Electron accelerators for ultrafast scattering and spectroscopy

Cecilia Abbamonte

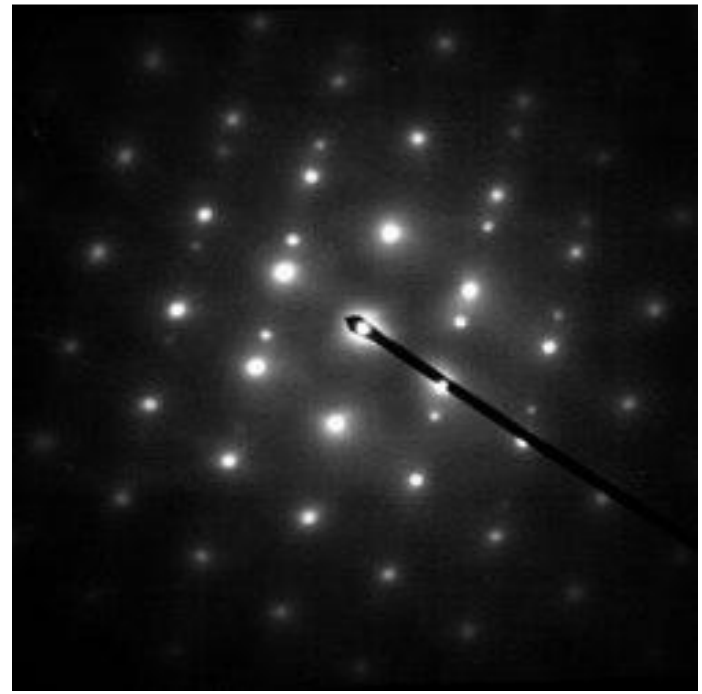
Center for Bright Beams annual meeting

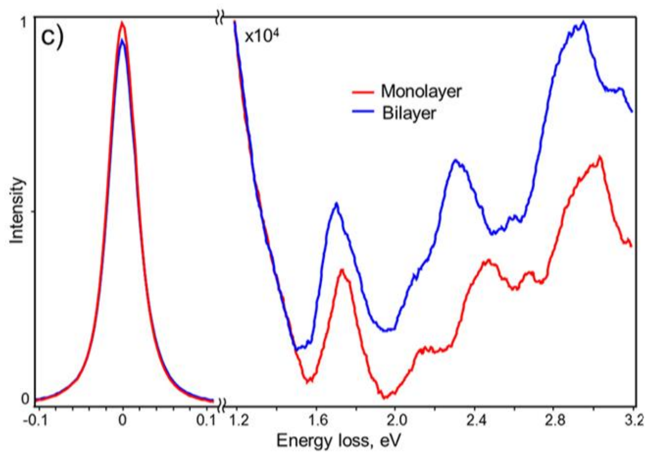
July 10, 2026

Outline

1. Ultrafast electron diffraction
2. Diffuse scattering
3. Electron energy loss spectroscopy
4. Monochromators

Electrons and materials science

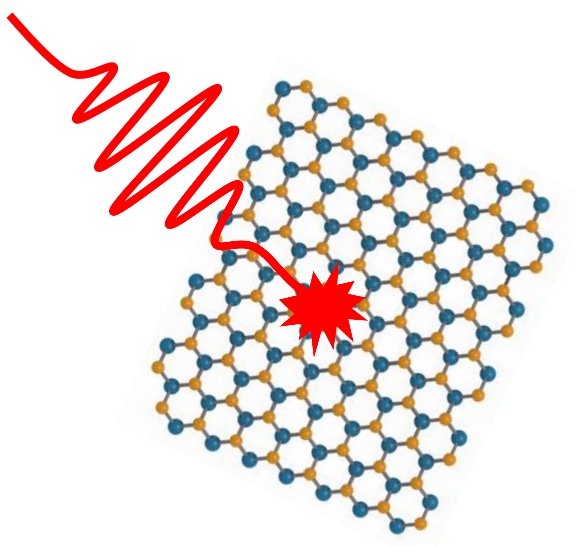




Ultrafast electron diffraction

A pump (usually a laser) excites a sample

- Promote electrons to higher energy levels
- Excite phonon modes

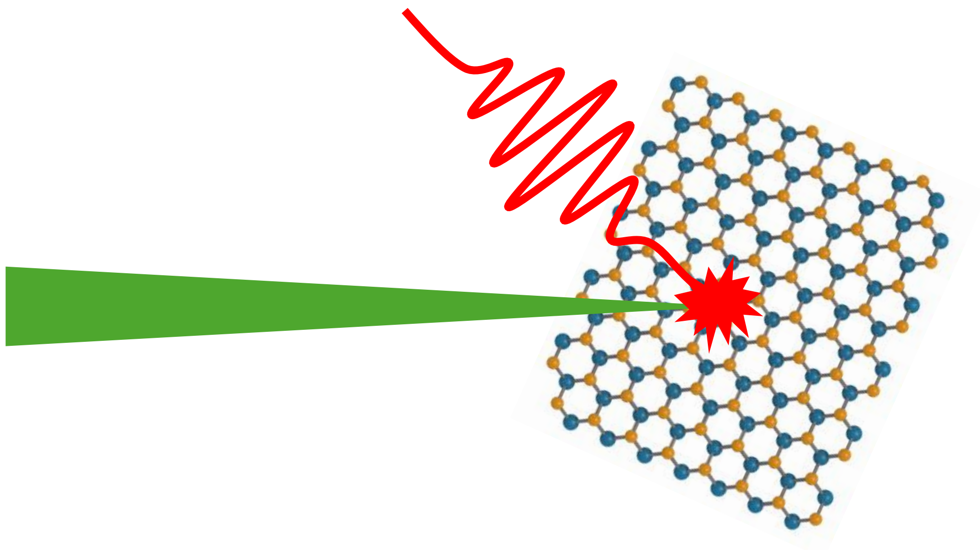


Ultrafast electron diffraction

A pump (usually a laser) excites a sample

- ➢ Promote electrons to higher energy levels
- ➢ Excite phonon modes

A probe (electron beam) follows at some time delay Δt later



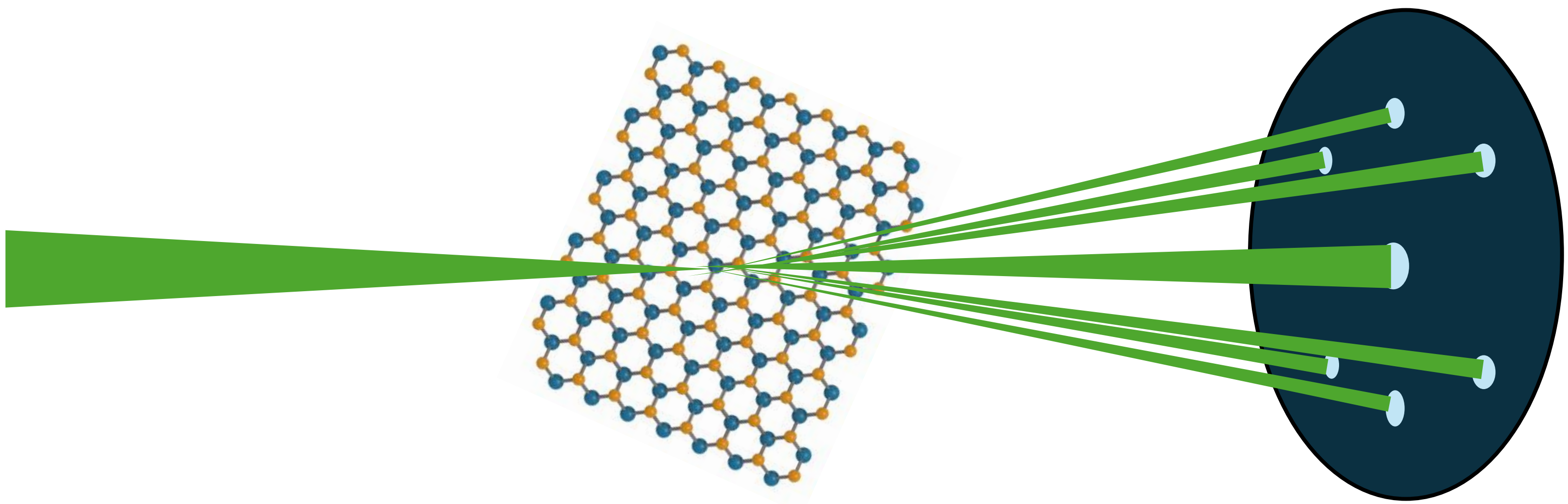
Ultrafast electron diffraction

A pump (usually a laser) excites a sample

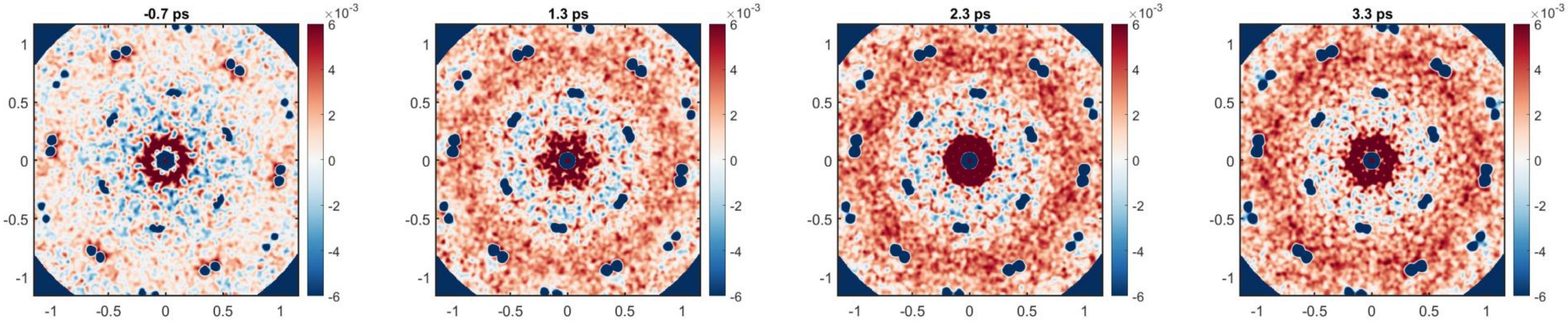
- Promote electrons to higher energy levels
- Excite phonon modes

A probe (laser or electrons) follows at some time delay Δt later

Diffraction pattern is captured on a detector

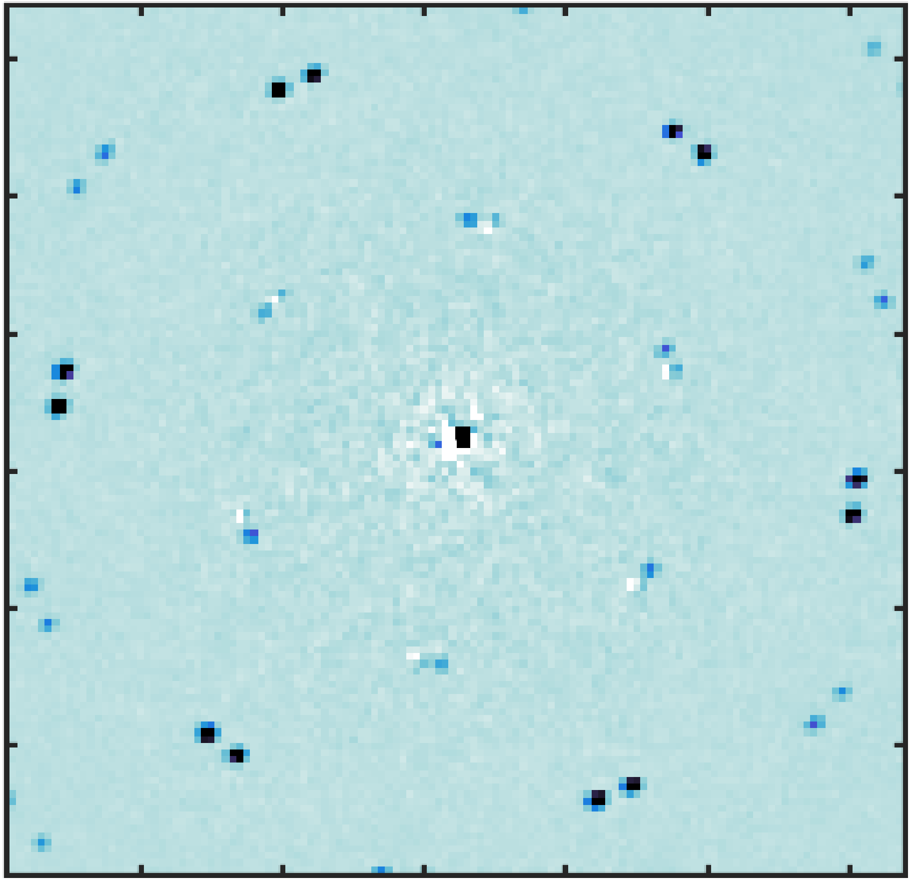


Ultrafast electron diffraction



time

Diffuse scattering



Diffuse scattering

Diffuse background in a diffraction pattern: Electrons exchange energy with the sample by exciting a phonon, momentum change is no longer necessarily a reciprocal lattice vector

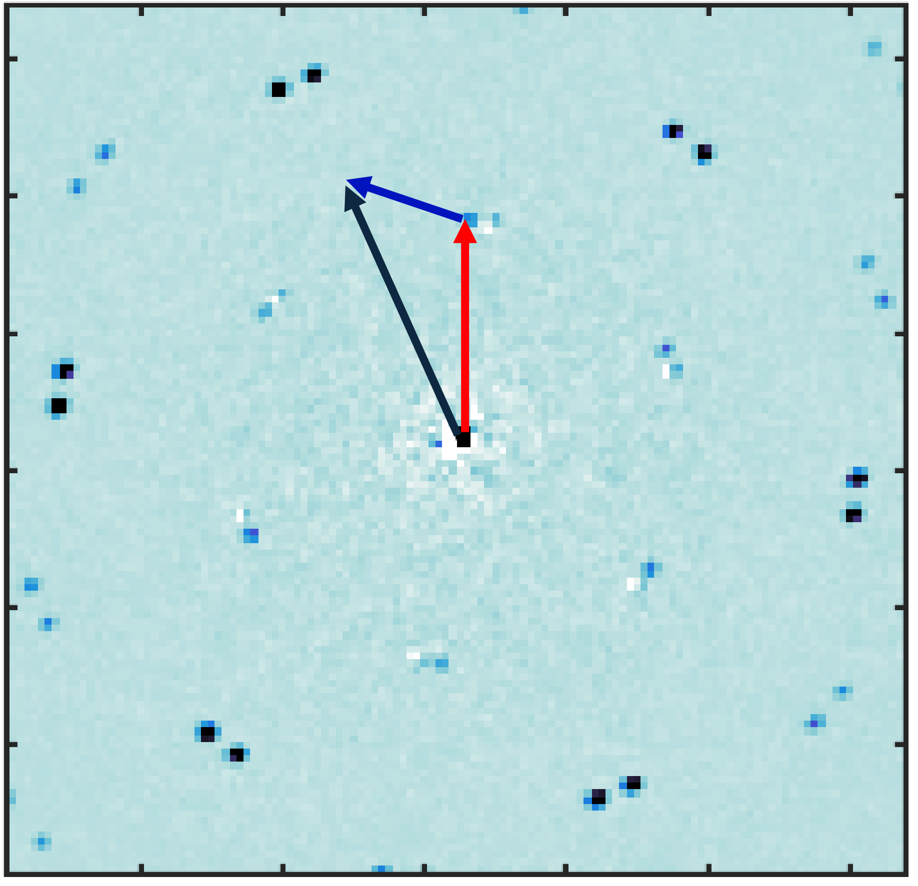
Final q vector

=

Bragg Scattering

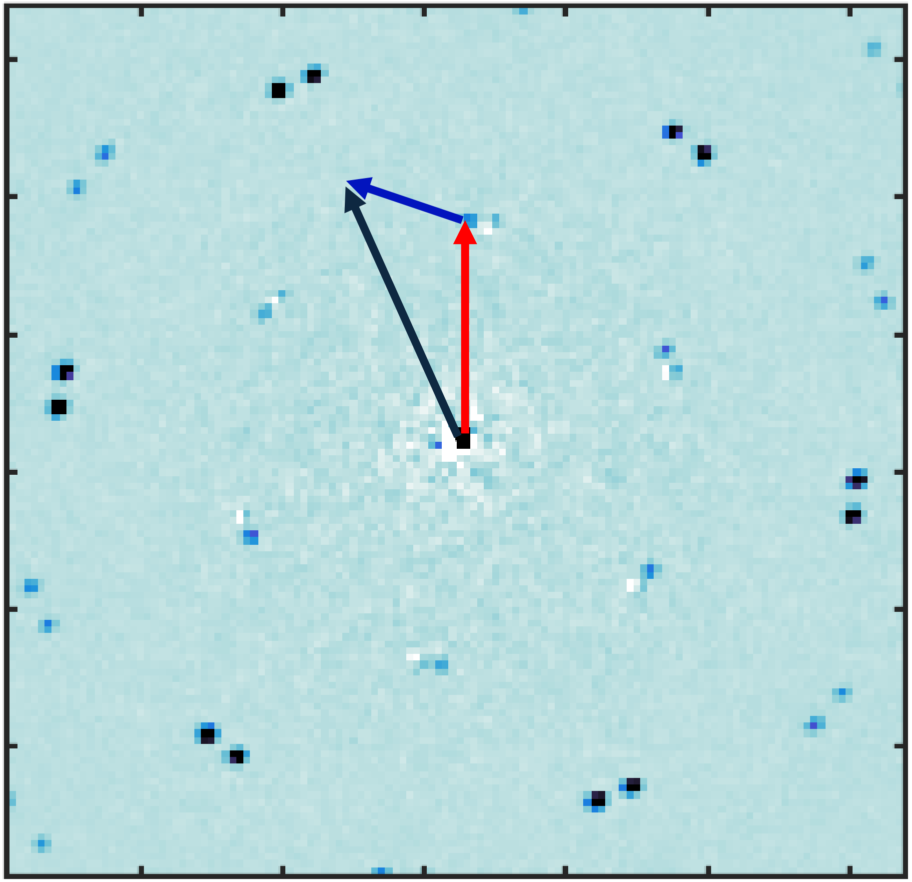
+

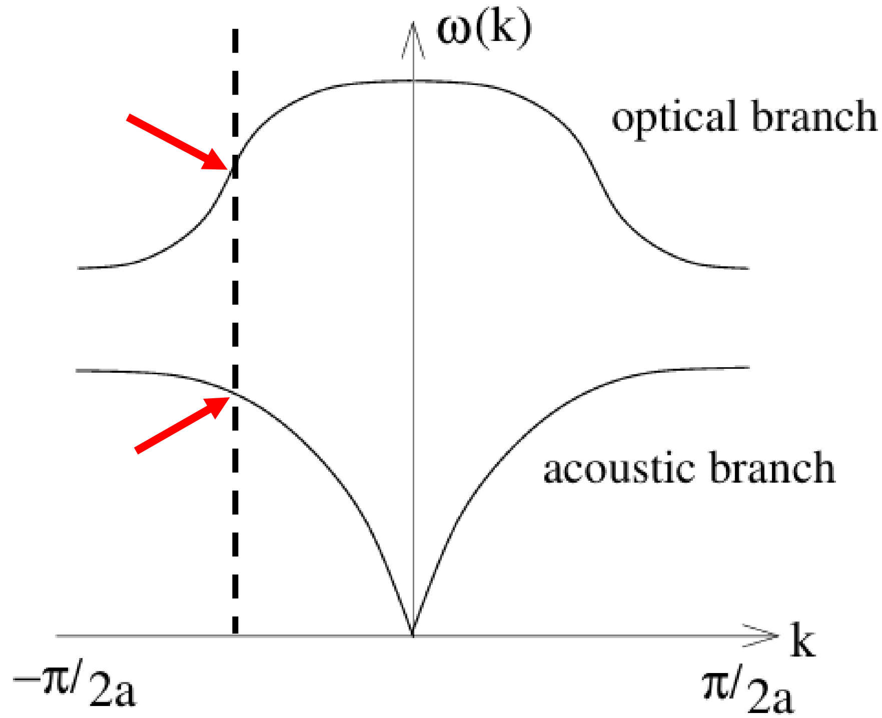
Phonon Scattering



Diffuse scattering

At any given k vector, multiple phonons could be contributing to the intensity!

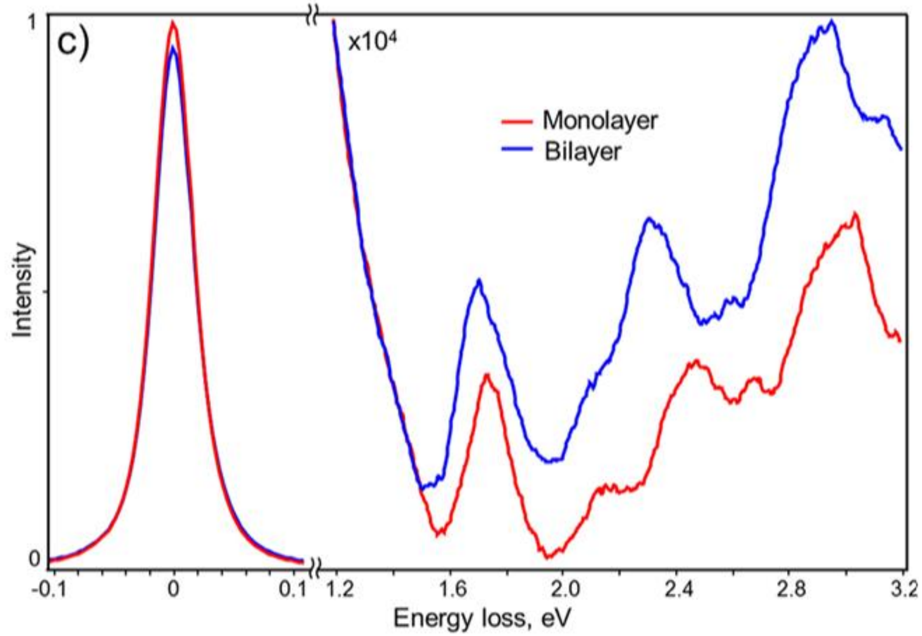




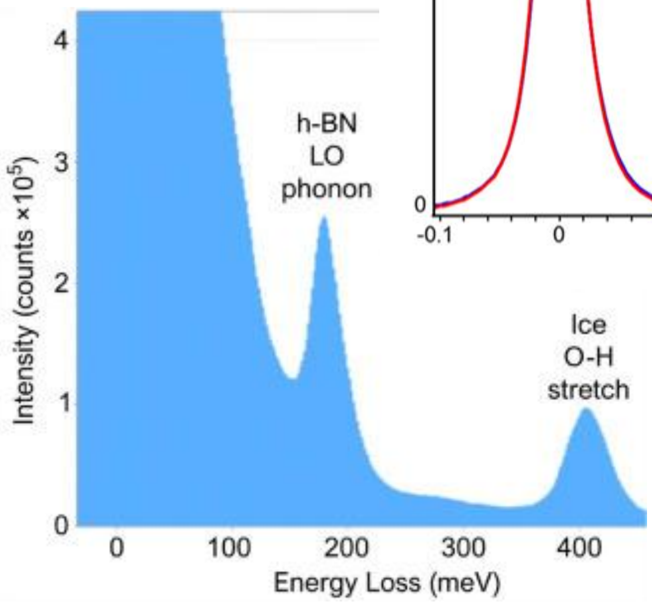
Diffraction is **momentum resolved** but **energy integrated**

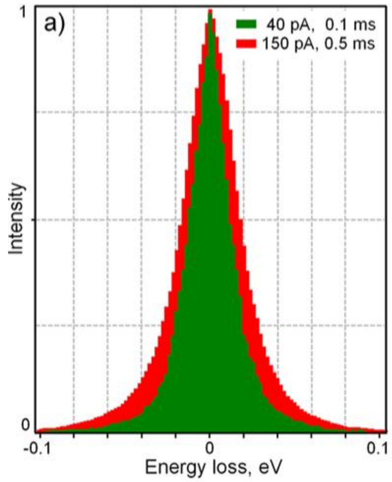
Electron energy loss spectroscopy

AKA EELS



Source: S Lopatin et al 2017





Source: T Hotz et al 2018

Inelastic scattering

What things can electrons cause to happen inside a material?

Inelastic scattering

What things can electrons cause to happen inside a material?

1. 100-1000 eV
    - Ionization of atoms by exciting core electrons
    - Used to identify chemical composition

Inelastic scattering

What things can electrons cause to happen inside a material?

1. 100-1000 eV
   - Ionization of atoms by exciting core electrons
   - Used to identify chemical composition
2. 10-100 eV
   - Oscillations of the free electrons (plasmons)
   - Useful for estimating the electron density of a metal

Inelastic scattering

What things can electrons cause to happen inside a material?

1. 100-1000 eV
   - Ionization of atoms by exciting core electrons
   - Used to identify chemical composition
2. 10-100 eV
   - Oscillations of the free electrons (plasmons)
   - Useful for estimating the electron density of a metal
3. 1-2 eV
   - Interband transitions from the valence band to conduction band in insulators or semiconductors.
   - Measure the electron band structure

Inelastic scattering

What things can electrons cause to happen inside a material?

1. 100-1000 eV
   - Ionization of atoms by exciting core electrons
   - Used to identify chemical composition
2. 10-100 eV
   - Oscillations of the free electrons (plasmons)
   - Useful for estimating the electron density of a metal
3. 1-2 eV
   - Interband transitions from the valence band to conduction band in insulators or semiconductors.
   - Measure the electron band structure
4. 1-10 meV
   - Lattice vibrations (phonons)
   - Electrons are very sensitive to motion of the nuclei

Electron energy loss spectroscopy

Challenge: transmission techniques require high energy electrons, but high energy electron beams have large energy spreads, so cannot resolve small energy loss features like phonons

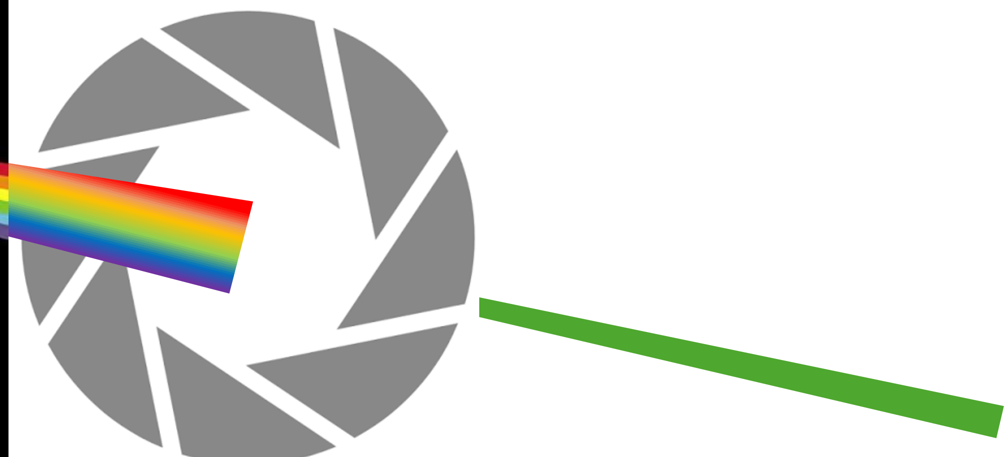
Monochromators

Disperse beam with a prism

Monochromators

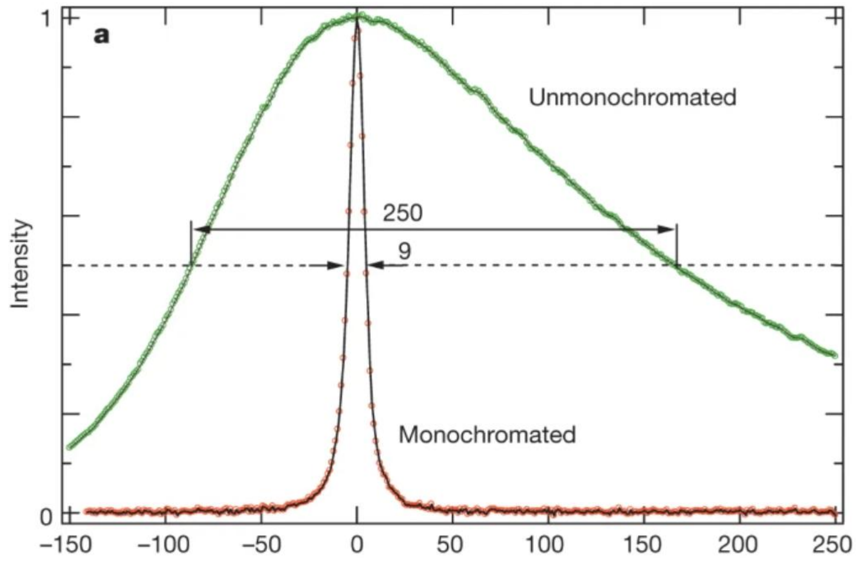
Disperse beam with a prism

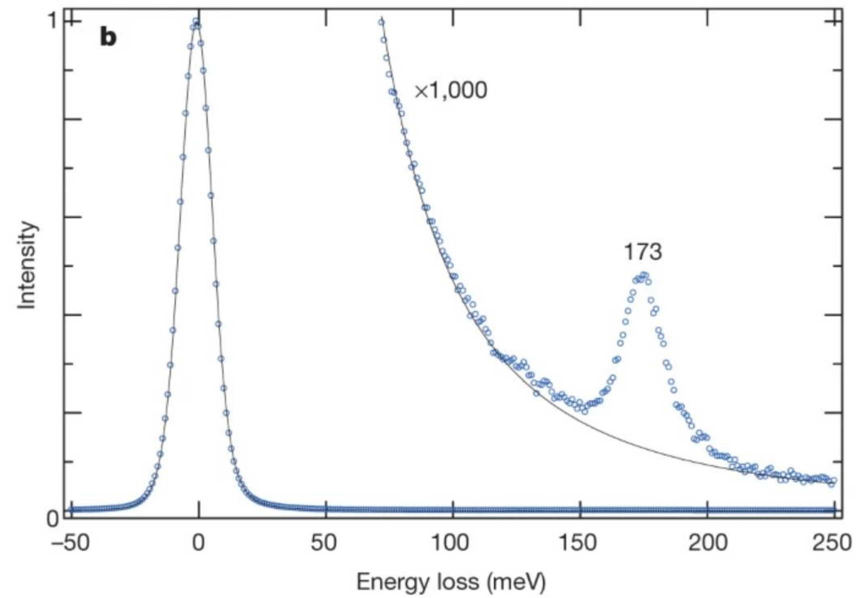
Collimate with an aperture



Monochromators

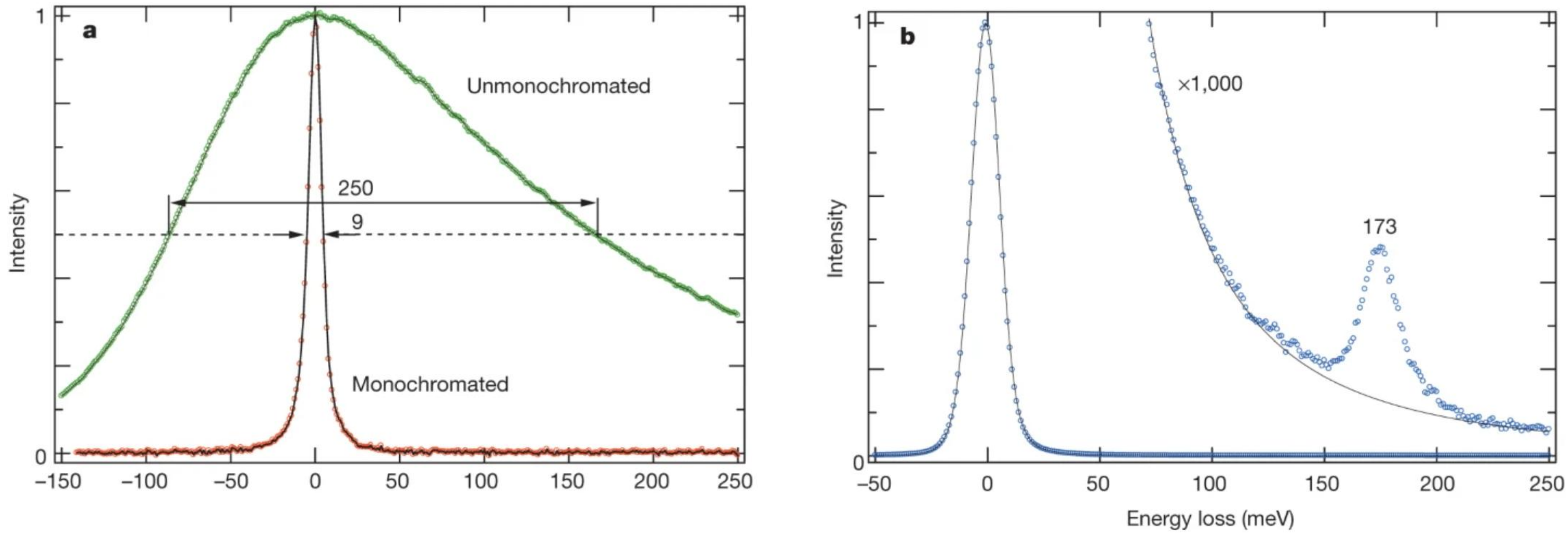
Source: O Krivanek et al 2014





Monochromators

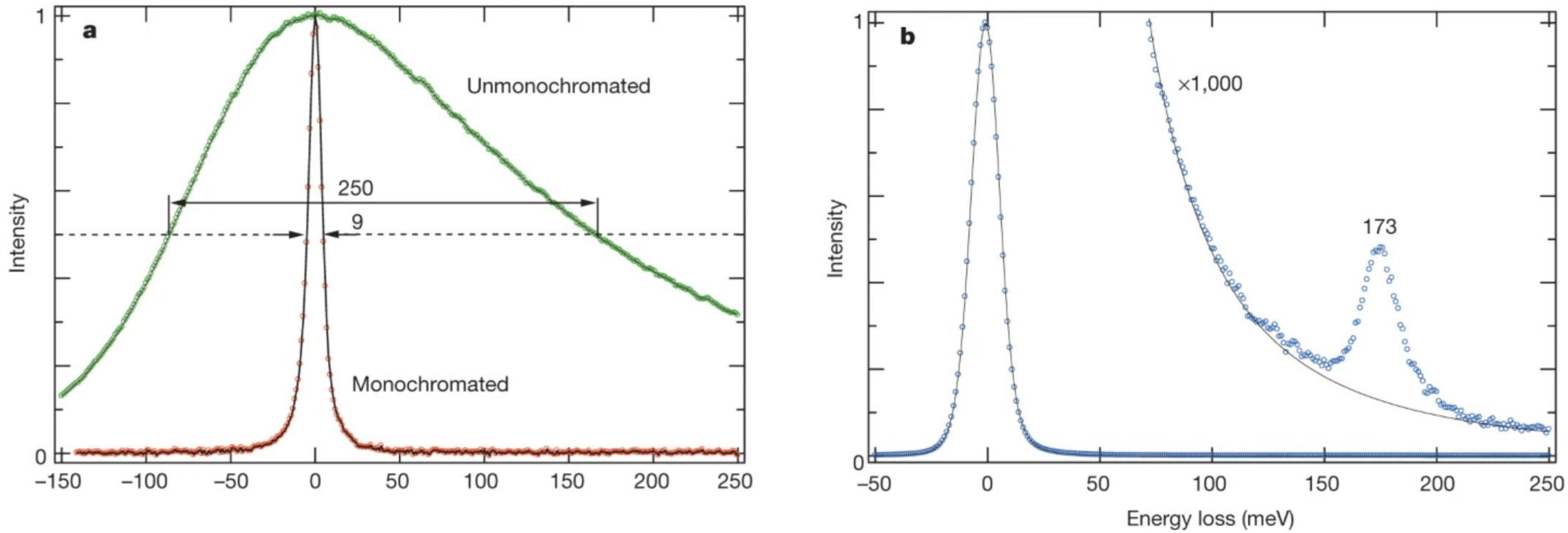
Source: O Krivanek et al 2014



250 eV -> 10eV = 25x reduction in beam current

Monochromators

Source: O Krivanek et al 2014



250 eV -> 10eV = 25x reduction in beam current

Challenge: Current loss would need to be too large to have enough signal left over to do an ultrafast experiment!

Lossless Monochromator?

Lossless Monochromation for Electron Microscopy with Pulsed Photoemission Sources and Radio-Frequency Cavities

C.J.R. Duncan,[1,*] D.A. Muller,[2] and J.M. Maxson[1,†]

[1] *Cornell Laboratory for Accelerator-Based Sciences and Education, Cornell University, Ithaca, New York 14853, USA*

[2] *School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853 USA*

1 eV -> 4 meV

Lossless Monochromator?

Lossless Monochromation for Electron Microscopy with Pulsed Photoemission Sources and Radio-Frequency Cavities

C.J.R. Duncan,[1,*] D.A. Muller,[2] and J.M. Maxson[1,†]

[1] *Cornell Laboratory for Accelerator-Based Sciences and Education, Cornell University, Ithaca, New York 14853, USA*

[2] *School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853 USA*

1 eV -> 4 meV

Lossless Monochromator in an Ultrafast Electron Microscope Using Near-Field THz Radiation

Michael Yannai,[1,2,*] Yuval Adiv,[1,2,*] Raphael Dahan,[1,2,*] Kangpeng Wang,[1,2,3] Alexey Gorlach,[1,2] Nicholas Rivera,[4,5] Tal Fishman,[1,2] Michael Krüger,[2,6] and Ido Kaminer[1,2,†]

[1] *Faculty of Electrical & Computer Engineering, Technion - Israel Institute of Technology, Haifa 3200003, Israel*

[2] *Solid State Institute, Technion - Israel Institute of Technology, Haifa 3200003, Israel*

[3] *Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201815, China*

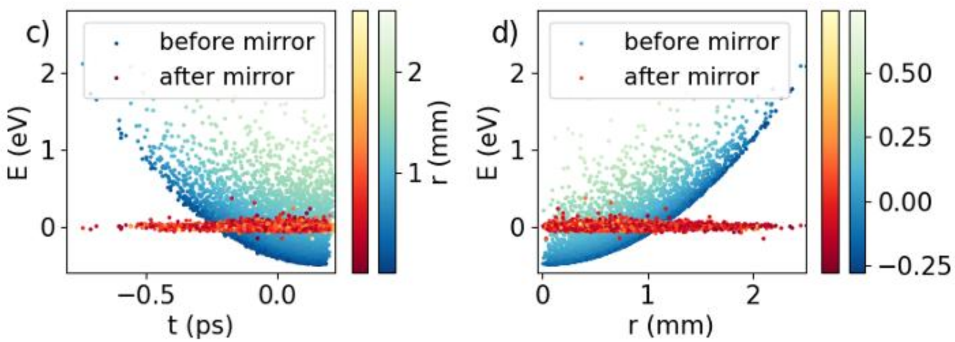
[4] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

[5] *Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

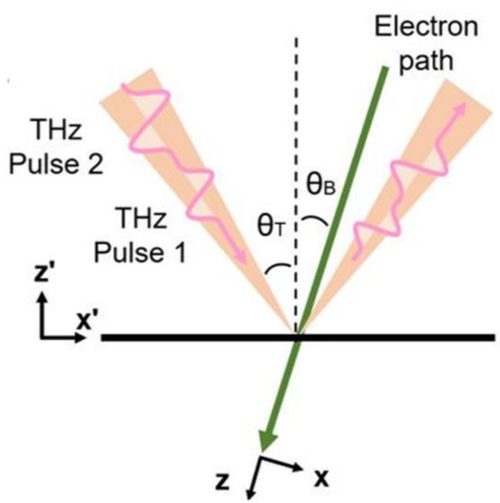
[6] *Department of Physics, Technion - Israel Institute of Technology, Haifa 3200003, Israel*

0.9 eV -> 400 meV

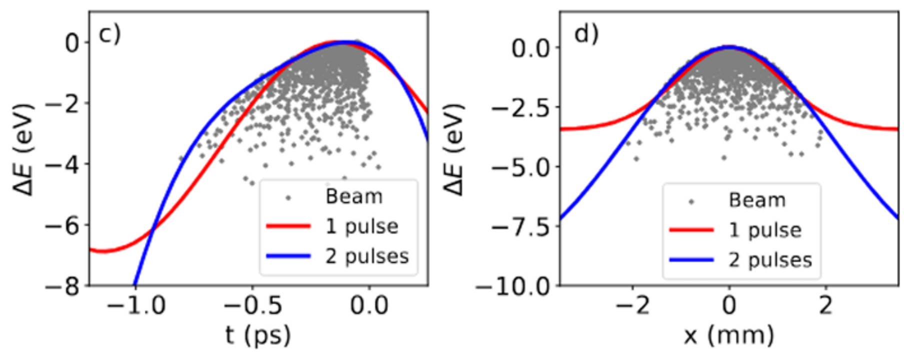
Lossless Monochromator?



$$E_{ideal}(r,t) = E_{gun} + \frac{r^2}{2mM_{12}^2} + \frac{t^2}{2mM_{56}^2}$$



Energy change for a 0.5 THz pulse:



$$\Delta E \approx A\left(1 - \frac{r^2}{w_0^2} - \frac{t^2\omega_0^2}{2}\right)$$

Conclusion

1. Ultrafast electron diffraction and EELS together provide a full picture of phonon populations and dispersion
2. Energy spread in typical TEMs is too large to resolve meV-scale phonons
3. Prism based monochromators require rejecting most of the beam leaving little signal for ultrafast experiments
4. We found that monochromation using the fields of rf cavities or THz pulses could produce comparable energy spread while preserving most of the current