ARC Centre of Excellence for
COHERENT X-RAY SCIENCE

Arbitrarily Shaped High-Coherence Electron and Ion Bunches from Laser-Cooled Atoms

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POSTERA CRESCAM LAUDE

With thanks to:

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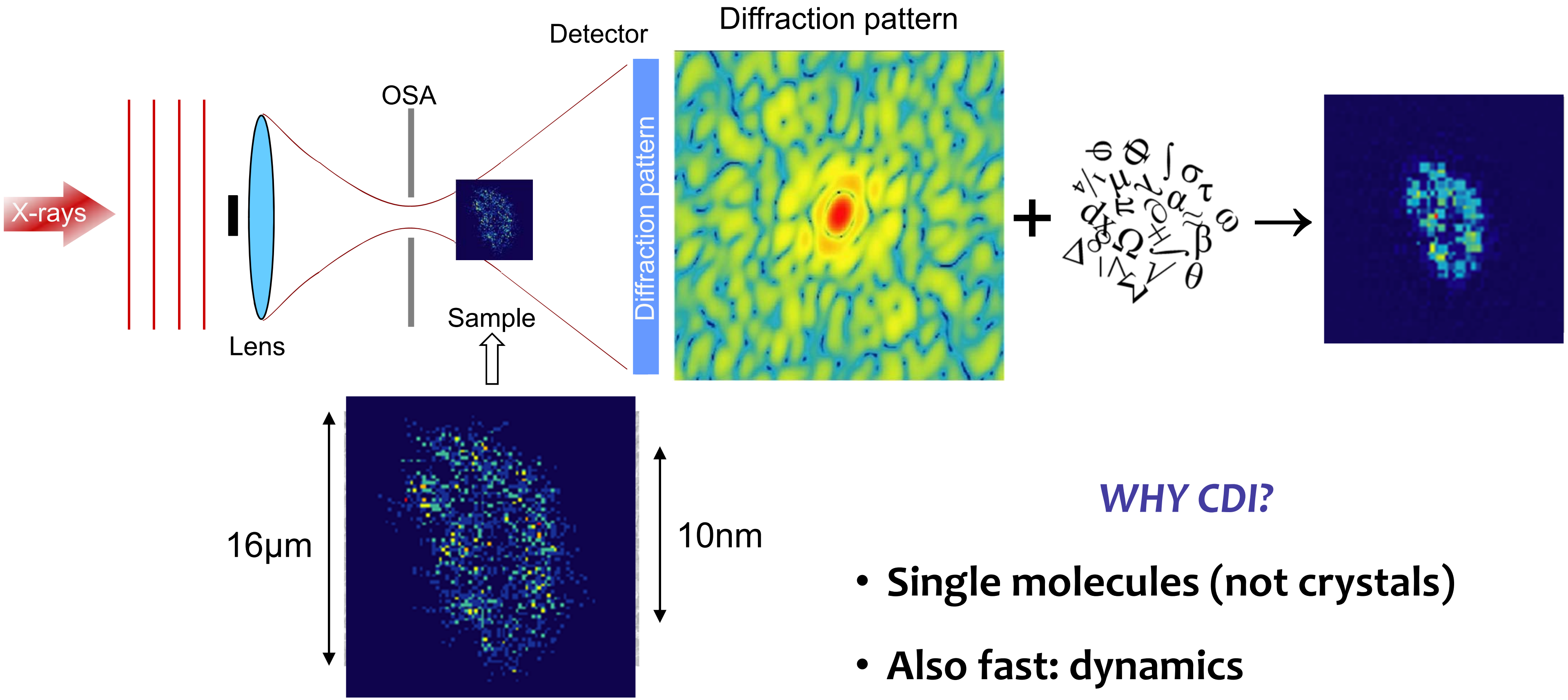
Australian Government
Australian Research Council

Imaging small things: diffractive (lensless) imaging

CDI – Coherent Diffractive Imaging

- Measure diffraction pattern for (non-crystalline) object illuminated by x-rays
- Measure intensity, recover phase algorithmically, to determine image of object
- Need a *coherent* source



WHY CDI?

- **Single molecules (not crystals)**
- **Also fast: dynamics**

Nugent and coworkers: Abbey et al. Nat Phot ***5*** *(2011); Whitehead et al. PRL* ***103*** *(2009)*

Electrons?

- Interaction 10^4 to 10^6 times stronger than X-rays
- Lower damage for bio-molecules
- Electron optics *extremely* advanced
- Detectors have good resolution, high efficiency
- Electron microscopy is fantastic, but…

Too slow †

- Molecules destroyed before imaged. No dynamics.
  - Space-charge repulsion limits brightness
  - Only ***one electron at a time*** in high-res electron microscope
  - Dynamics lost

CDI with electrons?

- Need high *brightness*, i.e. transverse *coherence* + high *current*

† See Bryan Reed's talk later in conference

So is CDI possible with electrons?

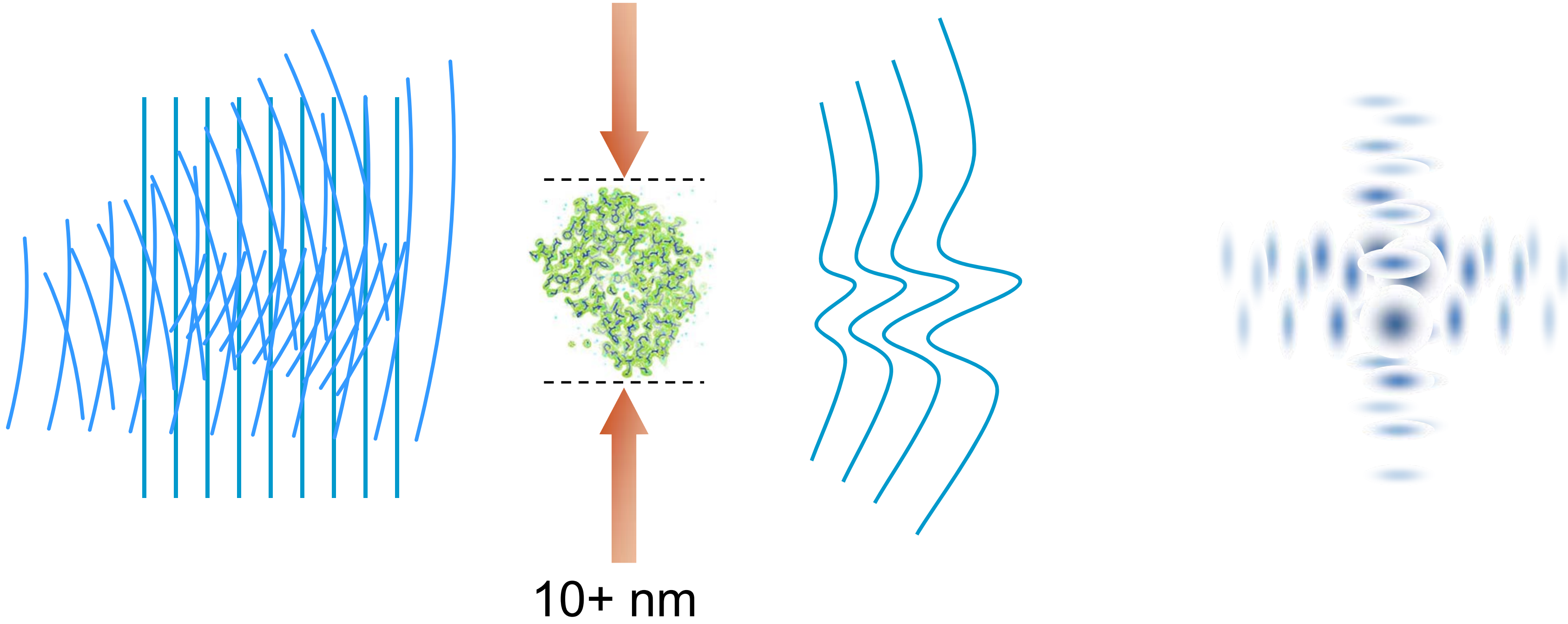
Coherence

Temporal coherence

$$L = \frac{c}{\Delta f} = \frac{h}{\Delta p}$$

Transverse spatial coherence

$$L_c = \frac{h}{\Delta p_x} = \frac{\lambda}{2\pi\,\Delta\theta} = \frac{\hbar}{\sqrt{m k_B T}}$$

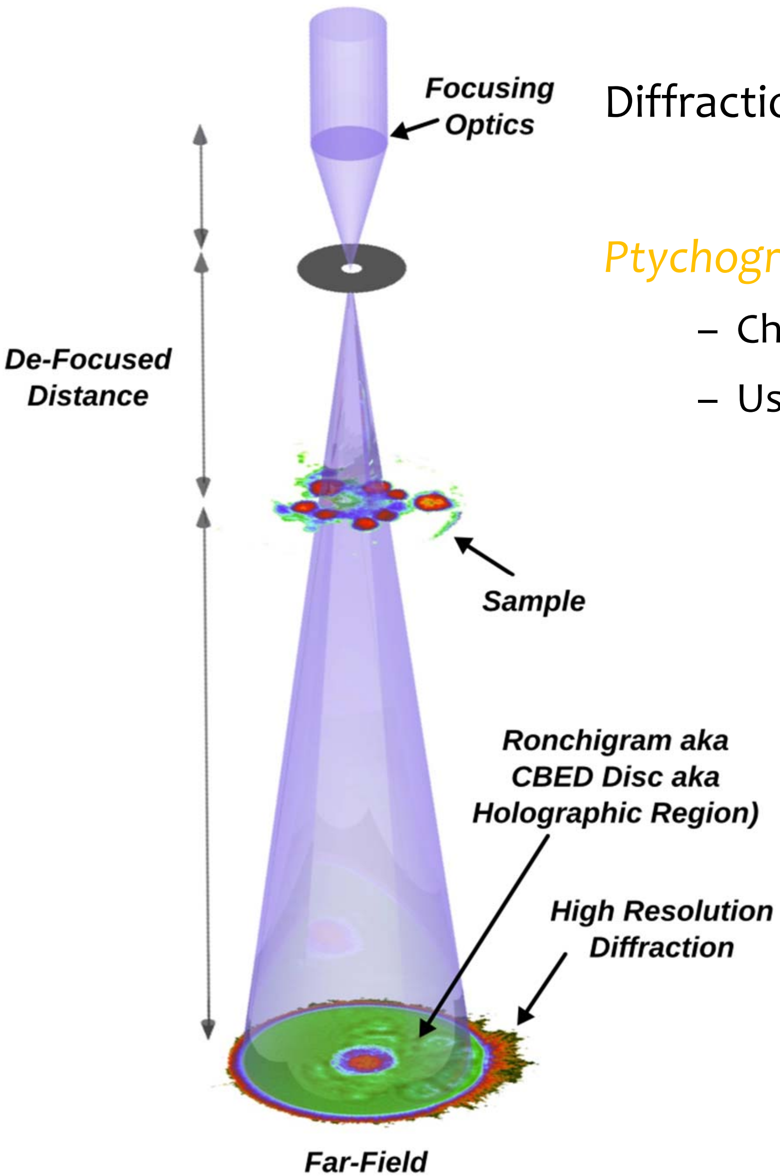


So is CDI possible with electrons?

RuBisCO molecule (carbon fixation)

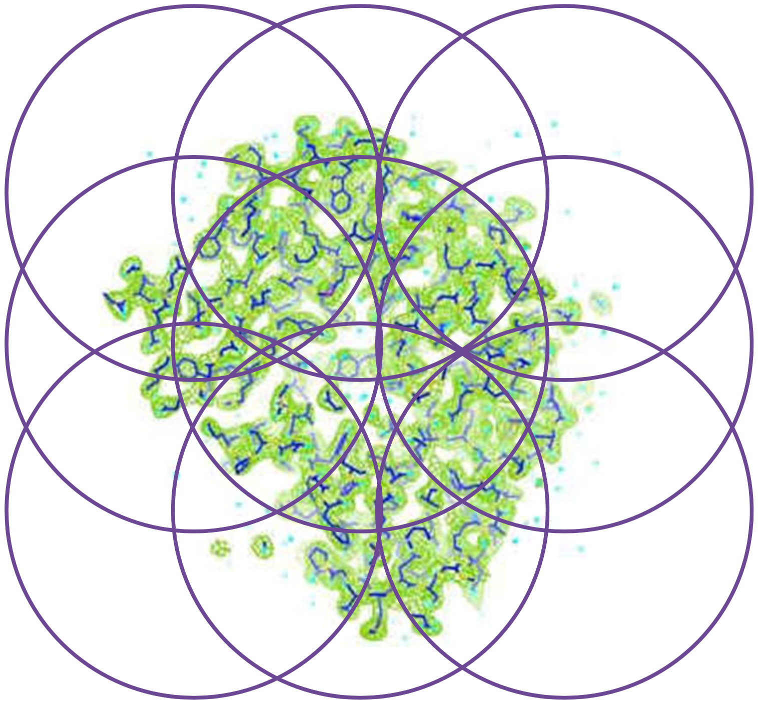
Electron CDI

Diffraction → intensity only: *phase ambiguity*



Ptychography

- Change phase, profile or position of illuminating beam
- Use two (or more) diffraction patterns to reconstruct



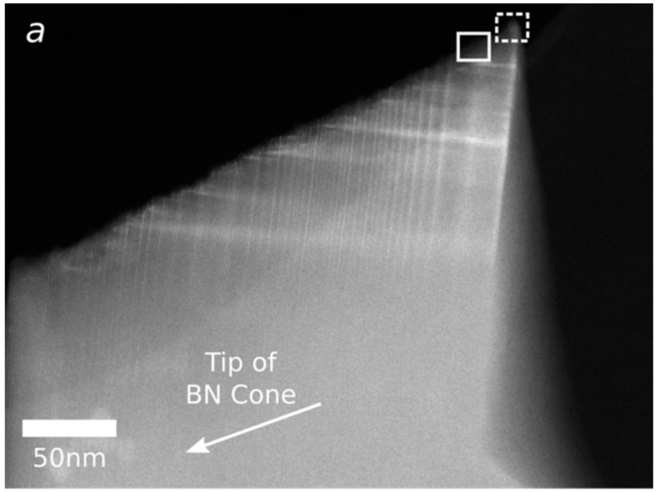
Atomic resolution ptychographic eCDI

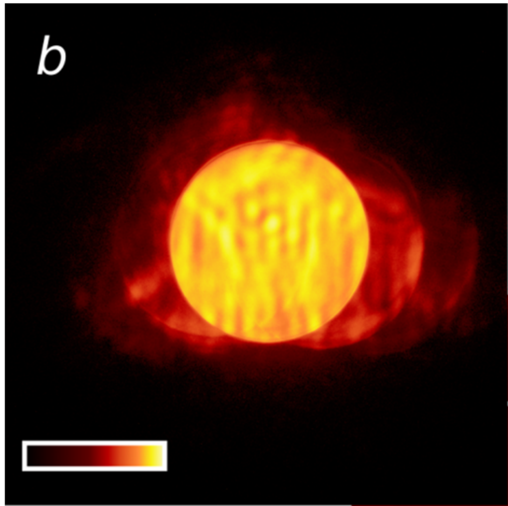
Boron nitride helical cones

FEI Titan microscope STEM 300keV λ = 2pm, over-focused

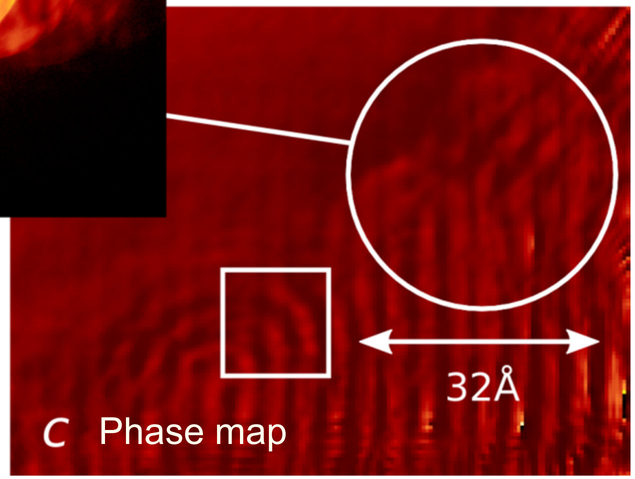
$L_c = 0.15\ \text{nm}$

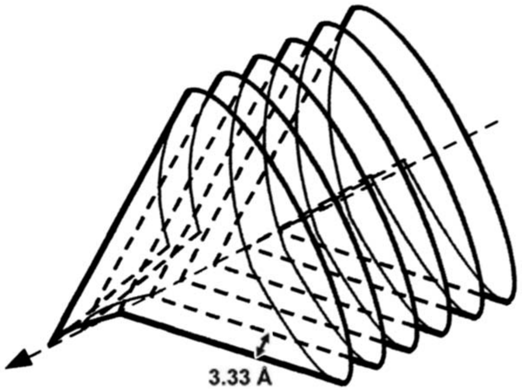
For given STEM probe, peCDI → resolution improvement





Diffraction data
(log scale)





CDI works with electrons …

…but very slowly

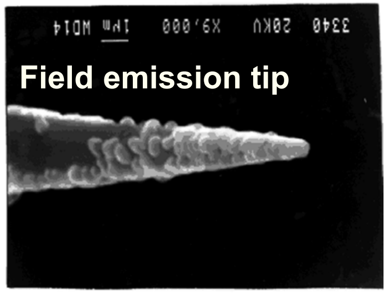
MONASH University
Centre for Electron Microscopy

Corey Putkunz *Physical Review Letters* **108** 073901 (2012)

Too slow: coherence not enough

Coherence good, but need *lots* of electrons

Brightness $$B_{\perp} = \frac{I}{4\pi\, \varepsilon_x \varepsilon_y} = \frac{mc^2 J}{\pi k T}$$ (thermal source)



Field emission tips: <u>*coherent*</u> but not high current

Photoemission: <u>*high current*</u> but not coherent

Magic: *high current and high coherence*

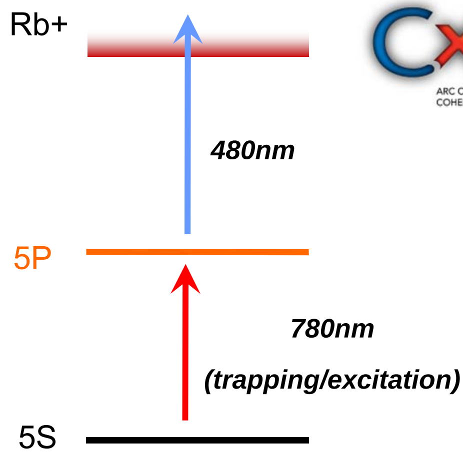
without space-charge explosion?

Electrons from cold atoms

Photoionise cold atoms

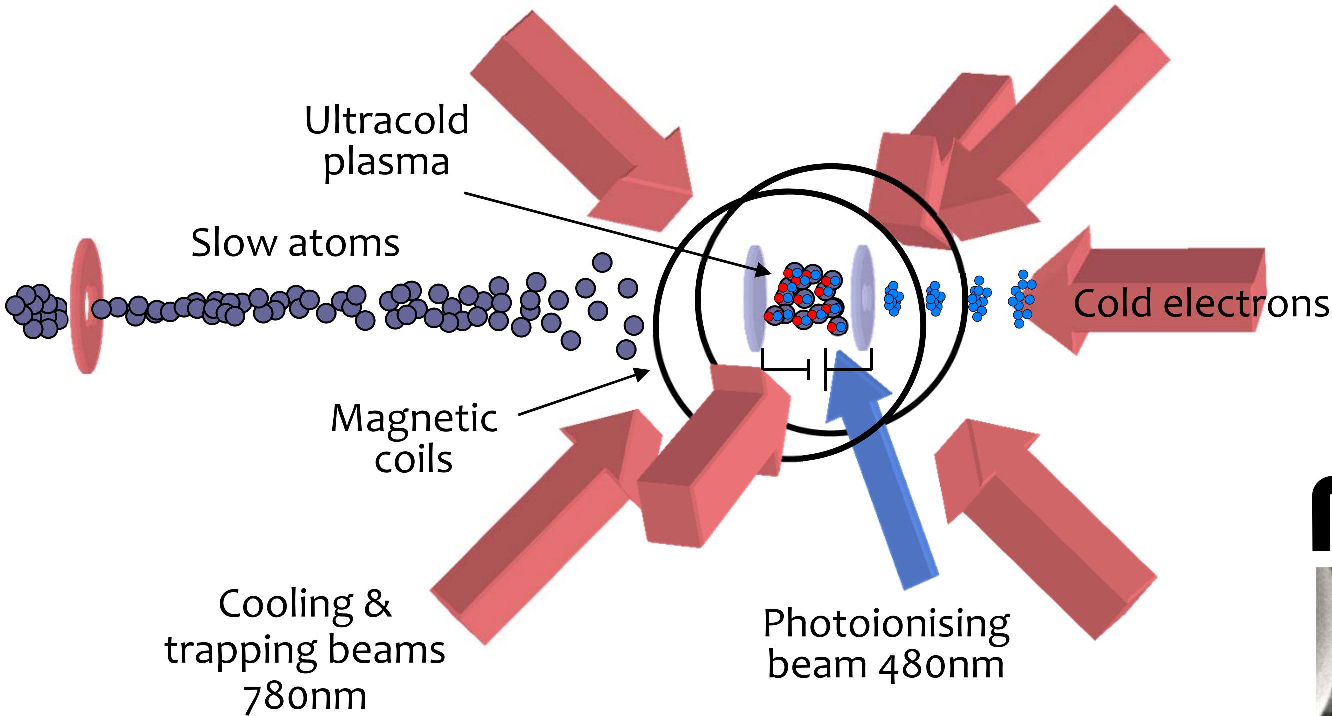
Narrow laser linewidth + Doppler-free

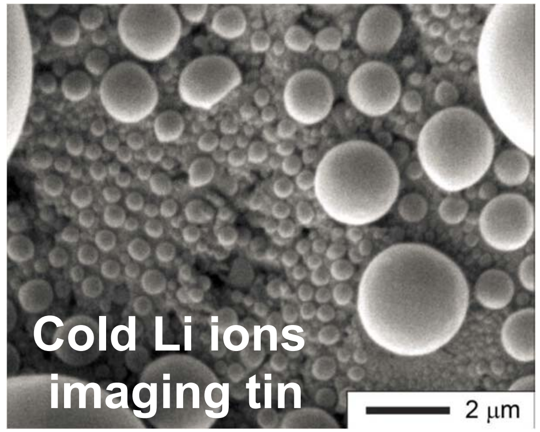
$\rightarrow$ small energy uncertainty (low T)



$$T \approx 10\,\mathrm{K}$$

$$L_c \propto \frac{1}{\sqrt{T}} \sim 8\,\mathrm{nm}$$



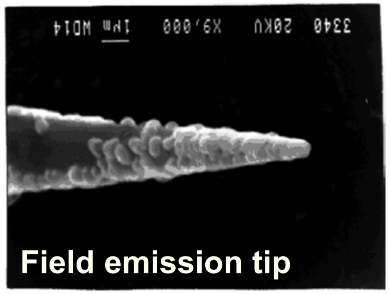


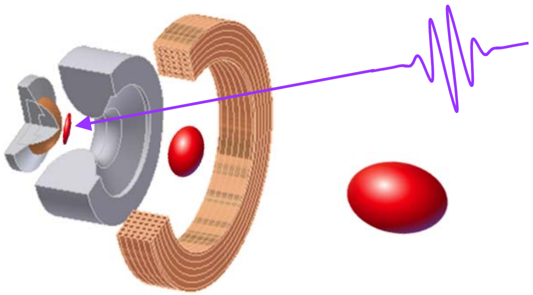
High coherence, but space-charge explosion?

Knuffman, Steele, Orloff, McClelland, New J Phys 13 103035 (2011)

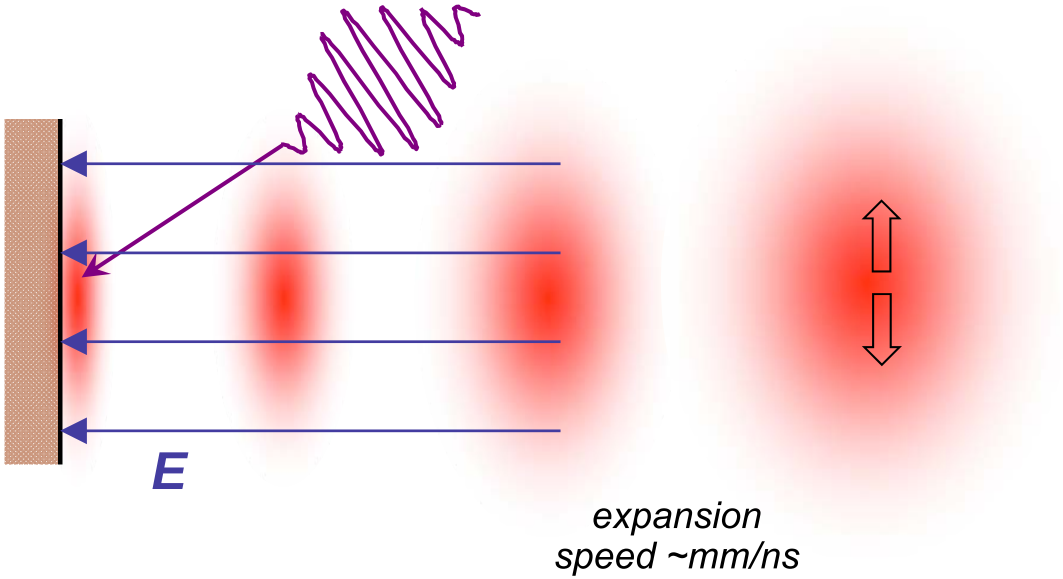
Coherence ✓ Brightness? Coulomb explosion

Short pulses, high electron density → Coulomb expansion





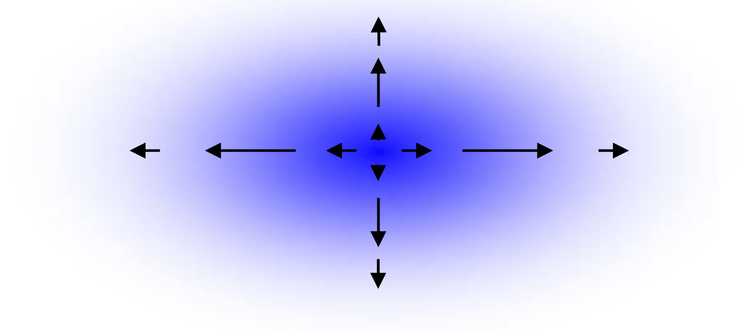
Photoemission source

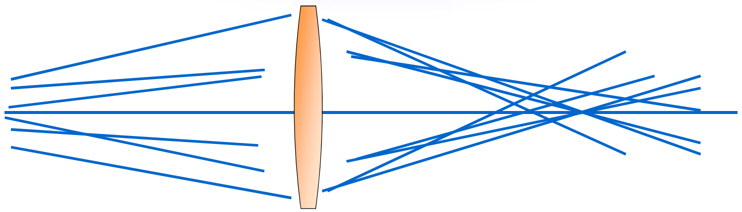


… ***irreversible*** space-charge explosion

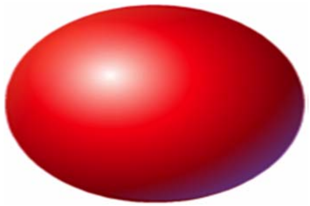
The problem and a solution

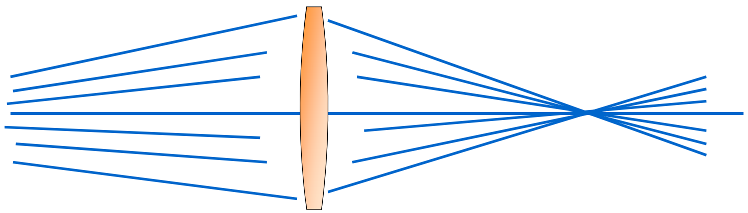
Gaussian bunch



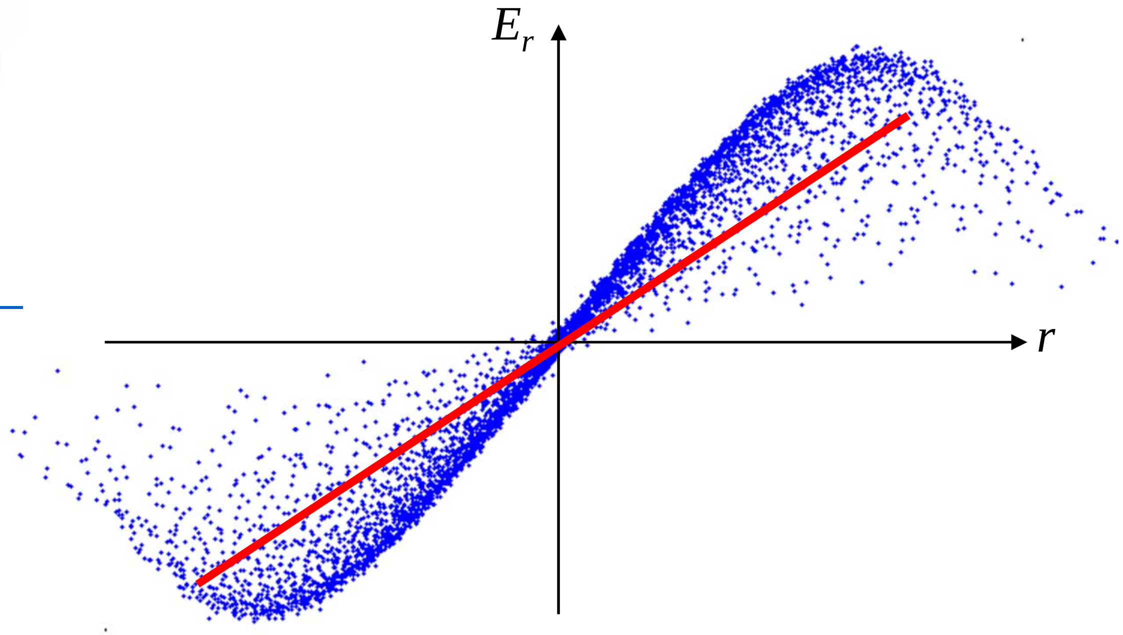


Uniform ellipsoidal bunch





Nonlinear space-charge forces;
Irreversible Coulomb expansion

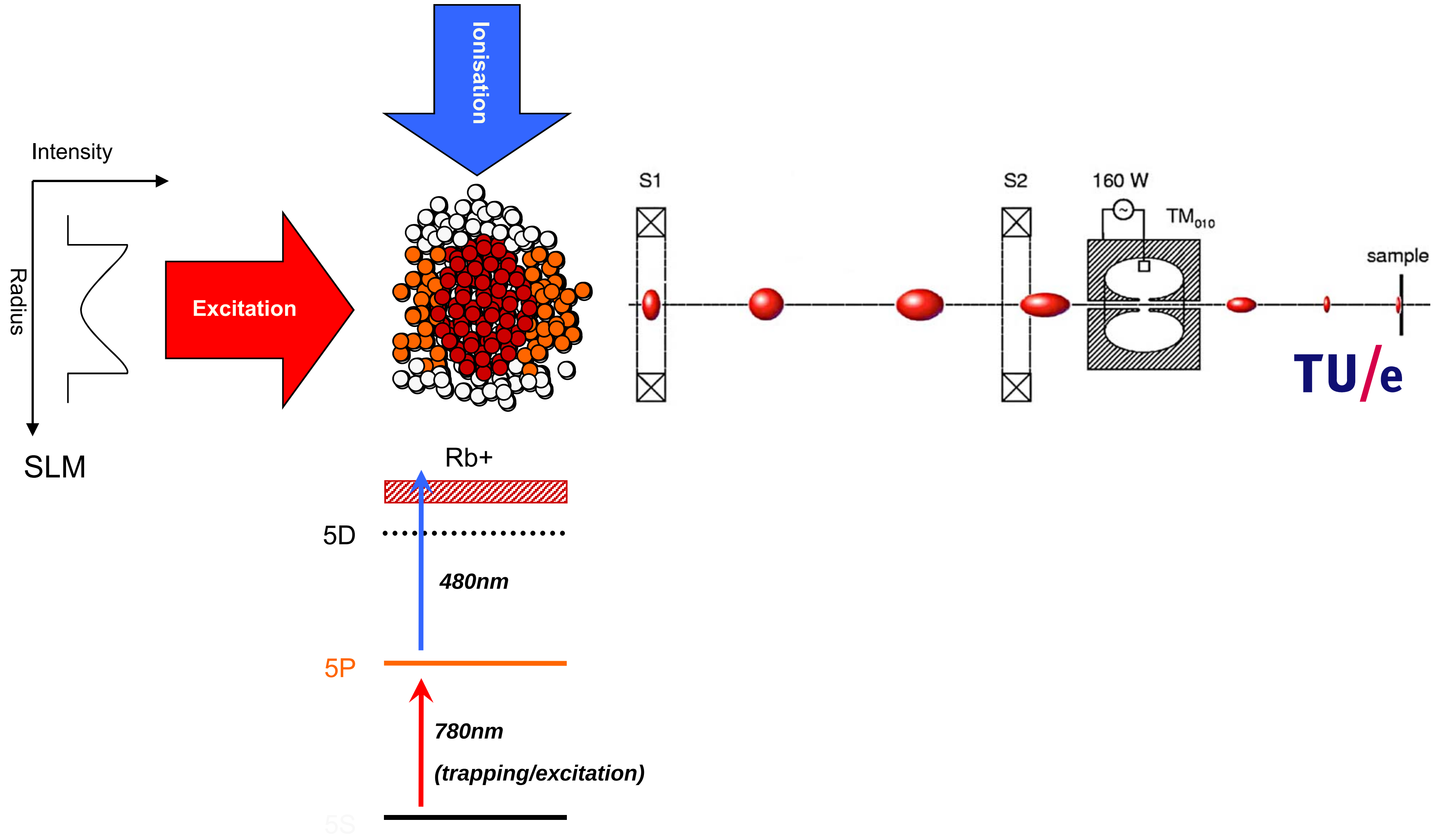


Linear space-charge forces;
Reversible Coulomb expansion

Kapchinskii and Vladimirskii, 1959

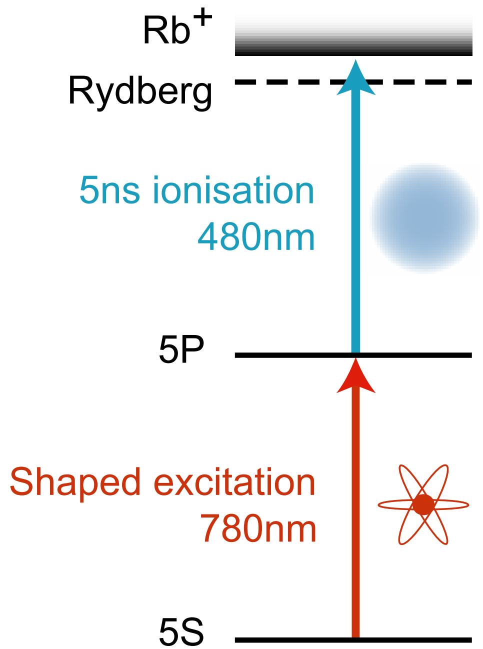
Bunch shaping to allow explosion reversal

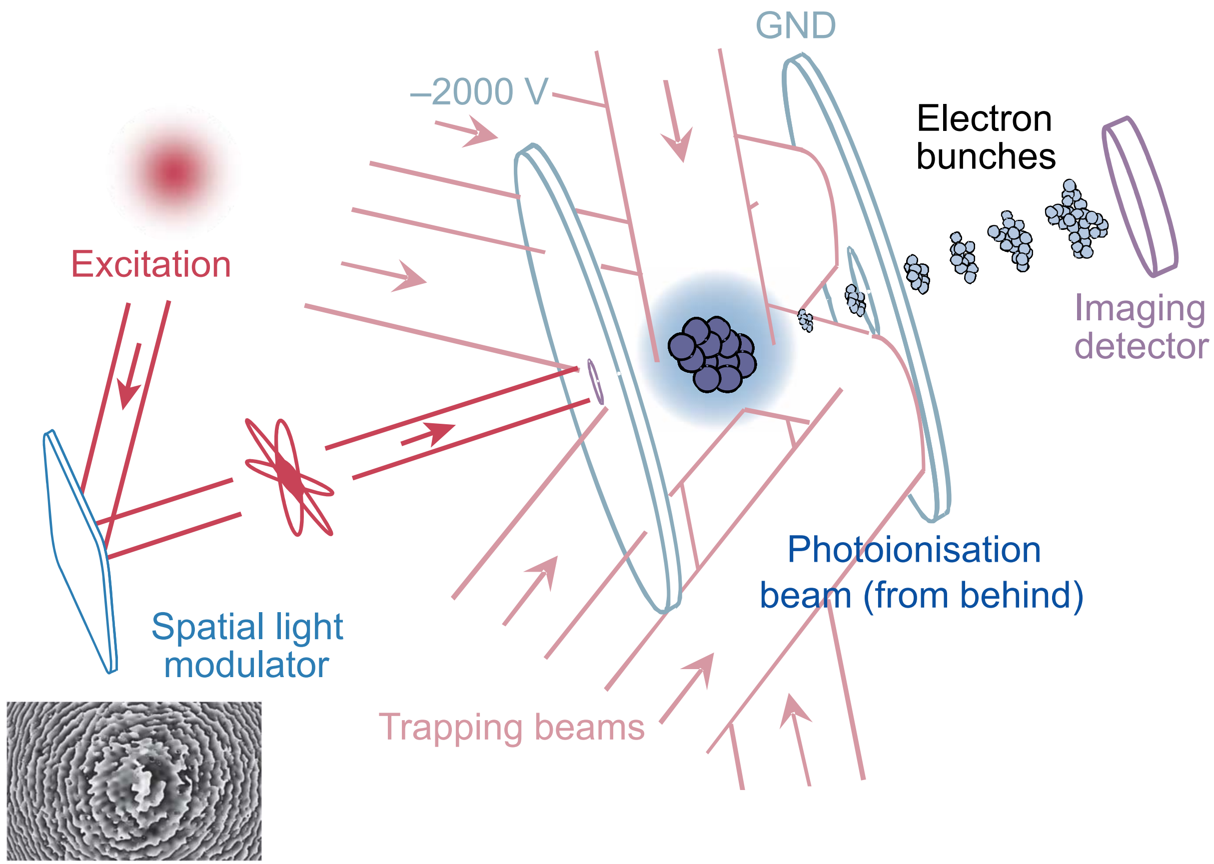
- Space-charge repulsion does ***not*** intrinsically reduce brightness
  - at least, not irreversibly
- Uniform density + elliptical bunch shape $\Rightarrow$ can refocus bunch



Bunch shaping

Cold atom electron source allows spatial control

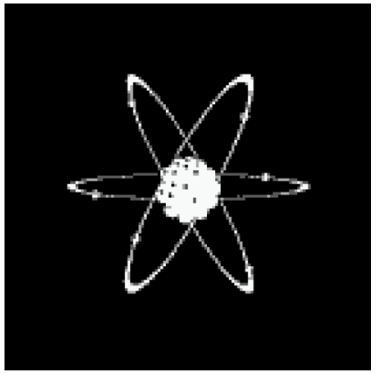




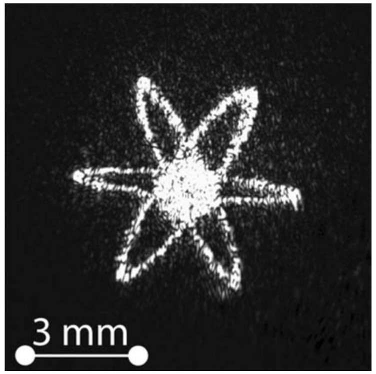
Andy McCulloch et al, Nature Physics **7** p785 (2011)

Arbitrary bunch shaping

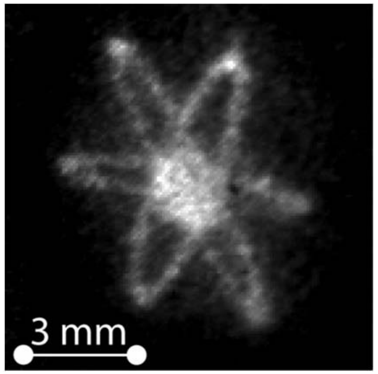
Desired

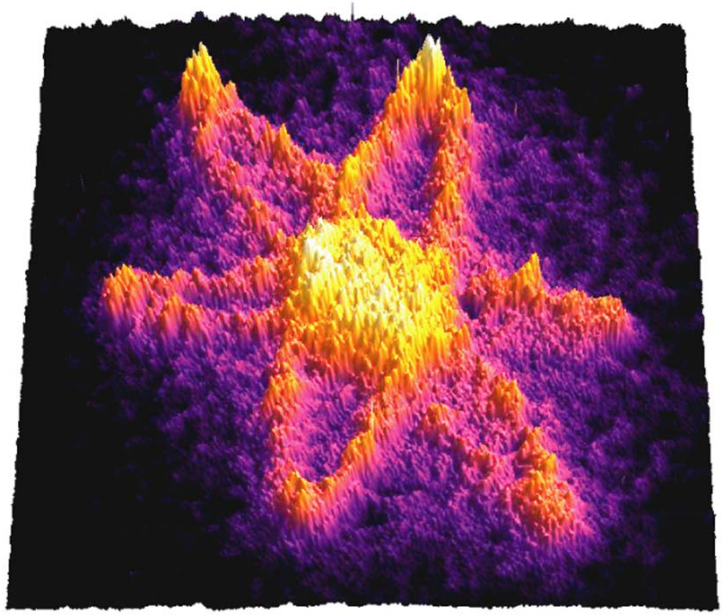


Excitation laser beam profile



Electron density





Propagation distance 24cm
Time of flight 14ns

Electron mass is *small*
10K = <1 meV, *v* = 17 km/s

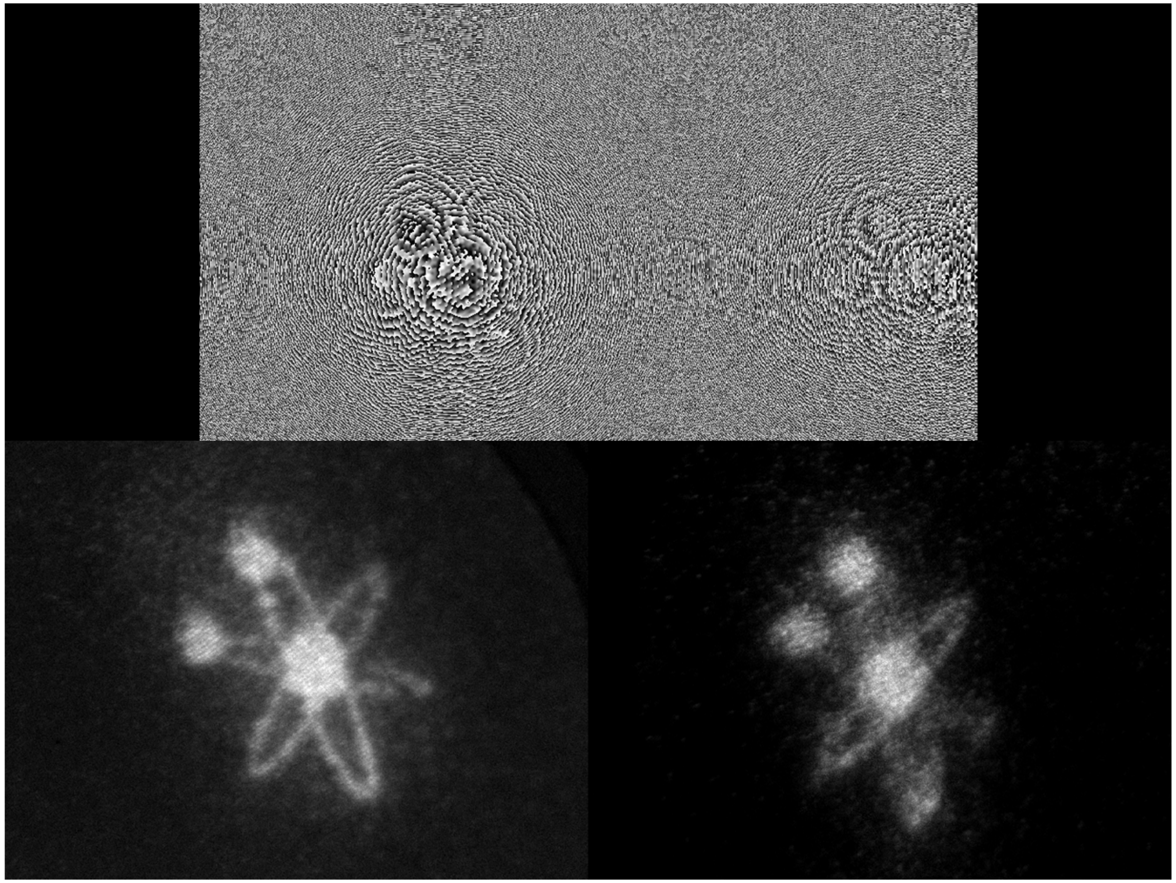
Andy McCulloch et al, Nature Physics **7** p785 (2011)

World's most expensive TV!

Update phase mask at 10Hz: *dynamically shape electron bunch*

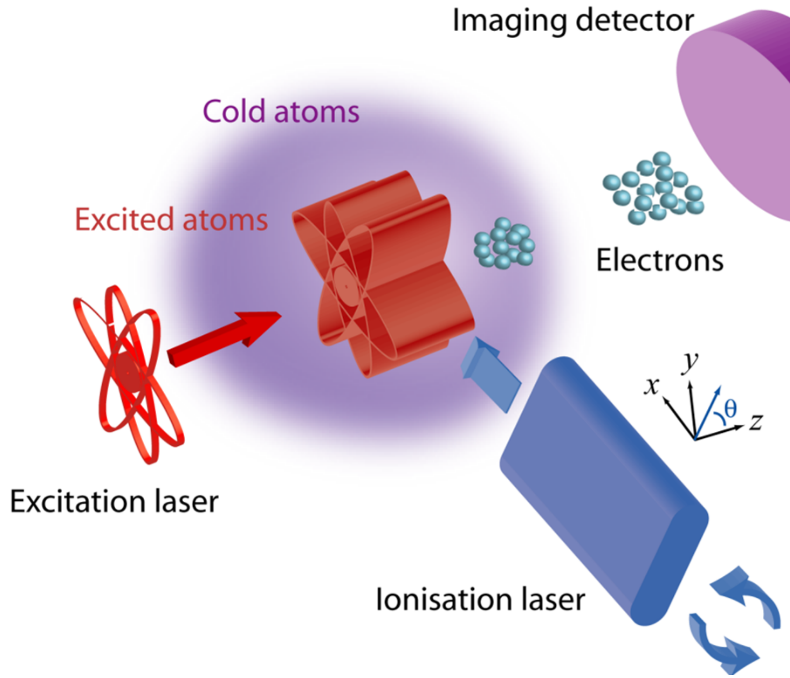
Phase mask on SLM

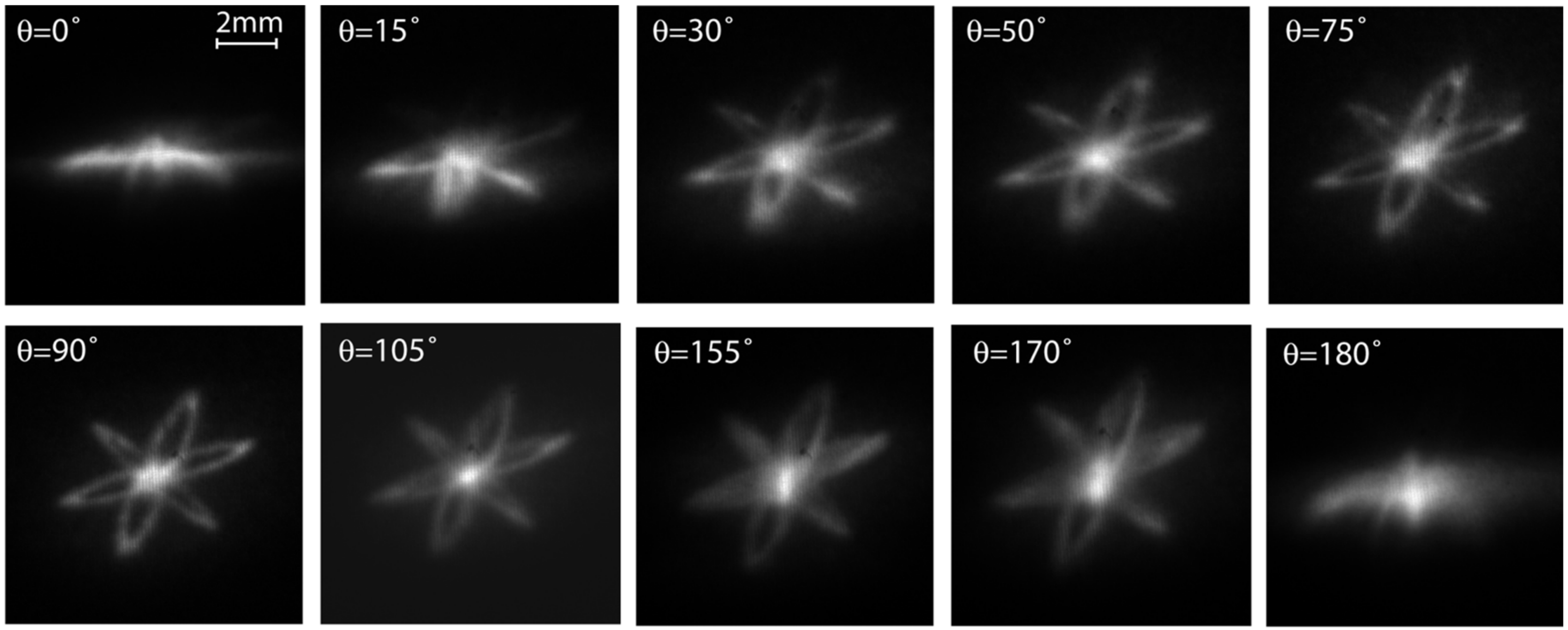
Free propagation – not reimaged



10-shot average Electrons Single-shot

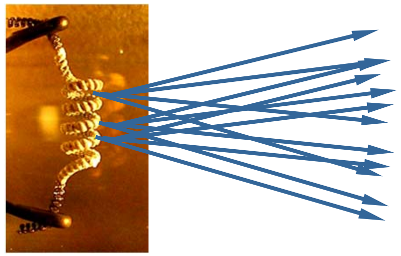
Longitudinal shaping too

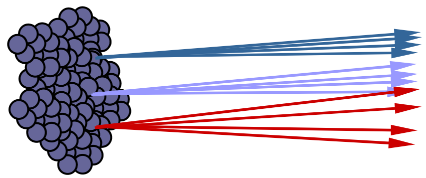




Temperature, coherence, emittance

Temperature and spatial coherence

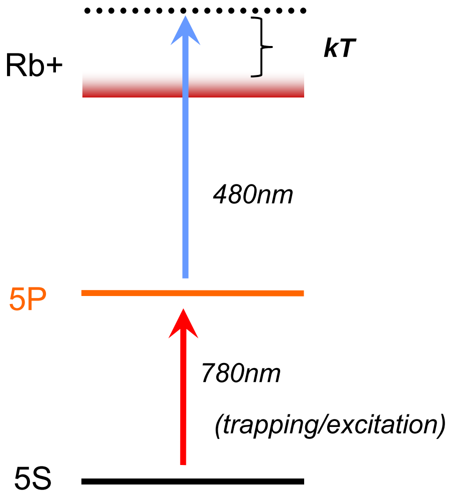


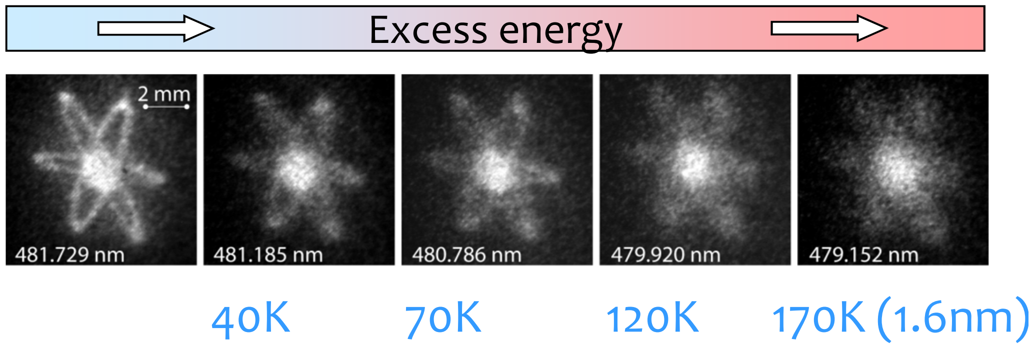


Electron mass is *small*
10K = <1meV, *v* = 17 km/s

- Control excess energy via laser λ

$$T \equiv \frac{hc}{k_B \lambda} \quad \Rightarrow \quad T = \frac{hc}{k_B}\left(\frac{1}{\lambda} - \frac{1}{\lambda_{ion}}\right) + T_0$$



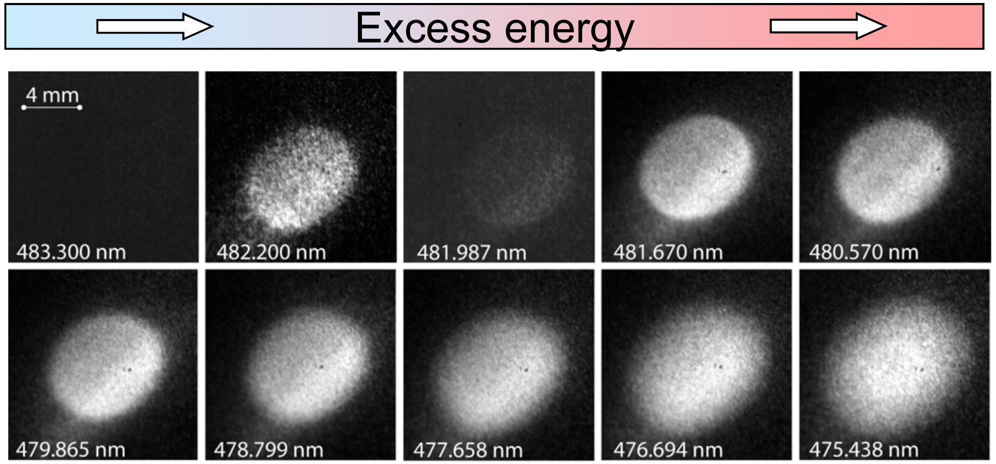


Measuring the electron coherence v1

Quantify

- SLM $\rightarrow$ uniform density pulses
- Measure *edge resolution*

$$\frac{dQ_e}{dr} \rightarrow \text{coherence } L_c \text{ and } T$$

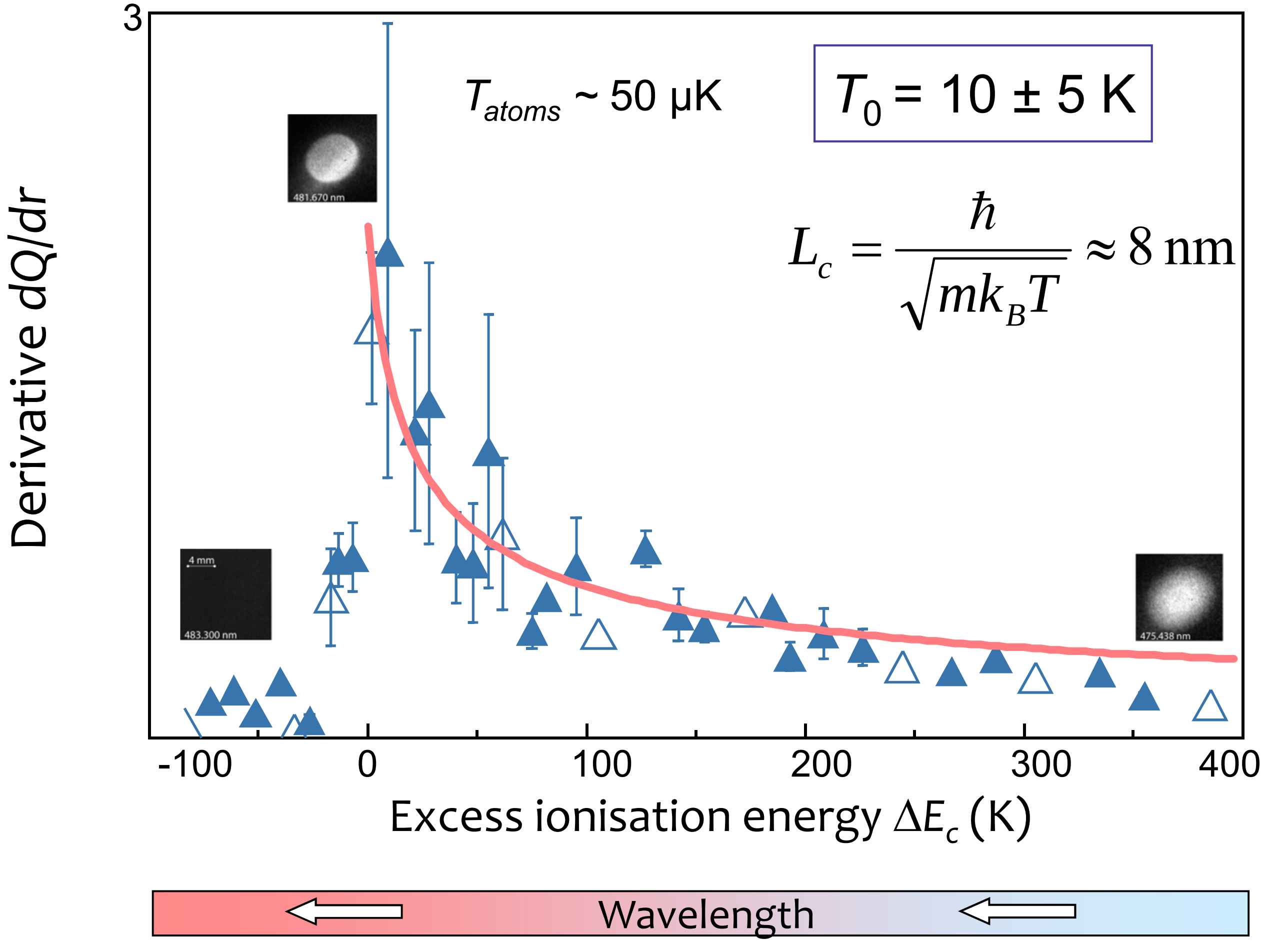


- Edge gradients related to
  - Accelerator geometry (distances d_1, d_2)
  - Excess photon energy
  - Minimum temperature T_0

$$\frac{dQ_e}{dr} \propto e \frac{d_1}{2d_1 + d_2} \frac{1}{\sqrt{d_1\left(k_B T_0 + \Delta E\right)}}$$

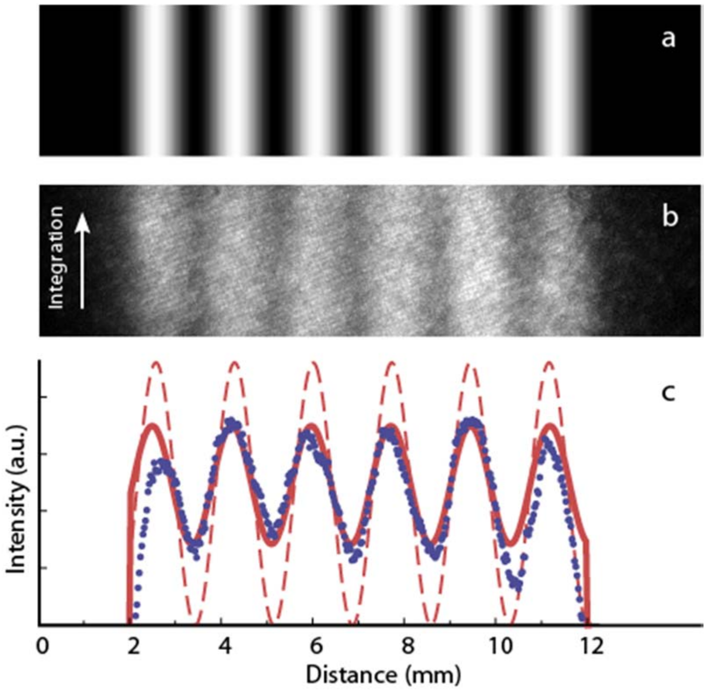
Andy McCulloch et al, *Nature Physics* **7** p785 (2011)

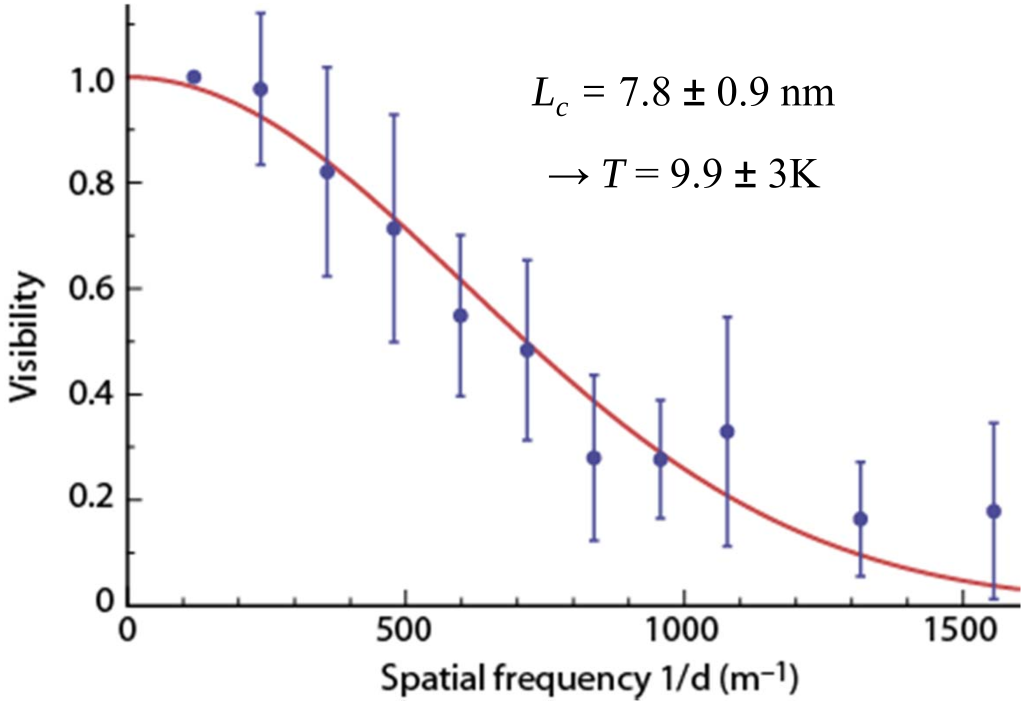
Measuring the electron coherence v1



Andy McCulloch et al, Nature Physics **7** p785 (2011)

Measuring the electron coherence v2





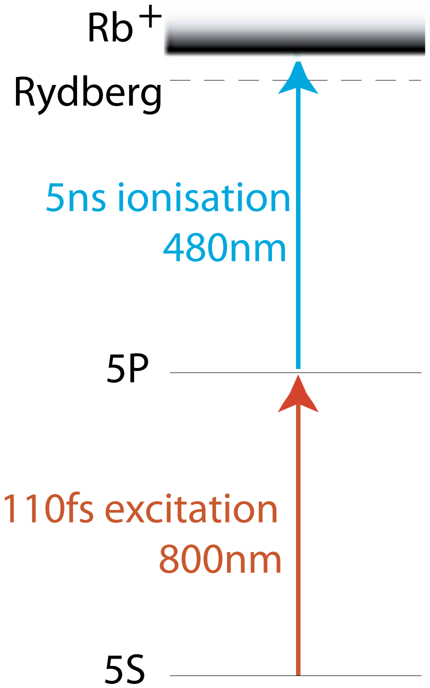
$$\mathcal{V}_{pc} = \exp\left[-\frac{2\pi^2\sigma_b^2}{d^2}\right] = \exp\left[-\frac{1/d^2}{m^2 l_c^2 / h^2 t^2}\right]$$

Saliba et al, Optics Express **20** 3967(2012)

Ultrafast

Ultrafast

- Slow photoionisation (5ns) + fast excitation (110fs)
- Detector-limited sub-ns pulses
- Geometry, extraction field: predict 150ps



Unpublished data was here

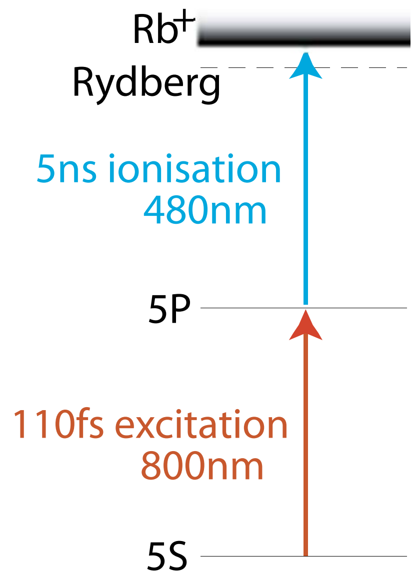
- High bandwidth (20nm): is temperature affected?

Multiphoton and two-colour processes

- Excitation
  - Coherent: One fs photon + one 5ns photon (two-colour)
  - REMPI: Multiple fs photons

- Coherent → cold

- REMPI → hot

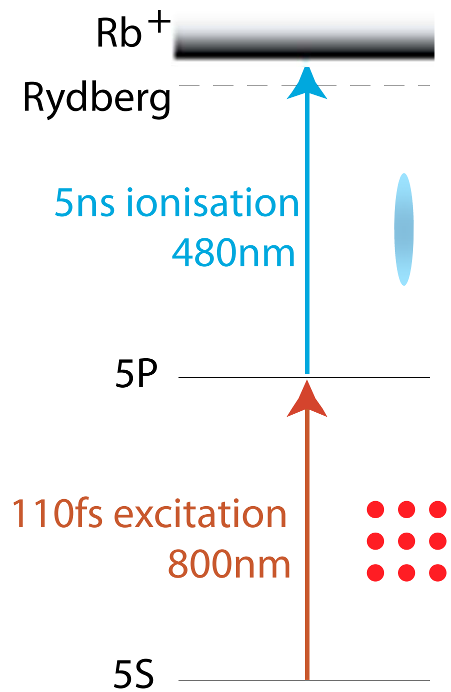


Unpublished data was here

Ultrafast pepperpots

Emittance

- Virtual pepperpot: holey mask → beamlets
- Divergence of beamlet → emittance



Unpublished data was here

Short cold bunches

- Emittance increases, but lower than expected from fs bandwidth
- Excess energy along propagation axis

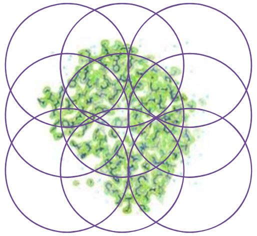
Bandwidth of fs laser
contributes to energy spread

Fast and cold

Unpublished data was here

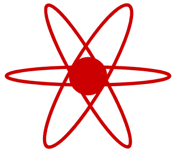
Excitation to Rydberg state
then field-ionised (Bordas saddle)

Main points



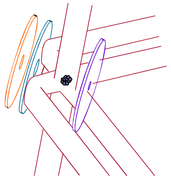
1. Electron coherent diffractive imaging

   → atomic resolution with field-emission source



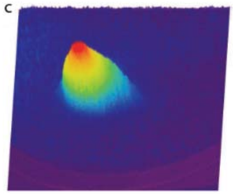
2. Cold atoms

   → cold electrons, high transverse coherence



3. Unique capability: 3D bunch shaping

   → reversal of Coulomb explosion?



4. Ultrafast with high coherence