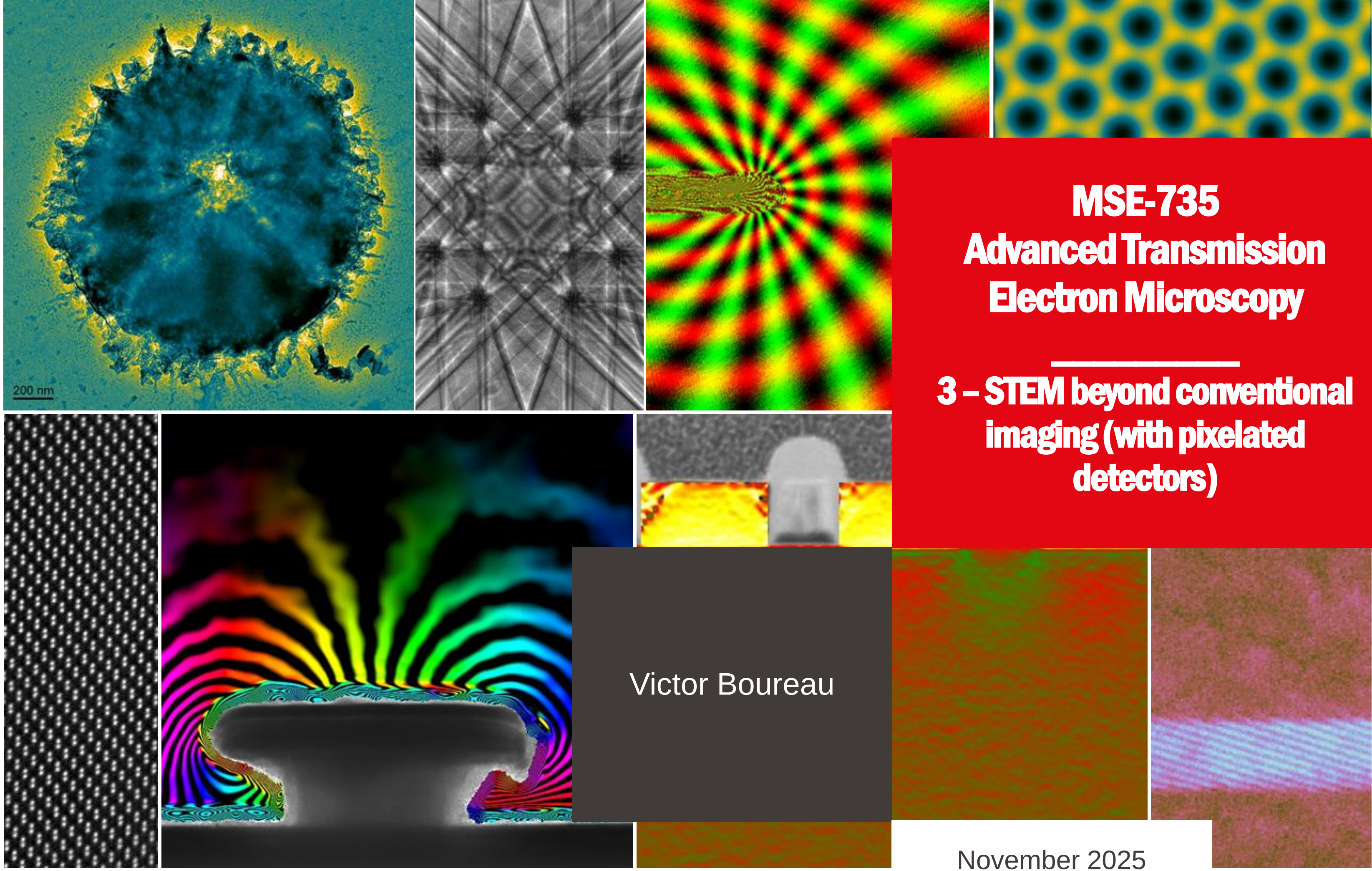


MSE-735
Advanced Transmission Electron Microscopy

3 – STEM beyond conventional imaging (with pixelated detectors)

Victor Boureau

November 2025

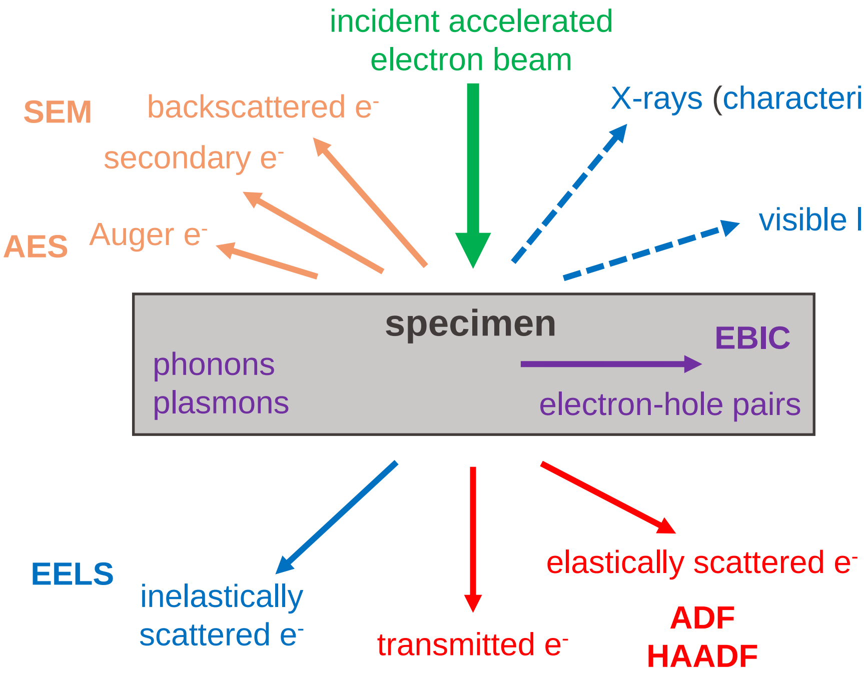
- **CIME**
Interdisciplinary Center for Electron Microscopy

Outline

1. **STEM basics**
2. Pixelated STEM detectors
3. DPC
4. 4D-STEM
5. Conclusion

Signals in STEM mode

STEM spectroscopy



incident accelerated electron beam

SEM backscattered e^-

secondary e^-

AES Auger e^-

X-rays (characteristic, bremsstrahlung)

EDX

visible light

CL

specimen

phonons
plasmons

EBIC

electron-hole pairs

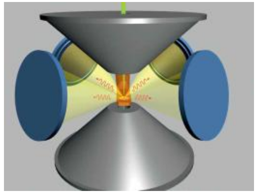
EELS inelastically scattered e^-

transmitted e^-

elastically scattered e^-

ADF
HAADF

BF
ABF



Super-X system, ThermoFisher

GIF continuum, Gatan

HAADF detector, Gatan

STEM imaging

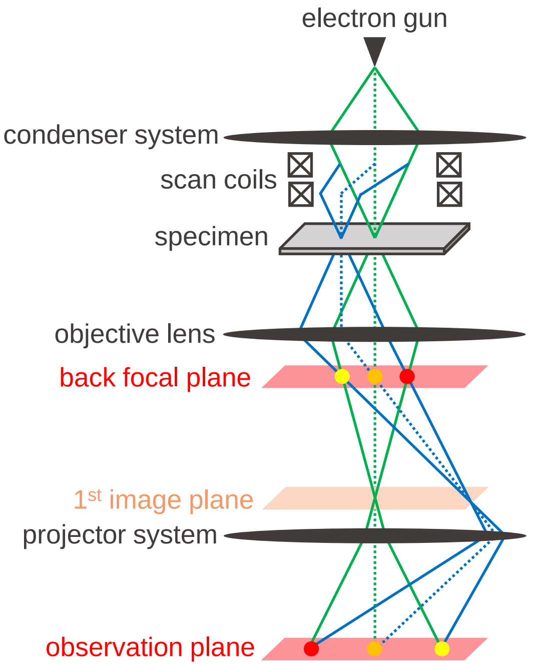
ABF: annular bright-field
HAADF: high-angle annular dark-field

STEM imaging detectors are:

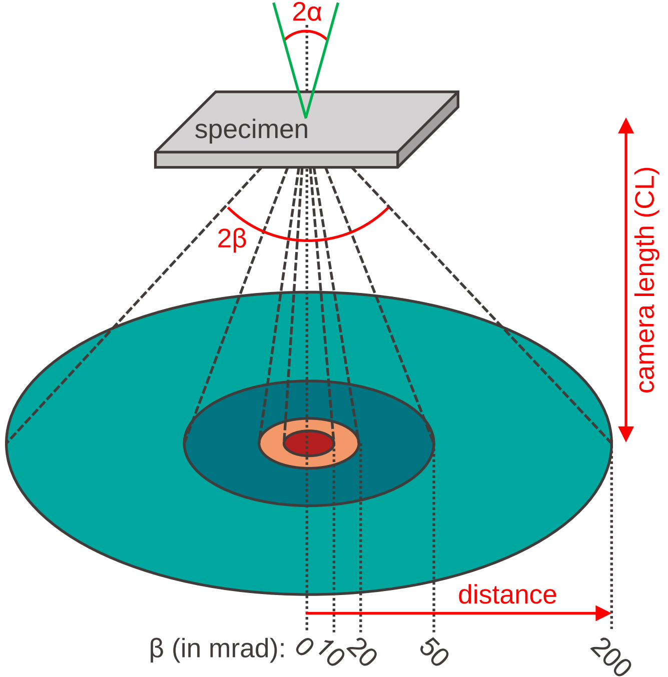
- Annular
- Monolithic

Imaging with STEM detectors

STEM optical diagram



STEM diagram



Detectors: BF ABF ADF HAADF

Scattering: coherent | incoherent

Imaging: coherent | incoherent

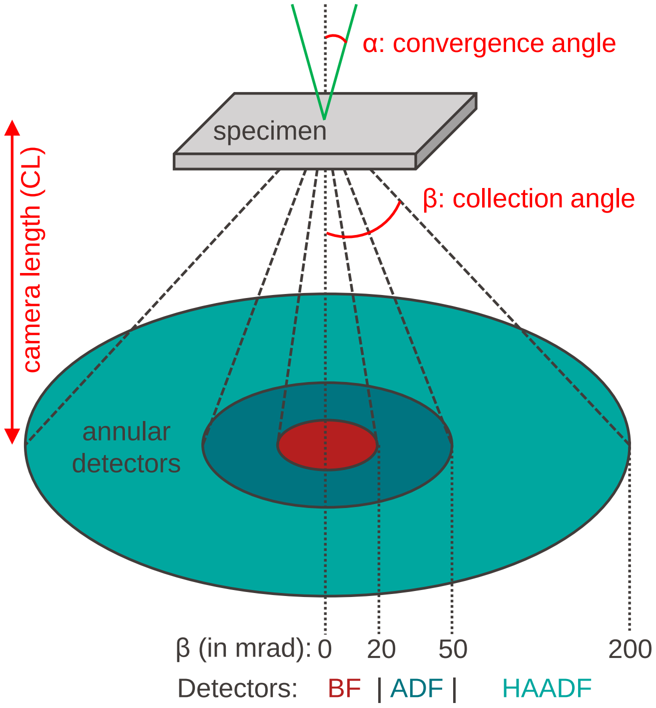
Image capture in STEM:

- Convergent beam raster-scanned on the sample
- Detectors placed in the diffraction plane

- Convergence angle α: defined by condenser system
- Camera length CL: defined by projector lens system
- **Diffraction plane: distance ∝ scattering angle**

Overview of STEM parameters for imaging

STEM diagram

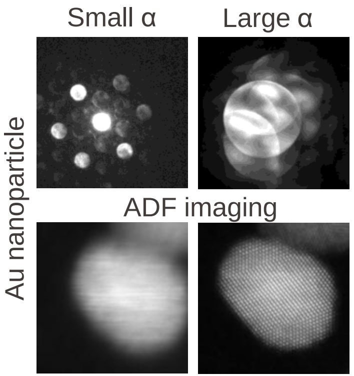


Are there other types of STEM detectors?

- Not annular
- Not monolithic

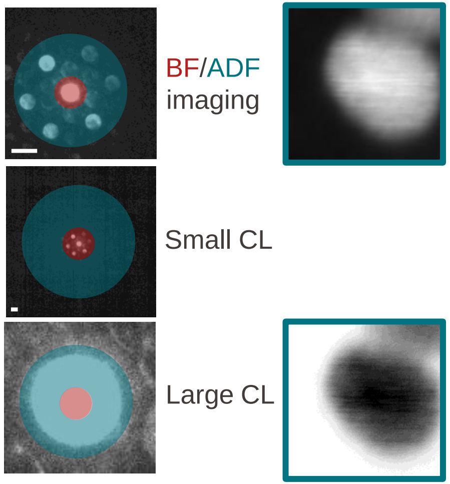
Experimental parameters

- Convergence angle:



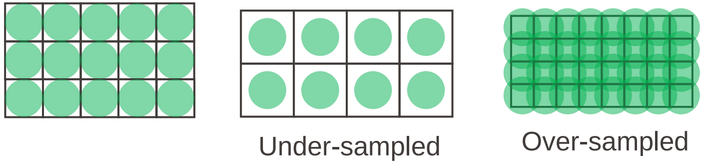
α defines the diffraction-limited probe size → spatial resolution

- Camera length:



- Probe current
- Dwell time
- Step size:

Electron dose: used to mitigate beam-induced damage



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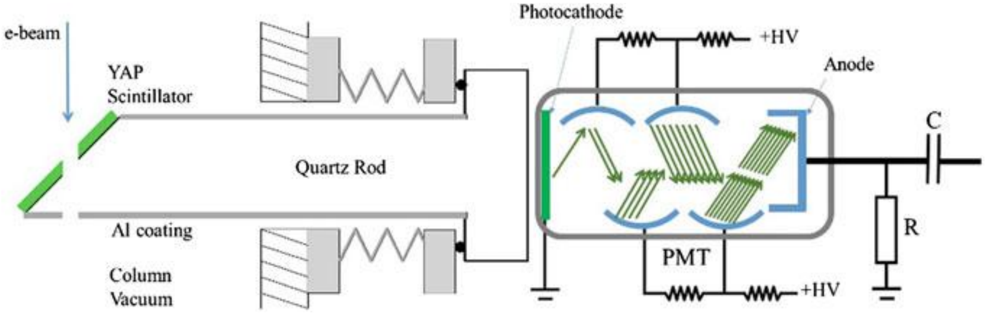
Monolithic annular STEM detectors: 2 types

Scintillator-photomultiplier detector

Principle

1. Scintillator: conversion of incident e$^-$ into photons
2. Optical coupling of photons
3. Photomultiplier (photocathode + dynodes + anode): detection of photons



Zuo & Spence, Advanced TEM (2017)

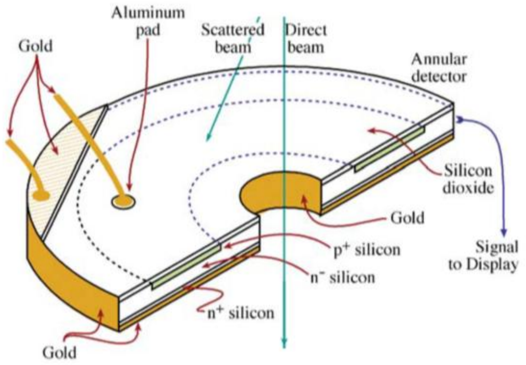
Specification	Application
Speed ~1 MHz Low noise Sensitive to beam damages	Imaging: HAADF

Semiconductor detector

Principle

Si *pn* diode, covered with metal contacts

1. Incident electrons generate e$^-$-hole pairs (3.6 eV)
2. Dissociation of e$^-$-hole pairs with built-in potential
3. Collection of current



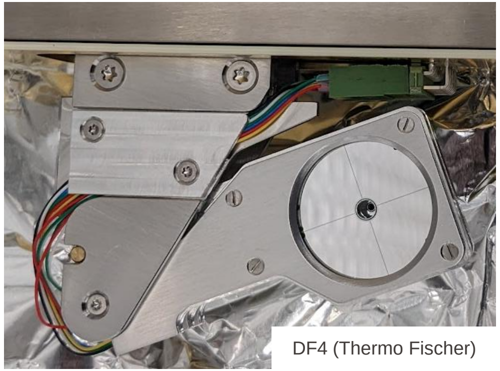
Williams & Carter, TEM (2009)

Specification	Application
Speed ~1 MHz Dark noise Cheap, any shape	Imaging: BF, ABF, ADF

Segmented detector for STEM

Segmented detector

4-segment detector:



DF4 (Thermo Fischer)

- Segmented detector is a **semiconductor detector** with independent active areas
- Exists since the 1980’s, nowadays 16-segments detectors commercially available

Specification

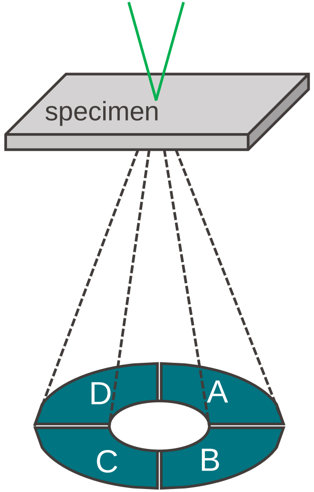
- Cheap
- 4 to 16 segments
- Speed ~1 MHz

STEM dwell time ~µs

Application

- Imaging (BF/ABF/ADF)
- Differential phase contrast (DPC)

STEM diagram:



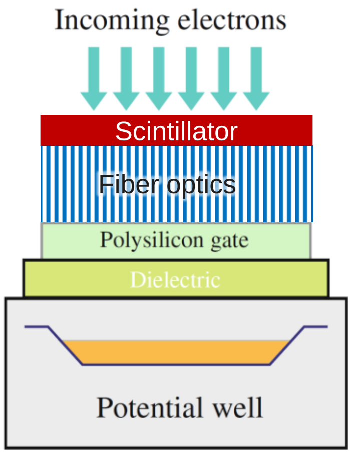
This is a 4-pixel detector!
➢ Equips most of the STEM nowadays

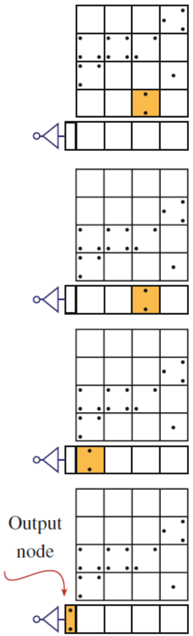
TEM cameras: 2 types

Charge-coupled device (CCD)

Principle

1. Scintillator: conversion of incident e^- into photons:
2. Optical coupling of photons: fiber optics
3. Array of Si *pn* diodes, biased to use it as potential well
4. Readout system using the capacitors to transfer the charges between neighboring pixels toward the output node





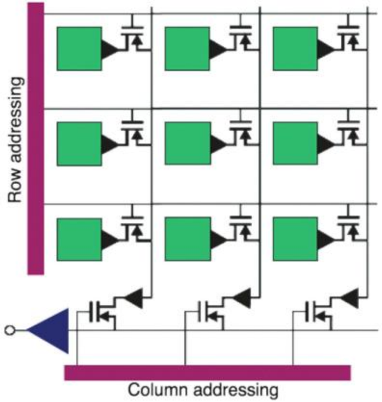
Specification

- Up to 4k x 4k pixels
- High linearity
- Low readout noise

Complementary metal-oxide-semiconductor (CMOS)

Principle

1. } Similar as CCD, to collect the signal
2.
3.
4. Dedicated readout for each pixel, addressed by row and column as in a memory chip, to convert charges to voltage



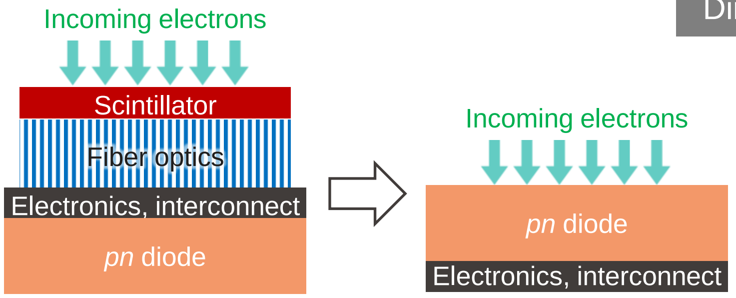
Specification w.r.t. CCD

- Faster
- Cheaper
- Higher readout noise

Not suitable for STEM!

- Slow (~10-100 Hz)
- Low dynamic range
- Sensitive to beam damages

Cameras for STEM



Direct detection cameras

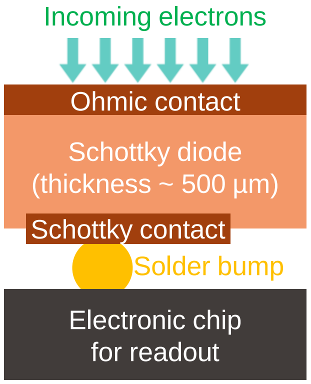
CMOS technology with no scintillator, no optical coupling
Revolution in the STEM world in 2015's

- **Robust to beam damages**
- **Single electron sensitivity (very high DQE)**
- **Fast**

PAD: pixel array detector

Principle

1. Array of Schottky diodes (thick Si chip)
2. Backside bonding to the readout chip for independent pixel reading




MerlinEM,
QuantumDetectors

Specification

- Up to 512 x 512 pix
- High dynamic range
- Speed ~1-10 kHz
  STEM dwell time ~ms

Application

- 4D-STEM

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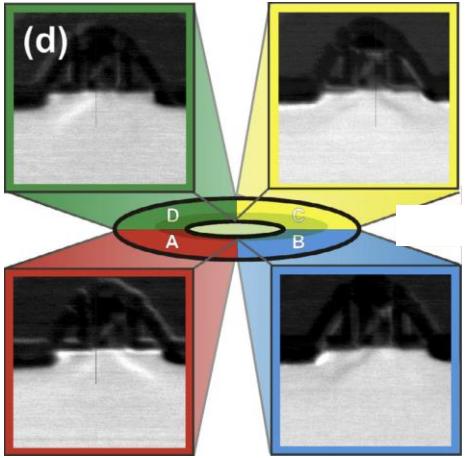
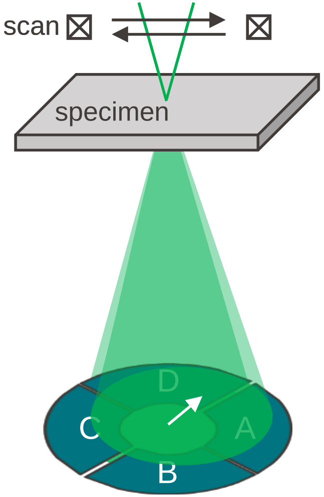
DPC imaging: another type of data

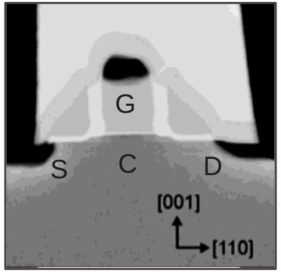
Segmented detector acquisition

4 integer images





Si-doped MOSFET

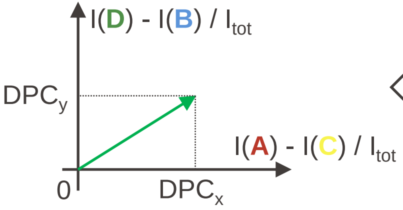


Monolithic reading:

- Annular detector
- ABF imaging

Data representation: vector image

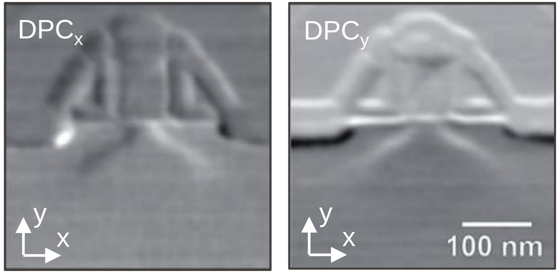
Movement of intensity of the transmitted beam

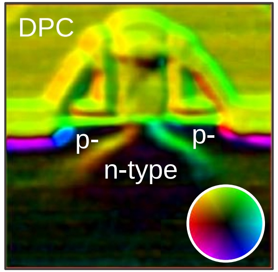


Center-of-mass (CoM) for an array of n.m pixels:

$$\mathrm{CoM}_x = \sum_{n,m} \frac{n.I_{n,m}}{I_{n,m}}$$

$$\mathrm{CoM}_y = \sum_{n,m} \frac{m.I_{n,m}}{I_{n,m}}$$





DPC imaging reveal the deflection of the transmitted beam:

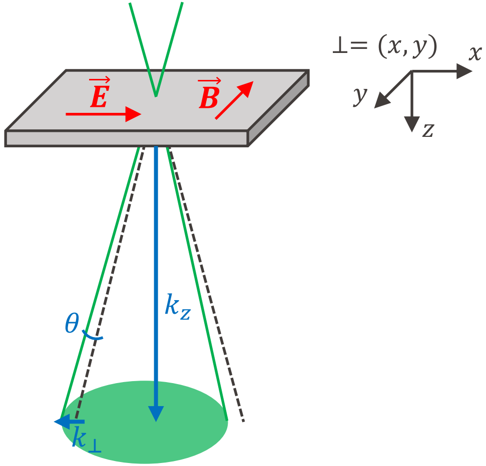
- Calculated by CoM

What information about the sample contains the DPC map?

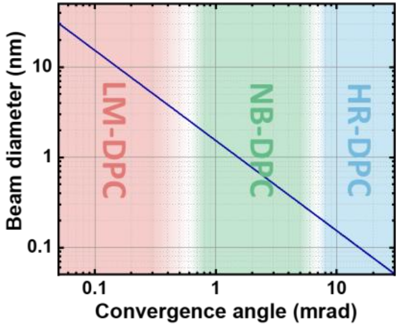
Haas et al., Ultramicroscopy 198, 58-72 (2019)

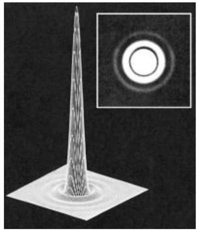
Theory of DPC for long-range EM fields

Hypothesis: electron probe << field variation



Diffraction-limited probe size (no aberrations):





Williams & Carter, TEM (2009)

Cooper et al., Micron 179, 103594 (2024)

Classical mechanics formalism

Lorentz force: $\overrightarrow{F_L} = -e(\vec{E} + \vec{v} \times \vec{B})$

Newton 2nd law: $\vec{F} = m\vec{a} = m\frac{d\vec{v}}{d\tau} = \frac{d\overrightarrow{p_\perp}}{d\tau}$

- ➢ Momentum transfer for electric field only: $\overrightarrow{p_\perp} = -e\int \overrightarrow{E_\perp}\, d\tau$

Definition: $p = hk = mv = \frac{h}{\lambda}$

Time to go throw the specimen: $d\tau = \frac{dz}{v}$

- ➢ Beam deflection: $\theta \approx \frac{k_\perp}{k_z} = \frac{p_\perp}{p_z} = \frac{-e\int E_\perp d\tau}{mv} = -\frac{e\lambda}{hv}\int E_\perp\, dz$

Lorentz deflection: $\theta = \begin{pmatrix}\theta_x \\ \theta_y\end{pmatrix} = -\frac{e\lambda}{hv}\int \begin{pmatrix}E_x \\ E_y\end{pmatrix} dz + \frac{e\lambda}{h}\int \begin{pmatrix}B_y \\ -B_x\end{pmatrix} dz$

- ➢ DPC signal, mapped by CoM

DPC enables quantitative mapping of the EM fields:
- ➢ Electric field
- ➢ Magnetic induction field

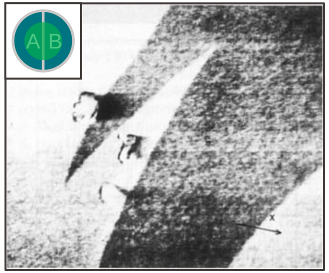
- ▪ The integral over the electron path is observed
- ▪ Insensitive to the out-of-plane component

DPC examples: long-range EM fields

Magnetic measurements

Permalloy (NiFe), ferromagnetic material:

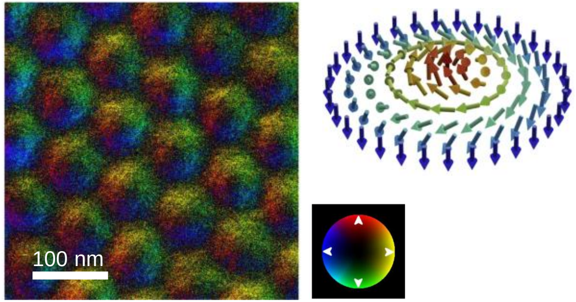
- Magnetization domains



Chapman et al., Ultramicroscopy 3, 203 (1978)

Bloch-type skyrmions lattice in FeGe:

- In-plane component of magnetic induction

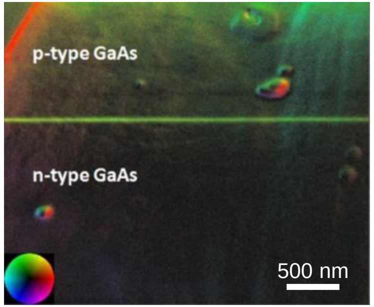


McGrouther et al., New J. Phys. 9, 095005 (2016)

Electric measurements

pn junction in GaAs:

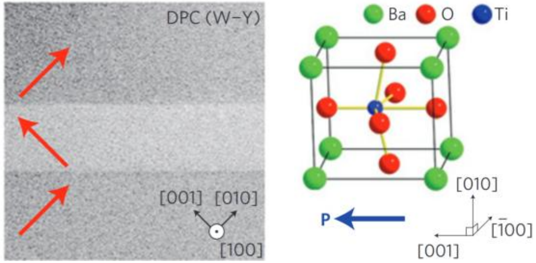
- Built-in electric field



Seki et al., Microscopy 70, 148-160 (2021)

$BaTiO_3$, ferroelectric material (tetragonal):

- Polarization domains



Shibata et al., Nature Physics 8, 611-615 (2012)

Restriction

- ➢ Unwanted contrasts from:
  - Variation of specimen thickness
  - Inhomogeneous material
  - Change of diffraction conditions
- ➢ Qualitative measurement in practice
  - DPC is more quantitative with 4D-STEM…

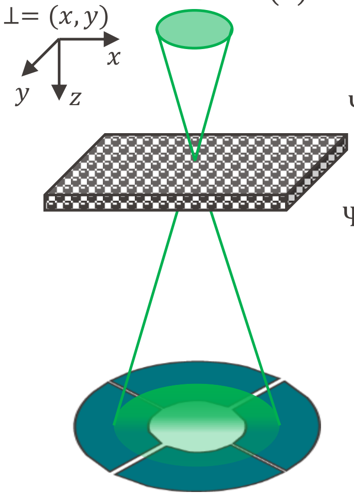
What happens at atomic resolution?

Theory of DPC for atomic electric field

Hypothesis: electron probe >> field variation

Fourier optics

Unit plane wave, time-independent writing, propagation along z, no initial phase shift: $\Psi_0(\vec{r}) = A_0(\vec{r})e^{i(2\pi\overrightarrow{k_0}.\vec{r}-\omega_0 t+\varphi_0)} = e^{i(2\pi k_z.\vec{r})}$



$\Psi_{probe}\left(\vec{k}\right) = E_a\left(\vec{k}\right)$, with E_a aperture function

Inverse Fourier transform

$\Psi_{probe}(\vec{r}) = FT^{-1}\left[E_a\left(\vec{k}\right)\right]$

Transmission function (POA)

$\Psi_{exit}(\vec{r}) = \Psi_{probe}(\vec{r}).e^{i\varphi(\vec{r})}$

Fourier transform

$\Psi_{diff}\left(\vec{k}\right) = FT[\Psi_{exit}(\vec{r})]$

Intensity on detector: $I\left(\vec{k}\right) = \left|\Psi_{exit}\left(\vec{k}\right)\right|^2$

DPC signal is [1]: $CoM\left[I\left(\vec{k}\right)\right] = \frac{1}{2\pi}\int\left|\Psi_{probe}(\vec{r})\right|^2 \otimes \vec{\nabla}\varphi(\vec{r})\, dz$

Quantum mechanics

It can be shown [2]: $\varphi(\vec{r}) = \sigma\int V(\vec{r})\, dz - \sigma v\int A_z(\vec{r})\, dz$

with: $\sigma = \frac{2\pi m e\lambda}{h^2} = \frac{2\pi e}{hv}$ the interaction constant

V is the electrostatic potential

A_z is the z component of the magnetic vector potential

DPC is sensitive to the gradient of the potentials, i.e. to the electric and magnetic fields

Fields derive from a potential:

$$\vec{E} = -\vec{\nabla}V$$
$$\vec{B} = \vec{\nabla}\times\vec{A}$$

DPC = “differential phase contrast”

- ➢ Probes the gradient of the phase shift induced by the sample

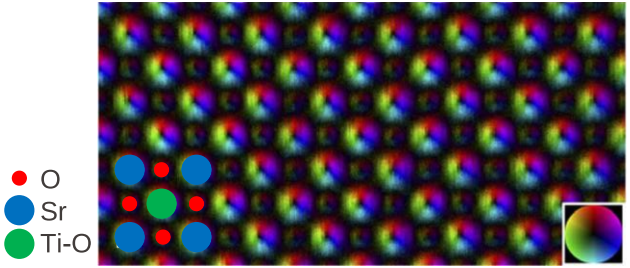
[1] Lazić et al., Ultramicroscopy 160, 265 (2016)

[2] Reimer & Kohl, TEM, Springer (2008)

DPC examples: atomic electric field in crystals

SrTiO$_3$ crystal (8 nm thick):

- Map $\propto \int \overrightarrow{E_\perp}\, dz$ field



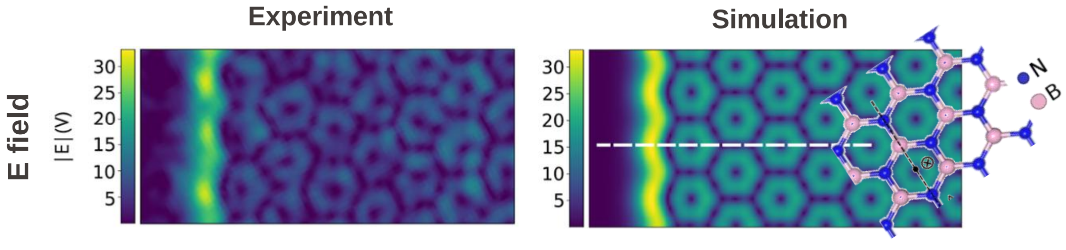
Shibata et al., Nat. comm. 8, 15631 (2017)

Restriction

- ➢ Unwanted contrasts from:
  - Variation of specimen thickness
  - Change of diffraction conditions
- ➢ Requires extremely thin materials, <10 nm
  - Phase object approximation (POA)

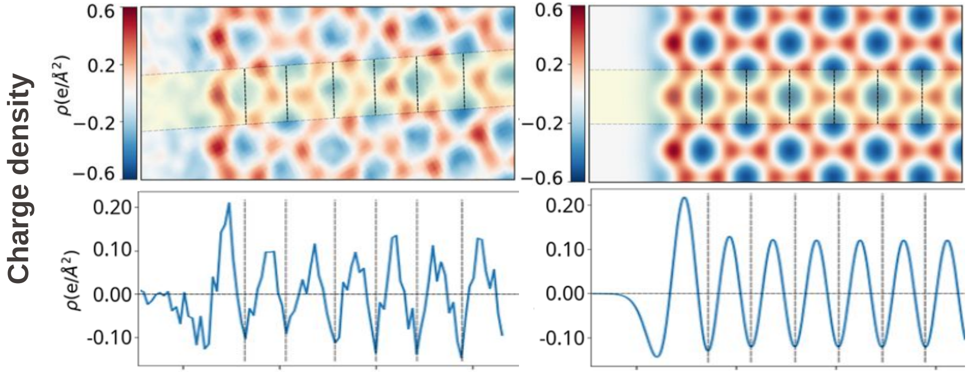
Derivative of the DPC signal:
➢ dDPC ∝ charge density ρ

Monolayer of h-BN (hexagonal boron nitride):



Maxwell-Gauss: $\rho = \varepsilon_0 \vec{\nabla}.\vec{E}$

$dDPC \propto \left|\Psi_{probe}(\vec{r})\right|^2 \otimes \int \rho(\vec{r})\, dz$



Susana et al., ACS Nano 18, 7424-7432 (2024)

iDPC imaging for atomic resolution

Principle [1]

DPC is sensitive to the electric field:

$$DPC \propto \left|\Psi_{probe}(\vec{r})\right|^2 \otimes \int \vec{E}(\vec{r})\, dz$$

$$\vec{E} = -\vec{\nabla} V$$

$$iDPC \propto \left|\Psi_{probe}(\vec{r})\right|^2 \otimes \int V(\vec{r})\, dz$$

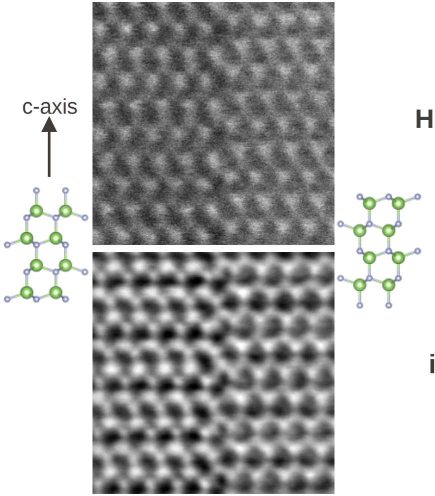
Integration of the DPC signal:
- ➢ iDPC ∝ electric potential

iDPC is popular for atomic resolution imaging

1. Good contrast with light atoms
   - Intensity scales with Z (vs. ~Z^2 for HAADF)
2. High dose efficiency
   - Collects the “strong” transmitted beam (vs. thermal diffuse scattering for HAADF)

Examples

GaN, polar inversion:

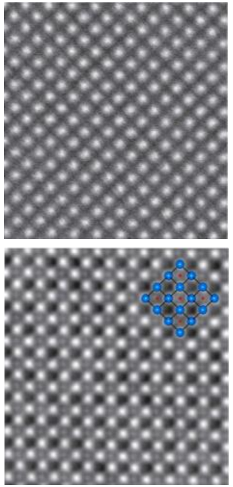


© V. Boureau

HAADF

iDPC

TiH crystal:



de Graaf et al., Sci. Adv. 6, eaay4312 (2020)

Restriction

- ➢ Phase contrast image: coherent
  - Contrast changes with material thickness, defocus, tilt, etc.
- ➢ iDPC imaging also works for “thicker” samples ☺

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[1] Lazić et al., Ultramicroscopy 160, 265 (2016)

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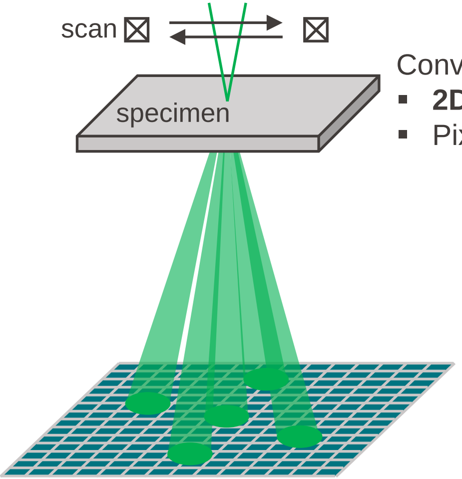
Recording new class of signal: 4D-STEM

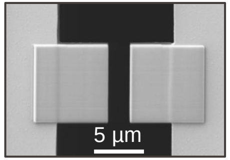


Convergent beam raster-scanned on the sample:
- **2D image of the specimen**
- Pixels defined by probe position (STEM)

At each probe position:
- **2D image of the diffraction pattern**
- Recorded by the fast camera

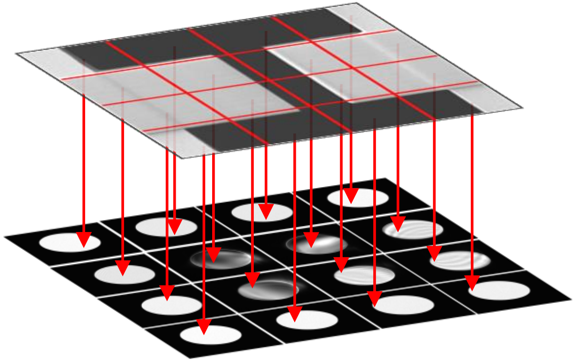
Example of data

STEM



Micro-capacitor

4D-STEM



4D-STEM dataset

- ➢ 2D in real space + 2D in diffraction space
- ➢ Collection of local diffraction patterns

Why?

- ➢ Comprehensive information of the diffraction
- ➢ Allows in-depth analysis in post processing

Challenge of 4D-STEM: data handling (storage, analysis)

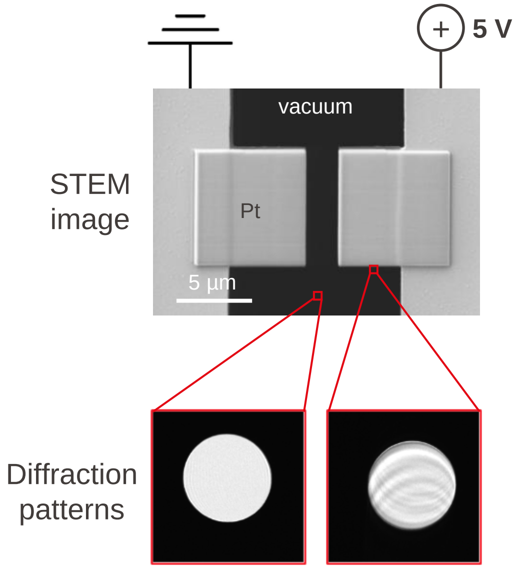
Example (MerlinEM camera):
- 512 x 512 pixels STEM image
- 256 x 256 pixels diffraction patterns, 12 bit depth
- ➢ 25 Gb dataset, acquired in 3 min!

➢ **Do not do 4D-STEM when not necessary!**

4D-STEM for EM field mapping by DPC

Example: Planar capacitor, biased [2]

Data acquisition



Transmitted beam

Data processing: DPC signal

Center-of-mass (CoM) for an array of n.m pixels:

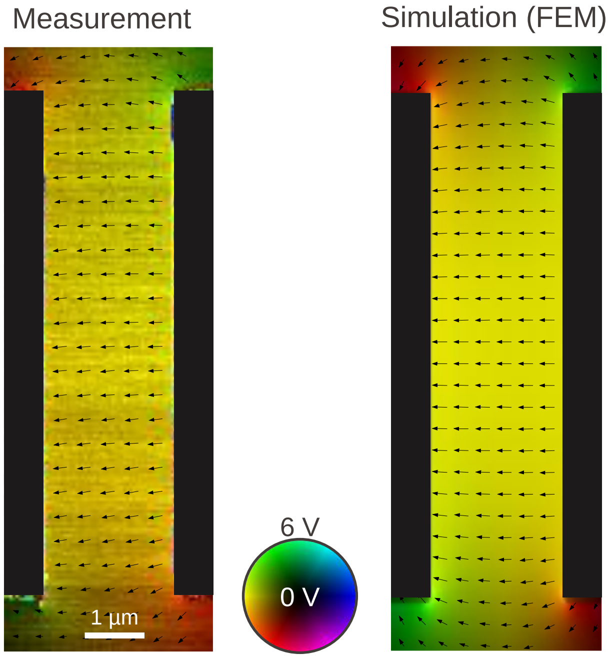
$$\mathrm{CoM}_x = \sum_{n,m} \frac{n.I_{n,m}}{I_{n,m}}$$

$$\mathrm{CoM}_y = \sum_{n,m} \frac{m.I_{n,m}}{I_{n,m}}$$

DPC with 4D-STEM configuration [2]

- Mapping of $\vec{E}$ and $\vec{B}$ fields
- Long-range fields: ☺
    - ➢ More easily quantitative
- Atomic fields: ☹
    - ➢ Too slow vs. segmented detector

Plot of $\int \vec{E}\, dz$



[1] Ranieri et al., submitted to Ultramicrocopy

[2] Boureau et al., J. Phys. D 54, 085001 (2021)

What are the applications of 4D-STEM?

Electromagnetic fields mapping

DPC

iDPC, dDPC

Crystal analysis

Crystal phase and orientation mapping (ASTAR)

Strain and rotation maps

HOLZ analysis

Symmetry analysis

Imaging

Virtual imaging

Phase contrast imaging

iDPC

Ptychograpy

Amorphous

Short-range ordering

Amorphous phase classification

Strain maps

Degree of crystallization

Fluctuation microscopy

Organic solids

Medium-range ordering

4D-STEM is a method of recording STEM data

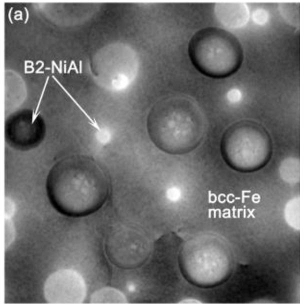
- Encompasses **many established techniques** for a wide range of applications
- 4D-STEM records all local diffractions :
  - ➢ Smart and **flexible data analysis** to retrieve the information of interest
  - ➢ **Specific acquisition parameters** should be used for a specific technique!

4D-STEM for imaging: virtual imaging

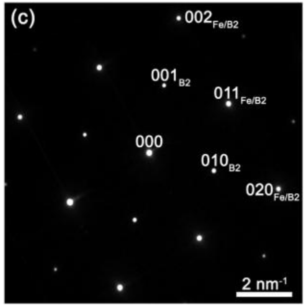
Example: Phase analysis of a complex FeAlNiCr alloy [1]

TEM data:

Imaging

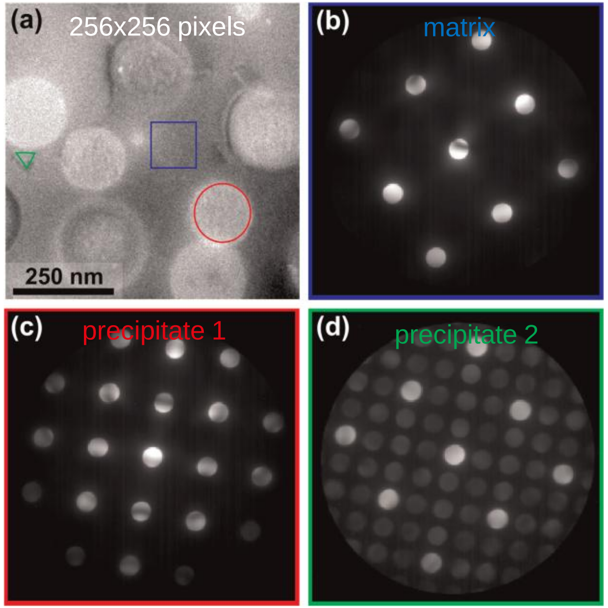


Diffraction



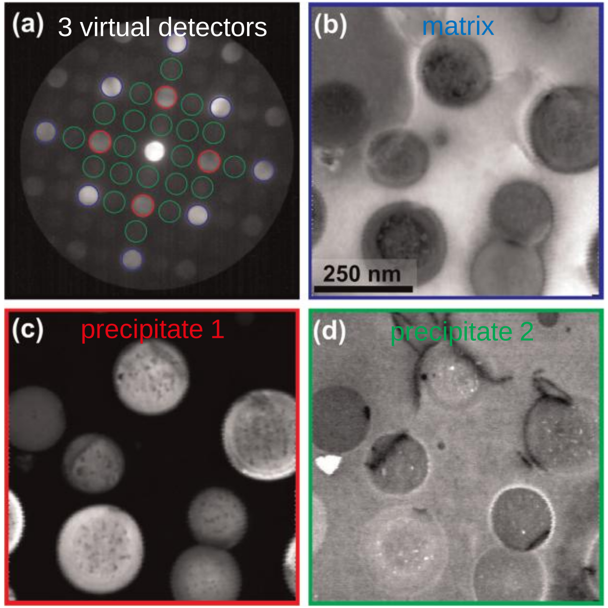
4D-STEM dataset:

Diffraction pattern at each pixel



Virtual dark-field imaging:

Image contrast built from virtual detectors



Strengths

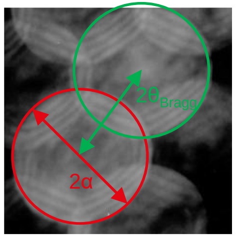
- Image reconstruction for any size/shape of virtual detector
- Versatile analysis of diffraction contrasts

Weaknesses

- Heavy dataset
- Slow acquisition vs. annular STEM detector

[1] Gammer & al., Ultramicroscopy 155, 1 (2015)

4D-STEM for super-resolution imaging: ptychography



Pennycook & Nellist, STEM (2011)

Example: MoS_2 monolayer [1]

Ptychographic imaging

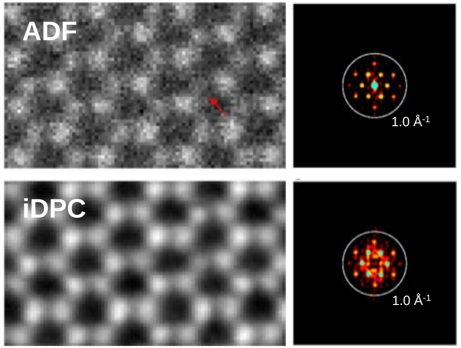
Iterative image reconstruction of the exit wavefunction

- Different class of algorithm: ePie, SSB, WDD [2]
- This is a phase imaging technique
- Allows for deconvolution of the probe aberrations

Interferences in the Bragg disks overlapping:

- ➢ Information limit for coherent STEM imaging
- ➢ Atomic plane resolved if $\theta_{Bragg} < \alpha$

STEM imaging: FFT:



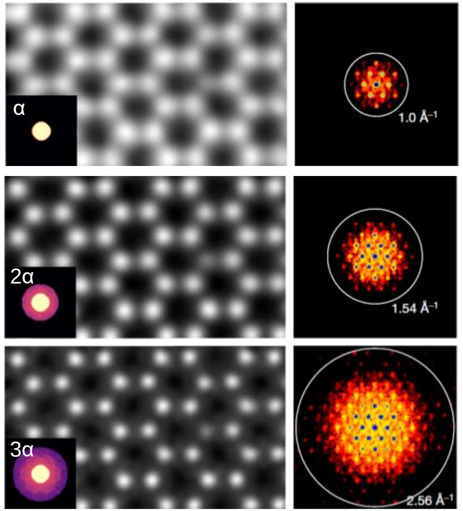
Strengths

- Very high dose efficiency
- Super-resolution, beyond the diffraction limit set by aperture

Weaknesses

- Advanced method and algorithms
- Limited to very thin samples (POA)
- ➢ Early results with iterative multislice reconstruction for thicker samples [3]

Ptychographic imaging (different cut-off): FFT:

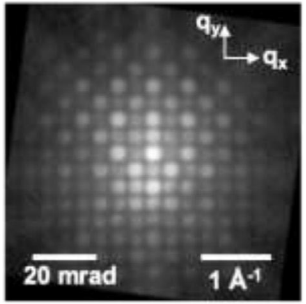


[1] Jiang et al., Nature 559, 343 (2018)
[2] O'Leary et al., Ultramicroscopy 221, 113189 (2021)
[3] Chen et al., Science 372, 826 (2021)

4D-STEM for strain mapping – in crystals

Principle

1. 4D-STEM acquisition

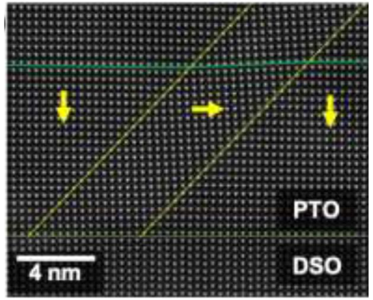


2. For each diffraction pattern, compute the Bragg vectors position ($\vec{g}$)
    - Different algorithms exists!

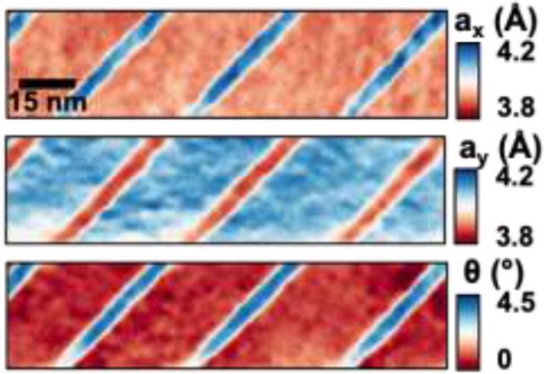
3. Compute the local strains and rotation (or lattice parameters), from the local $\vec{g}$ vectors
    - Strain field: $\varepsilon = \frac{g^{ref} - g}{g}$
    - Lattice d-spacing: $d_{hkl} = \frac{1}{g_{hkl}}$

Example: $PbTiO_3$ grown on $DyScO_3$ [1]

HAADF STEM image



Strain and rotation maps:



Evidence of lattice distortions induced by ferroelectric domains

Elastic strain mapping in (mono-)crystalline samples

- In-plane components (2D): strain and rotation
- Quantitative measurement
- ➢ Beam precession improves accuracy [2]

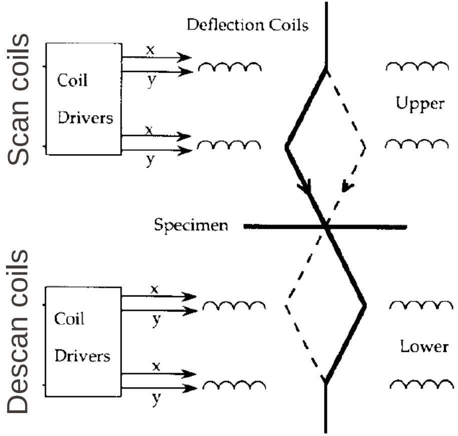
---

[1] Padgett et al., Ultramicroscopy 214, 112994 (2020)

[2] Rouvière et al., Appl. Phys. Lett. 103, 241913 (2013)

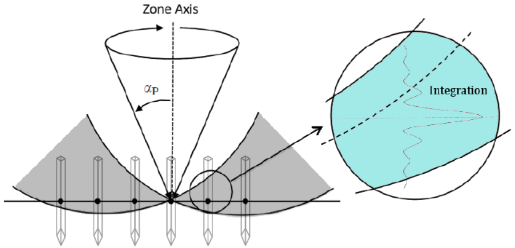
Application of beam precession to 4D-STEM

Principle [1]:

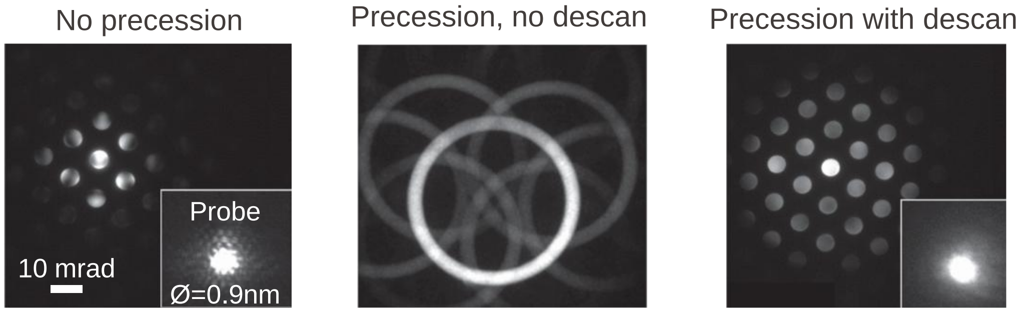


Dynamic tilting of the Ewald sphere during imaging

- ➢ Ewald sphere intersection with reciprocal lattice rod (reldod) intensity gives the Bragg intensity
- ➢ Precession integrates relrod intensity over the excitation error on the Bragg conditions



Example: diffraction of Si(110) crystal [2]


No precession
Precession, no descan
Precession with descan

- ➢ **Pseudo-kinematical diffraction conditions**
  - ▪ Diffraction contrasts weakened
  - ▪ Diffracted beam intensities closer to the structure factor

Why using precession?

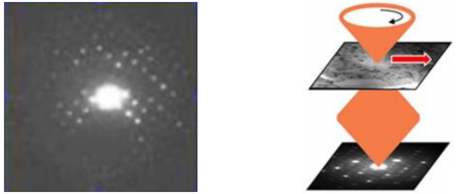
- ➢ Reliable Bragg intensities
- ➢ Accurate localization of the diffracted beams
  - ▪ Improved **crystal strain** measurement [2]
  - ▪ Improved **DPC** long-range field mapping [3]
  - ▪ Improved **crystal phases and orientation** mapping [4]

[1] Vincent & Midgley, Ultramicroscopy 53, 271 (1994)
[2] Rouvière et al., Appl. Phys. Lett. 103, 241913 (2013)
[3] Bruas et al., J. App. Phys. 127, 205703 (2020)
[4] Vilado et al., J. of Microscopy 252, 23 (2013)

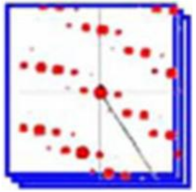
4D-STEM for crystal phase and orientation mapping

Principle: ASTAR [1]

1. 4D-STEM acquisition, in precession mode



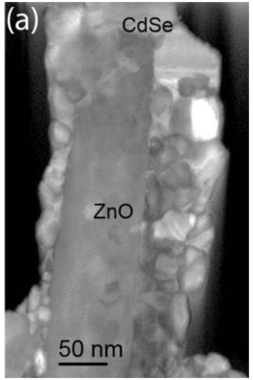
2. Simulation of a database of diffraction patterns
   - For all crystal phases in the sample
   - For all orientations of the crystals



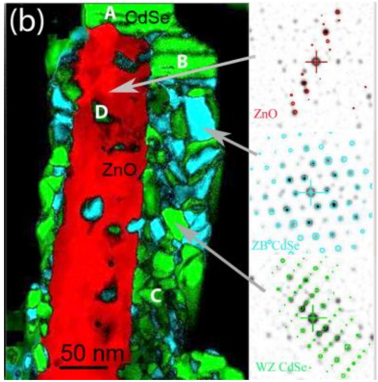
3. Matching between experimental patterns and the database with correlation-based algorithm
   - The most similar diffraction pattern is assigned to each local diffraction

Example: ZnO/CdSe core/shell nanowires [2]

Virtual BF

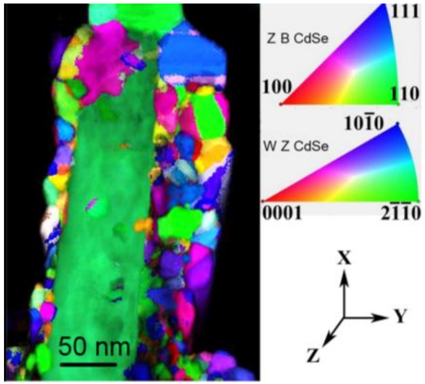


Crystal phase map:



ZnO: wurtzite
CdSe: zinc-blende + wurtzite

Orientation map:



Crystal phase and orientation mapping in polycrystalline samples

- Crystal grains > specimen thickness
- ➢ Requires beam precession to be in pseudo-kinematical diffraction conditions

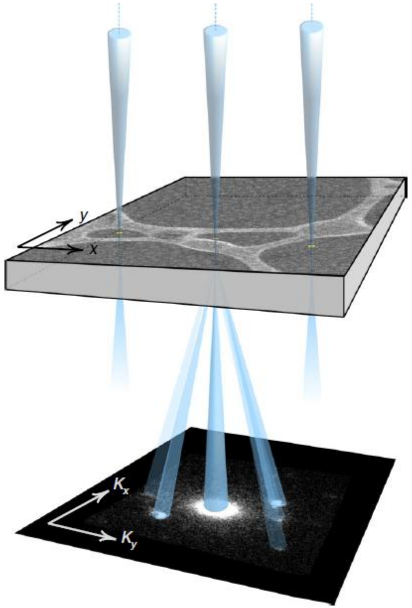
[1] Vilado et al., J. of Microscopy 252, 23 (2013)

[2] Consonni et al., Nanotechnology 27, 445712 (2016)

4D-STEM for orientation mapping – in polymers

Principle

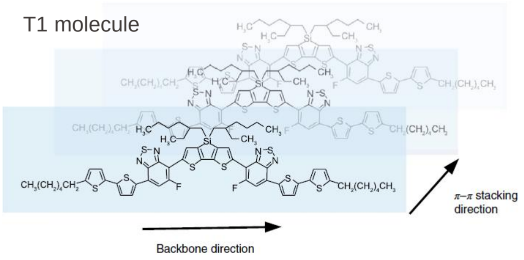
1. Record the 4D-STEM dataset



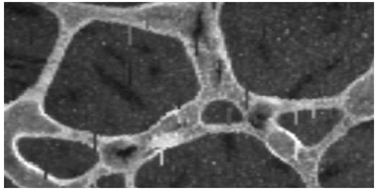
2. Compute the orientation of the principal Bragg diffracted beams

Example: Stacking orientation of a thin film of organic semiconductor [1]

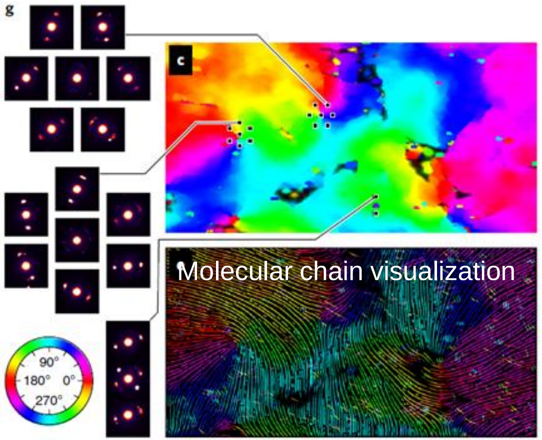
T1 molecule



HAADF STEM image



Orientation map:



Medium-range ordering mapping in polymers

- ➢ Requires extreme care with data acquisition of beam-sensitive materials!

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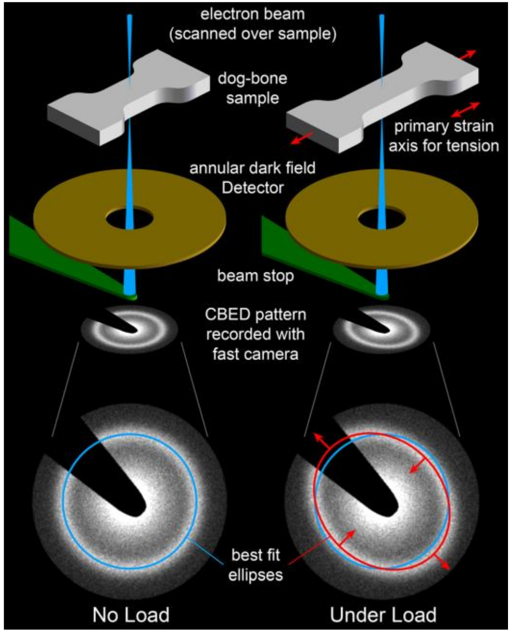
[1] Panova et al., Nat. Mater. 18, 860 (2019)

4D-STEM for strain mapping – in amorphous

Principle

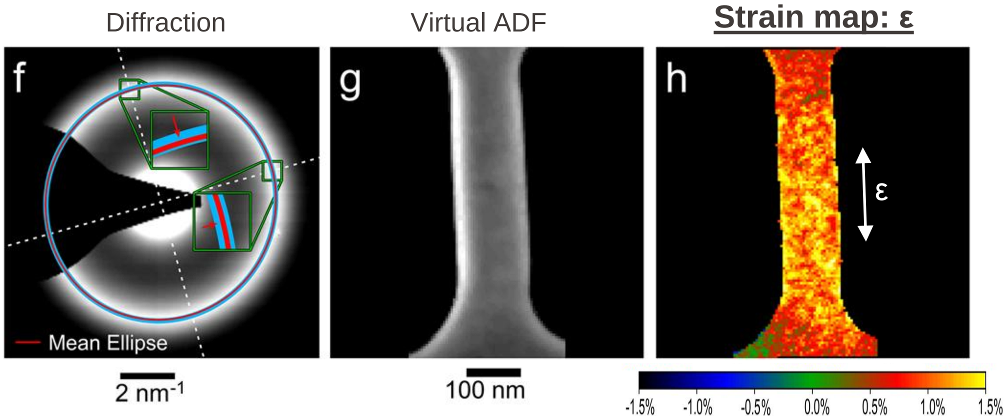
1. 4D-STEM acquisition



2. Fit an ellipse to each amorphous diffraction pattern to compute the strain (and orientation) from the elliptic distortions

Example: In-situ traction of an amorphous CuZrAlAg metallic glass [1]

After application of a tensile strain:


Diffraction

Virtual ADF

Strain map: ε

Strain mapping in amorphous samples

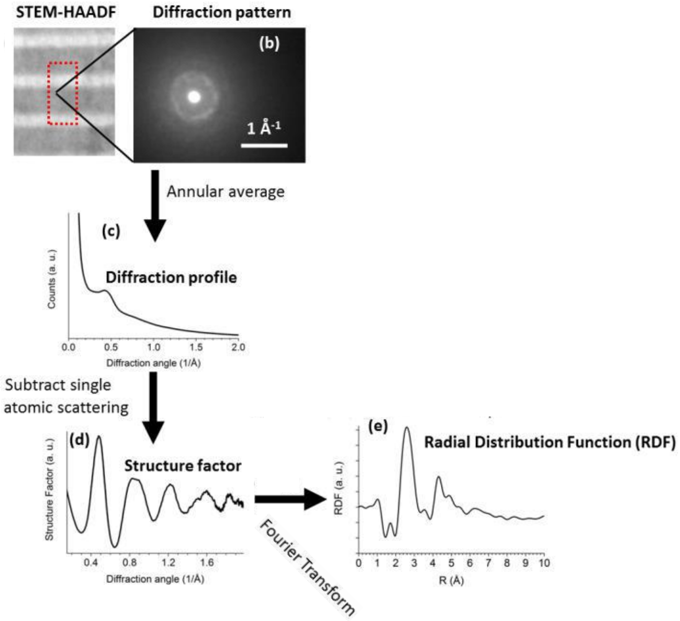
- In-plane strain components (2D): magnitude and orientation
- Quantitative measurement

[1] Gammer et al., Appl. Phys. Lett. 112, 171905 (2018)

4D-STEM for amorphous materials phase mapping

Principle [1]:

1. 4D-STEM acquisition
2. Compute the RDF for each diffraction



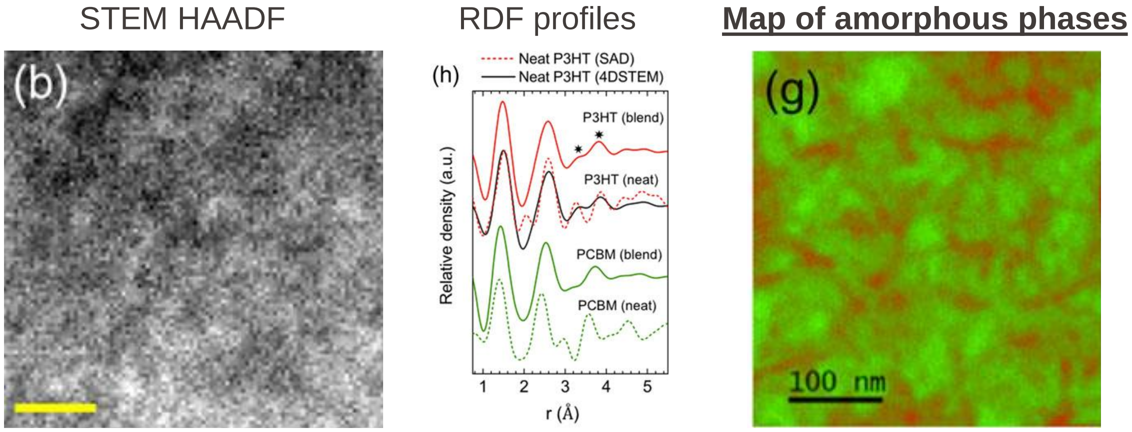
3. Classify the RDF profiles using hyperspectral analysis, e.g. MLLS fitting (multiple linear least square)

Radial distribution function (RDF) shows the short-range atomic order

RDF ≡ pair distribution function (PDF)

➢ RDF is the fingerprint of the amorphous structure

Example: Mapping of PC$_{61}$BM and P3HT amorphous materials [2]



STEM HAADF

RDF profiles

<u>**Map of amorphous phases**</u>

Amorphous sample phase mapping

➢ Requires care with data acquisition:
  - Often beam sensitive materials
  - Weak scattering signal

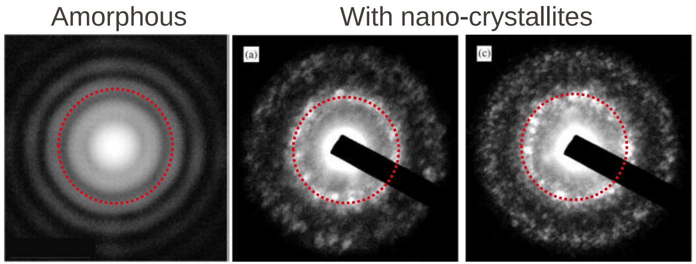
[1] Mu et al., Ultramicroscopy 168, 1 (2016)

[2] Mu et al., Microscopy 68, 301 (2019)

4D-STEM for fluctuation microscopy

Principle [1]:

1. 4D-STEM acquisition



2. For each diffraction pattern, compute the variance of the azimuthal profile:

$$V = \sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2$$

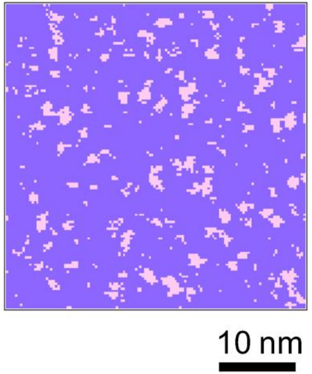
$V \sim 0$ for a perfect amorphous

V increases when crystal ordering increases

3. Data representation

Example: Local heterogeneities in $Zr_{55}Co_{25}Al_{20}$ glass [2]

Distribution of nano-crystallites:



Thresholding of the higher degrees of crystal ordering

Map of the **degree of crystallinity of amorphous / nanocrystalline samples**

- ➢ Statistical method
- ➢ Observation of crystal nanoclusters in amorphous

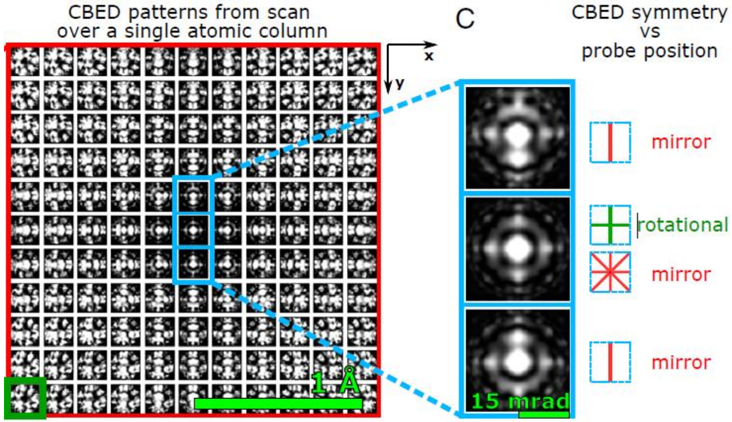
[1] Voyles & Muller, Ultramicroscopy 93, 147 (2002)

[2] Im et al., Ultramicroscopy 195, 189 (2018)

4D-STEM for atomic-resolution symmetry imaging

Principle:

1. 4D-STEM acquisition

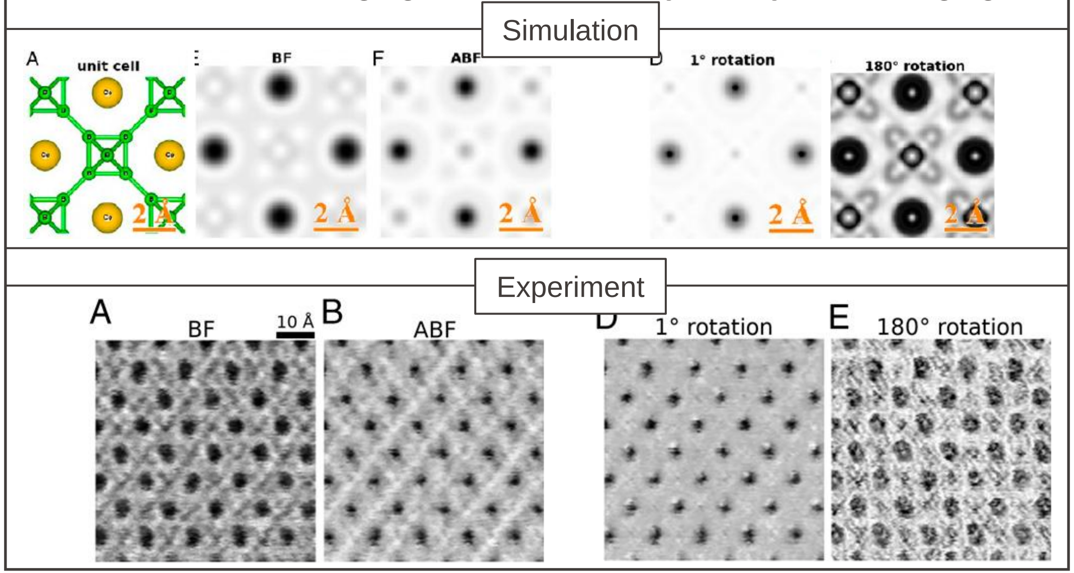


2. Processing to create contrasts according to a certain degree of symmetry

Example: Proof of concept of symmetry imaging on CeB_6 [1]

STEM imaging:

Symmetry STEM imaging:



Atomic resolution **imaging with contrast based on local symmetry**

- Study of crystal symmetries
- For imaging:
  - Robust contrast vs. defocus, thickness, etc. (incoherent type)
  - Low dose

[1] Krajnak et al., PNAS 117, 27805 (2020)

Outline

1. STEM basics
2. Pixelated STEM detectors
3. DPC
4. 4D-STEM
5. **Conclusion**

Conclusion

- DPC
  - Mapping of phase gradient ≡ in-plane $\vec{E}$ and $\vec{B}$ fields
  - Field quantification difficult, improved with 4D-STEM detector
  - iDPC is great for atomic-resolution imaging, with a segmented detector
    - Light atoms visible
    - Highly dose efficient

- 4D-STEM: method of recording the local diffraction at each pixel of the STEM image
  - Heavy dataset and slow acquisition
    - Better to use conventional STEM approach when possible
  - Give access to a wide range of data analyses
    - Many established techniques to apply
    - Pertinent for quantitative measurement techniques
    - Comprehensive information on the sample to be explored
  - STEM parameters should be chosen wisely!

  - Data processing is often the bottleneck
    - Standard applications have existing resources: Python toolboxes, DigitalMicrograph plugins, etc.
    - Requires advanced coding for fancy applications

- Contact CIME to discuss potential applications to your research ☺

Resources and contact

- Books
  - Williams & Carter, TEM, Springer (2009)
  - Reimer & Kohl, TEM, Springer (2008)
  - Hawkes & Spence, Science of microscopy, Springer (2007)
  - Pennycook & Nellist, STEM: imaging and analysis, Springer (2011)
  - Zuo & Spence, Advanced TEM: imaging and diffraction in nanoscience, Springer (2017)
  - De Graef & Zhu, Magnetic Imaging and its Applications to Materials, Academic press (2001)

- Direct electron detectors
  - Faruqi & McMullan, Nucl. Instrum. Methods Phys. Res. A 878, 180 (2018)

- Review on 4D-STEM applications and processing
  - Ophus, Microsc. Microanal. 25, 563 (2019)
  - Savitzky et al., Microsc. Microanal., 1 (2021)

Website: www.epfl.ch/research/facilities/cime

Email: victor.boureau@epfl.ch