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

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With thanks to:

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**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

\[ L = \frac{c}{\Delta f} = \frac{\hbar}{\Delta p} \]

Transverse spatial coherence

\[ L_c = \frac{\hbar}{\Delta p_x} = \frac{\lambda}{2\pi \Delta \theta} = \frac{\hbar}{\sqrt{mk_B T}} \]

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 $\lambda = 2$pm, over-focused

For given STEM probe, peCDI $\rightarrow$ resolution improvement

$L_c = 0.15$ nm

CDI works with electrons …

… but very slowly

Corey Putkunz  
Too slow: coherence not enough

Coherence good, but need *lots* of electrons

Brightness

\[
B_{\perp} = \frac{I}{4\pi \varepsilon_x \varepsilon_y} \frac{mc^2 J}{\pi kT} \quad \text{(thermal source)}
\]

*Field emission tips:* coherent but not high current

*Photoemission:* high current 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

→ small energy uncertainty (low $T$)

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*High coherence, but space-charge explosion?*

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**Knuffman, Steele, Orloff, McClelland, New J Phys 13 103035 (2011)**
Coherence ✅ Brightness? Coulomb explosion

Short pulses, high electron density → Coulomb expansion

... irreversible space-charge explosion
The problem and a solution

Gaussian bunch

Nonlinear space-charge forces; Irreversible Coulomb expansion

Uniform ellipsoidal bunch

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**

- Control excess energy via laser $\lambda$

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

Electron mass is small

$10K = \langle 1 \text{meV} \rangle, \quad v = 17 \text{ km/s}$

**Excess energy**

- $40K$
- $70K$
- $120K$
- $170K (1.6 \text{nm})$
Measuring the electron coherence v1

Quantify
• SLM → 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 \(T_0\)

\[
\frac{dQ_e}{dr} \propto e^{d_1} \frac{1}{2d_1 + d_2} \frac{1}{\sqrt{d_1(k_B T_0 + \Delta E)}}
\]

Andy McCulloch et al, Nature Physics 7 p785 (2011)
Measuring the electron coherence v1

\[ T_{\text{atoms}} \sim 50 \, \mu\text{K} \]

\[ T_0 = 10 \pm 5 \, \text{K} \]

\[ L_c = \frac{\hbar}{\sqrt{m k_B T}} \approx 8 \, \text{nm} \]

Andy McCulloch et al, Nature Physics 7 p785 (2011)
Measuring the electron coherence v2

$L_c = 7.8 \pm 0.9 \text{ nm}$

$\rightarrow T = 9.9 \pm 3 \text{K}$

\[ V_{pc} = \exp \left[ -\frac{2\pi^2 \sigma_b^2}{d^2} \right] = \exp \left[ -\frac{1/d^2}{m^2 l_c^2 / h^2 l^2} \right] \]

Saliba et al, Optics Express 20 3967(2012)
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 $\rightarrow$ beamlets
- Divergence of beamlet $\rightarrow$ 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

Unpublished data was here

Fast and cold

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

1. Electron coherent diffractive imaging
   \[ \rightarrow \text{atomic resolution with field-emission source} \]

2. Cold atoms
   \[ \rightarrow \text{cold electrons, high transverse coherence} \]

3. Unique capability: 3D bunch shaping
   \[ \rightarrow \text{reversal of Coulomb explosion?} \]

4. Ultrafast with high coherence