Design of a High-Performance Post-Column Imaging Energy Filter for (S)TEM Instruments

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System configuration

- 200 kV Transmission Electron Microscope (TEM) with Schottky Field Emission Gun (Schottky-FEG)
- TVIPS TemCam-XF416 CMOS camera (4k, 15.5 μm pixel size)
- CEOS Energy Filtered Imaging Device: CEFID
Major Operation Modes

- **Electron-Spectroscopic-Imaging (ESI)/**
  **Energy-Filtered-Transmission-Electron-Microscopy (EFTEM)**

Pre-filter TEM image  

![Energy loss spectrum]

CEFID

Post-filter camera
Major Operation Modes

- Electron-Energy-Loss-Spectroscopy (EELS)
3D Perspective View

Beam from microscope
Cross-Sections

Piezo Driven Slit Blades

Cross-section plane

Upper blade

Lower blade

X

dispersive

Z beam

non-dispersive

Y
Camera Plane

Cross-section plane

Detector Chip

X, dispersive

Y, non-dispersive

Z beam
Ideal System: Mid-Section Symmetry

- Beam profile symmetric w.r.t. mid-section plane
Ideal System: Mid-Section Symmetry

- Beam profile symmetric w.r.t. mid-section plane
- In an ideal system: only "unrotated" multipoles required, e.g.:
  - Quadrupoles
Ideal System: Mid-Section Symmetry

- Beam profile symmetric w.r.t. mid-section plane
- In an ideal system: only "unrotated" multipoles required, e.g.:
  - Quadrupoles
  - Sextupoles
Unrotated Quadrupole

Symmetry plane
Unrotated Quadrupole

Symmetry plane

dispersive
non-dispersive
Unrotated Quadrupole

Symmetry plane

B

N
S

dispersive
non-dispersive

X
Y
Z beam
Rotated Quadrupole

Symmetry plane

45°

dispersive

Z beam

non-dispersive

X
Unrotated Sextupole

Symmetry plane

dispersive

non-dispersive
Unrotated Sextupole
Device Coordinate System Orientation

Aperture plane

Slit plane
- Upper blade
- Lower blade

Detector Plane
Commonly used Coordinate System Orientation

Aperture plane

Slit plane

Detector Plane

\( y \) non-dispersive

\( x \) dispersive

Lower blade

Upper blade
Ideal System, Gaussian Optics

Aperture plane

Image plane
no dispersion

Pre-Slit optics

Slit plane
Fourier plane
large dispersion
(5.1 μm/eV at 200 kV)

Lower blade

Upper blade

Detector Plane

Counts

Spectrum at Slit Plane

Energy loss (ΔE)

0 eV
Ideal System, Gaussian Optics

ESI

Aperture plane

Image plane
no dispersion

Pre-Slit optics

Slit plane

Fourier plane
large dispersion
(5.1 μm/eV at 200 kV)

Post-Slit optics

Detector Plane

Image plane
no dispersion

Lower blade

Upper blade

Spectrum at Slit Plane

Counts

0 eV

Energy loss (ΔE)
Ideal System, Gaussian Optics

ESI

Aperture plane

Image plane
no dispersion

Pre-Slit optics

Slit plane

Fourier plane
large dispersion
(5.1 μm/eV at 200 kV)

Post-Slit optics

Detector Plane

Image plane
no dispersion

Lower blade

Upper blade

Counts

Spectrum at Slit Plane

0 eV

Energy loss (ΔE)
Ideal System, Gaussian Optics
From ESI to EELS

Aperture plane

Image plane
no dispersion

Pre-Slit optics

Slit plane

Fourier plane
large dispersion

Post-Slit optics

Detector Plane

Image plane
no dispersion

Lower blade

Upper blade

Spectrum at slit plane

Counts

0 eV

Energy loss ($\Delta E$)

Y
non-dispersive

X
dispersive

Z beam
Ideal System, Gaussian Optics

EELS

Aperture plane

Image plane
no dispersion

Pre-Slit optics

Slit plane

Fourier plane
large dispersion

Post-Slit optics
Reconfigured

Detector Plane

Fourier plane
Magnified spectrum

Lower blade

Upper blade

Counts
Line Scan of Spectrum

Energy loss ($\Delta E$)

y
dispersive
non-dispersive

x
beam
Ideal System, Gaussian Optics

EELS

Aperture plane

Slit plane

Detector Plane

Image plane
non-dispersive

Pre-Slit optics

Fourier plane
large dispersion

Post-Slit optics

Fourier plane
Magnified spectrum

Nearly same for EELS and ESI

Lower blade

Upper blade

Counts

Line Scan of Spectrum

Y
non-dispersive

X
dispersive

Z beam
Ideal System, Gaussian Optics

EELS

Aperture plane

Slit plane

Detector Plane

Image plane
no dispersion

Pre-Slit optics

Fourier plane
large dispersion

Post-Slit optics

Fourier plane
Magnified spectrum

Pre- and Post-Slit are decoupled!
Ideal System, Gaussian Optics

ESI

Aperture plane

Image plane
no dispersion

Pre-Slit optics
3 unrotated Quadrupoles

Slit plane

Fourier plane
large dispersion

• Dispersion
• x-Focus
• y-Focus

Post-Slit optics
3 out of 4 unrotated Quadrupoles

Detector Plane

Image plane
no dispersion

• No dispersion
• x-Magnification
• y-Magnification

non-dispersive

y

X

beam
dispersive

Z
Real System Suffering from Intrinsic and Parasitic Aberrations

Two major types of aberrations (linear and higher order):

Symmetric w.r.t mid-section

Intrinsic aberrations

Un-rotated multipoles

Non-Symmetric w.r.t mid-section

Parasitic aberrations (Material and manufacturing imperfections, ...)

Rotated multipoles
Real System Suffering from Intrinsic and Parasitic Aberrations

Aperture plane

Image plane no dispersion
Pre-Slit optics

Slit plane
Fourier plane large dispersion

Upper blade

Post-Slit optics

Detector Plane
Image plane no dispersion

Vacuum
Zero-Loss-Peak (ZLP)

y non-dispersive

x dispersive
Real System Suffering from Intrinsic and Parasitic Aberrations

Aperture plane

Image plane
no dispersion

Pre-Slit optics

Slit plane

Fourier plane
large dispersion

Post-Slit optics

Detector Plane

Image plane
no dispersion

Vacuum

y non-dispersive

x z beam dispersive

Upper blade
Real System Suffering from Intrinsic and Parasitic Aberrations

Aperture plane

Image plane  
no dispersion

Pre-Slit optics

Fourier plane  
large dispersion

Post-Slit optics

Detector Plane  
Image plane  
no dispersion

Vacuum

y  
non-dispersive

x  
dispersive

Upper blade

Shift caustic towards slit blade by changing HT offset
Real System Suffering from Intrinsic and Parasitic Aberrations

Aperture plane

Image plane
no dispersion

Pre-Slit optics

Fourier plane
large dispersion

Post-Slit optics

Detector Plane

Image plane
no dispersion

Vacuum

Non-dispersive

Shift caustic towards slit blade by changing HT offset

Upper blade
Definition of Non-Isochromaticity

Attenuation pattern

Counts

HT offset
Definition of Non-Isochromaticity

Attenuation pattern

Counts vs. HT offset
Definition of Non-Isochromaticity

Attenuation pattern

Counts

HT offset
Definition of Non-Isochromaticity

Attenuation pattern

Counts

HT offset
Definition of Non-Isochromaticity

Attenuation pattern

Counts

Max. Non-Isochromaticity

HT offset
Meaning of Attenuation Curve of One Spot of Sample Region

Attenuation pattern

Counts

Max. Non-Isochromaticity

HT offset
Meaning of Attenuation Curve of One Spot of Sample Region

Slit plane

- Caustic of electron from one sample point
- no blurring by off-axial aberrations

Counts
Electron energy
Energy distribution of gun

Counts
Electron energy
Upper Blade

HT offset
Meaning of Attenuation Curve of One Spot of Sample Region

Slit plane

Upper Blade

Counts

HT offset
Meaning of Attenuation Curve of One Spot of Sample Region

Slit plane

Counts

Upper Blade

HT offset
Meaning of Attenuation Curve of One Spot of Sample Region

Slit plane

Counts

Upper Blade

HT offset
Meaning of Attenuation Curve of One Spot of Sample Region

Slit plane

Counts
Energy distribution of gun
Electron energy

Upper Blade

Counts
HT offset
Electron energy
Meaning of Attenuation Curve of One Spot of Sample Region

Slit plane

Counts

Electron energy

Energy distribution of gun

$\Delta E_{\text{FWHM}}$

Upper Blade

Counts

HT offset

$\Delta E_{\text{FWHM}}$

100%

88%

12%
Non-Isochromaticity Correction

Multipole Attenuation Patterns

- Quadrupole
- Sextupole
- Octupole

Decomposition

Rotated

Unrotated

Symmetry plane
Non-Isochromaticity Correction

Multipole Attenuation Patterns

- Quadrupole
- Sextupole
- Octupole

Decomposition

Unrotated

Rotated

Counterbalancing using unrotated and rotated Pre-Slit quadrupoles, sextupoles and octupoles

Symmetry plane

Attenuation pattern corrected state
Minimized Non-Isochromaticity

Attenuation pattern

Counts

HT offset
Minimized Non-Isochromaticity

Attenuation pattern

Counts

HT offset
Minimized Non-Isochromaticity

Attenuation pattern

Counts

Max. Non-Isochromaticity

HT offset
Distortion Measurement
Record ESI Image of Mask Holes

Aperture plane

Aperture Mask
5×5 sub grid

CEFID ESI Mode

Camera image

Image of holes of
5×5 sub grid
Distortion Measurement
Reconstruct Grid

Aperture plane

Detector chip

Aperture Mask
5×5 sub grid
Distortion Measurement
Linear Imaging Least Square Fit

Aperture plane

Detector chip

Aperture Mask
5×5 sub grid
Distortion Measurement
Linear Imaging Least Square Fit

Aperture plane

Aperture Mask
5×5 sub grid

Detector chip
Distortion Measurement
Parameters describing a Linear Imaging
Distortion Measurement
Parameters describing a Linear Imaging

- Isotropic magnification
Distortion Measurement
Parameters describing a Linear Imaging

- Isotropic magnification
- Shear angle
Distortion Measurement
Parameters describing a Linear Imaging

- Isotropic magnification
- Shear angle
- Aspect ratio violation
Distortion Measurement
Parameters describing a Linear Imaging

- Isotropic magnification
- Shear angle
- Aspect ratio violation
- Image rotation
Distortion Measurement
Parameters describing a Linear Imaging

- Isotropic magnification
- Shear angle
- Aspect ratio violation
- Image rotation
- Image shift
Linear Dispersion in X- and Y-Direction
Linear Dispersion in X- and Y-Direction

- Image shifts proportional to HT offset change
- Must be compensated
Corrected or Adjusted ESI Imaging Properties

- Isotropic magnification
Corrected or Adjusted ESI Imaging Properties

- Isotropic magnification
- Aspect ratio violation
Corrected or Adjusted ESI Imaging Properties

- Isotropic magnification
- Aspect ration violation
Corrected or Adjusted ESI Imaging Properties

- Isotropic magnification
- Aspect ratio violation
- Dispersion in x-Direction
Corrected or Adjusted ESI Imaging Properties

- Isotropic magnification

- Aspect ratio violation

- Dispersion in x-Direction
Corrected or Adjusted ESI Imaging Properties

- Isotropic magnification
- Aspect ration violation
- Dispersion in x-Direction
- One limiting third order aberration
Corrected or Adjusted ESI Imaging Properties

- Isotropic magnification
- Aspect ratio violation
- Dispersion in x-direction
- One limiting third order aberration
Corrected or Adjusted ESI Imaging Properties

- Isotropic magnification
- Aspect ratio violation
- Dispersion in x-Direction
- One limiting third order aberration

4 unrotated quadrupoles
Corrected or Adjusted ESI Imaging Properties

- Shear angle
Corrected or Adjusted ESI Imaging Properties

- Shear angle
Corrected or Adjusted ESI Imaging Properties

- Shear angle
- Dispersion in y-Direction
Corrected or Adjusted ESI Imaging Properties

- Shear angle
- Dispersion in y-Direction
Corrected or Adjusted ESI Imaging Properties

- Shear angle
- Dispersion in y-Direction

2 rotated quadrupoles
Corrected or Adjusted ESI Imaging Properties

- Three mid-section symmetric aberrations of 3rd order

3 unrotated sextupoles
Definition of Maximum/RMS Residual Distortion

- Before tuning
Definition of Maximum/RMS Residual Distortion

- Before tuning
- After tuning
Definition of Maximum/RMS Residual Distortion

- Before tuning
- After tuning
- Least Square fit with parameters:
  - Isotropic Mag.
Definition of Maximum/RMS Residual Distortion

- Before tuning
- After tuning
- Least Square fit with parameters:
  - Isotropic Mag.
Definition of Maximum/RMS Residual Distortion

- Before tuning
- After tuning
- Least Square fit with parameters:
  - Isotropic Mag.
  - Image rotation
Definition of Maximum/RMS Residual Distortion

• Before tuning
• After tuning
• Least Square fit with parameters:
  • Isotropic Mag.
  • Image rotation
• Determine distances between measured and fitted hole positions
Definition of Maximum/RMS Residual Distortion

- Before tuning
- After tuning
- Least Square fit with parameters:
  - Isotropic Mag.
  - Image rotation
- Determine distances between measured and fitted hole positions
- Determine maximum and RMS of distances
Definition of Maximum/RMS Residual Distortion

- Before tuning
- After tuning
- Least Square fit with parameters:
  - Isotropic Mag.
  - Image rotation
- Determine distances between measured and fitted hole positions
- Determine maximum and RMS of distances
- Divide them by length of half diagonal of detector chip
Definition of Maximum/RMS Residual Chromatic Distortion

- Record hole positions for HT offsets
  - $-\Delta E/2$
Definition of Maximum/RMS Residual Chromatic Distortion

- Record hole positions for HT offsets
  - $-\Delta E/2$
  - $+\Delta E/2$
Definition of Maximum/RMS Residual Chromatic Distortion

- Record hole positions for HT offsets
  - $-\Delta E/2$
  - $+\Delta E/2$
- Determine shift vector for each hole
Definition of Maximum/RMS Residual Chromatic Distortion

- Record hole positions for HT offsets
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Definition of Maximum/RMS Residual Chromatic Distortion

- Record hole positions for HT offsets
  - $-\Delta E/2$
  - $+\Delta E/2$
- Determine shift vector for each hole
- Determine maximum and RMS of shift vector magnitudes
Definition of Maximum/RMS Residual Chromatic Distortion

- Record hole positions for HT offsets
  - $-\Delta E/2$
  - $+\Delta E/2$
- Determine shift vector for each hole
- Determine maximum and RMS of shift vector magnitudes
- Divide them by length of half diagonal of detector chip
Three Available ESI-Modes

12 mm Mode
Mag: 7.4

Virtual aperture size in aperture plane: **12 mm**

63.5 mm

Detector chip
Three Available ESI-Modes

10 mm Mode
Mag: 8.8

Virtual aperture size in aperture plane: 10 mm

Detector chip

63.5 mm
Three Available ESI-Modes

8 mm Mode
Mag 11.1

Virtual aperture size in aperture plane: 8 mm

63.5 mm

Detector chip
Performance of ESI modes: 12 mm

Distortion: Max.: 1.00 % (28.6 px)
RMS: 0.41 % (11.9 px)

Chromatic Distortion: Max.: 0.18 % (5.3 px)
RMS: 0.08 % (2.2 px)
Performance of ESI modes: 10 mm

Distortion:
Max.: 0.72 % (21.0 px)
RMS: 0.31 % (11.1 px)

Chromatic Distortion:
Max.: 0.18 % (5.1 px)
RMS: 0.08 % (2.2 px)

±25 V
Performance of ESI modes: 8 mm

Distortion:
- Max.: 0.65 % (18.9 px)
- RMS: 0.45 % (12.9 px)

Chromatic Distortion:
- Max.: 0.17 % (4.8 px)
- RMS: 0.09 % (2.5 px)
ESI modes: Non-Isochromaticity

<table>
<thead>
<tr>
<th>Size</th>
<th>Maximum</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 mm</td>
<td>2170 meV</td>
<td>278 meV</td>
</tr>
<tr>
<td>10 mm</td>
<td>469 meV</td>
<td>71 meV</td>
</tr>
<tr>
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ESI modes: Non-Isochromaticity

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- Maximum: 104 meV
- RMS: 25 meV
Electron Optical Limit for EELS Energy resolution: Estimation from Non-Isochromaticity

5 mm EELS Aperture
Electron Optical Limit for EELS Energy resolution: Estimation from Non-Isochromaticity

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RMS: 25 meV
Electron Optical Limit for EELS Energy resolution: Estimation from Non-Isochromaticity

5 mm EELS Aperture

Maximum: 104 meV
RMS: 25 meV

Assuming a monochromatic source

Total ZLP width = max. Non-Isochromaticity
EM-Spectro (TVIPS)

EELS (at 200 kV): 1024 eV over camera

EELS of Boron Nitride on Carbon
EELS (at 200 kV): 256 eV over camera

EELS of Boron Nitride on Carbon

EM-Spectro (TVIPS):
Background subtraction at Boron K-Edge (188 eV)
EELS (at 200 kV): ESI of Boron Nitride on Carbon

EM-Spectro (TVIPS)
Elemental Mapping with Three-Window-Method

- 20 eV energy window
- Three exposures for each core-loss: two pre-edge, one post-edge

Boron K-Edge: 188 eV
Carbon K-Edge: 284 eV
Nitrogen K-Edge: 401 eV
EELS (at 200 kV): ESI of Boron Nitride on Carbon

Elemental Mapping with Three-Window-Method

Boron K-Edge (188 eV)

Carbon K-Edge (284 eV)

Nitrogen K-Edge (401 eV)

EM-Spectro (TVIPS)
Additional EELS overview mode: 4096 eV at 200 kV

- Ray path in pre-slit differs significantly from regular EELS modes (from 8 eV to 1024 eV at 200 kV):
  - Dispersion in slit plane greatly reduced
  - No Fourier plane in slit plane anymore
EELS (at 80 kV): 1696 eV range (4096 eV at 200 kV)
Recorded using CEOS Image Processing Solution

Boron Nitride

Boron K-Edge: 188 eV
Nitrogen K-Edge: 400 eV
Long-Term Stability EELS High-Res

First measurement of ZLP

16 eV
Long-Term Stability EELS High-Res

Eight hours later
Reproducibility when switching Modes

- EELS measurement at 16 eV
- Accumulated Peaks for HT offsets:
  - -10 V
  - -5 V
  - 0 eV (ZLP)
  - +5 V
  - +10 V
Switched to ESI 10 mm and normalized

Distortion: Maximum: 0.73 % (21.0 px)  
RMS: 0.38 % (11.1 px)

Chromatic Distortion: Maximum: 0.19 % (5.5 px)  
RMS: 0.08 % (2.3 px)
Switched back to EEL 16 eV and Normalized

ZLP EELS 16 eV
Image Processing and Filter Control Solution

- Python based
- Supports Scripting using Python
- Framework for integrating new hardware, e.g. cameras from different manufacturers
- Integrated Filter Control Applet for:
  - Switching modes
  - Tuning the modes using measurement procedures and a set of Alignment Tools
  - Fully automatic filter tuning (work in progress)
Summary

- Excellent optical performance, both ESI and EELS
- EELS ranges from 8 eV to 4096 eV at 200 kV
- Default 4k × 4k fast CMOS detector, other options possible
- Thanks to decoupled Pre-Slit and Post-Slit modes:
  - Robust and fast switching between ESI and EELS Modes with minimum need for retuning
  - Excellent long term stability of tuning quality of all modes
- Extensible image processing solution
- Support for running user scripts written in Python
- Open software interface for integrating multiple camera types and microscopes
Current State and Outlook

- Adding more application support to our image processing software
- Adding STEM EELS functionality

For more information please contact us:
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