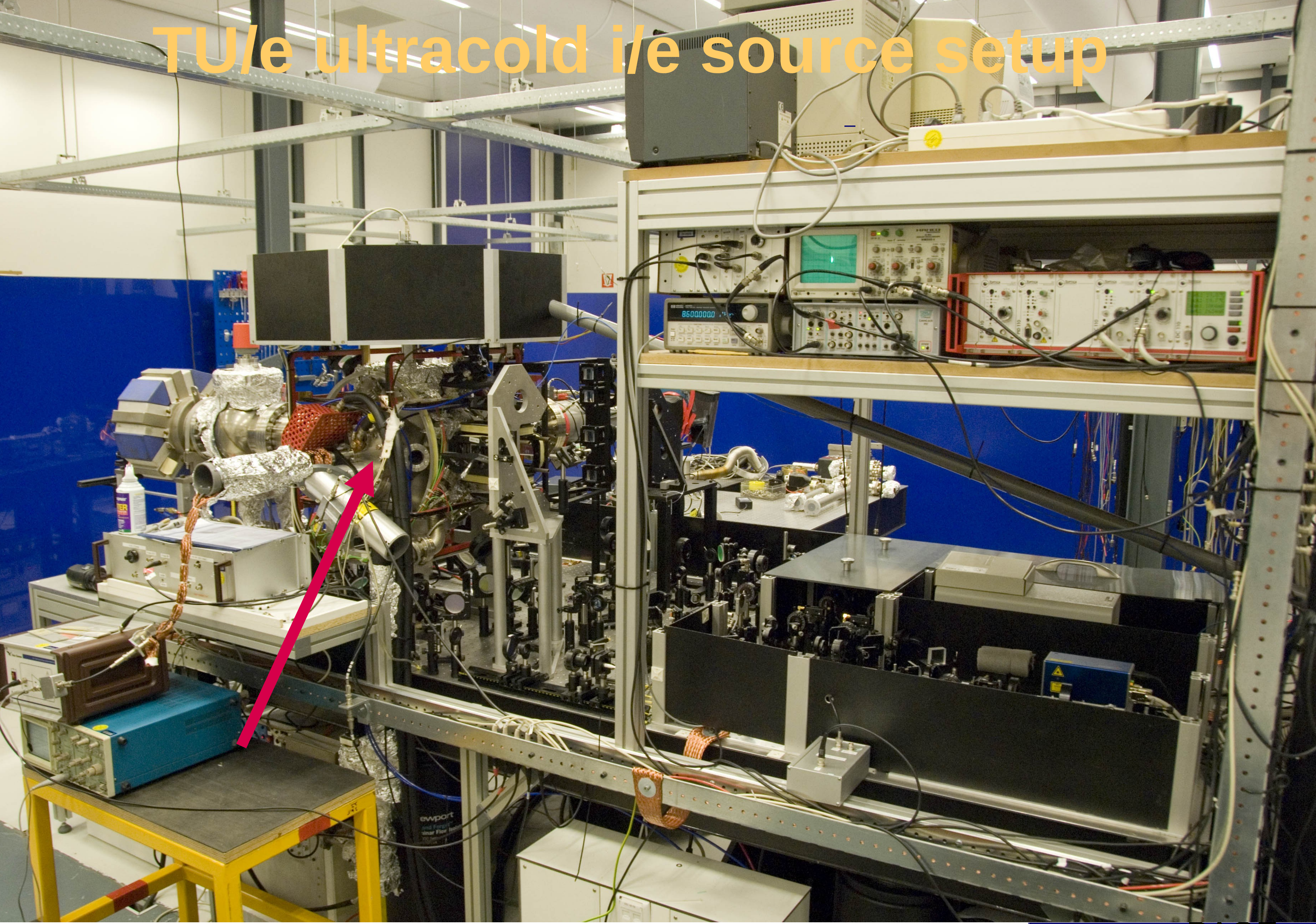
1 eV ion beams

20 meV energy spread

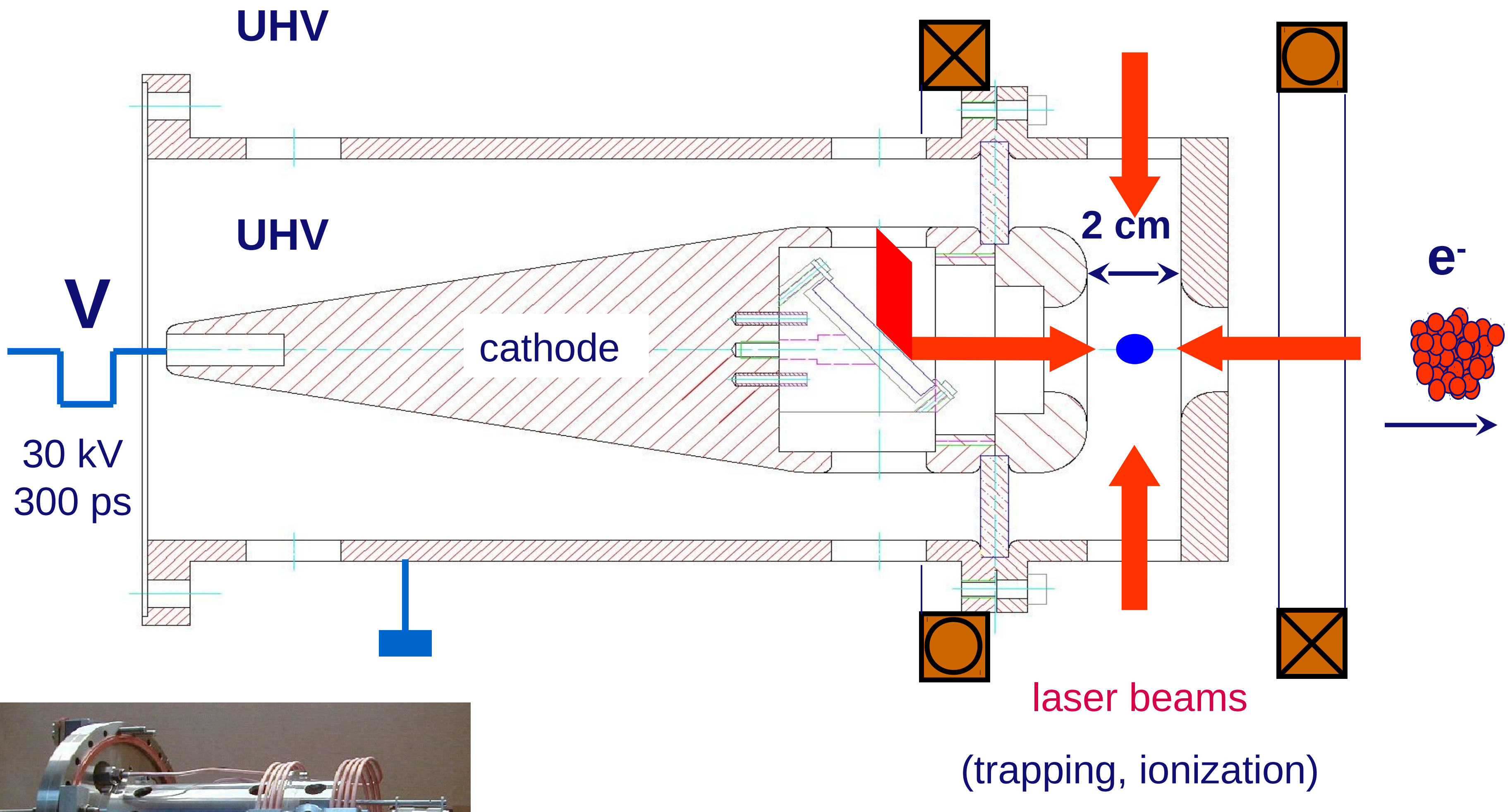
Luiten group @ TU/e:

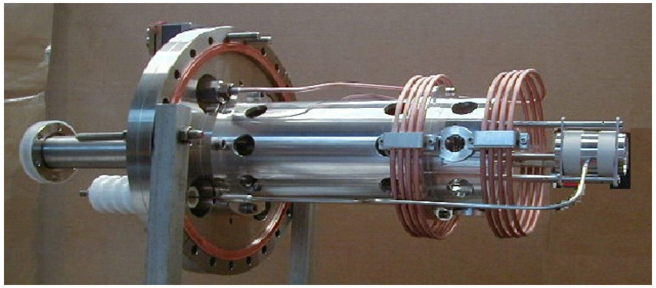
- develop into practical source
- investigate properties: cold!

TU/e ultracold i/e source setup

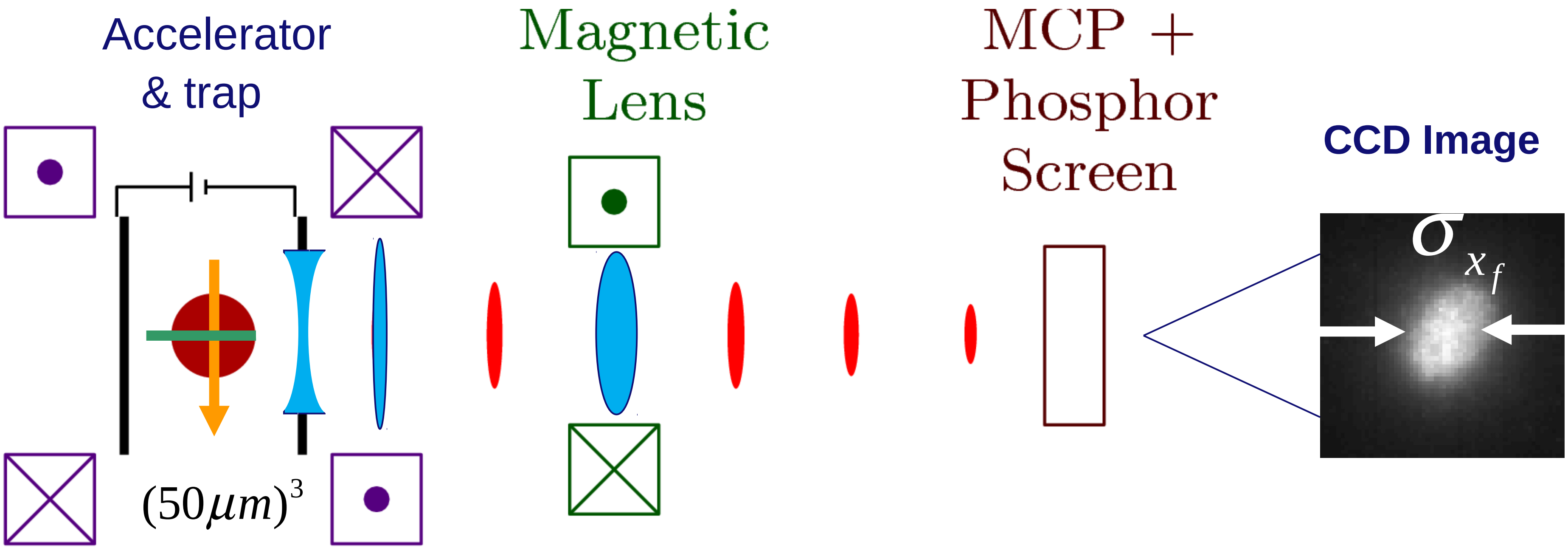


Atom trap inside coaxial accelerator (cross section)





Electron temperature from spot size



linear beam transport

$$\sigma_{x_f}^2 = A^2\sigma_{x_i}^2 + B^2\sigma_{\alpha_i}^2$$

spot size **measure**

source size **known**

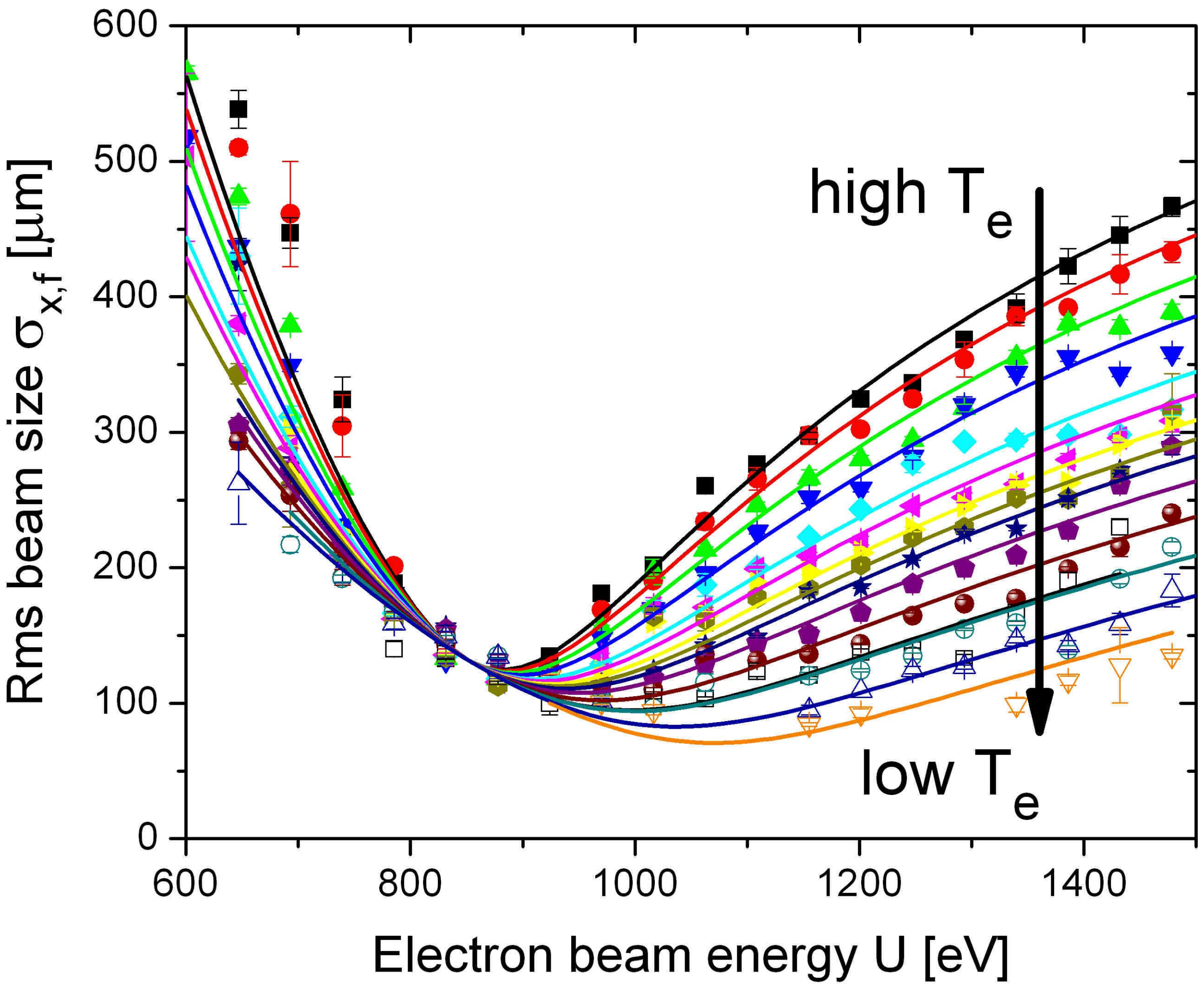
diver-gence **extract**

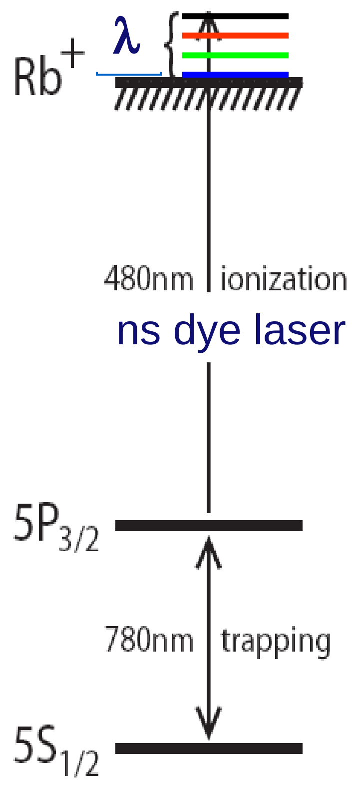
transport coefs A,B known

$$\sigma_{\alpha_i} = \sqrt{\frac{k_B T_e}{2U}} = \frac{\sigma_{v_\perp}}{< v_{//} >}$$

Electron spot size vs. beam energy: "waist scan"

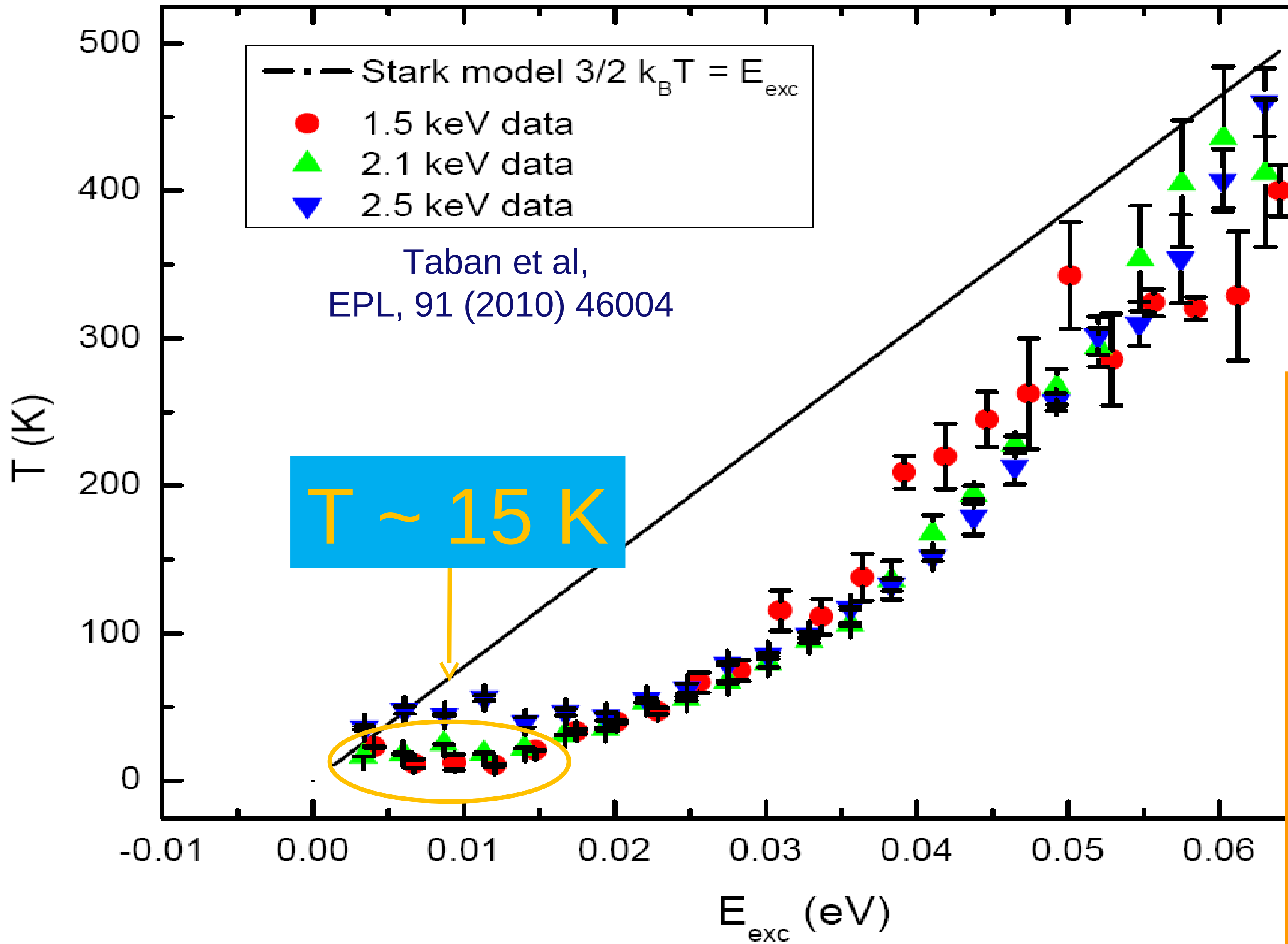
data & GPT particle tracking simulations

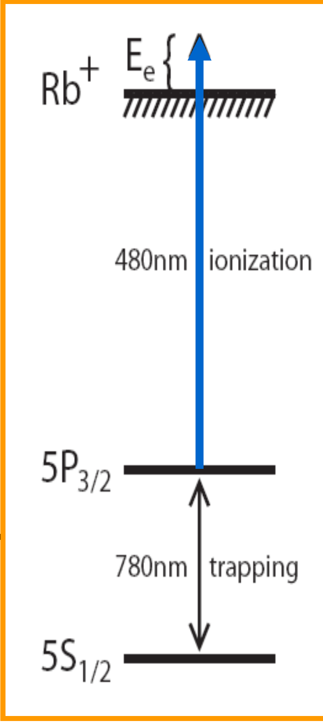




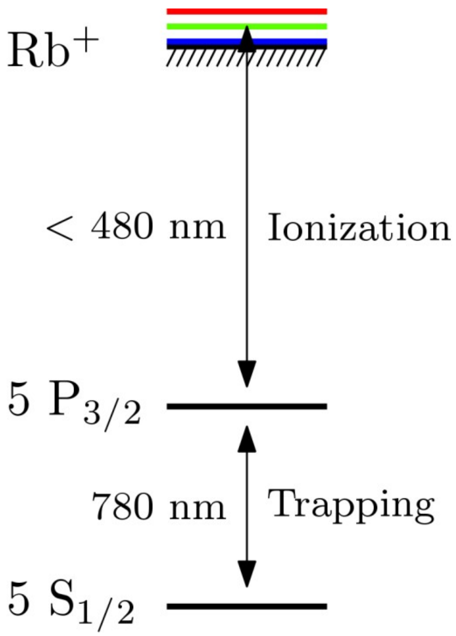
Taban et al,
EPL, 91 (2010) 46004

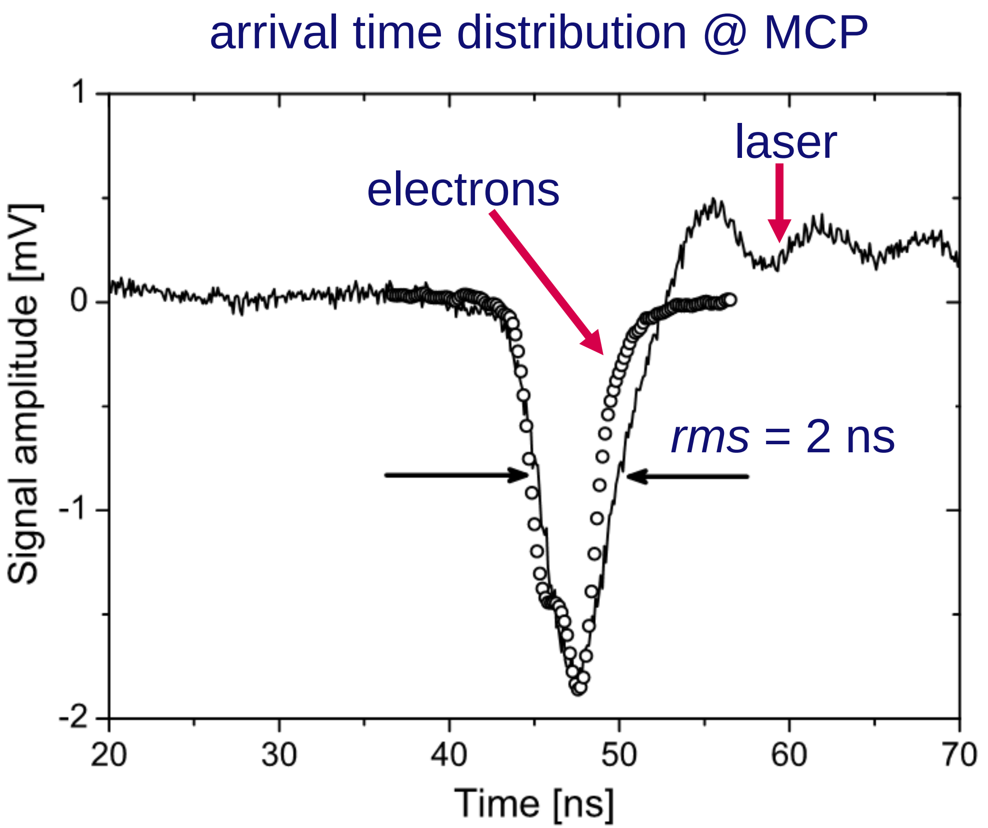
Temperature vs. excess energy





Temporal bunch length

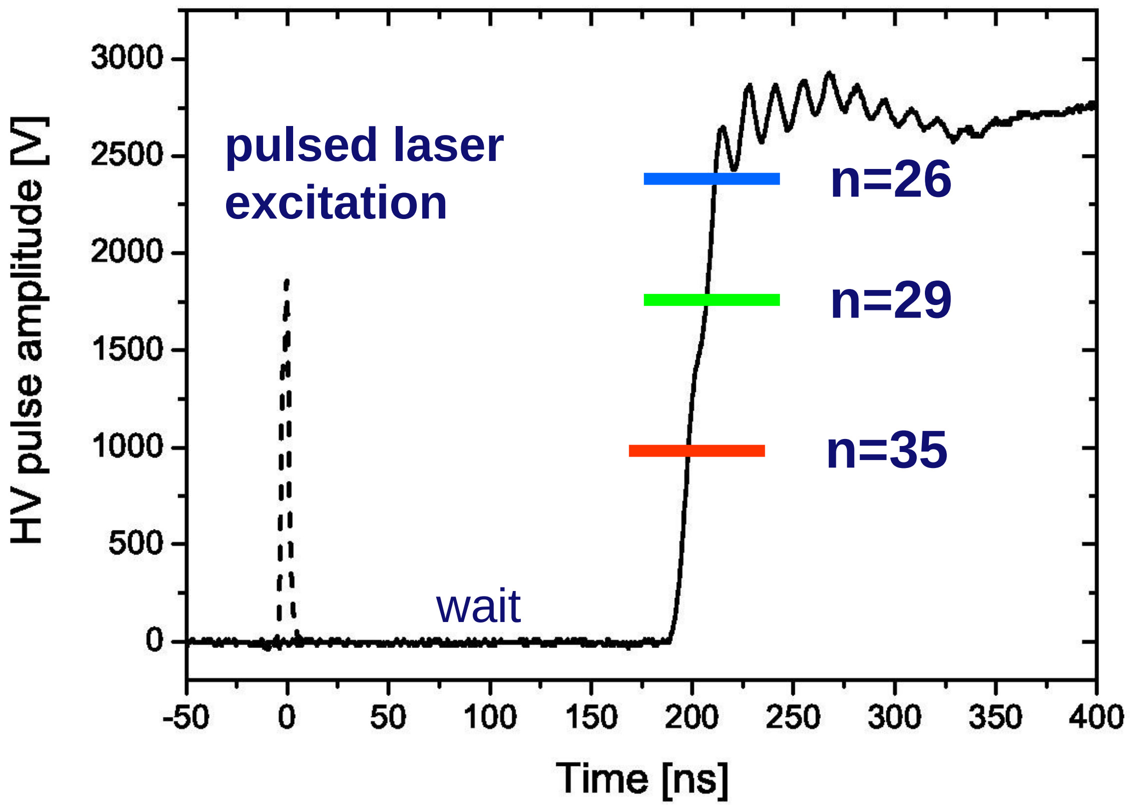


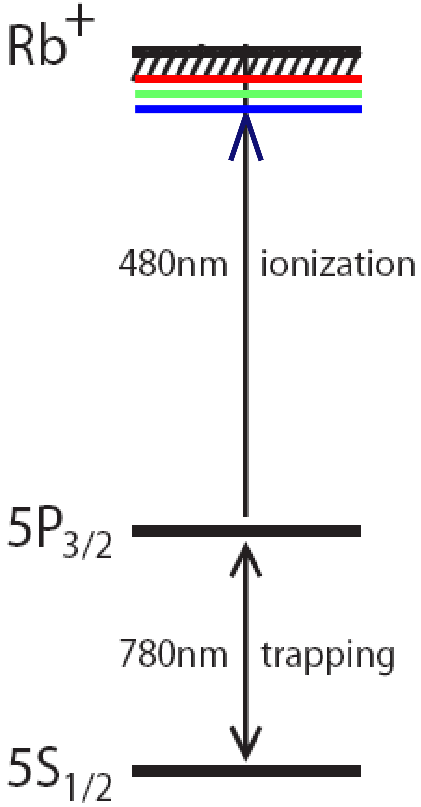


- τ **= 2 ns *rms* @ 30 cm**
- **limited by pulse length laser (YAG-pumped dye)**
- **photo-ionization in a DC field**
- **would like shorter bunches < 1 ps**

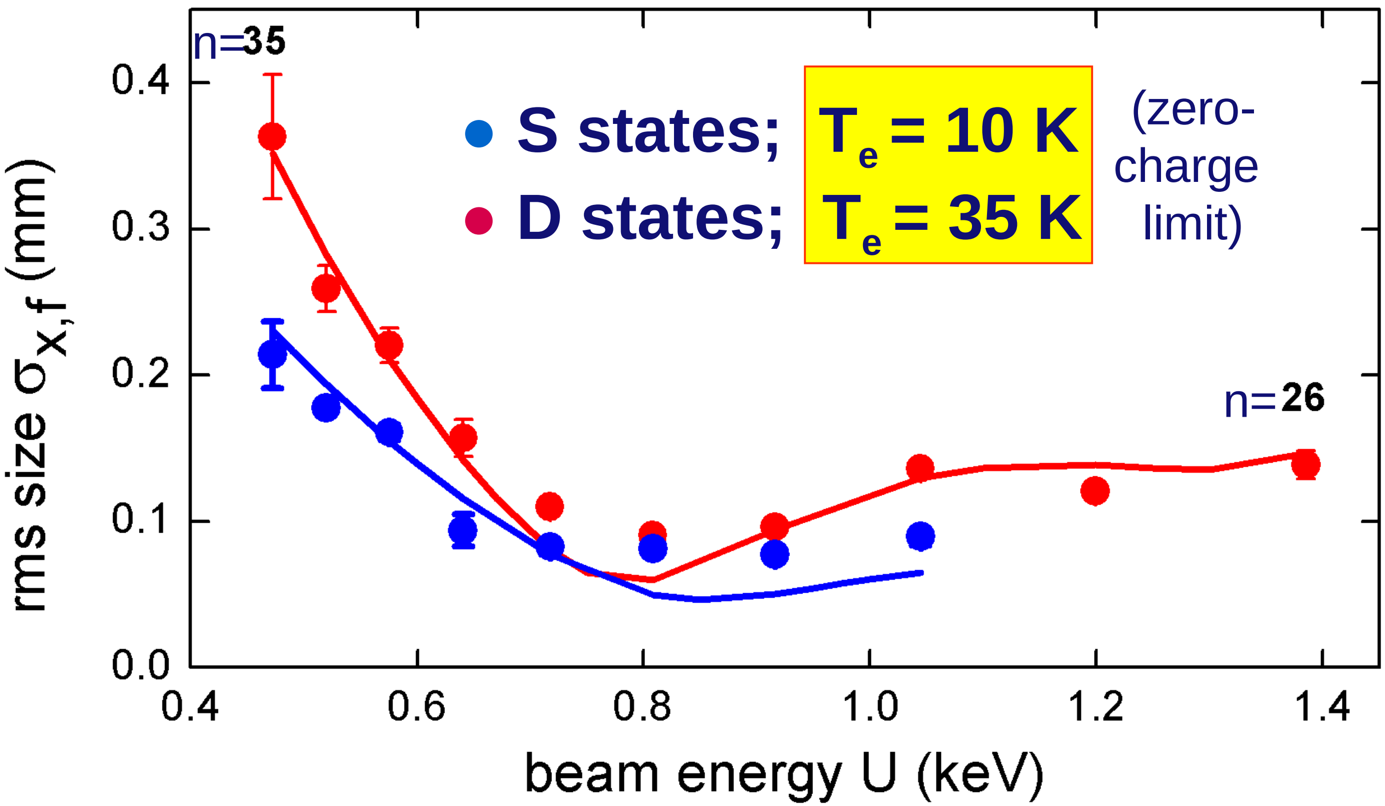
Shorter bunches: "frozen" Rydberg gas

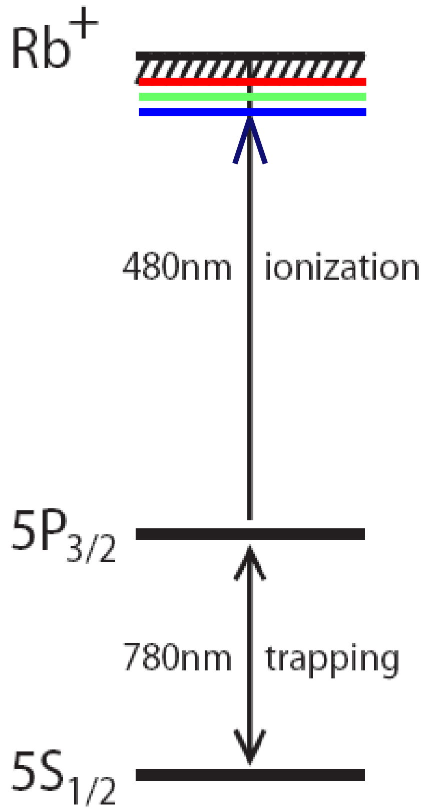
- pulsed field-ionization of excited Rydberg atoms
- principal quantum number *n*
- higher *n* → lower ionization field → smaller U





Field ionization experiment: “waist scan”

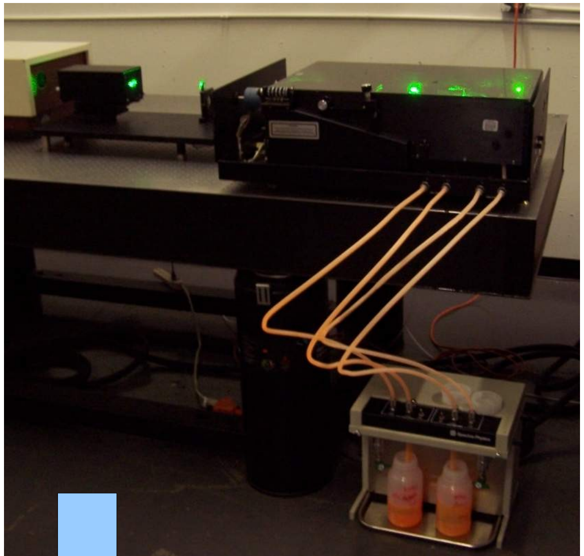


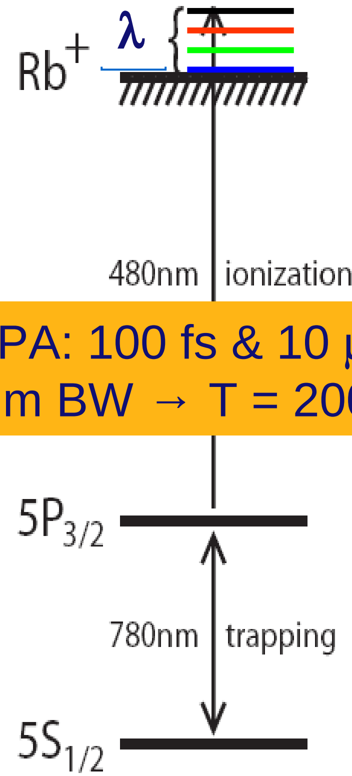


bunch length

- **measurement: 0.8 ns rms (electronics)**
- **simulations: τ = 50 ps (?) @ 30 cm from source**
  (limited by field homogeneity accelerator)
- **atomic physics (*Robicheaux*, Auburn): τ = 0.5 ns**

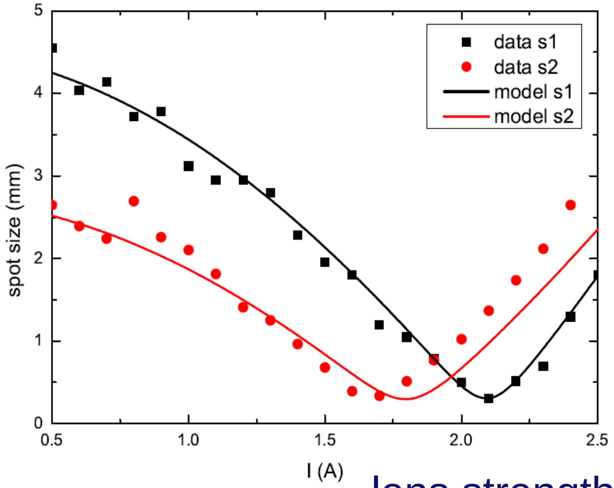
Faster pulses: femtosecond OPA





OPA: 100 fs & 10 μJ
4 nm BW → T = 200 K

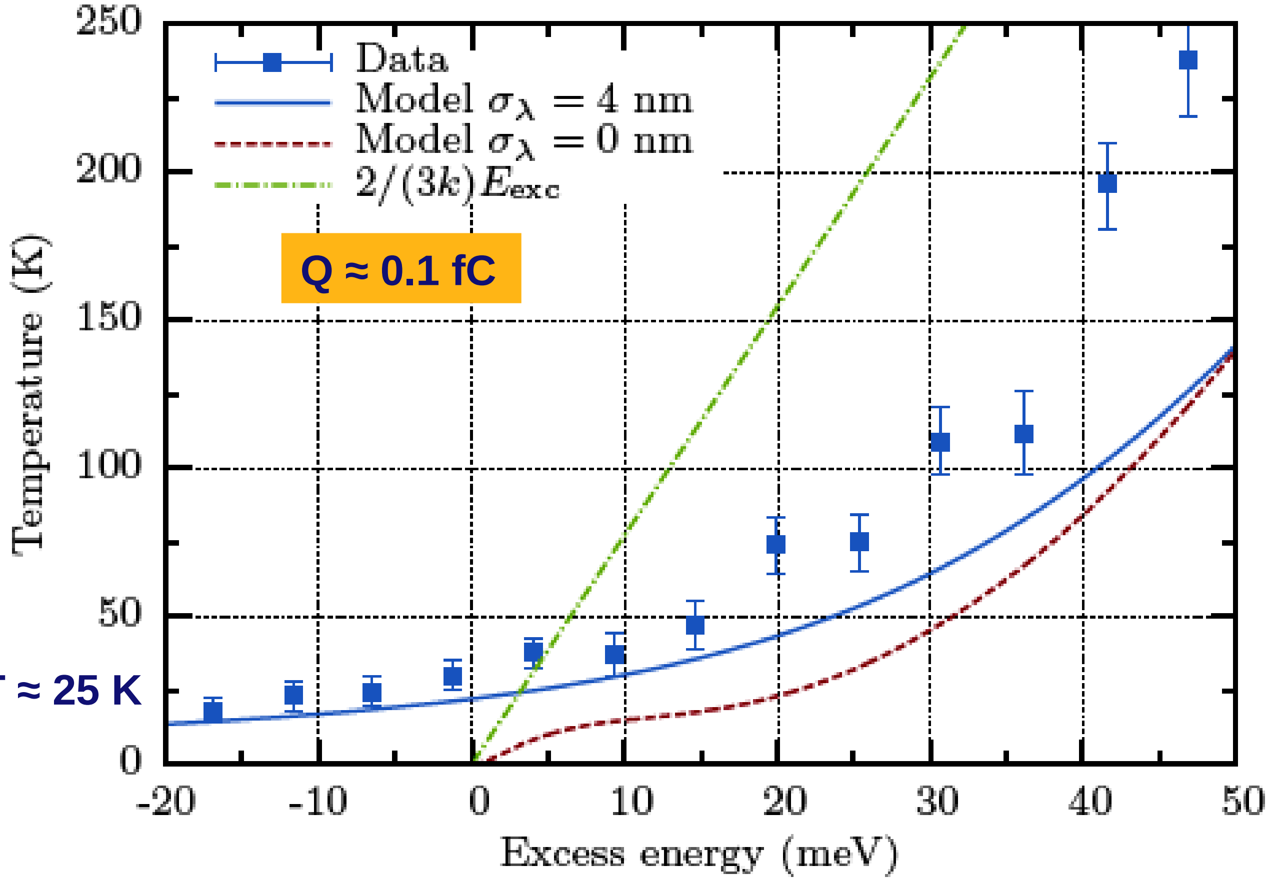
waist scan



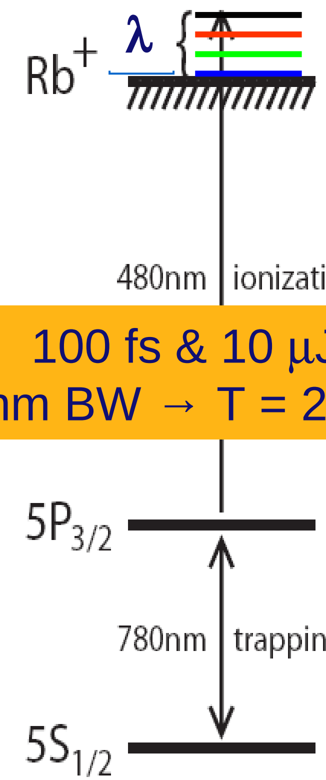
lens strength

- **vary wavelength and field strength (excess energy)**
- **similar analysis → source temperature**

Femtosecond OPA results



T ≈ 25 K



100 fs & 10 μJ
4 nm BW → T = 200 K

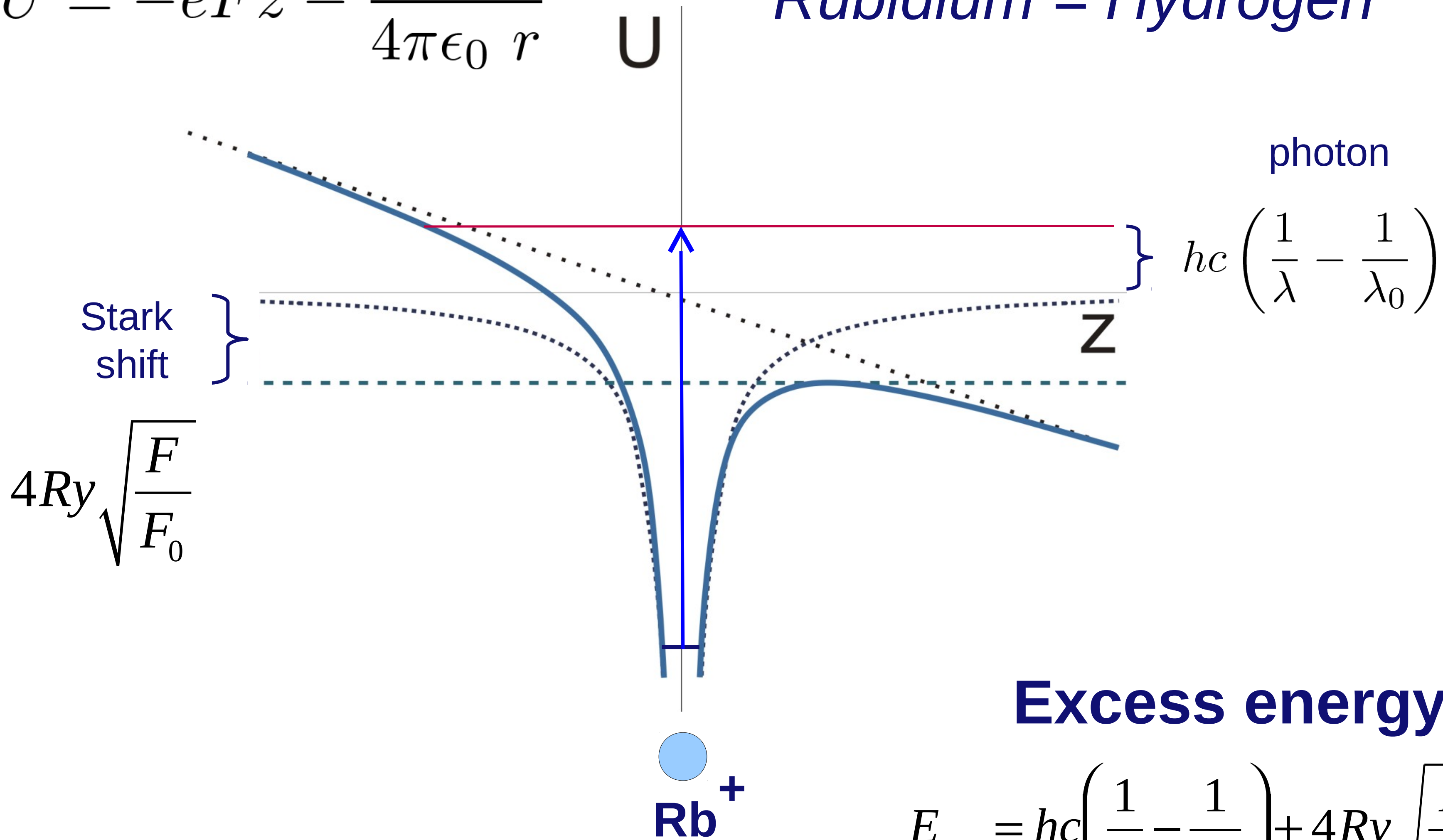
2011: **still achieve T ≈ 25 K near threshold ! (?)**

Scholten (Melbourne): similar results

Dynamics: potential landscape

$$U = -eFz - \frac{e^2}{4\pi\epsilon_0\, r}$$

Rubidium = Hydrogen

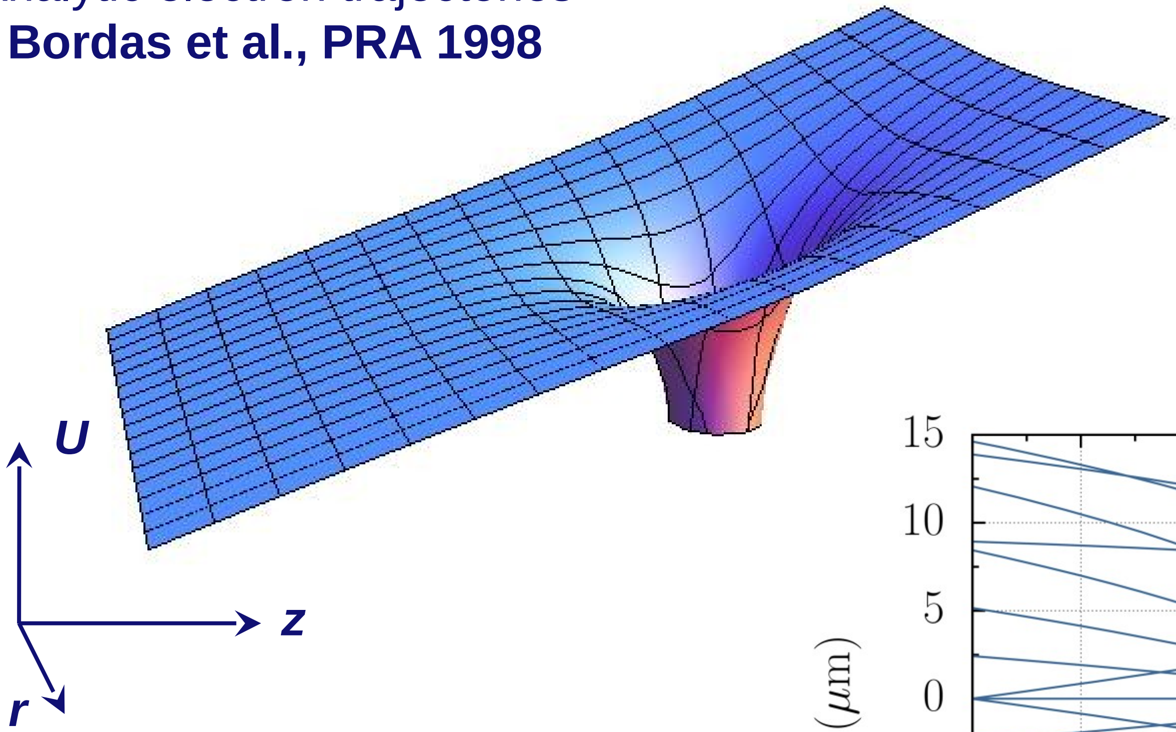


Excess energy

$$E_{exc} = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) + 4Ry\sqrt{\frac{F}{F_0}}$$

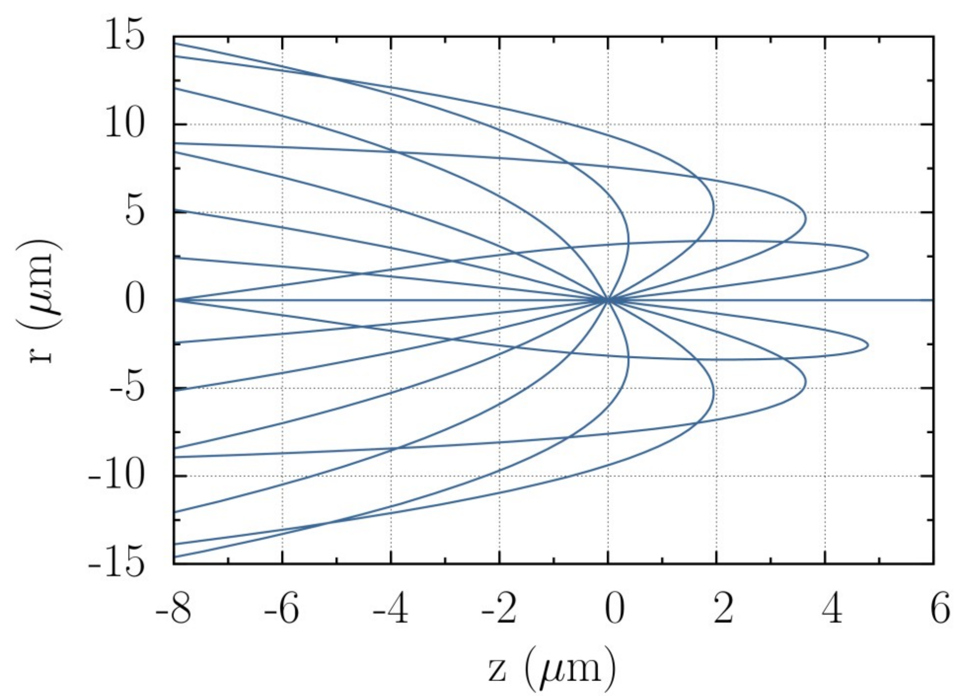
Classical electron trajectories

Analytic electron trajectories
Bordas et al., PRA 1998



3/2 kT < E_{exc}

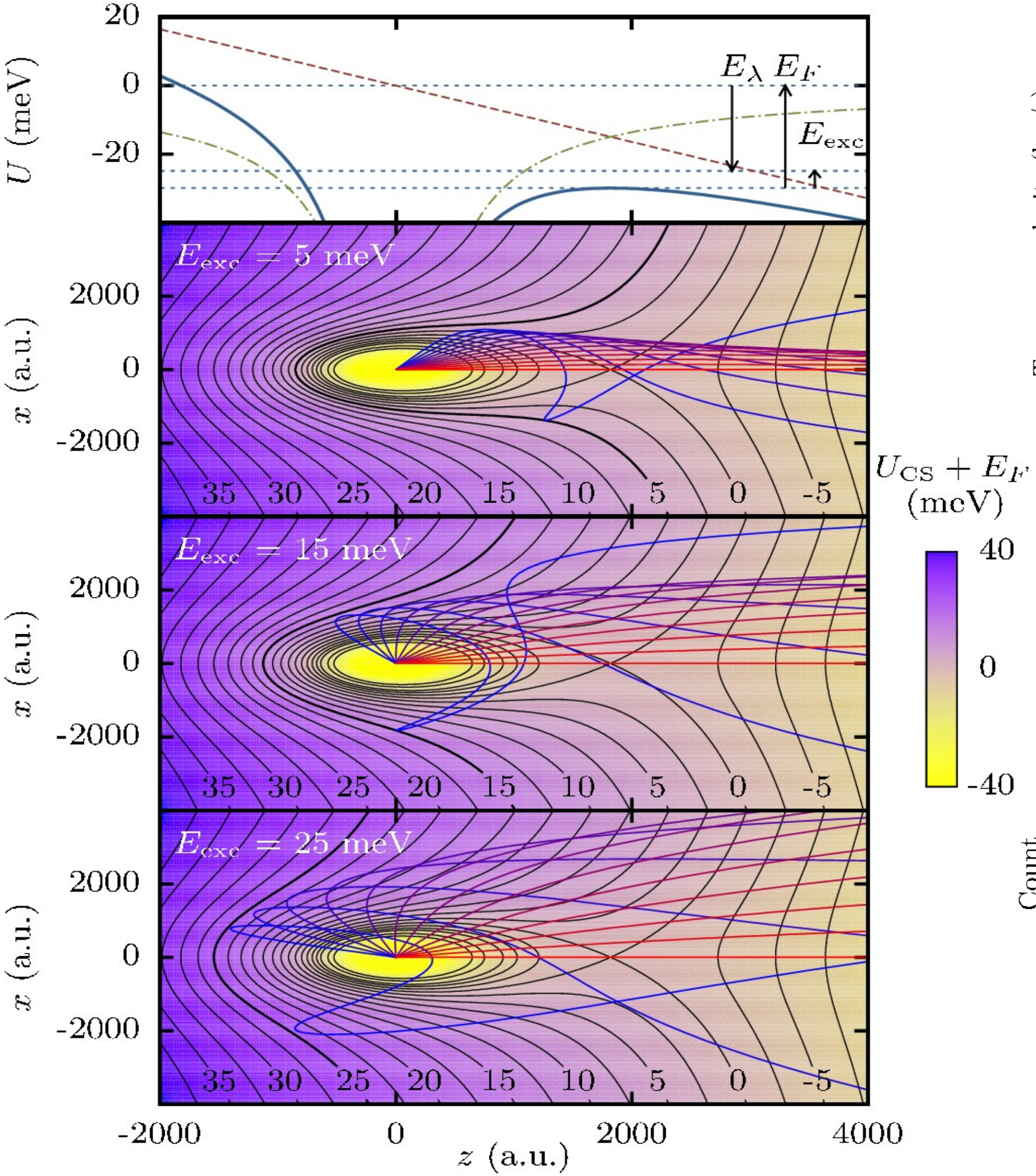
not equipartitioned

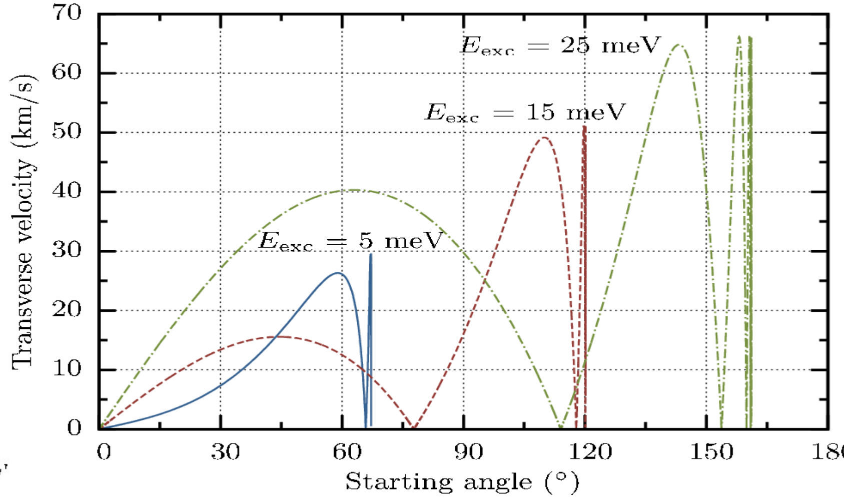


dynamics from Coulomb and Stark potential

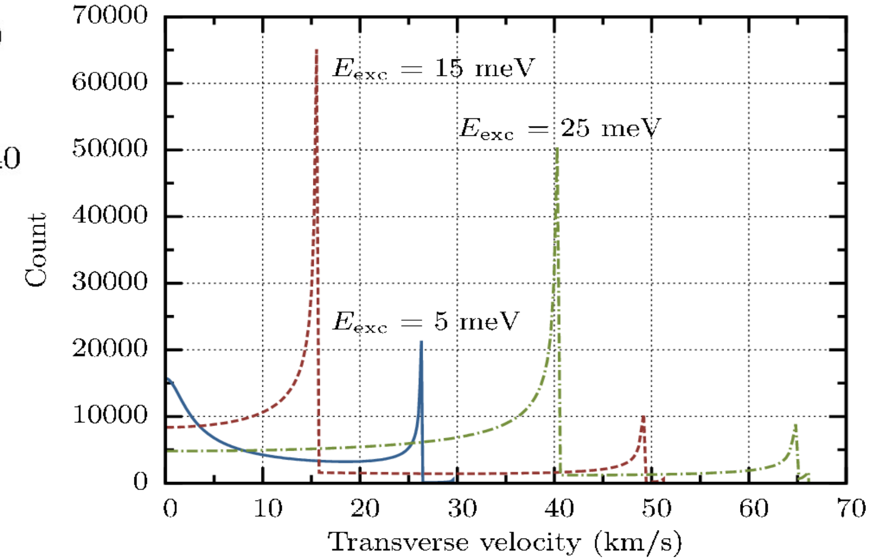
Also: Scholten et al (Melbourne)

Electron trajectories: forward emission

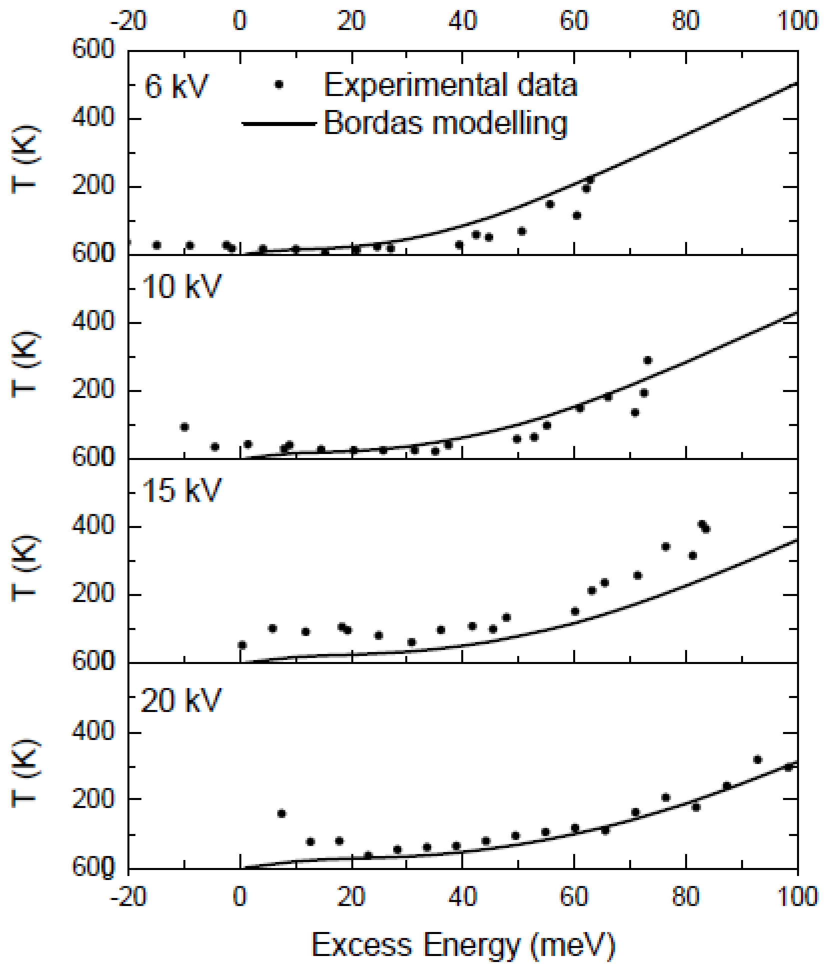


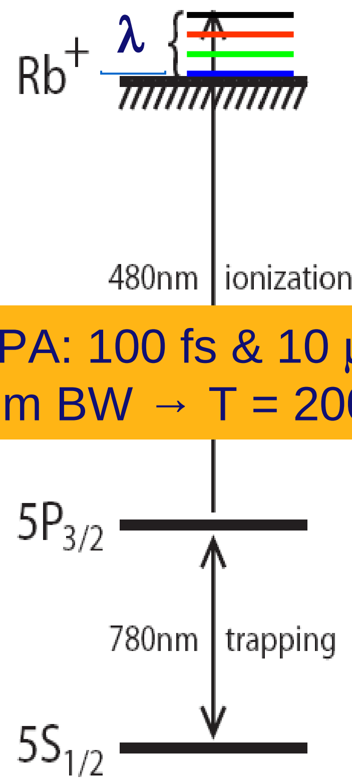


Limited "escape angle"
Beyond: bound states



Femtosecond OPA results vs. Bordas model





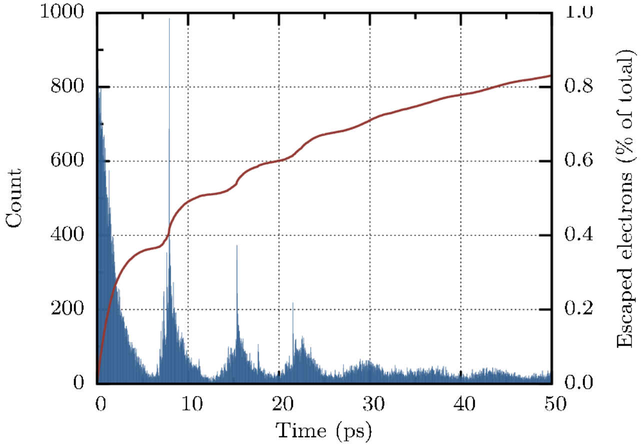
OPA: 100 fs & 10 μJ
4 nm BW → T = 200 K

- **dynamics model (Bordas) explains *fs* data ! (?)**
- **possible to get few K electrons with fs lasers**

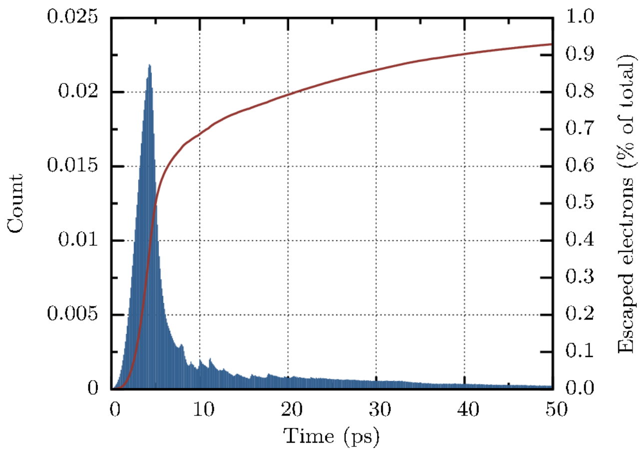
Temporal structure: ps time resolution

Also: *Scholten et al,* Melbourne

ps lasers



fs OPA



VOLUME 76, NUMBER 11 PHYSICAL REVIEW LETTERS 11 MARCH 1996

Streak-Camera Probing of Rubidium Rydberg Wave Packet Decay in an Electric Field

G. M. Lankhuijzen and L. D. Noordam

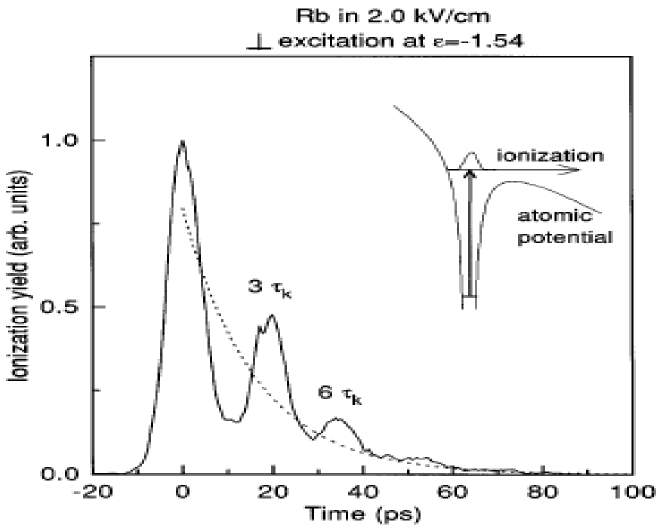


FIG. 2. Measured decay of an autoionizing electronic wave packet (full line). The wave packet is created above the classical field ionization limit at a scaled energy of $\epsilon = -1.54$. The laser polarization is perpendicular to the electric field of 2.0 kV/cm. The calculated angular recurrence time using the hydrogenic model is $\tau_k = 5.7$ ps. The dotted line is an exponential fit with a decay time of 16 ps.

different context: series of papers by Noordam, Robicheaux, Van Linden van den Heuvell, Vrakking (1993-2000)

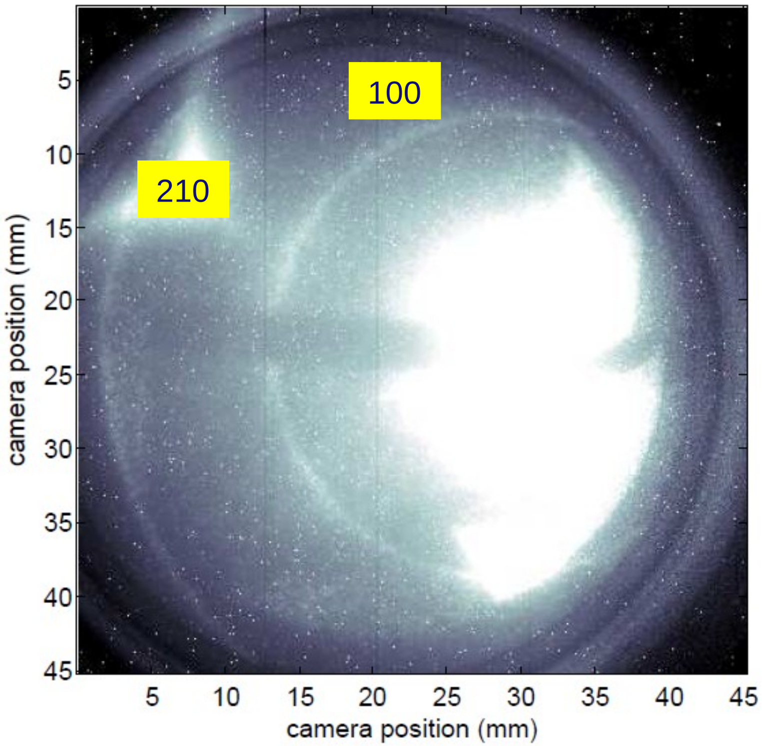
Few-ps time resolution is possible !

Application: diffraction patterns from graphite flakes

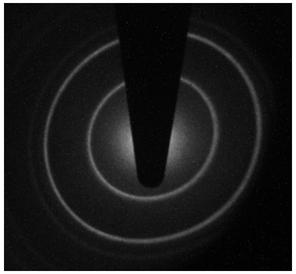
ns dye laser 480 nm
U = 11 keV
≈ 20 µm spot size, 50 K

Daniël Bakker, Sept 25, 2012 1000 shots

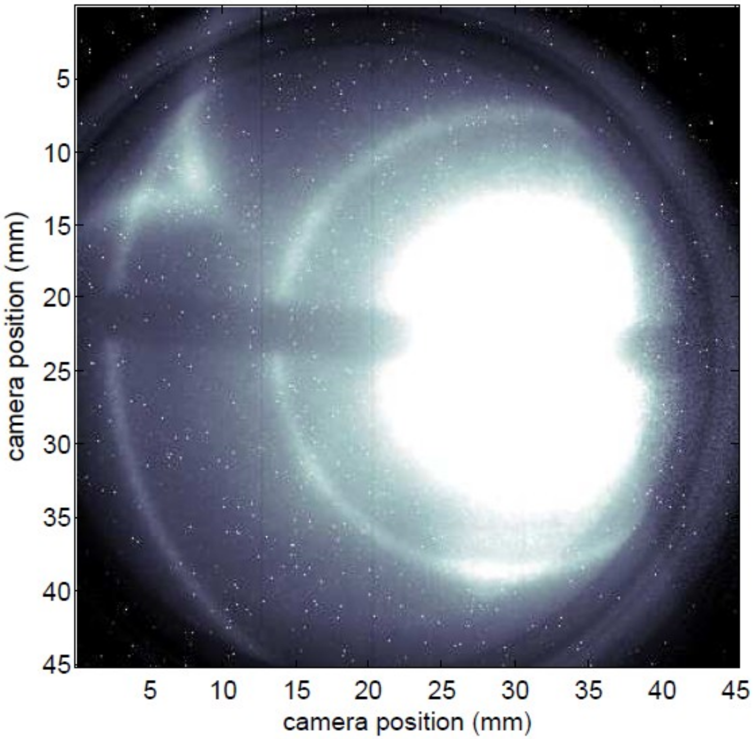
fs OPA 480 nm
U = 11 keV
≈ 20 µm spot size, 50 K



100 keV
Cu cathode



Pasmans, van Lieshout, Luiten



→ use this to measure coherence length

?

Conclusions

- **Demonstrated application of the UCP:**
  ultracold electron (and ion) source
- **Alternate way to achieving**
  high brightness; large coherence length; low energy spread
- **Applications in UED, FIB and electron/ion microscopy**
- **Ultrafast & cold electron source for *UED***

  $T \approx 25$ K, $\tau < 1$ ns (ps), 10^5 e p.p.

- ***quantum degenerate* electron beams? $n=10^{18}/m^3$, T=1 mK**

Claessens *et al*., PRL **95,** 164801 (2005)
Claessens *et al*., Phys. Plasmas **14**, 093101 (2007)
Van der Geer *et al*., JAP **102**, 094312 (2007)
Taban *et al*., PRST-AB **11**, 050102 (2008)
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V.d. Geer *et al.*, Microscopy and Microanalysis **15**, 282 (2009)
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Taban *et al*., EPL **91,** 46004 (2010)
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