Aberration Correctors and Monochromators

Martin Linck

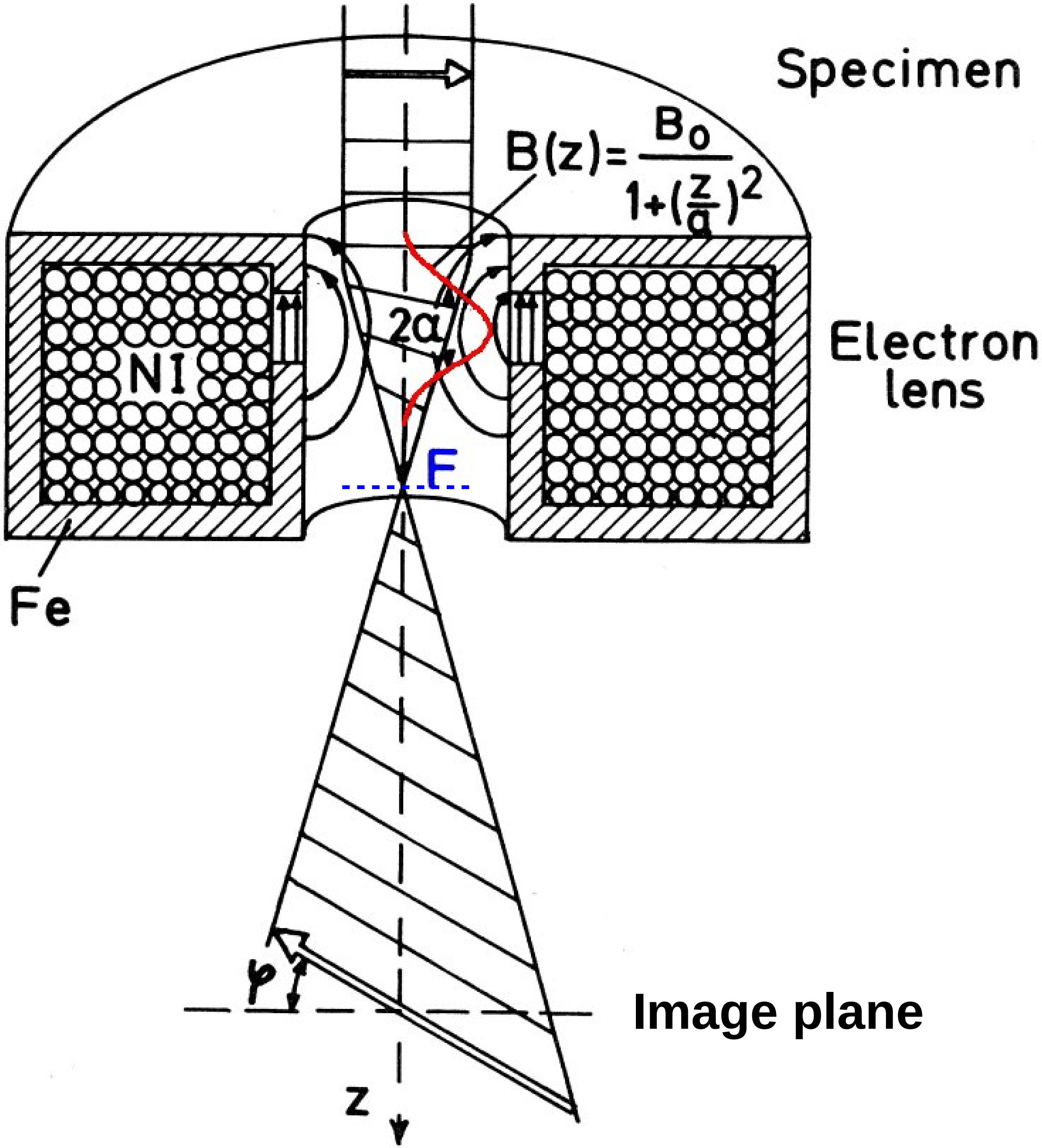
- Research & Development -
Corrected Electron Optical Systems GmbH,
Englerstr. 28, D-69126 Heidelberg

CEOS

Corrected Electron Optical Systems GmbH

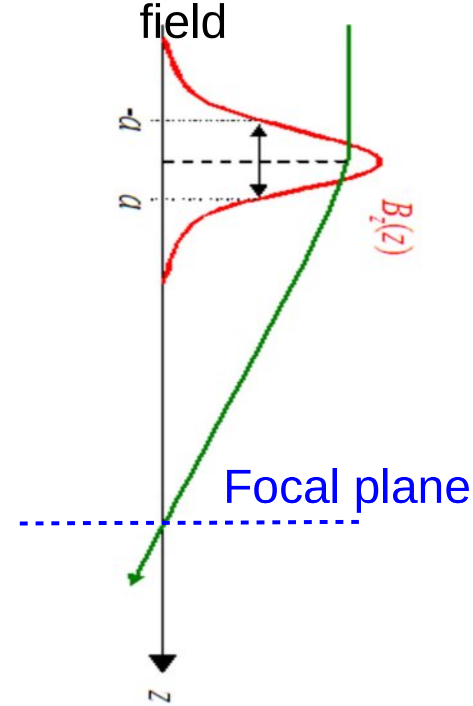
Invention of the Transmission Electron Microscope

Magnetic Lens for Electrons



Glaser's “Glockenfeld”

bell-shaped, axial magnetic field



Otto Scherzer: Z. f. Physik 101 (1936), 593-603.

CEOS
Corrected Electron Optical Systems GmbH

Über einige Fehler von Elektronenlinsen.

Von **O. Scherzer** in Darmstadt.

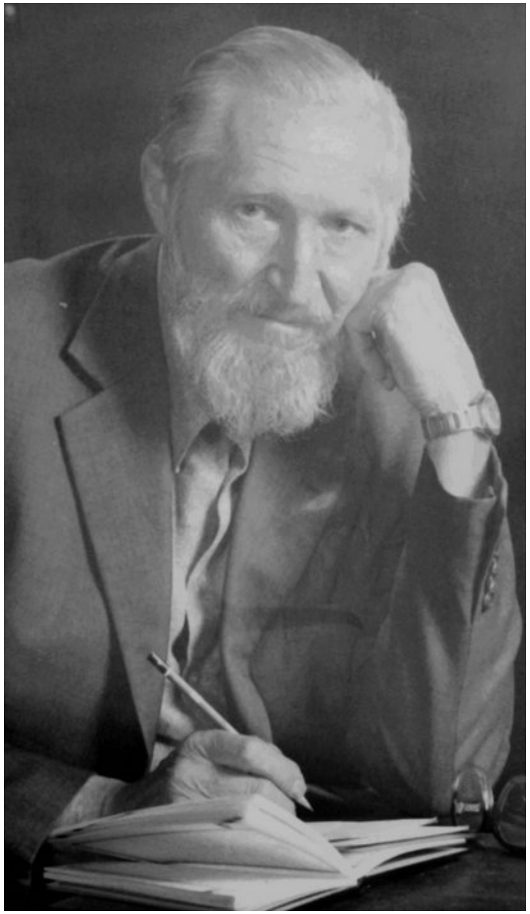
Mit 3 Abbildungen. (Eingegangen am 4. Juni 1936.)

Unmöglichkeit des Achromaten. Die Bildfehler dritter Ordnung. Unvermeidbarkeit der sphärischen Aberration.

Die Bewegung der achsennahen Elektronen (Gaußscher Strahlengang) genügt bekanntlich der Gleichung

$$\Phi r'' + \frac{1}{2}\Phi' r' = -\frac{r}{4}\Phi'' - \frac{e\,r}{8\,m}\mathfrak{H}^2. \qquad (1)$$

r ist der Abstand des Elektrons von der optischen Achse (z-Achse), Φ ist das auf dieser Achse gemessene Potential und $\mathfrak{H}$ die auf der Achse gemessene magnetische Feldstärke. Die Striche bedeuten Differentiationen nach z.



Prof. Otto Scherzer
(TU Darmstadt)

Über einige Fehler von Elektronenlinsen.

Von **O. Scherzer** in Darmstadt.

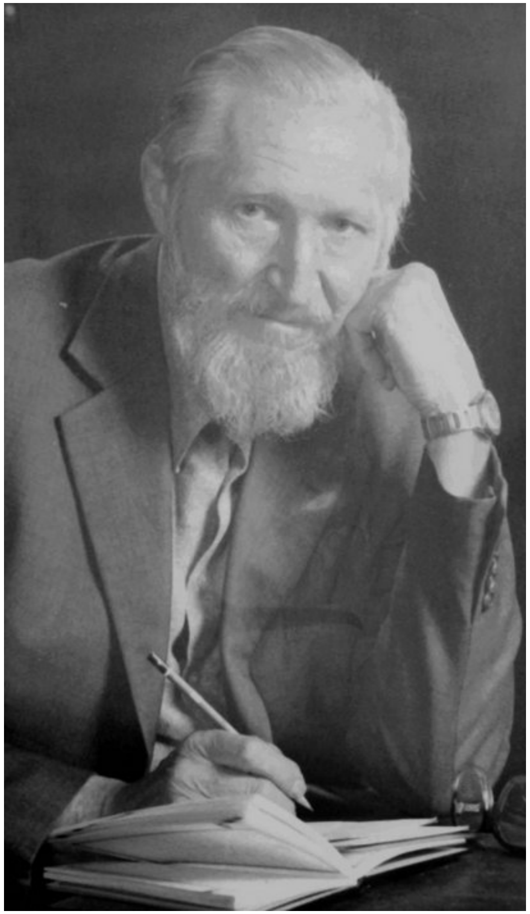
Mit 3 Abbildungen. (Eingegangen am 4. Juni 1936.)

Unmöglichkeit des Achromaten. Die Bildfehler dritter Ordnung. Unvermeidbarkeit der sphärischen Aberration.

Path deviation of the charged particle:

$$\varrho = \frac{V}{16\sqrt{\Phi_a}} \int_{z_a}^{z_b} \Phi^{1/2} \left[\frac{5}{4}\left(\frac{\Phi''}{\Phi} + \frac{\Phi' r'}{\Phi r} - \frac{\Phi'^2}{\Phi^2}\right)^2 + \frac{\Phi'^2}{\Phi^2}\left(\frac{r'}{r} + \frac{7}{8}\frac{\Phi'}{\Phi}\right)^2 + \frac{e}{m\Phi}\left(\mathfrak{H}' + \mathfrak{H}\frac{r'}{r} - \frac{5}{4}\mathfrak{H}\frac{\Phi'}{\Phi}\right)^2 + \frac{e}{m}\frac{\mathfrak{H}^2}{\Phi}\left(\frac{r'}{r} + \frac{1}{4}\frac{\Phi'}{\Phi}\right)^2 + \frac{1}{64}\frac{\Phi'^4}{\Phi^4} + \frac{e^2\mathfrak{H}^4}{4m^2\Phi^2} + \frac{e\mathfrak{H}^2}{32m}\frac{\Phi'^2}{\Phi^3} \right] r^4 \, \mathrm{d}z .$$

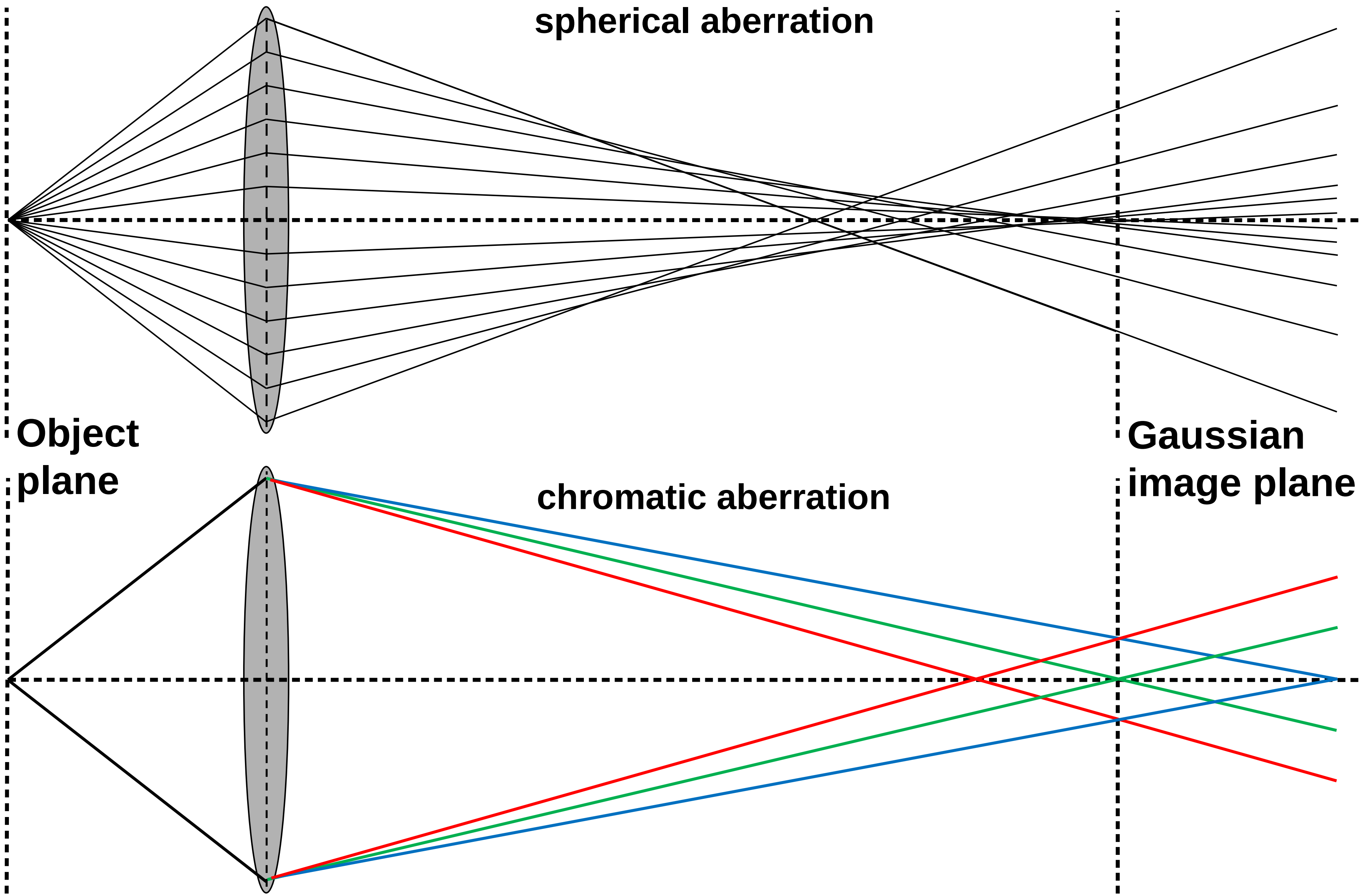
Die rechte Seite von Gleichung (13) enthält nur Quadrate mit *gleichem* Vorzeichen. Da Φ immer positiv ist, kann sie nur verschwinden, wenn *alle* Quadrate, also auch Φ' und $\mathfrak{H}$, gleich Null sind. Es ist somit unmöglich, die sphärische Aberration einer raumladungsfreien Elektronenlinse restlos zu beseitigen[1]). Die Aufgabe der Theorie ist also nicht die Ermittlung aberrations*freier* Linsen, sondern nur die Ermittlung von Linsen mit *möglichst geringer* sphärischer Aberration[2]).



Prof. Otto Scherzer
(TU Darmstadt)

Imaging by a lens

CEOS
Corrected Electron Optical Systems GmbH



Otto Scherzer: Optik 2 (1947), 114-132.

Sphärische und chromatische Korrektur von Elektronen-Linsen.

Von O. Scherzer, z. Zt. USA.

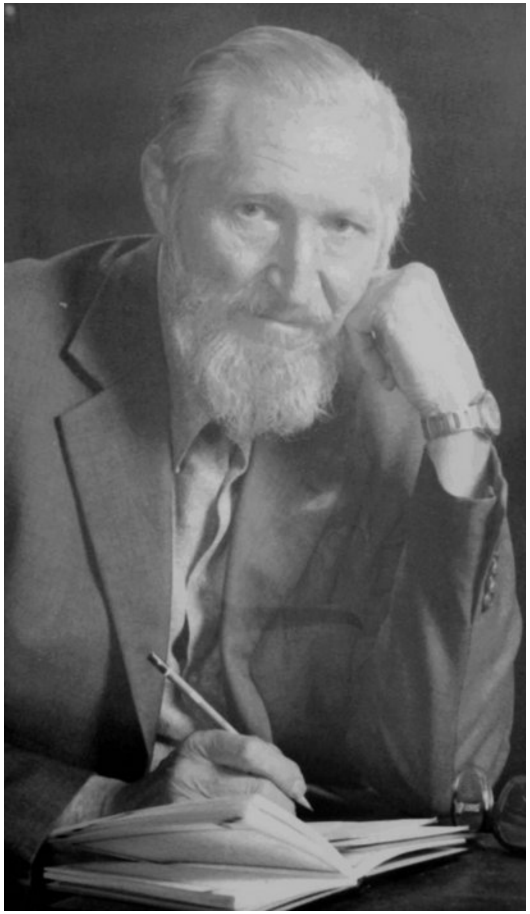
(Aus den Süddeutschen Laboratorien in Mosbach.)

(Mit 7 Textabbildungen.)

Die Brauchbarkeit des Elektronenmikroskops bei hohen Vergrößerungen wird durch den Öffnungsfehler und die chromatische Aberration beeinträchtigt. Beide Fehler sind unvermeidlich, solange die abbildenden Felder rotations-symmetrisch, ladungsfrei und zeitlich konstant sind. Die vorliegende Untersuchung soll zeigen, daß die Aufhebung irgendeiner dieser drei Einschränkungen genügt, um den Weg zur sphärischen und chromatischen Korrektur und damit zu einer erheblichen Steigerung des Auflösungsvermögens freizugeben.

Solange nicht klar zu sehen ist, welche Art Linsen das beste Mikroskop ergibt, müssen alle sich bietenden Wege verfolgt werden. Es scheint daher angebracht, etwas ausführlicher auf die verschiedenen Arten korrigierter Linsen einzugehen.

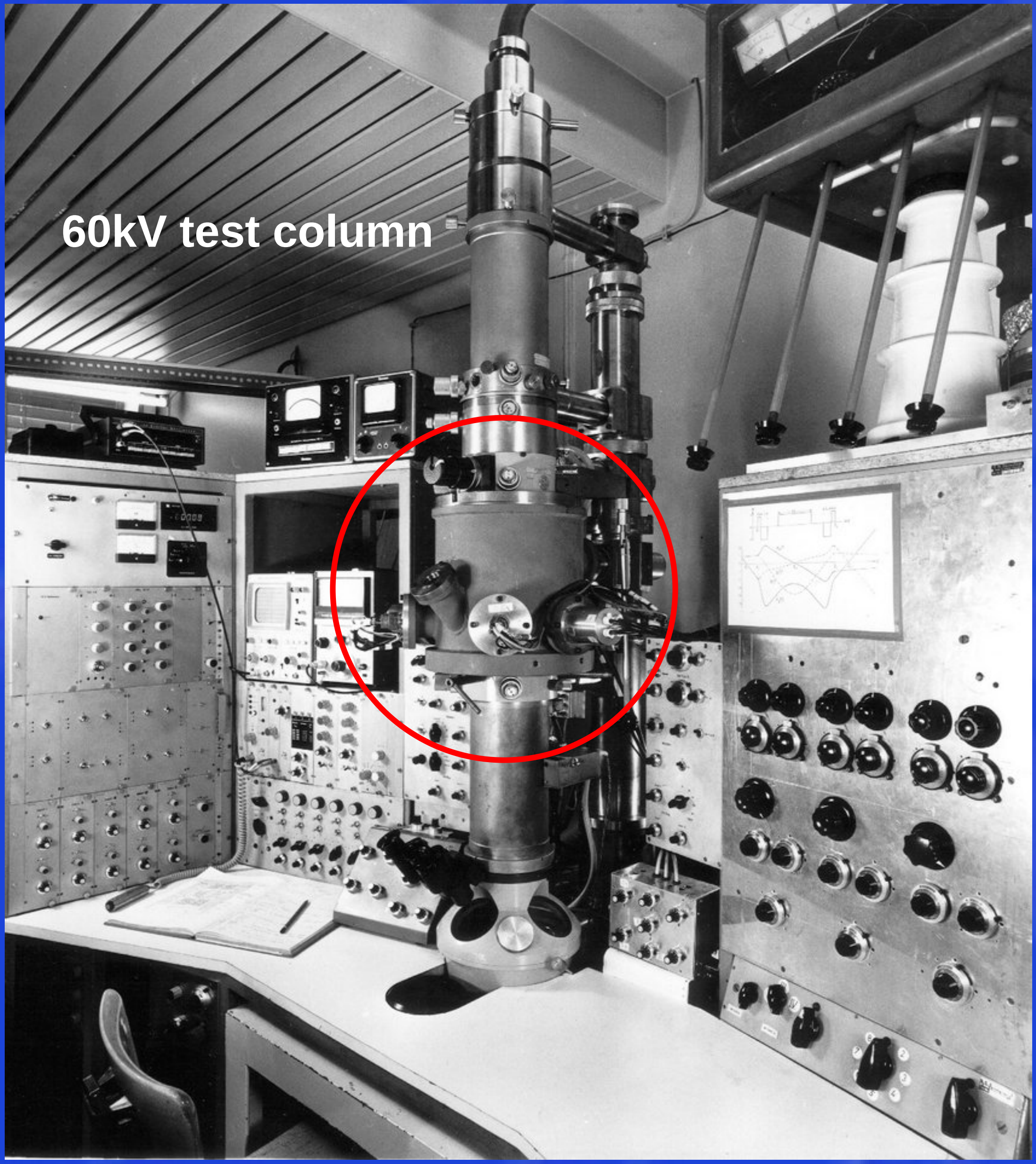
- **violation of rotational symmetry**
- **space charge lenses**
- **high-frequency lenses**



Prof. Otto Scherzer
(TU Darmstadt)

The Darmstadt project: 1974-1982

CEOS
Corrected Electron Optical Systems GmbH

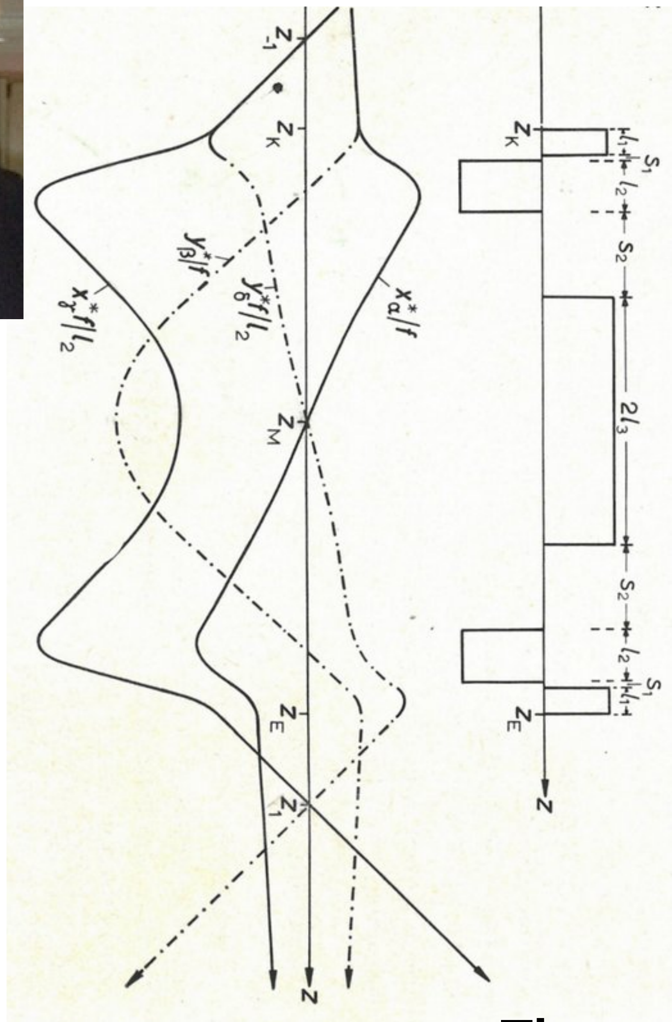


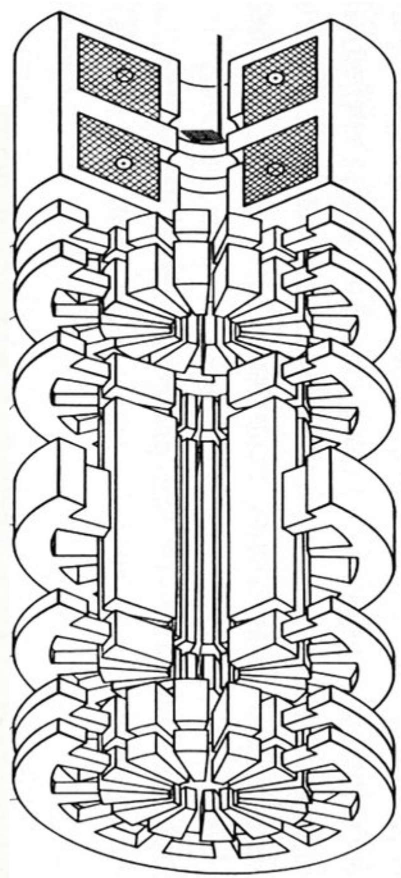
C_C- and C_S-correction at Uni Darmstadt (Scherzer & Rose)

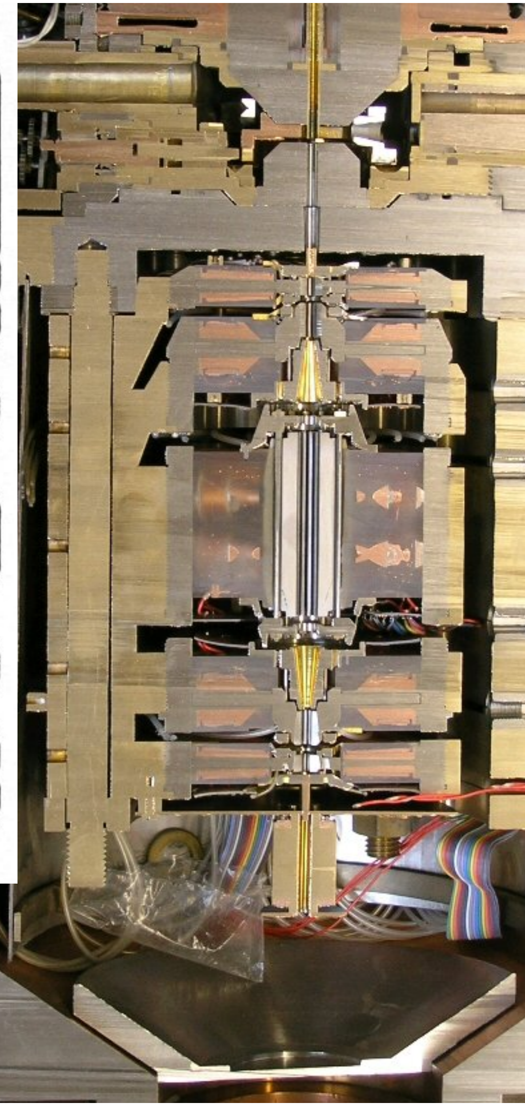
The Darmstadt project: 1974-1982

CEOS
Corrected Electron Optical Systems GmbH

H. Rose, Optik 34 (1971) 284.



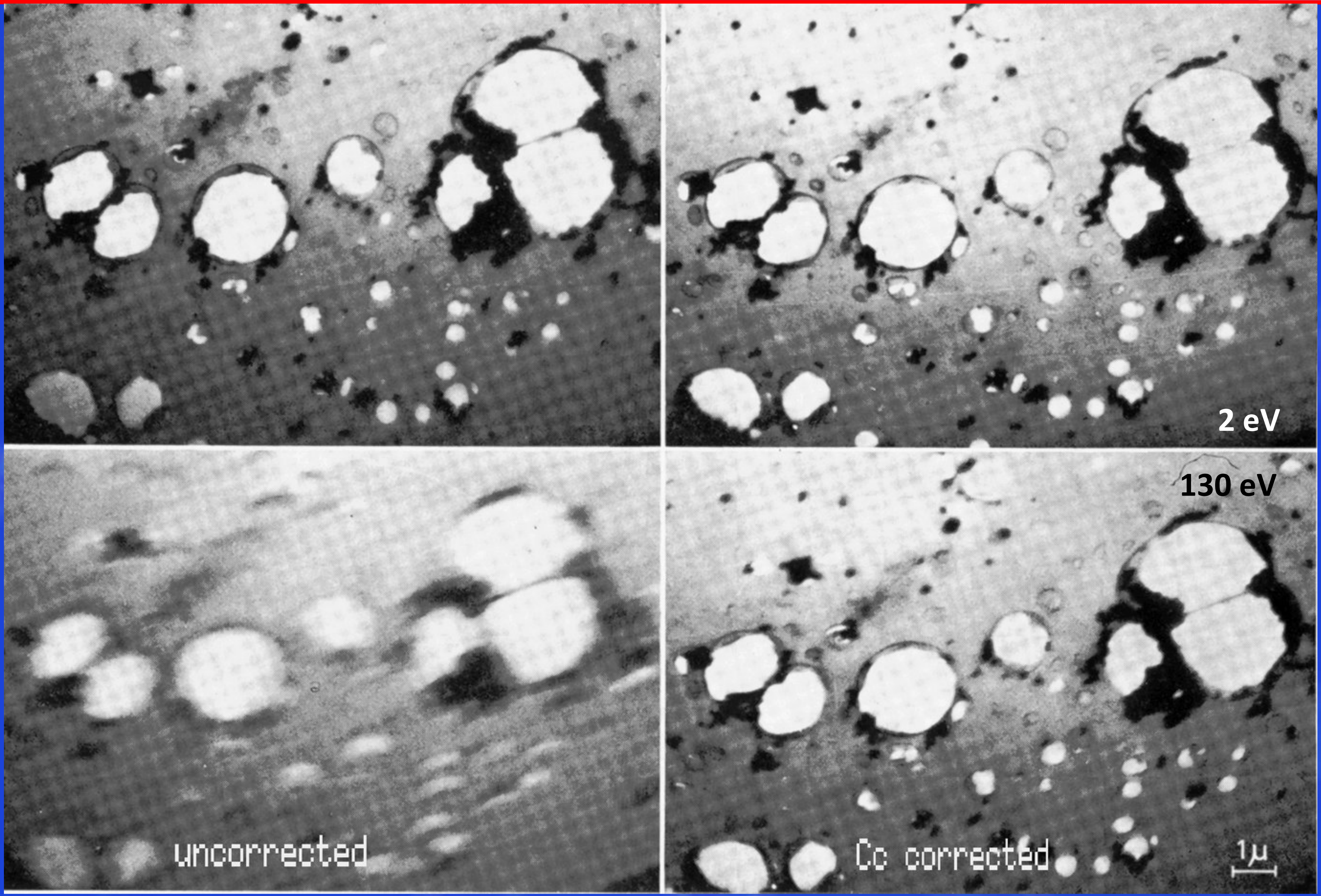




Theory **Experiment**

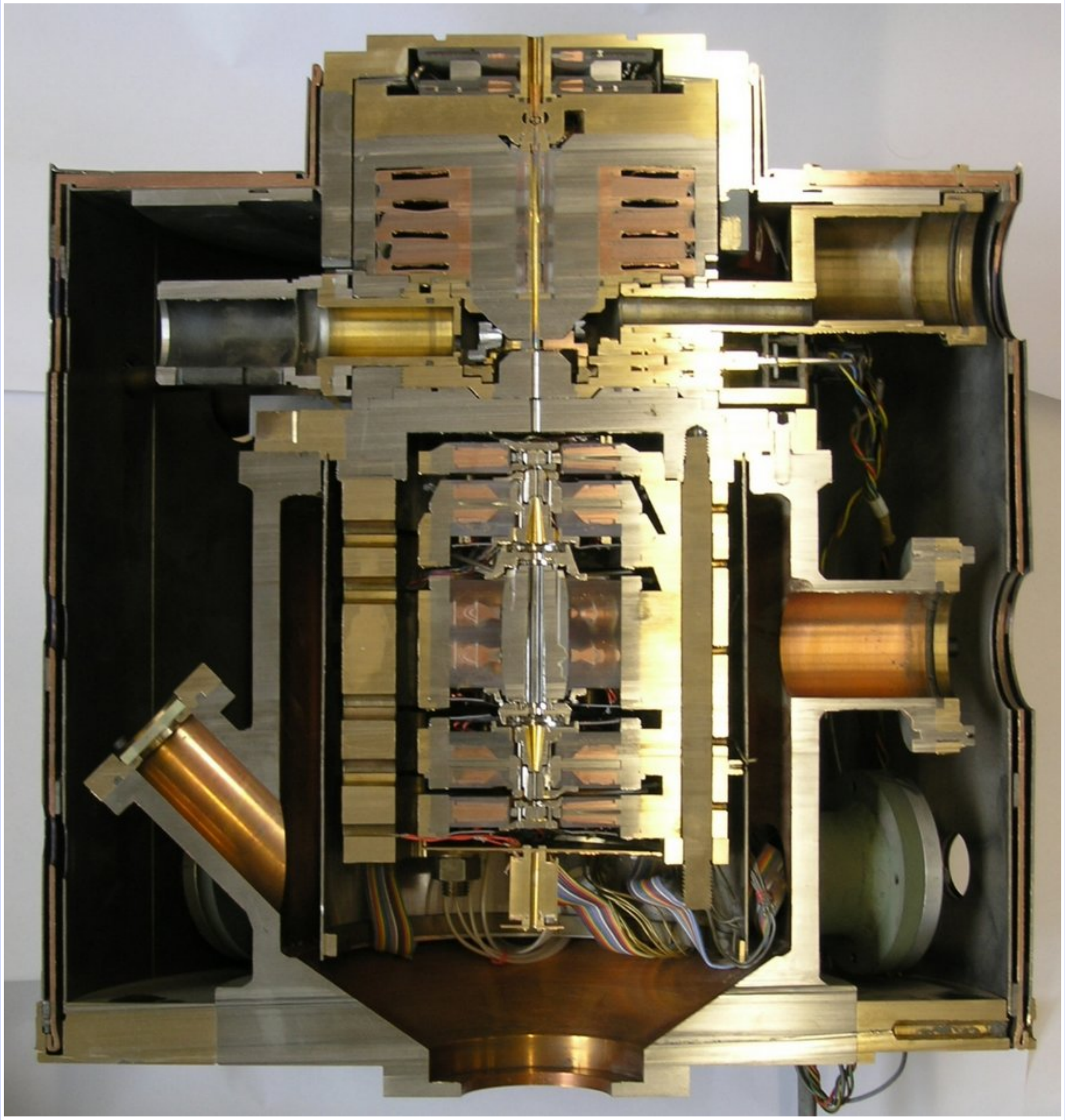
Proof of principle of C_C-correction (1980)

CEOS
Corrected Electron Optical Systems GmbH



CEOS museum

CEOS
Corrected Electron Optical Systems GmbH



Darmstadt 1980
C_c-C_s-corrector
Scherzer & Rose

Aberration correction was successfully shown in principle but did not improve the image resolution of the electron microscope.

- lack of precision machining
- lack of stability
- lack of aberration measurement
- ...

➡ **No more funding ...**

Optik 85, No. 1 (1990) 19–24 © Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart

Outline of a spherically corrected semiaplanatic medium-voltage transmission electron microscope

H. Rose
Insitut für Angewandte Physik Technische Hochschule Darmstadt, FRG

...until in 1990 …

Outline of a spherically corrected semiaplanatic medium-voltage transmission electron microscope. A spherically corrected semiaplanatic objective lens for a subangstrom medium-voltage transmission electron microscope (TEM) is outlined. The aplanatic corrector consists of two telescopic round-lens doublets and two sextupoles centered about the nodal points of the second doublet. If the corrector is incorporated into a 300 kV TEM equipped with a field emission gun a resolution limit of 0.6 Å and 10^4 equally-well-resolved image points per diameter can be obtained. For achieving this performance the magnetic field of the objective lens must be stabilized with a relative accuracy of 1 ppm, while the fields of the corrector elements require at most a stability of 10 ppm.

Entwurf eines sphärisch korrigierten semiaplanatischen Mittelspannungs-Elektronenmikroskops. Eine in dritter Ordnung sphärisch korrigierte rein magnetische Objektivlinse, deren isotrope Koma beseitigt ist, wird vorgeschlagen. Das korrigierte Objektiv besteht aus einer Objektivlinse, zwei teleskopischen Rundlinsen-Dubletts und zwei Sextupolen, deren Mitten in den Knotenebenen des zweiten Dubletts liegen. Falls der Korrektor in ein 300 kV Transmissions-Elektronenmikroskop eingebaut wird, das mit einer Feldemissionskathode ausgestattet ist, können 10^4 Bildpunkte pro Durchmesser mit einer Auflösungsgrenze von 0.6 Å gleich gut aufgelöst werden. Um eine solche Auflösung zu erzielen, müssen die Beschleunigungsspannung und das Magnetfeld der zu korrigierenden Objektivlinse auf 1 ppm stabil gehalten werden. Für die Felder der Korrektorelemente genügt dagegen eine Stabilität von 10 ppm.

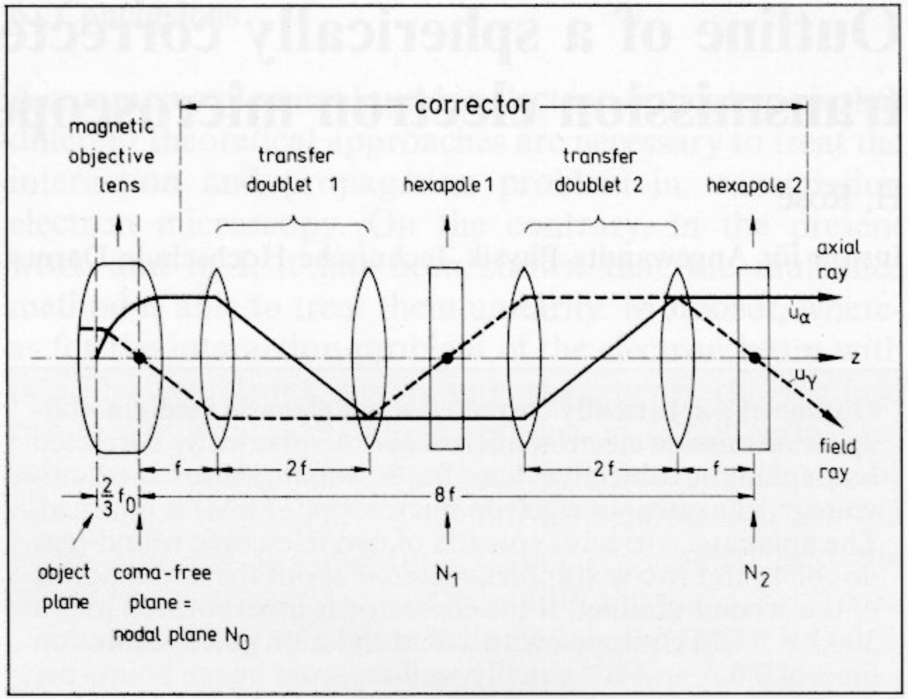
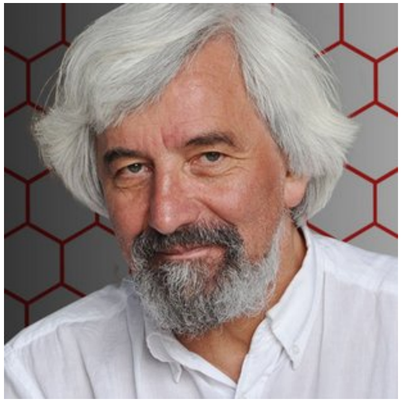
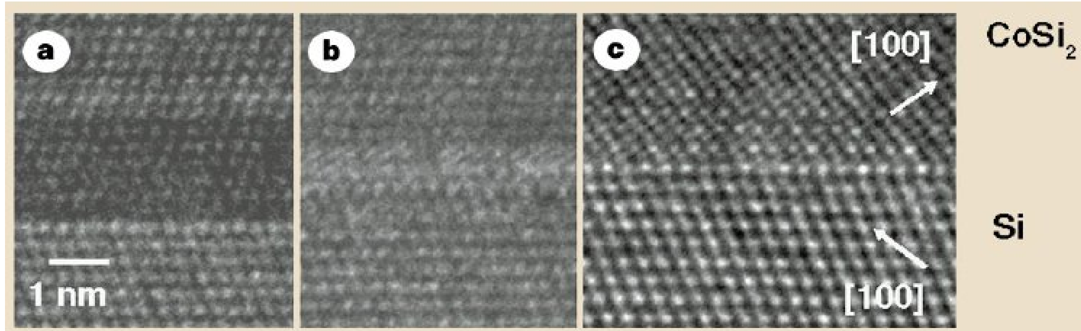


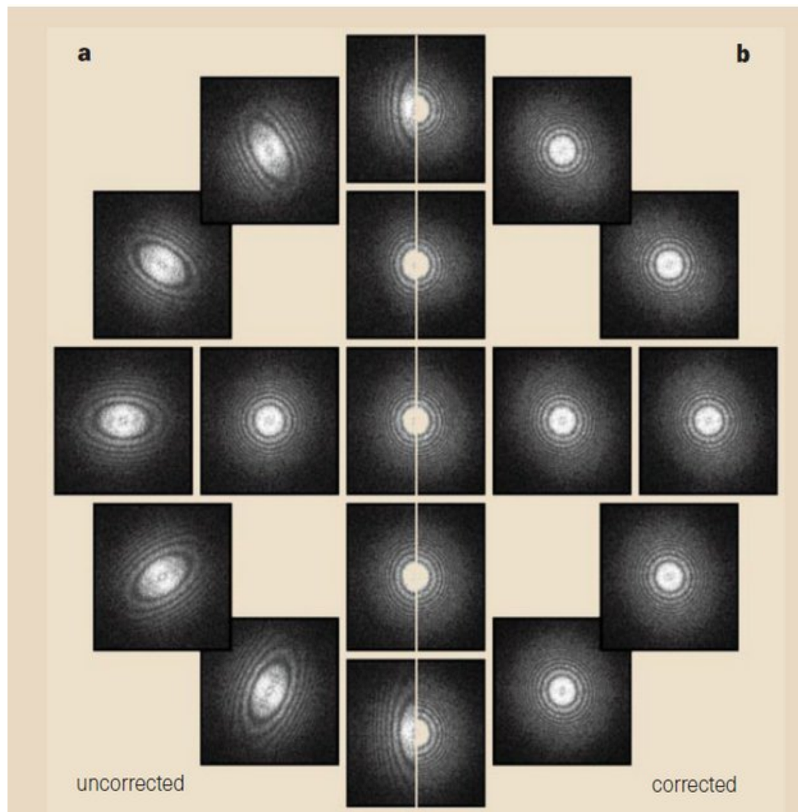
Fig. 2. Schematic arrangement of the elements of the spherically corrected semiaplanatic objective lens.

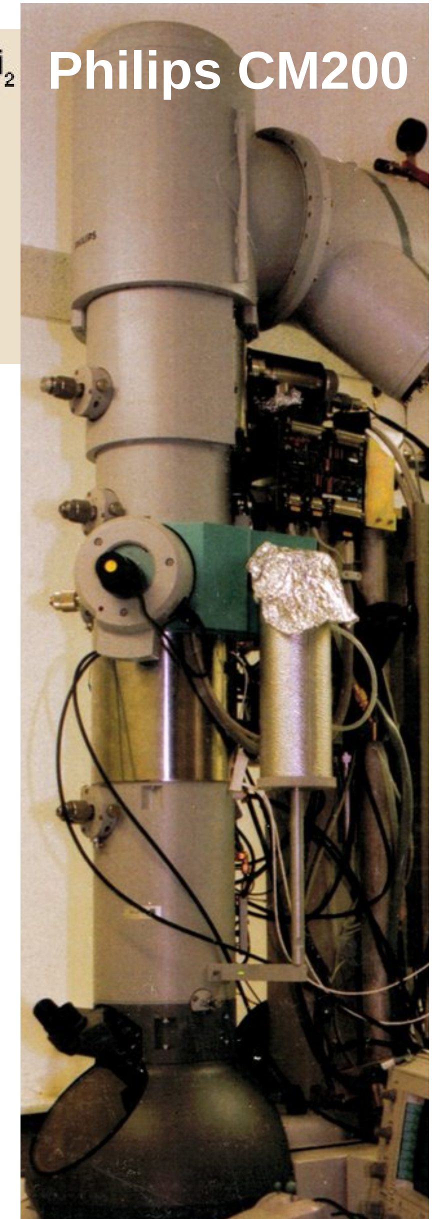
1997: Breakthrough in C_s-correction for TEM



Prof. Max Haider







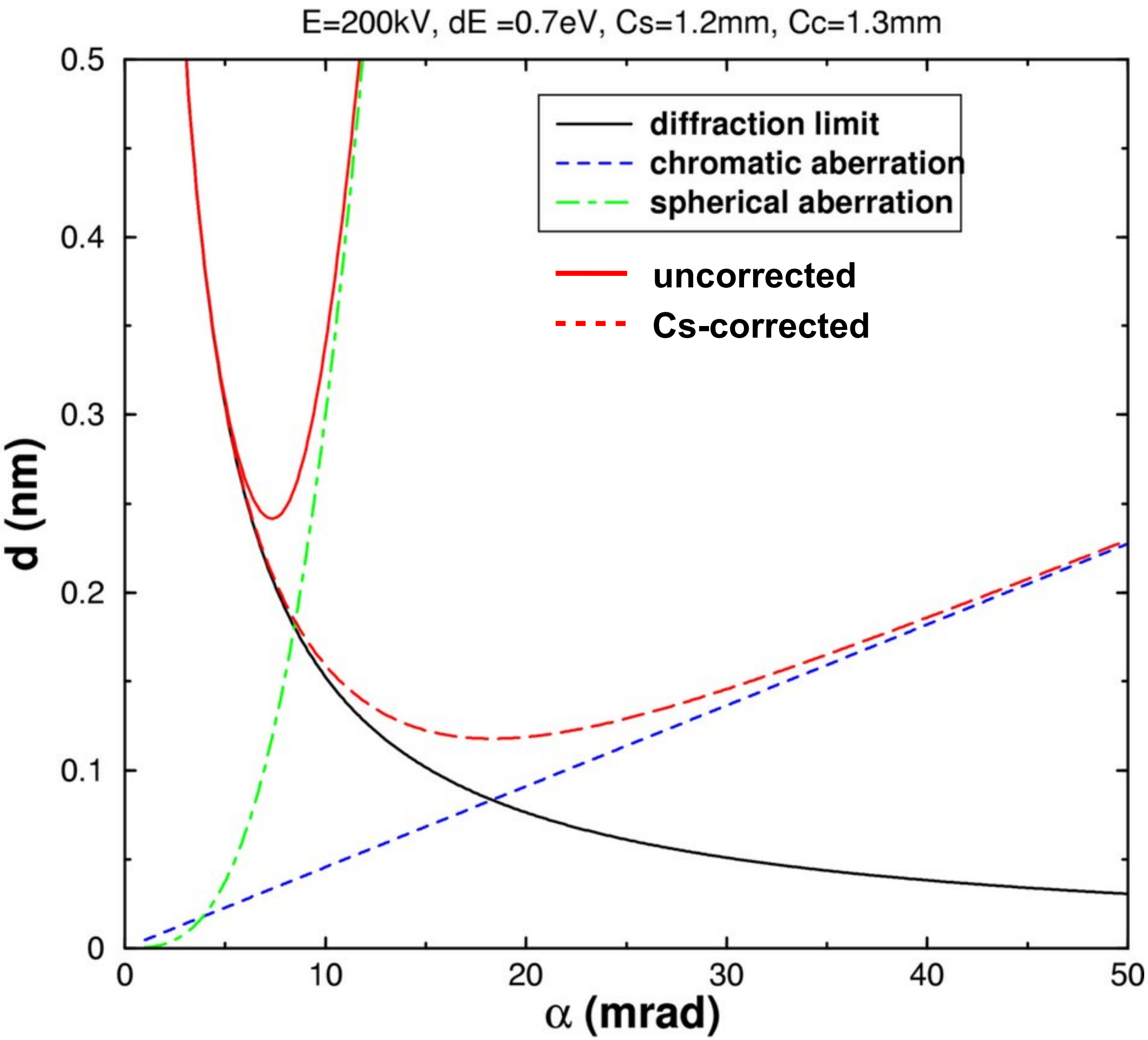
Electron microscopy image enhanced

NATURE | VOL 392 | 23 APRIL 1998

Maximilian Haider*, Stephan Uhlemann*, Eugen Schwan
European Molecular Biology Laboratory, Postfach 102209, 69012 Heidelberg, Germany
**Present address: CEOS GmbH, Im Neuenheimer Feld 519, 69120 Heidelberg, Germany*
Harald Rose
Institut für Angewandte Physik, Technische Hochschule Darmstadt, 64289 Darmstadt, Germany
Bernd Kabius, Knut Urban
Institut für Festkörperforschung, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

Resolution in microscopy

impact of C_s, C_c and diffraction limit

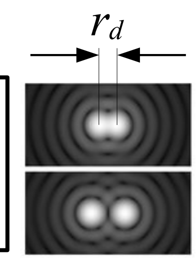


Resolution

$$d = \sqrt{r_d^2 + r_c^2 + (r_s/4)^2}$$

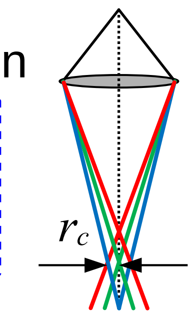
Rayleigh criterion

$$r_d = \frac{0.61 \cdot \lambda}{\alpha},$$



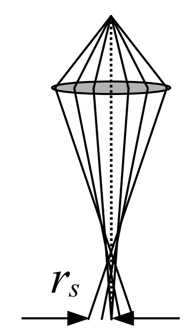
Chromatic aberration

$$r_c = \alpha \frac{dE \cdot C_c}{E},$$



Spherical aberration

$$r_s = \alpha^3 C_s$$



Improving resolution

CEOS
Corrected Electron Optical Systems GmbH

Optimize diffraction limit:

a) Decrease wave length λ

→ increase electron energy *E*

b) Increase optical aperture α

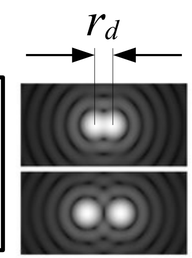
→ stronger impact of aberrations

Resolution

$$d = \sqrt{r_d^2 + r_c^2 + (r_s/4)^2}$$

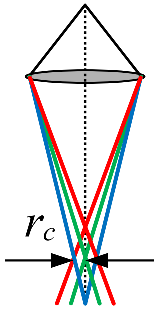
Rayleigh criterion

$$r_d = \frac{0.61 \cdot \lambda}{\alpha},$$



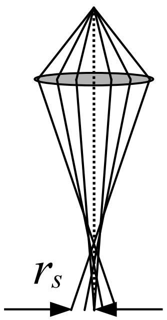
Chromatic aberration

$$r_c = \alpha \frac{dE \cdot C_c}{E},$$



Spherical aberration

$$r_s = \alpha^3 C_s$$



Reduce the effect of chromatic aberration:

a) **Larger electron energy *E***
(increase high tension)

b) **Monochromator/Gun: *dE***

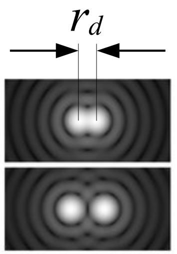
c) **C_c-corrector**

Resolution

$$d = \sqrt{r_d^2 + r_c^2 + (r_s/4)^2}$$

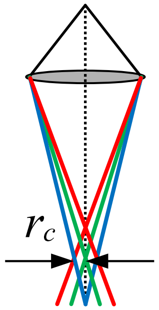
Rayleigh criterion

$$r_d = \frac{0.61 \cdot \lambda}{\alpha},$$



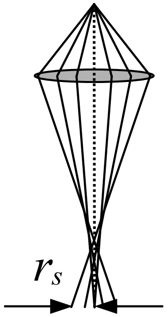
Chromatic aberration

$$r_c = \alpha \frac{dE\, C_c}{E},$$



Spherical aberration

$$r_s = \alpha^3 C_s$$



Reduce the effect of spherical aberration

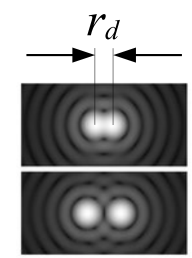
a) C_s-corrector

Resolution

$$d = \sqrt{r_d^2 + r_c^2 + (r_s/4)^2}$$

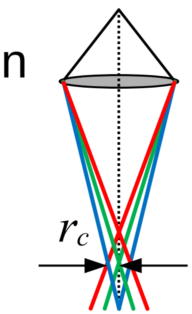
Rayleigh criterion

$$r_d = \frac{0.61 \cdot \lambda}{\alpha},$$



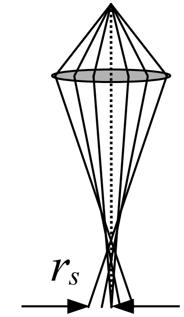
Chromatic aberration

$$r_c = \alpha \frac{dE \cdot C_c}{E},$$



Spherical aberration

$$r_s = \alpha^3 C_s$$



Milestones in C_c- and C_s-correction

- 1936 … Scherzer's theorem
- 1947 … Scherzer proposed multipole corrector
- 1960's … Deltrap's corrector for STEM (UK)
- 1970's … Darmstadt corrector (Germany)
- 1970's/80's … Crewe et al. (Chicago, U.S.)

First successful attempts: (resolution improvements)

Zach & Haider	(LVSEM)	C_S & C_C	1990 - 1995
Haider et al.	(TEM)	C_S	1992 - 1997
Krivanek et al.	(STEM)	C_S	1995 - 1998
Schmidt et al.	(LEEM/PEEM)	C_S & C_C	1995 - 2006

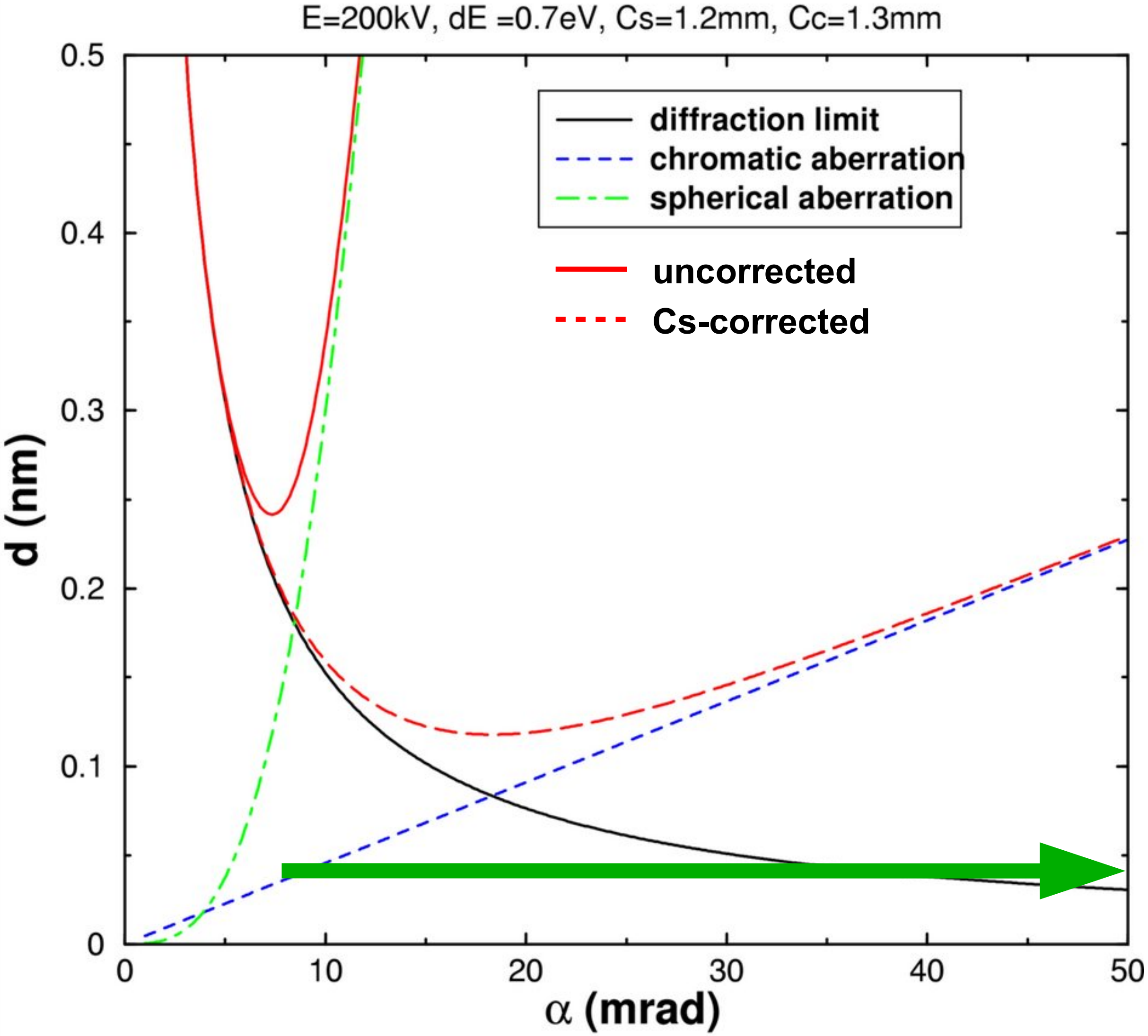
Quadrupoles and octupoles

Two hexapoles

Electron mirror

Resolution vs. optical aperture

impact of C_s, C_c and diffraction limit



Aim of aberration correction …

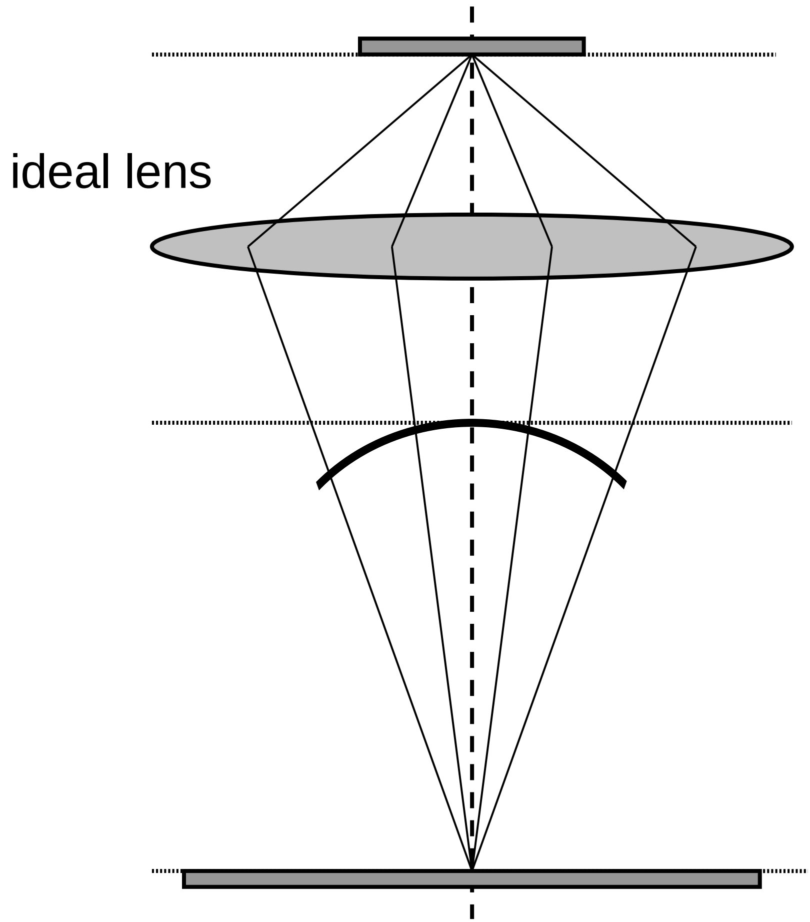
open up the aperture

Better and better correctors for more and more aberrations!

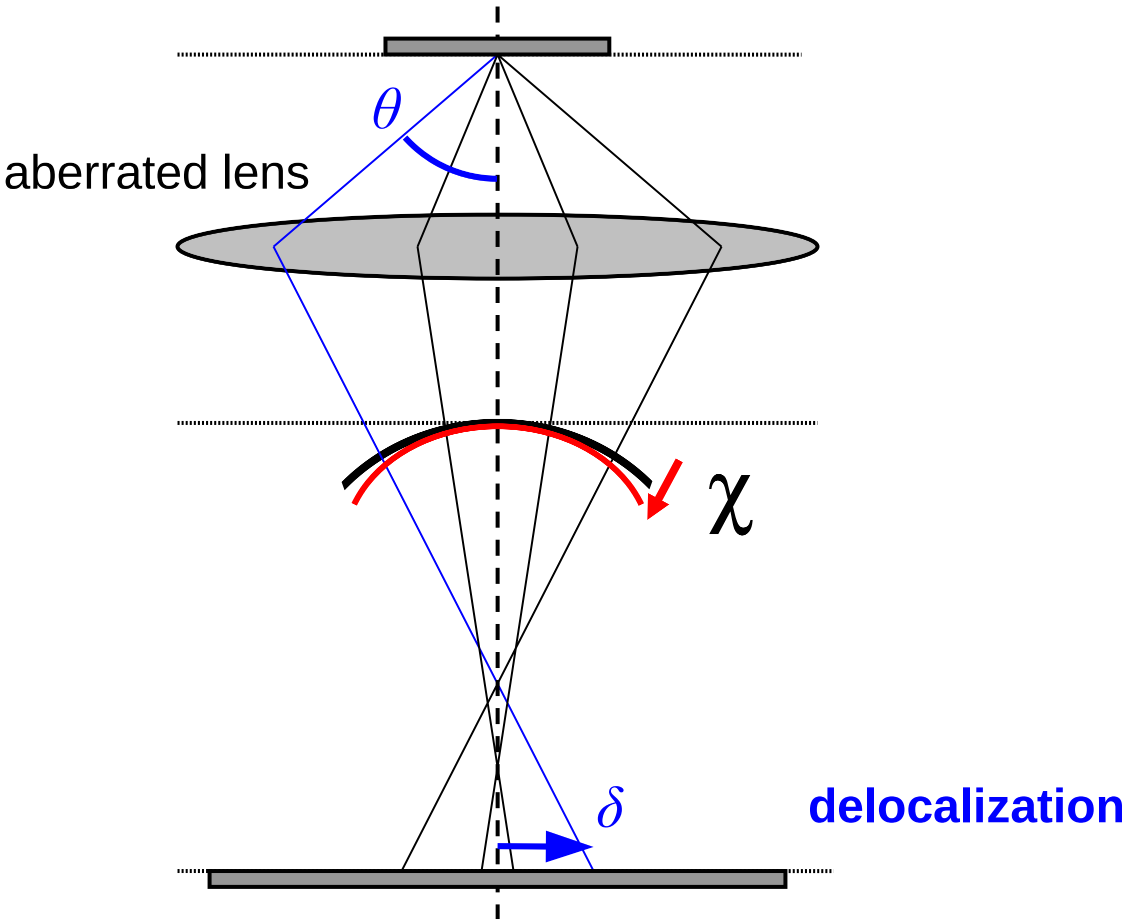
Electron optical elements and aberrations

CEOS
Corrected Electron Optical Systems GmbH

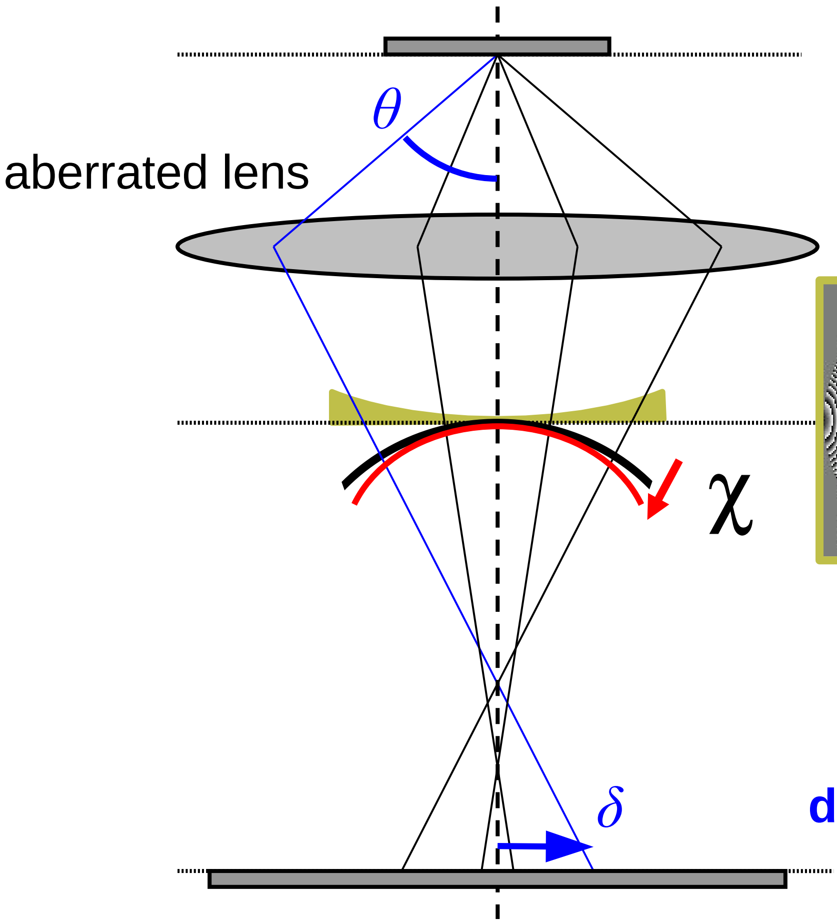
Lens aberrations

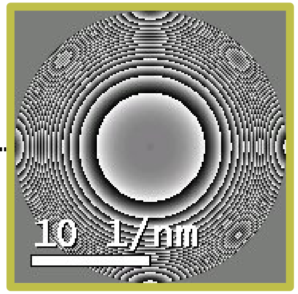


Lens aberrations: Spherical aberration



Lens aberrations: Spherical aberration





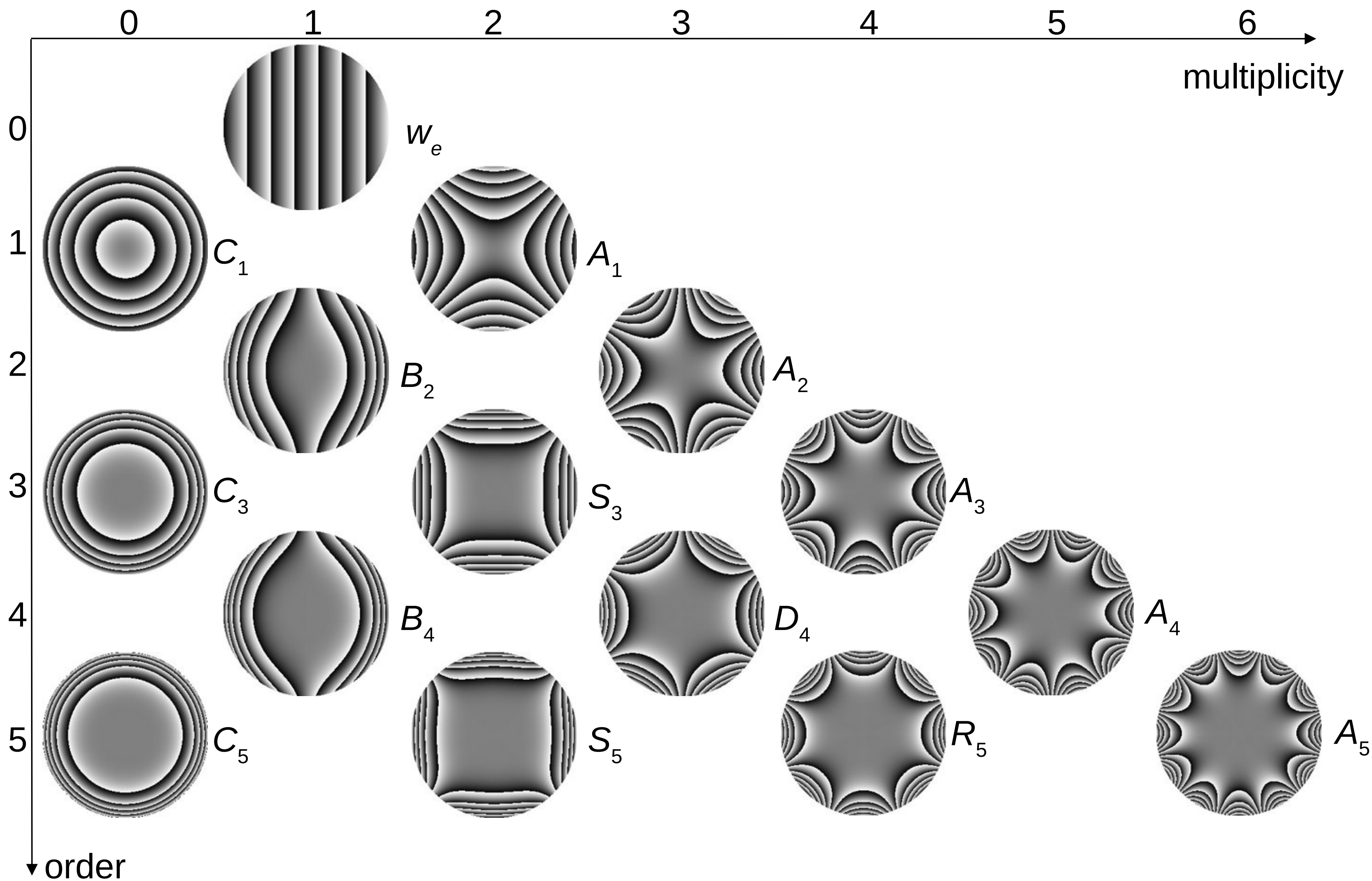
phase plate

$$\exp\{-i\chi\}$$

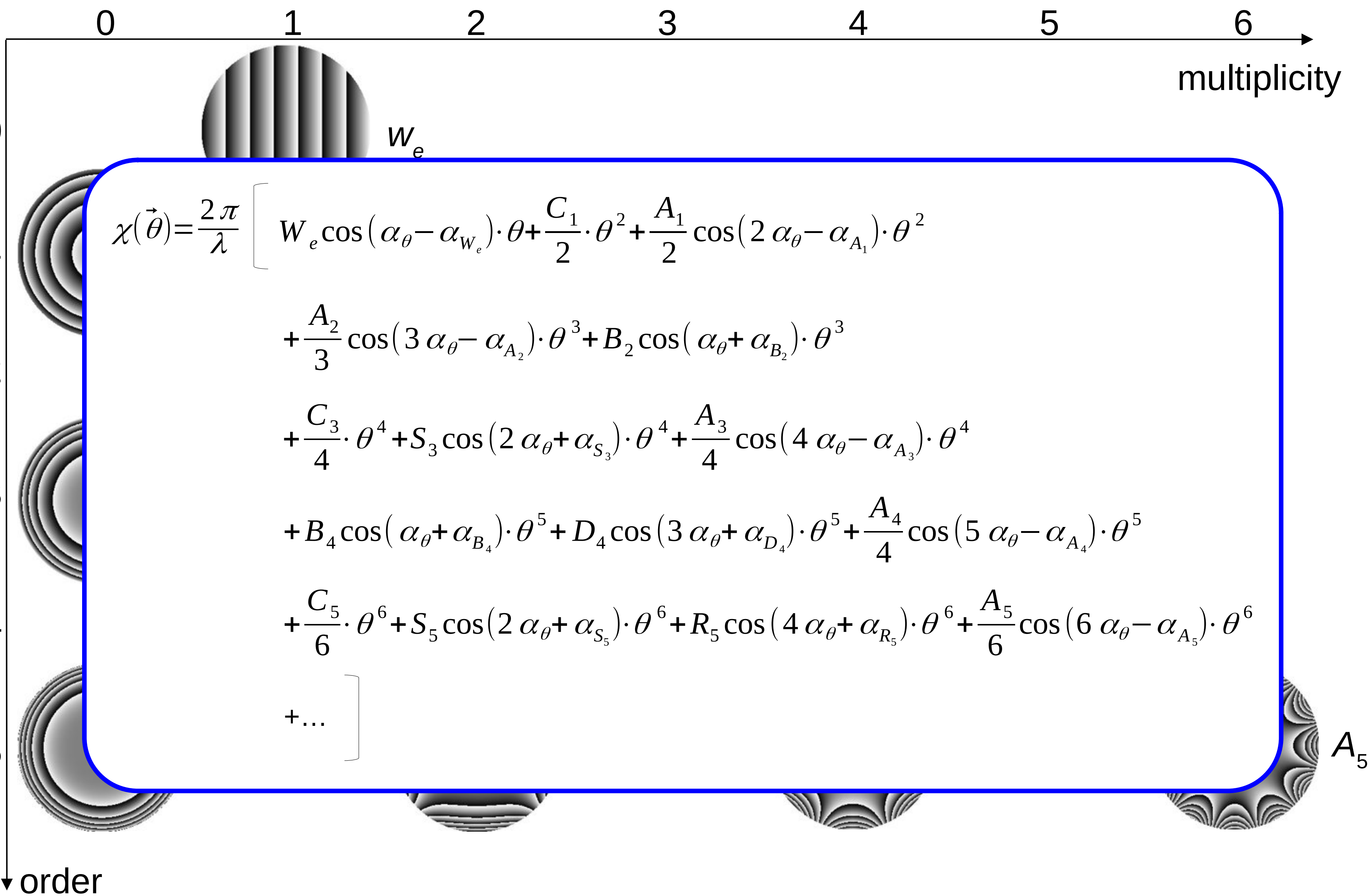
$$\chi = \frac{2\pi}{\lambda} \cdot \frac{C_3}{4}\,\theta^4$$

delocalization: $\delta = \frac{\nabla \chi}{2\pi} = C_3 \cdot \theta^3$

Wave aberration χ

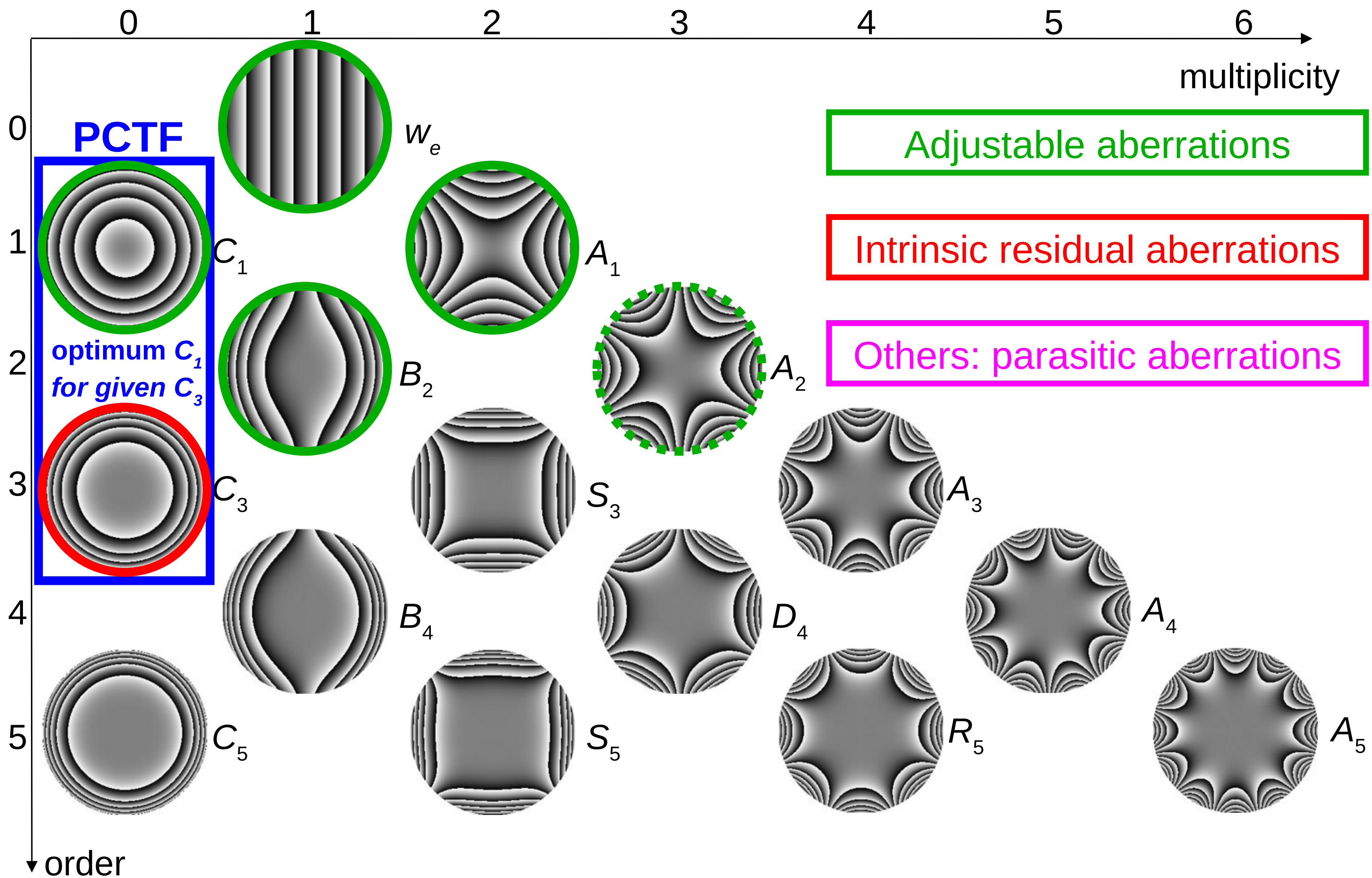


Wave aberration χ

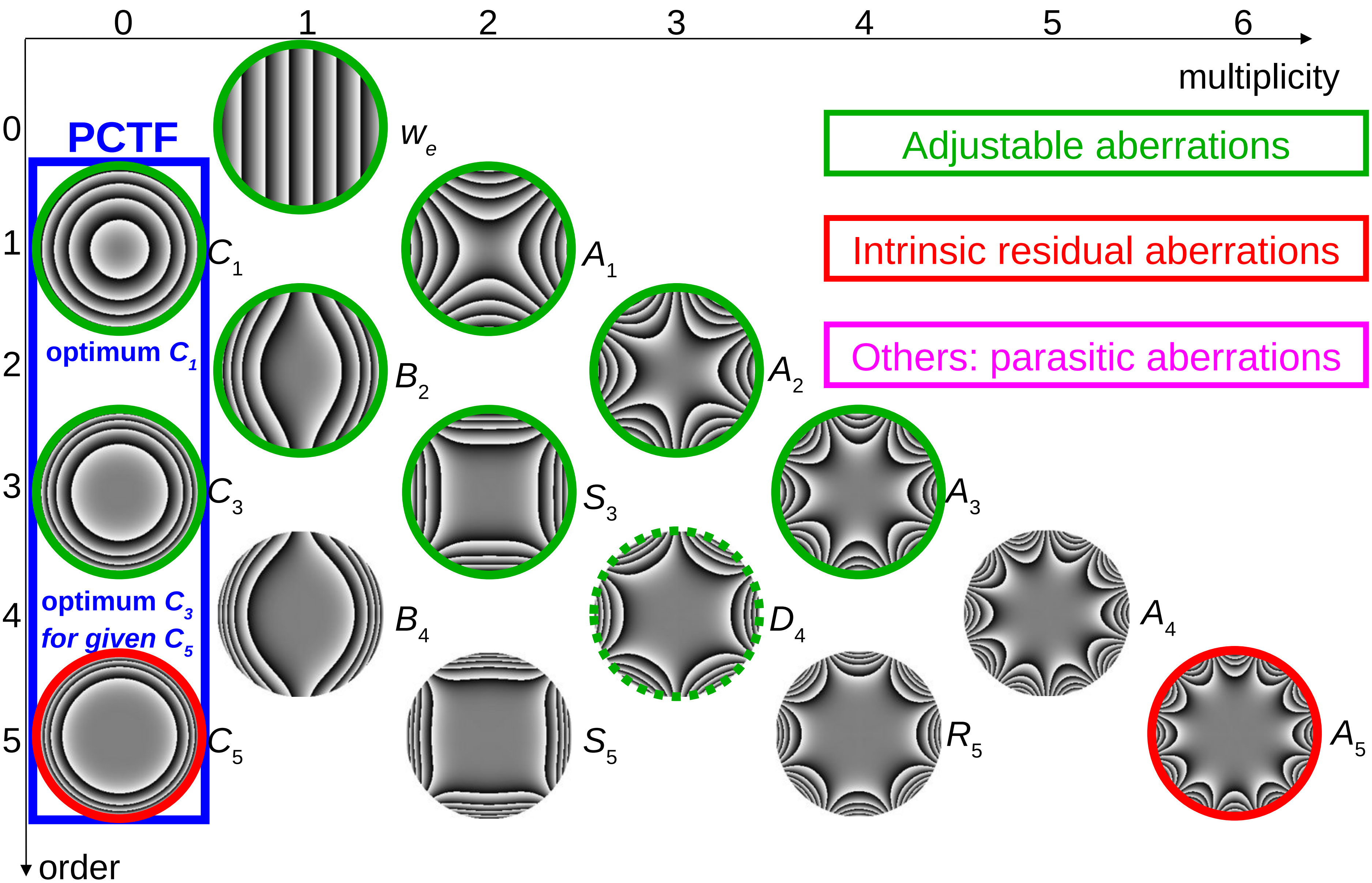


$$
\begin{aligned}
\chi(\vec{\theta}) = \frac{2\pi}{\lambda} \Big[& W_e \cos(\alpha_\theta - \alpha_{W_e}) \cdot \theta + \frac{C_1}{2} \cdot \theta^2 + \frac{A_1}{2} \cos(2\alpha_\theta - \alpha_{A_1}) \cdot \theta^2 \\
& + \frac{A_2}{3} \cos(3\alpha_\theta - \alpha_{A_2}) \cdot \theta^3 + B_2 \cos(\alpha_\theta + \alpha_{B_2}) \cdot \theta^3 \\
& + \frac{C_3}{4} \cdot \theta^4 + S_3 \cos(2\alpha_\theta + \alpha_{S_3}) \cdot \theta^4 + \frac{A_3}{4} \cos(4\alpha_\theta - \alpha_{A_3}) \cdot \theta^4 \\
& + B_4 \cos(\alpha_\theta + \alpha_{B_4}) \cdot \theta^5 + D_4 \cos(3\alpha_\theta + \alpha_{D_4}) \cdot \theta^5 + \frac{A_4}{4} \cos(5\alpha_\theta - \alpha_{A_4}) \cdot \theta^5 \\
& + \frac{C_5}{6} \cdot \theta^6 + S_5 \cos(2\alpha_\theta + \alpha_{S_5}) \cdot \theta^6 + R_5 \cos(4\alpha_\theta + \alpha_{R_5}) \cdot \theta^6 + \frac{A_5}{6} \cos(6\alpha_\theta - \alpha_{A_5}) \cdot \theta^6 \\
& + \ldots \Big]
\end{aligned}
$$

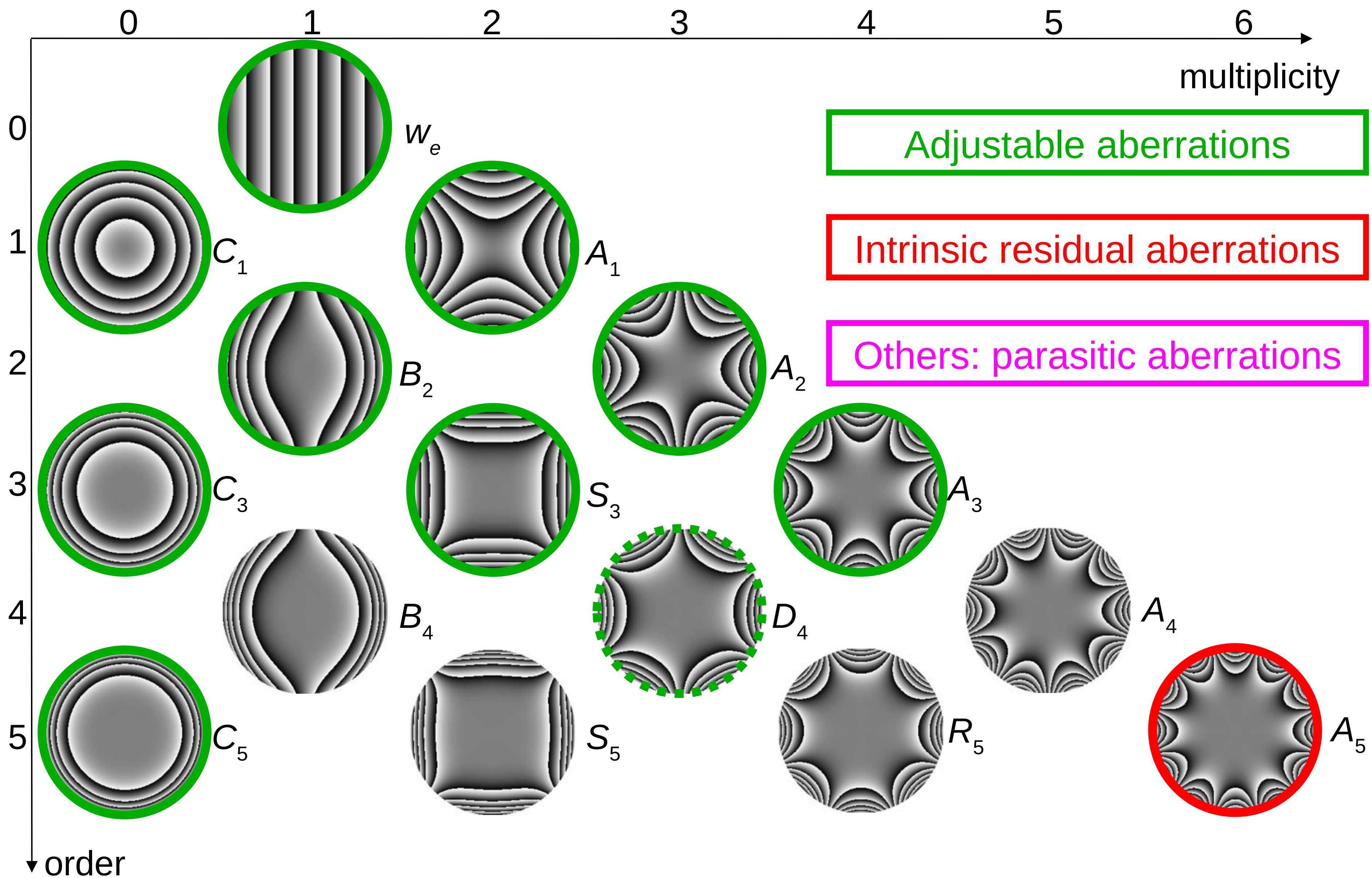
Axial aberrations in uncorrected TEM/STEM



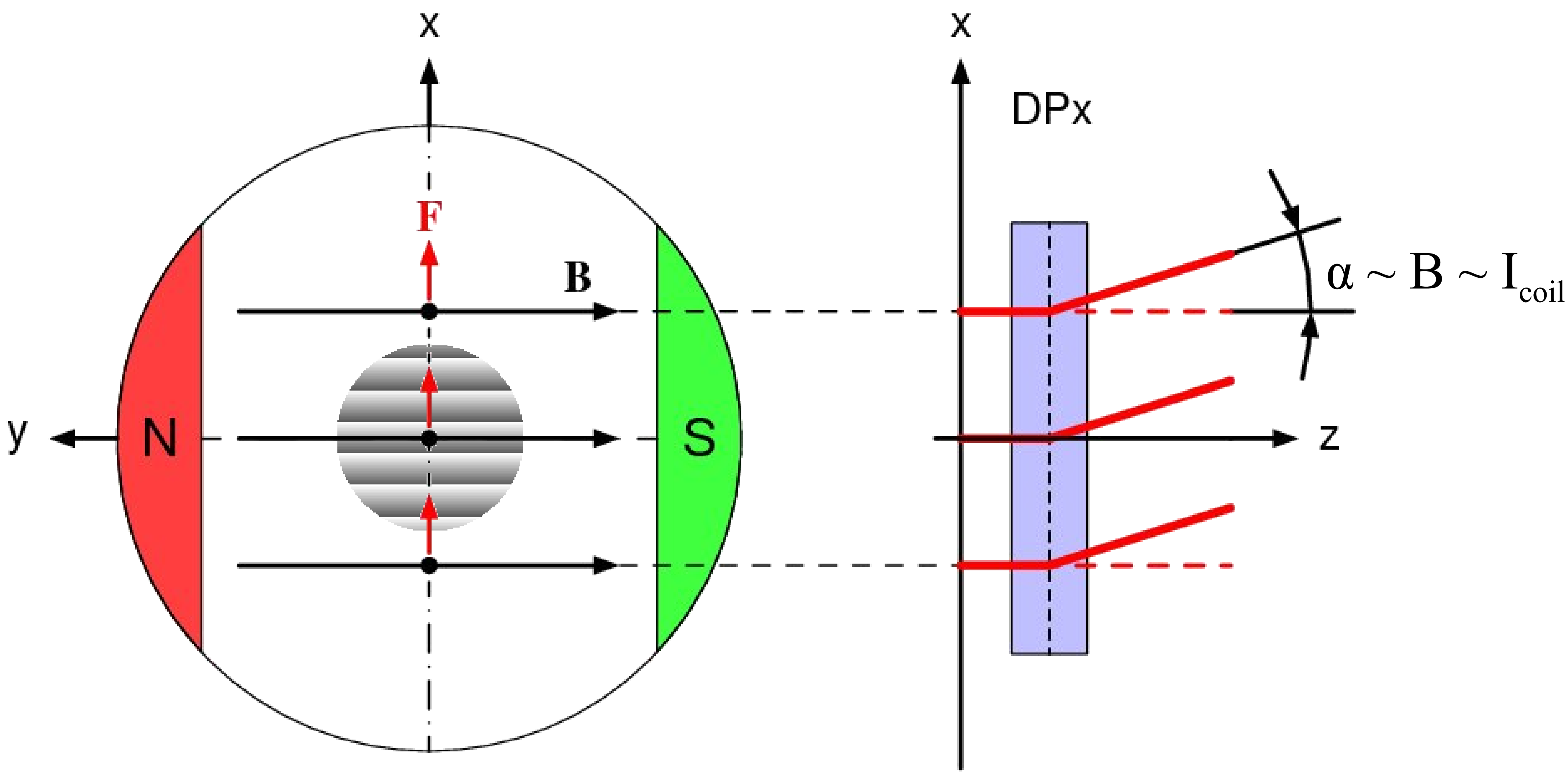
Axial aberrations in C_s-corrected TEM



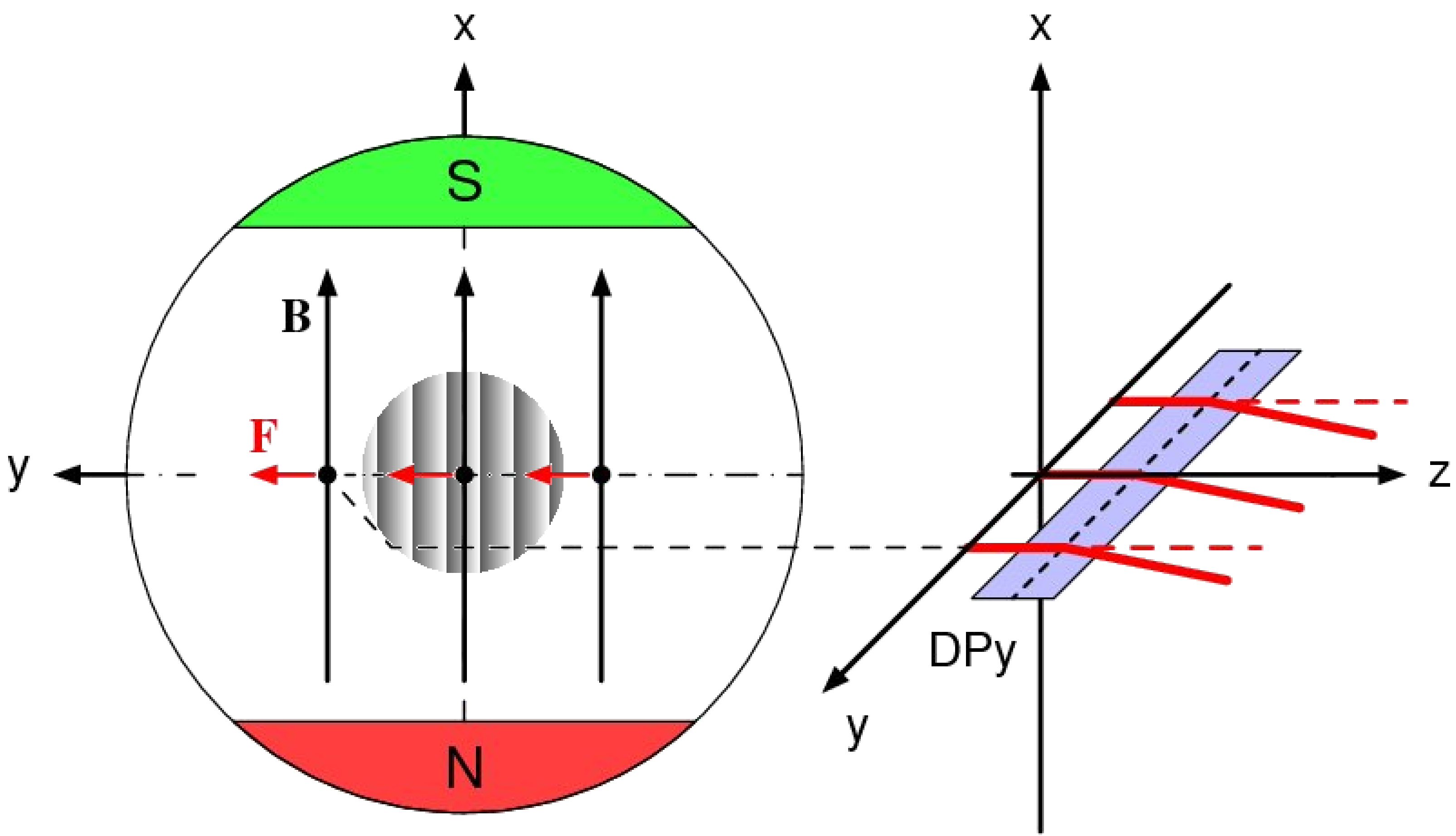
Axial aberrations in C_s-corrected STEM



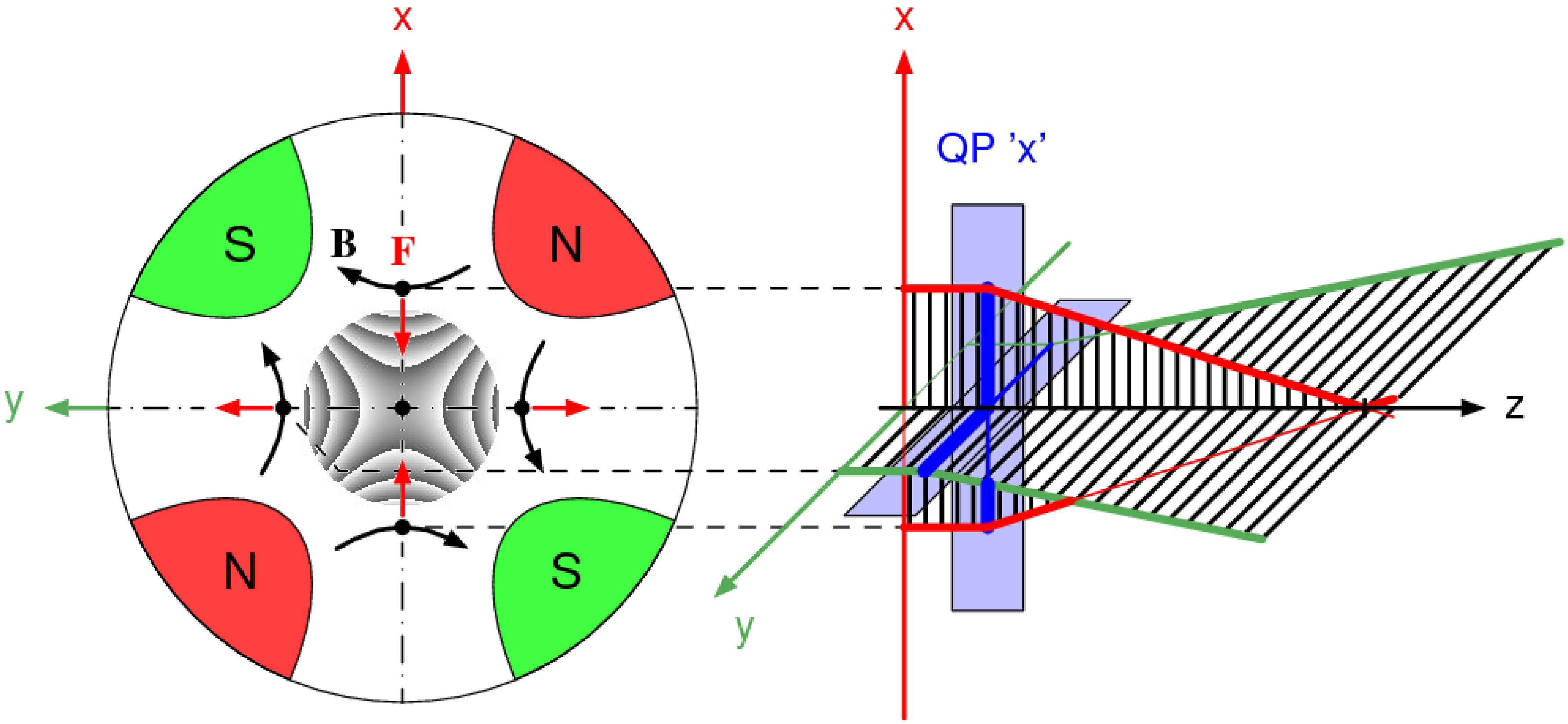
Dipoles – deflecting elements: x-section



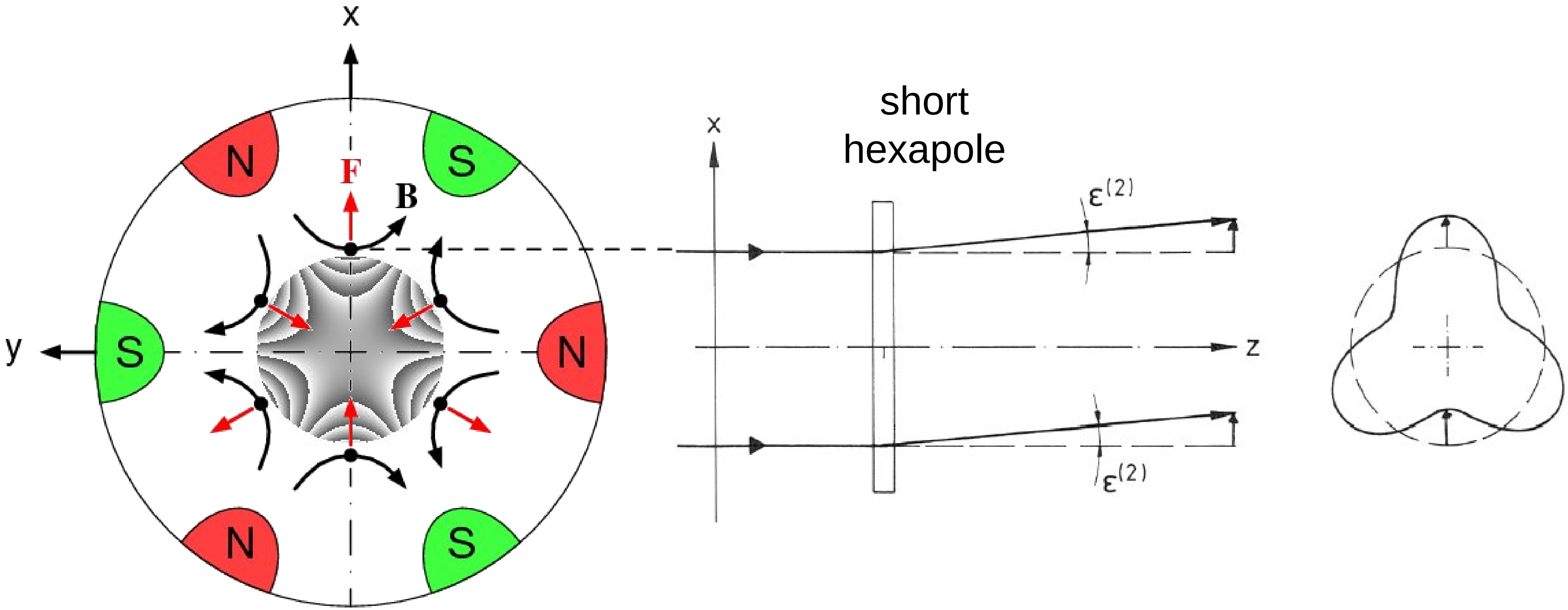
Dipoles – deflecting elements: x-section



Quadrupoles – Stigmators



Hexapoles – 3-fold Stigmators



Aberration correction for electron lenses using hexapoles

CEOS
Corrected Electron Optical Systems GmbH

Aberration correction by means of hexapoles

CEOS
Corrected Electron Optical Systems GmbH

Optik 85, No. 1 (1990) 19–24 © Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart

Outline of a spherically corrected semiaplanatic medium-voltage transmission electron microscope

H. Rose
Insitut für Angewandte Physik Technische Hochschule Darmstadt, FRG

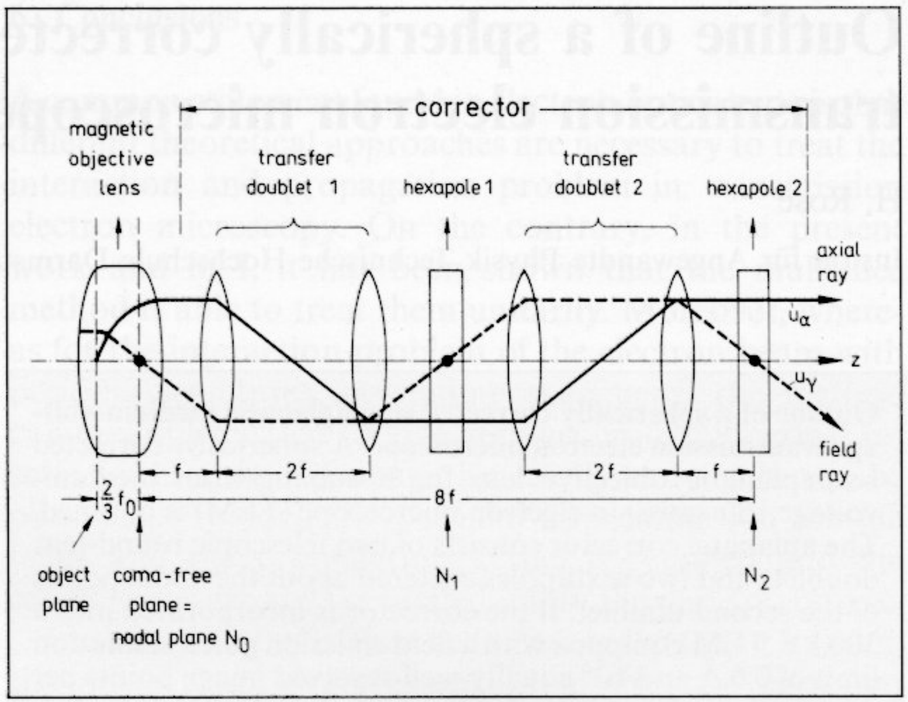
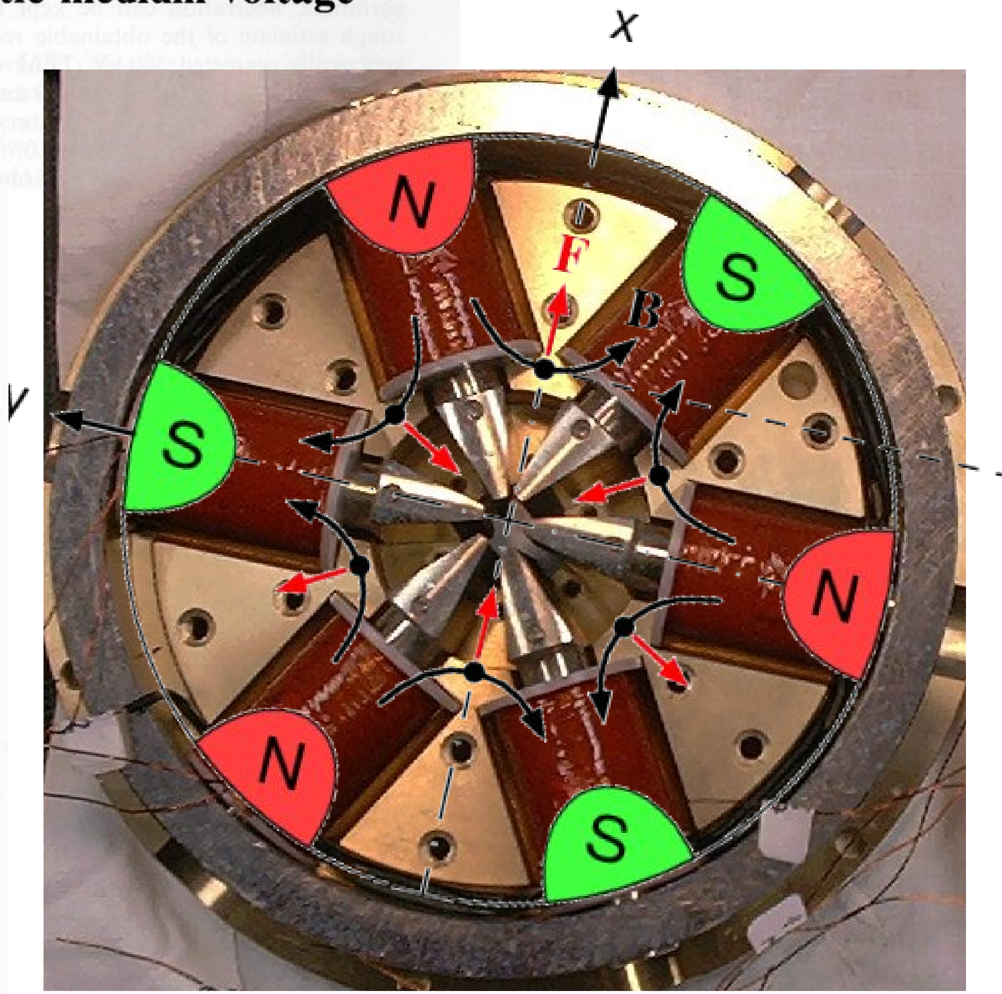


Fig. 2. Schematic arrangement of the elements of the spherically corrected semiaplanatic objective lens.



Aberration correction by means of hexapoles

Optik 85, No. 1 (1990) 19–24 © Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart

Outline of a spherically corrected semiaplanatic medium-voltage transmission electron microscope

H. Rose
Insitut für Angewandte Physik Technische Hochschule Darmstadt, FRG

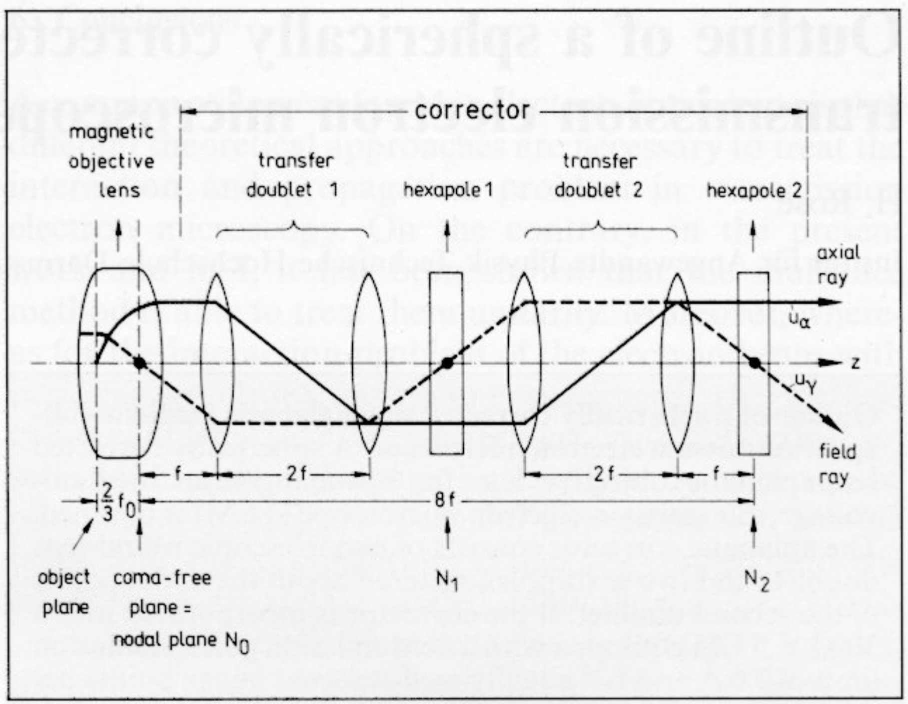
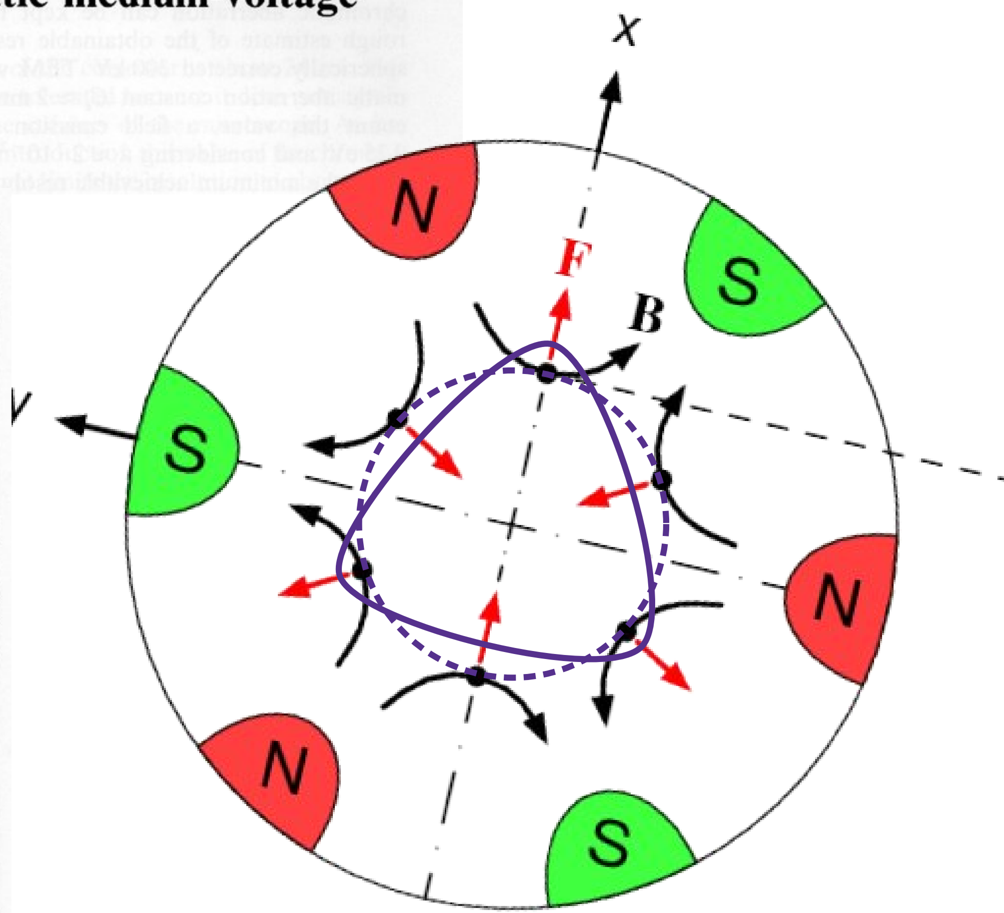
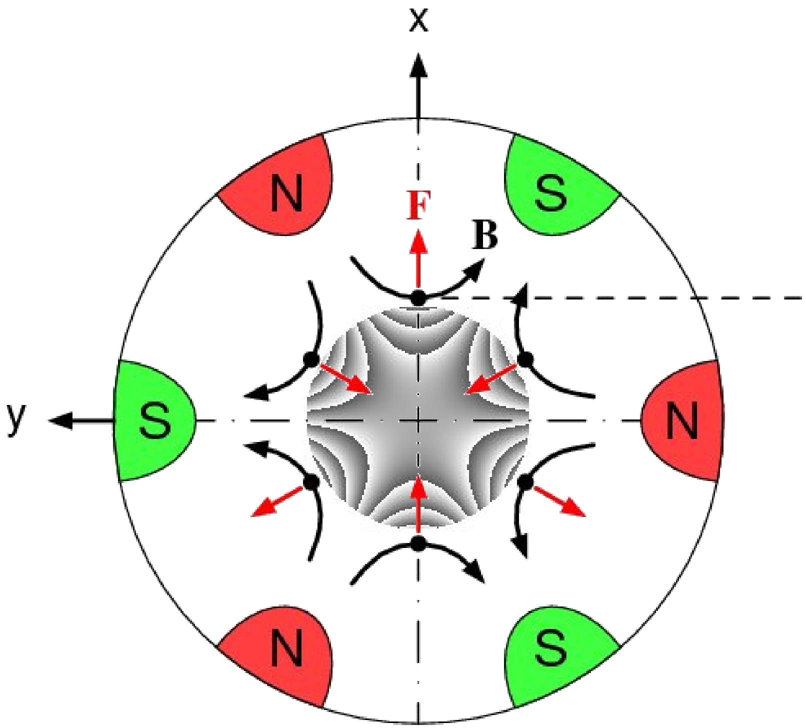
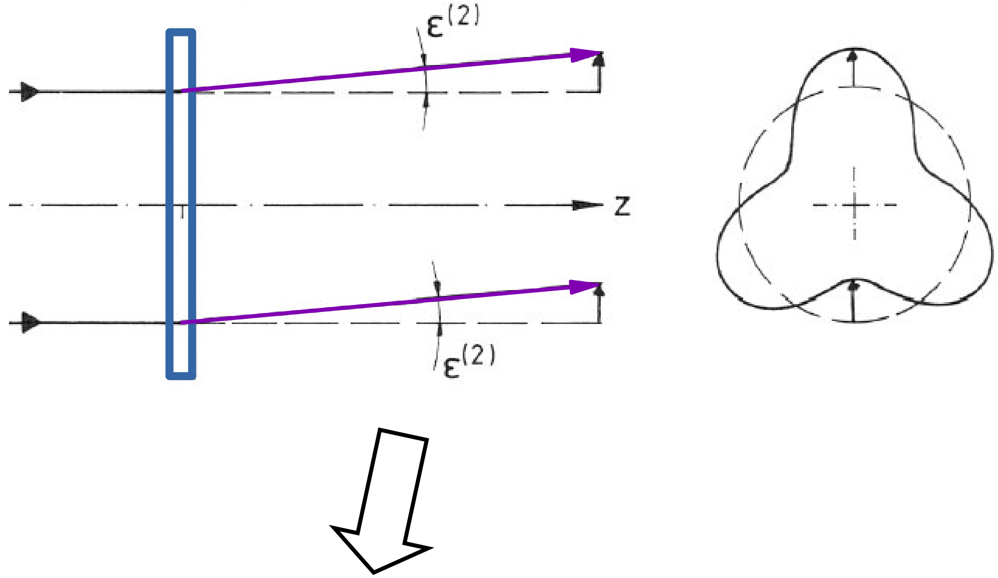


Fig. 2. Schematic arrangement of the elements of the spherically corrected semiaplanatic objective lens.



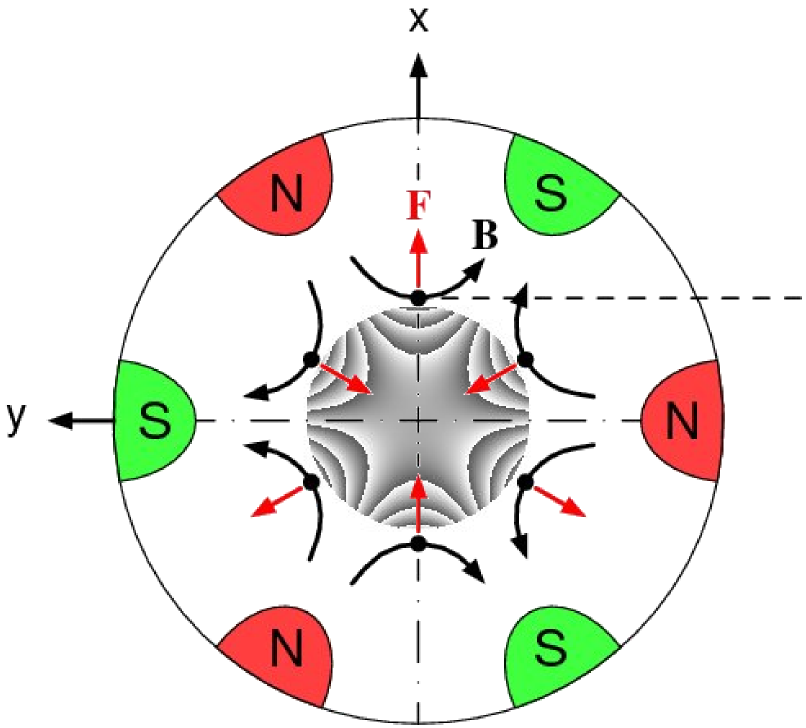
Aberration correction by means of hexapoles



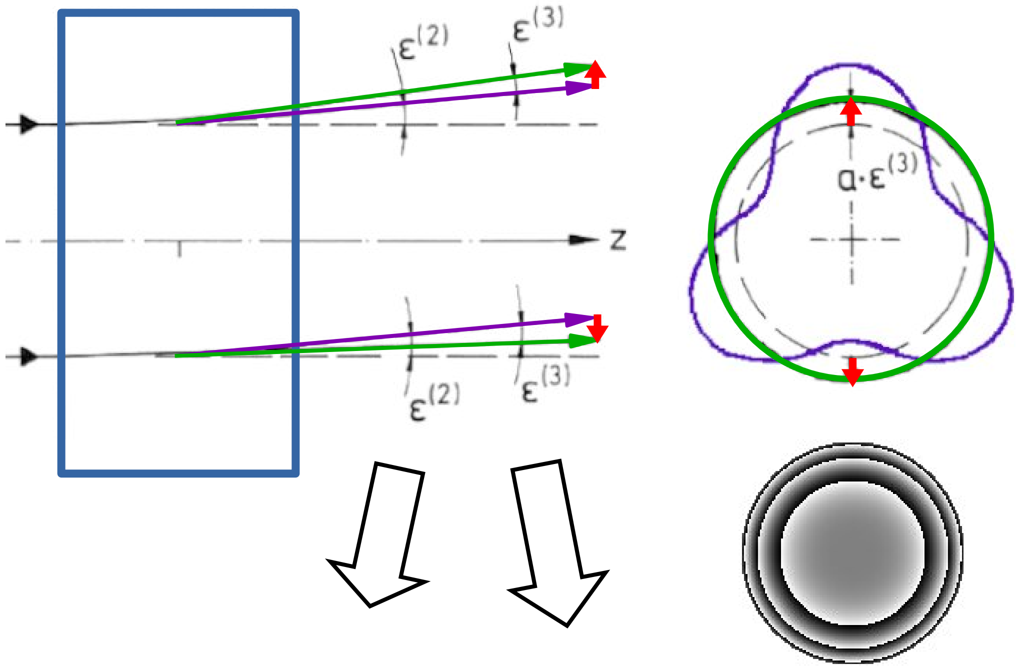


2nd order aberration
(three-fold astigmatism)

Aberration correction by means of hexapoles



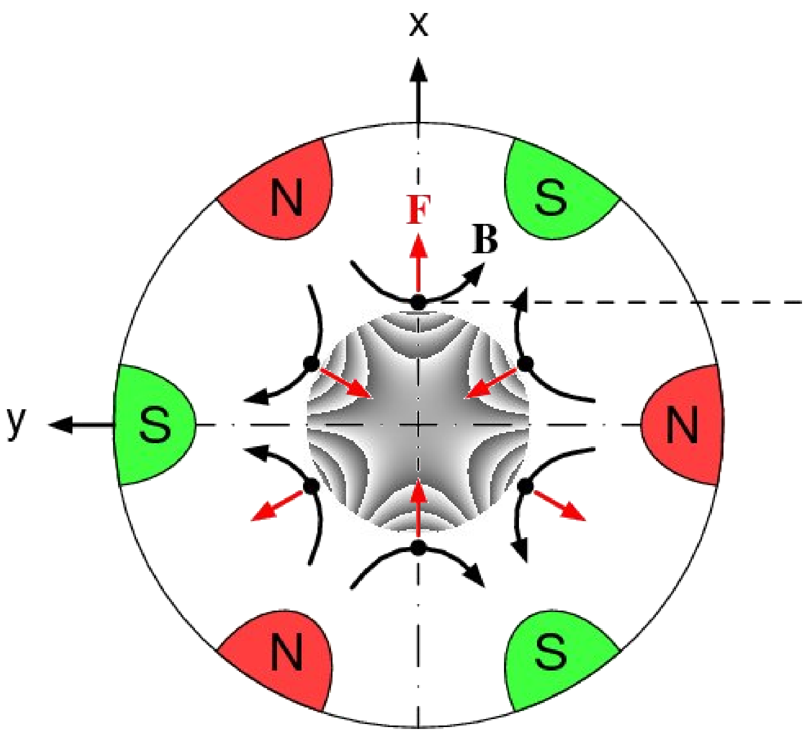
extended hexapole

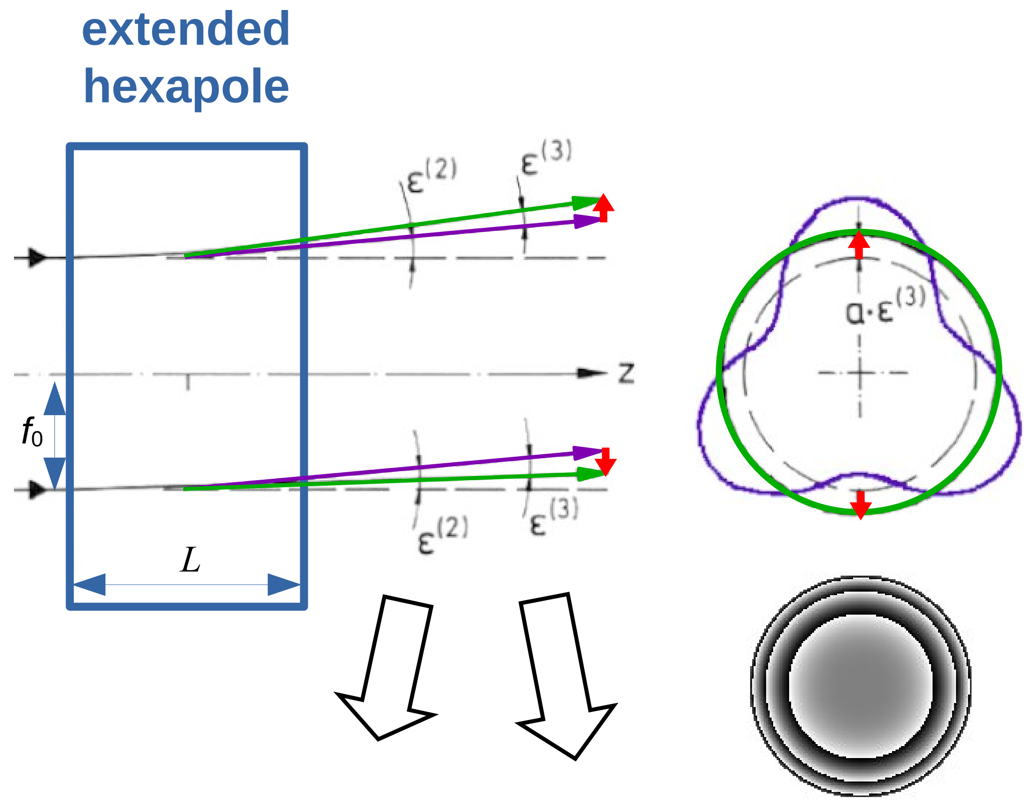


2nd order aberration
(three-fold astigmatism)

3rd order aberration
(negative spherical aberration)

Aberration correction by means of hexapoles





2nd order aberration
(three-fold astigmatism)

$$A_2 = 3\,\eta\Psi_{3S}\,L\,f_0^3$$

3rd order aberration
(negative spherical aberration)

$$C_3 = -3\,|\eta\Psi_{3S}|^2\,L^3 f_0^4 < 0$$

Ψ_{3S} … magnetic potential
L … hexapole length
f_0 … paraxial ray height

η … constant: $\eta = \sqrt{\dfrac{|e|}{2 m_0 U_0^*}}$

M. Haider et al., AIEP Vol. 153 (2008), 43-119, https://doi.org/10.1016/S1076-5670(08)01002-1

Aberration correction by means of hexapoles

CEOS

Corrected Electron Optical Systems GmbH

Optik 85, No. 1 (1990) 19–24 © Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart

Outline of a spherically corrected semiaplanatic medium-voltage transmission electron microscope

H. Rose

Insitut für Angewandte Physik Technische Hochschule Darmstadt, FRG

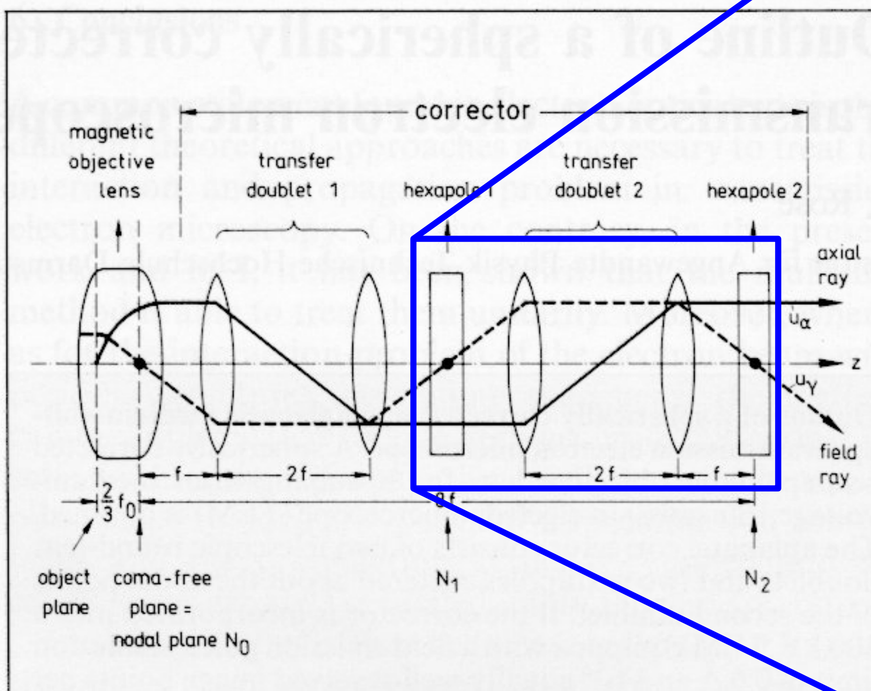
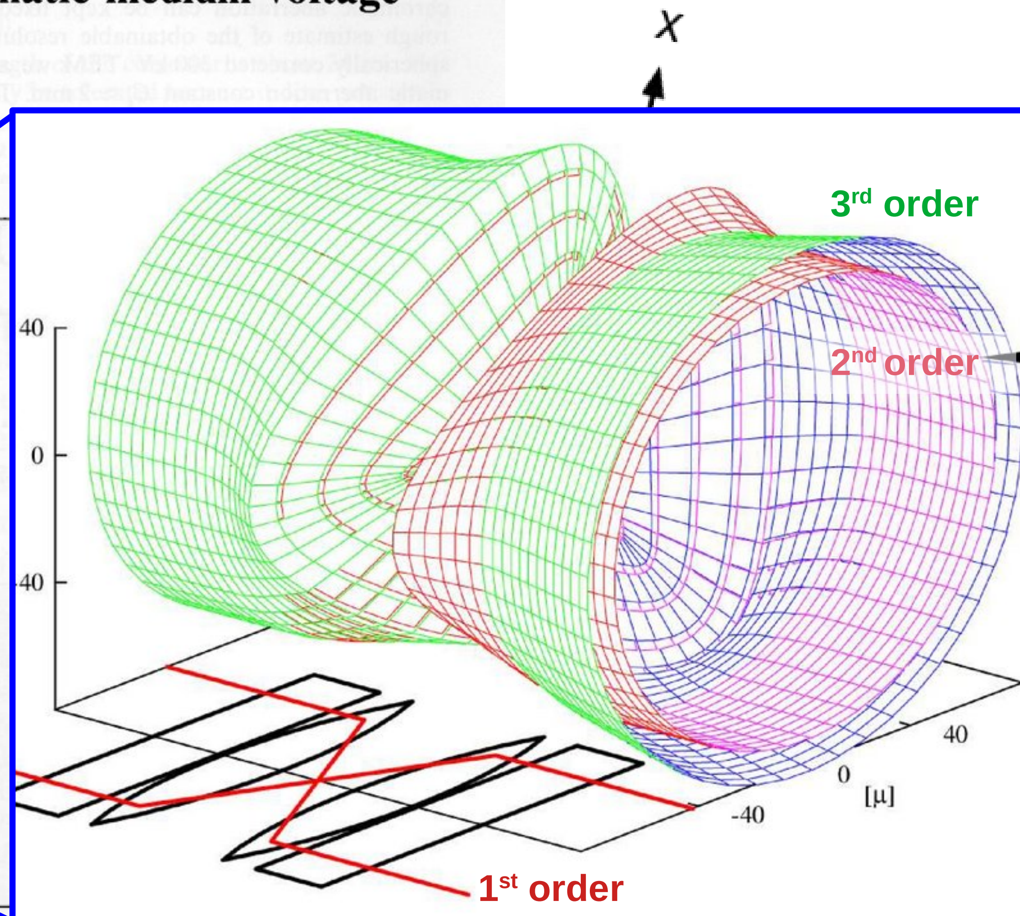
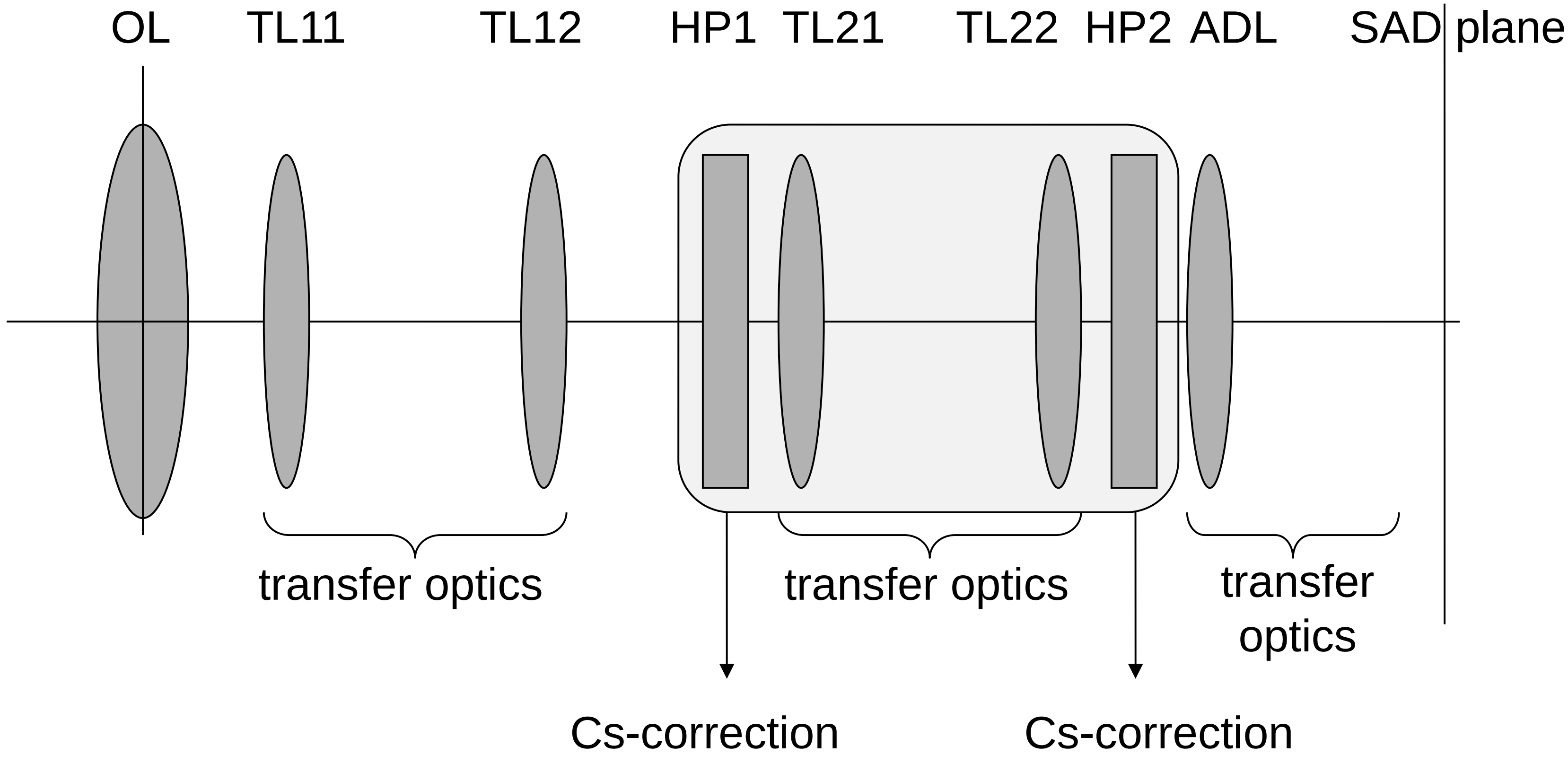


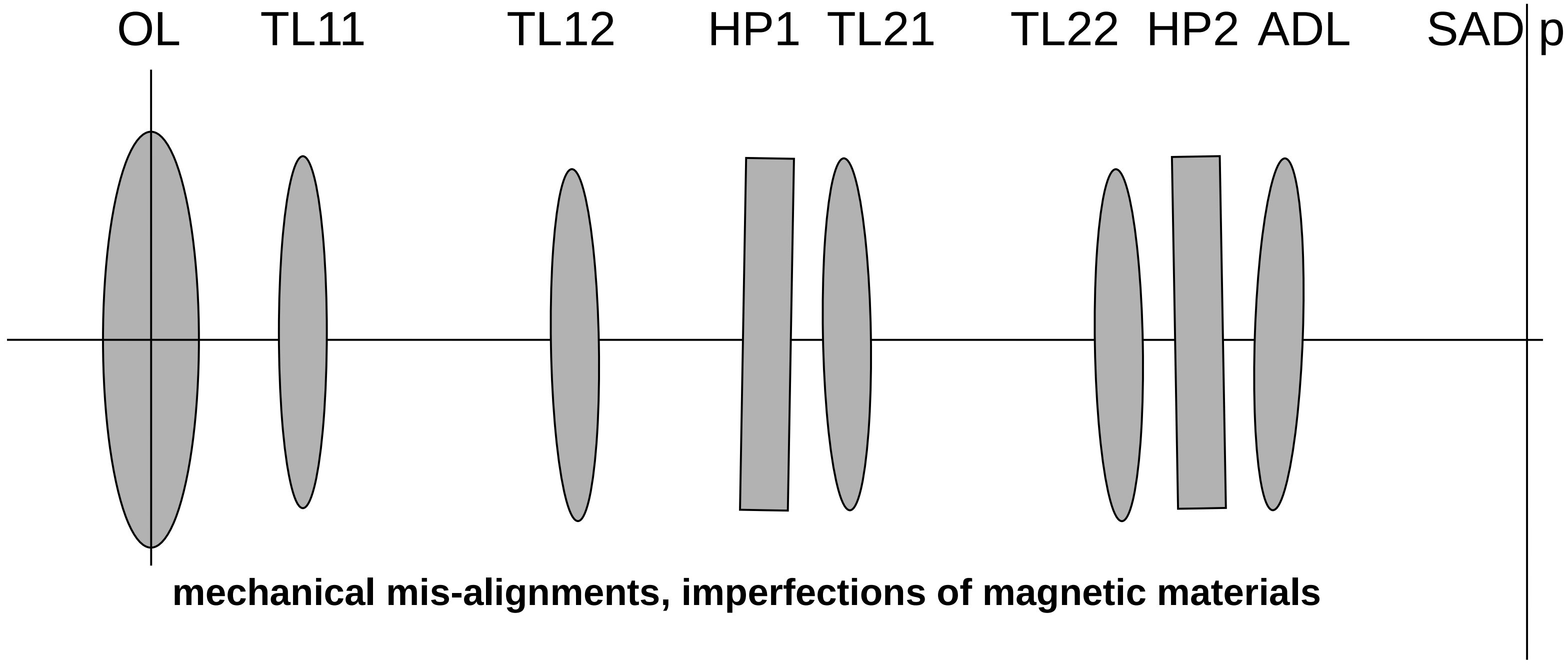
Fig. 2. Schematic arrangement of the elements of the spherically corrected semiaplanatic objective lens.



Ideal system ...



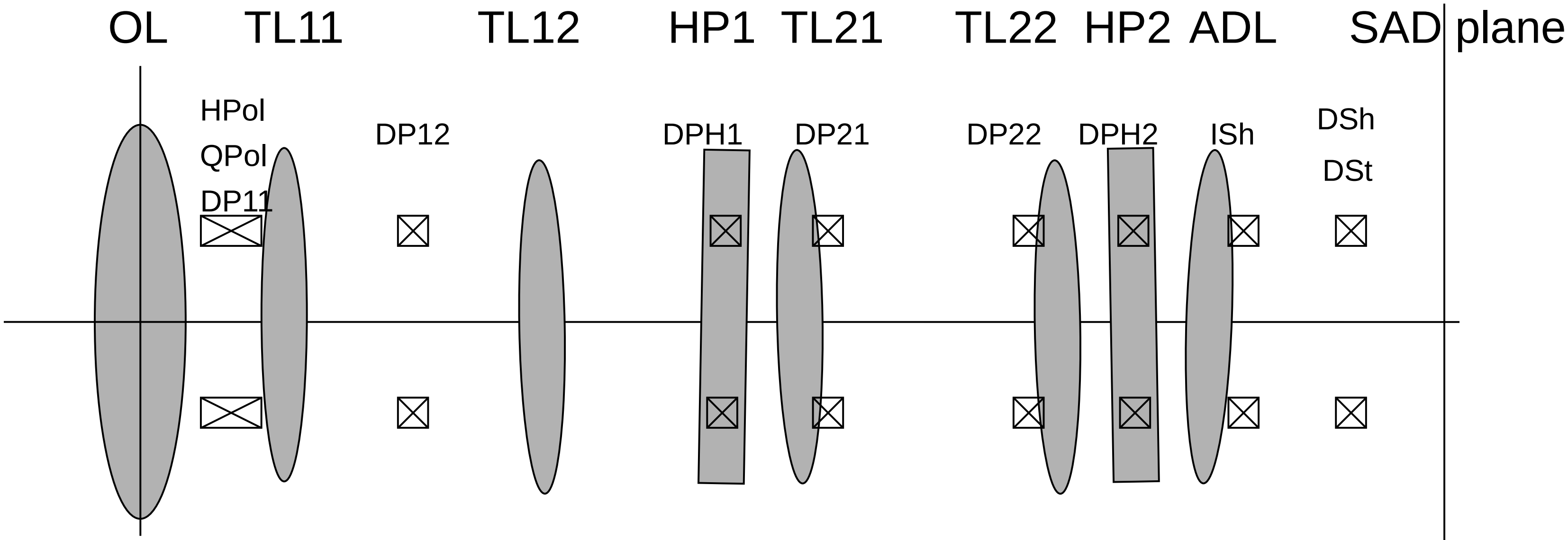
Ideal system vs. real system: small imperfections due to limited manufacturing precision



mechanical mis-alignments, imperfections of magnetic materials

Aberration correction by means of hexapoles

Ideal system vs. real system: small imperfections due to limited manufacturing precision



mechanical mis-alignments, imperfections of magnetic materials

⇒ **additional alignment channels required:** deflectors, quadrupoles, hexapoles

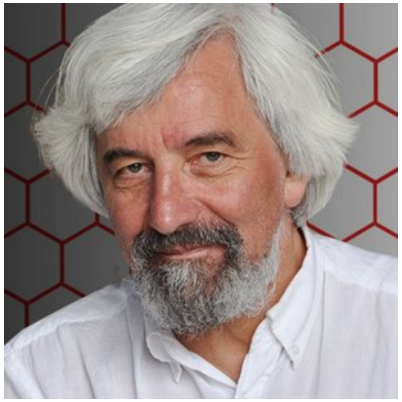
Fundamental corrector alignment:

- Factory adjustment = fingerprint of machining tolerances and mechanical mis-alignments
- No change over time! *… not even when moving a corrector to a different microscope*

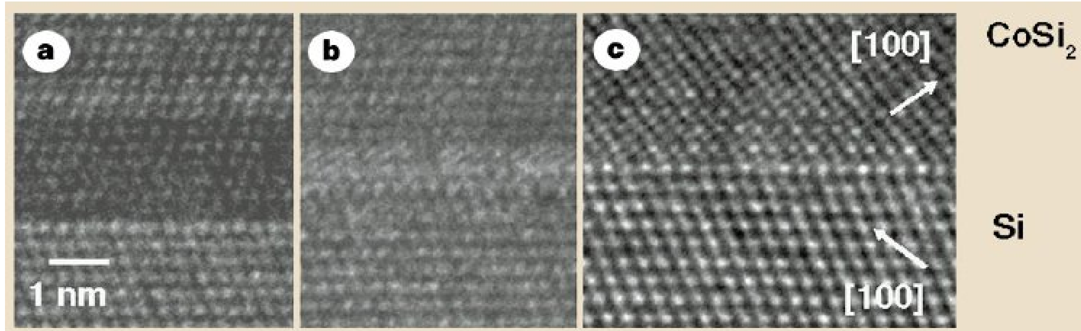
Daily corrector alignment procedure:

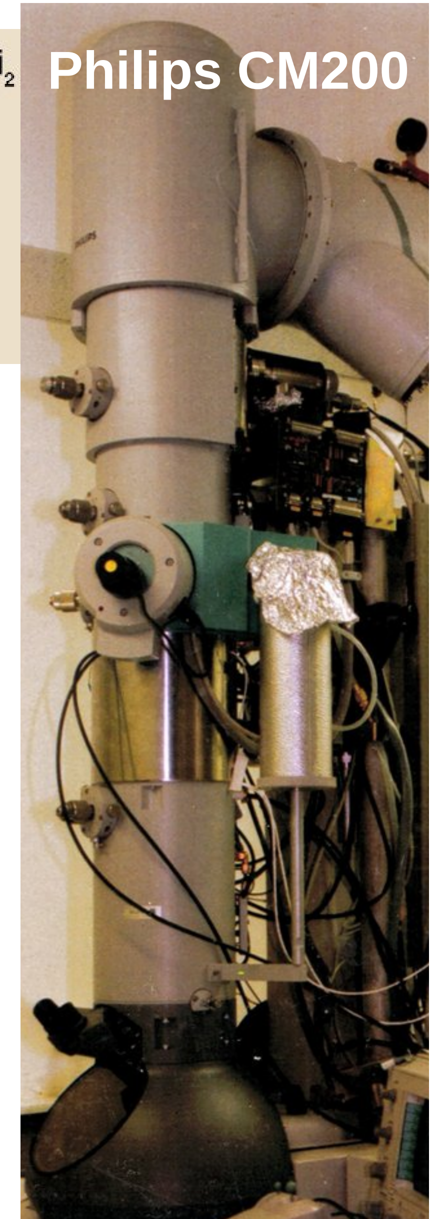
- Fine-tuning against hysteresis of magnetic elements and thermal drift.

1997: Breakthrough in C_s-correction for TEM



Prof. Max Haider

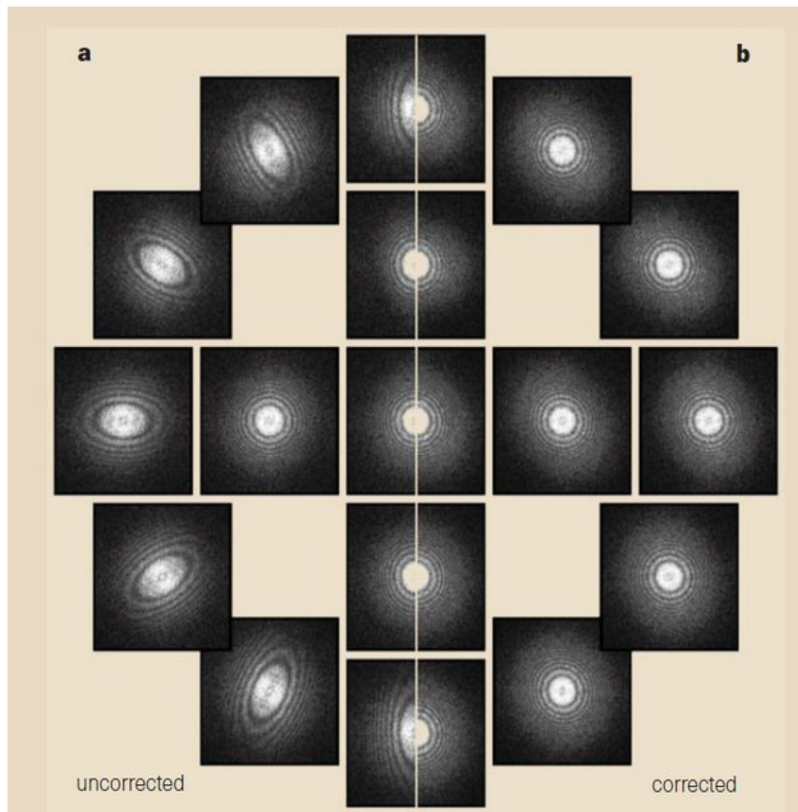


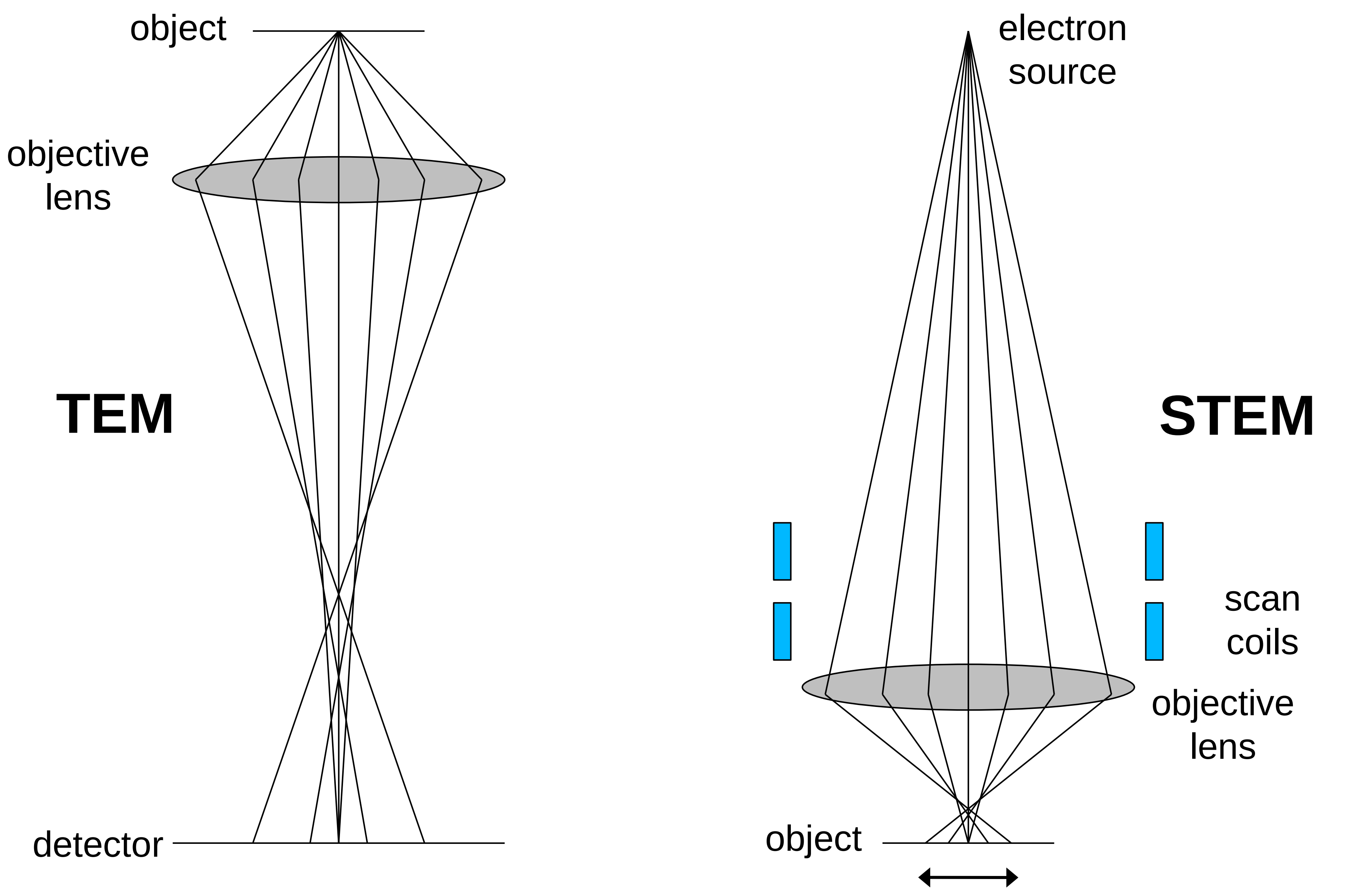


Electron microscopy image enhanced

NATURE | VOL 392 | 23 APRIL 1998

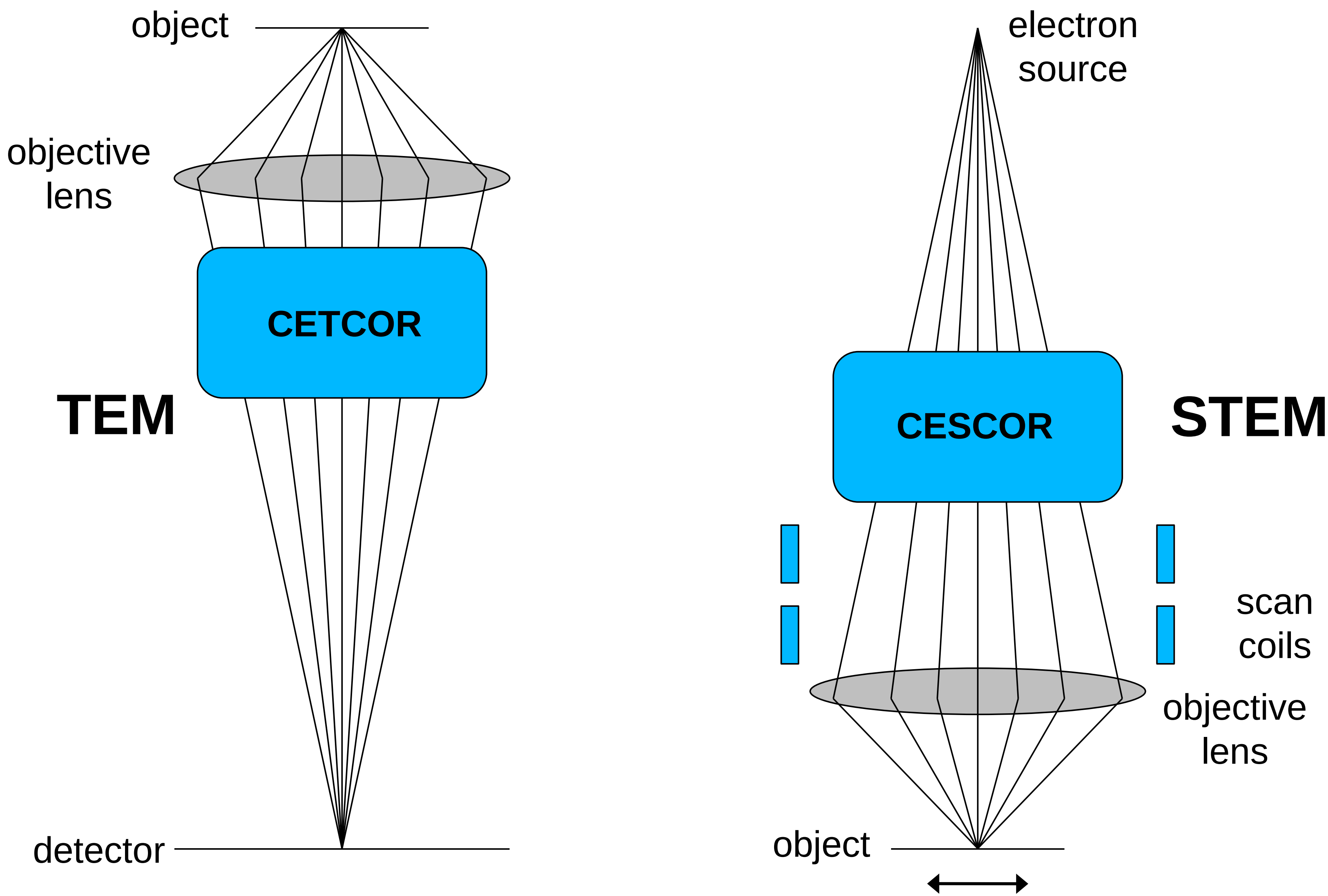
Maximilian Haider*, Stephan Uhlemann*, Eugen Schwan
European Molecular Biology Laboratory, Postfach 102209, 69012 Heidelberg, Germany
**Present address: CEOS GmbH, Im Neuenheimer Feld 519, 69120 Heidelberg, Germany*
Harald Rose
Institut für Angewandte Physik, Technische Hochschule Darmstadt, 64289 Darmstadt, Germany
Bernd Kabius, Knut Urban
Institut für Festkörperforschung, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany





object
objective lens
TEM
detector
electron source
STEM
scan coils
objective lens
object

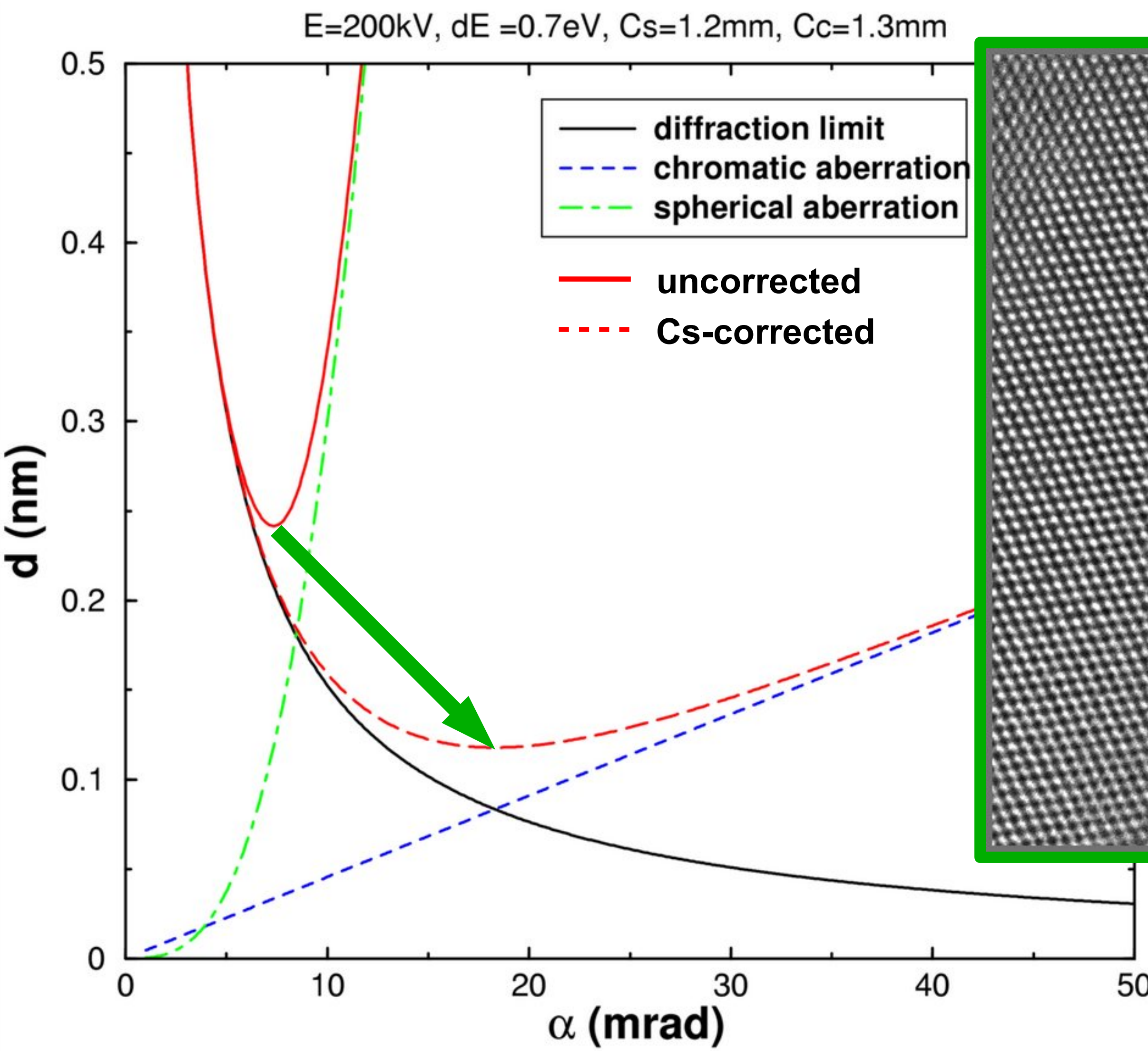
Aberration-correction for TEM and STEM

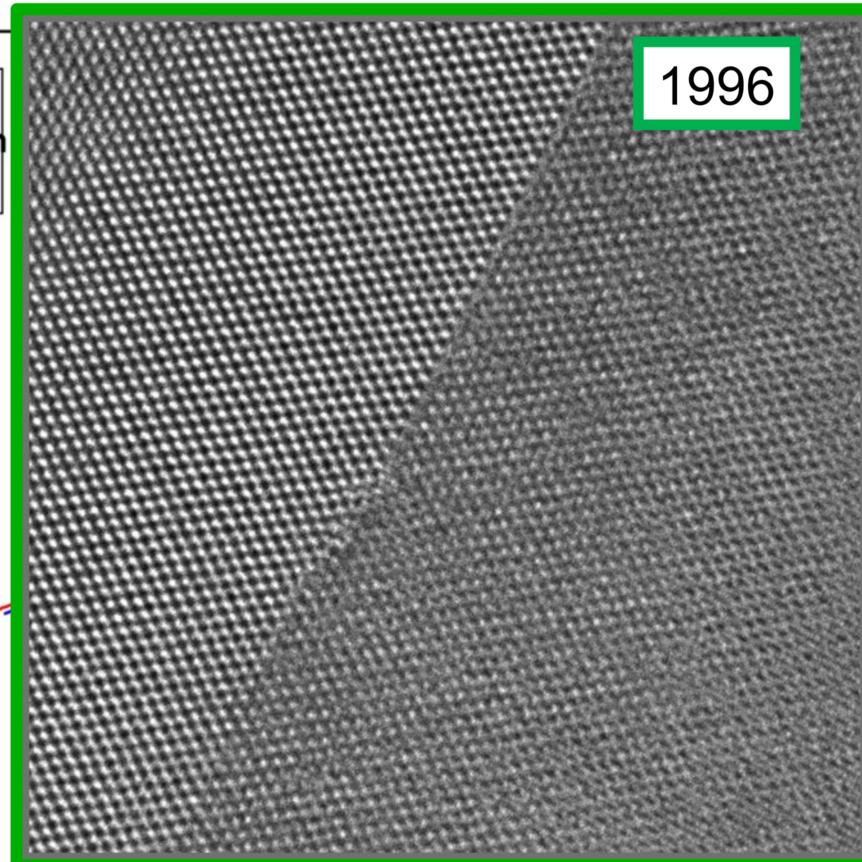


Aberration-correction for TEM

CEOS
Corrected Electron Optical Systems GmbH

resolution enhancement from 0.23nm to 0.13nm



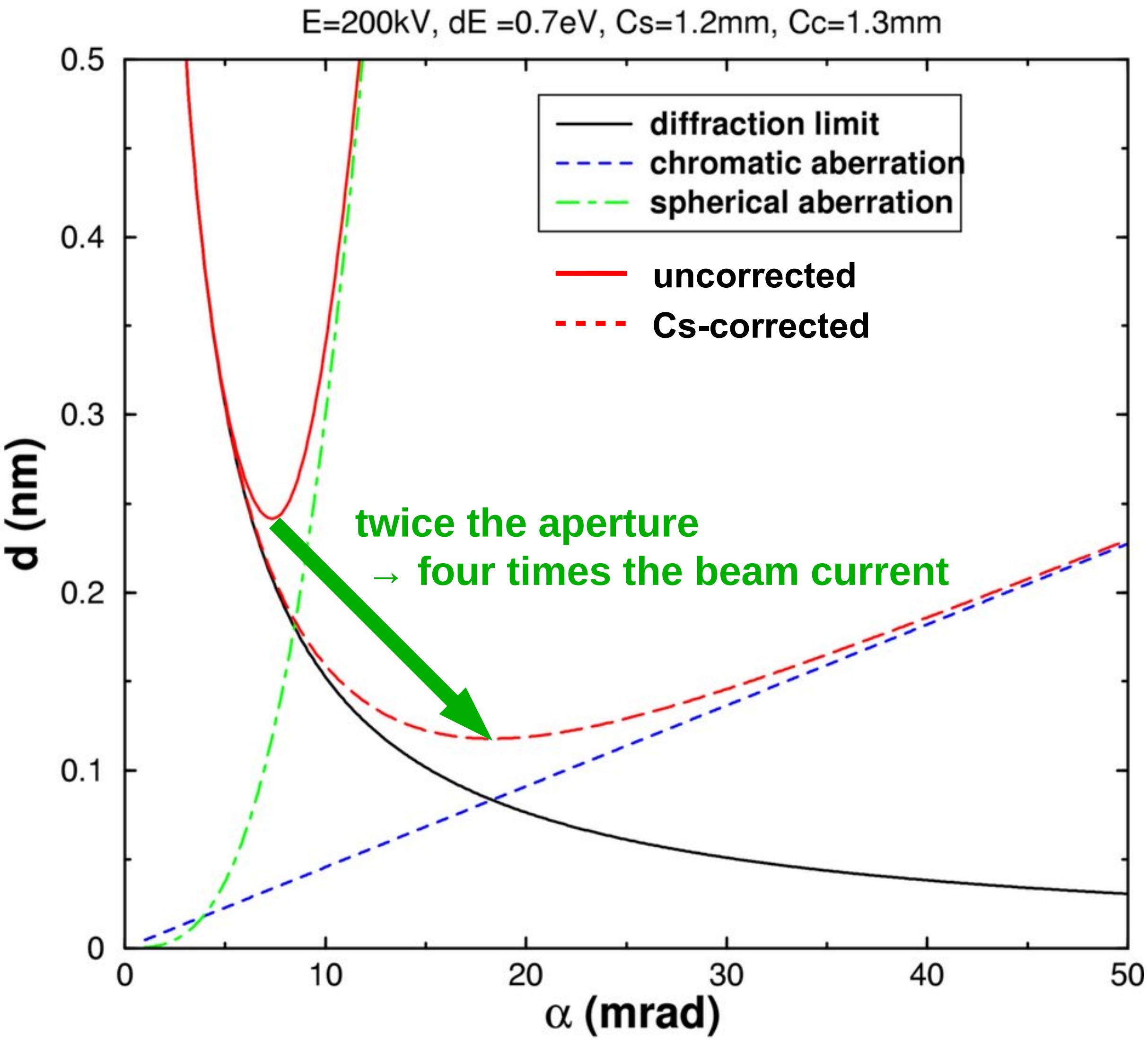


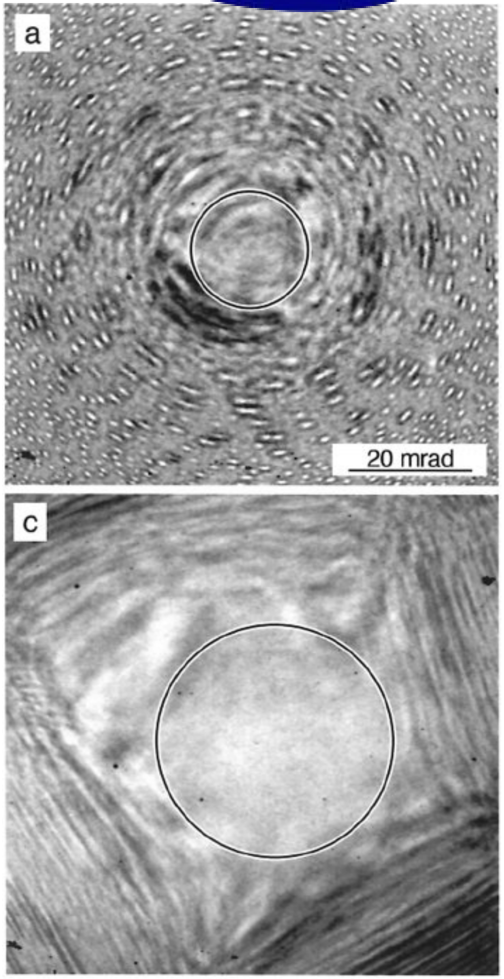
Haider et al. Nature 392, 768 (1998)

Aberration-correction for STEM

CEOS
Corrected Electron Optical Systems GmbH

resolution enhancement from 0.25nm to 0.136nm



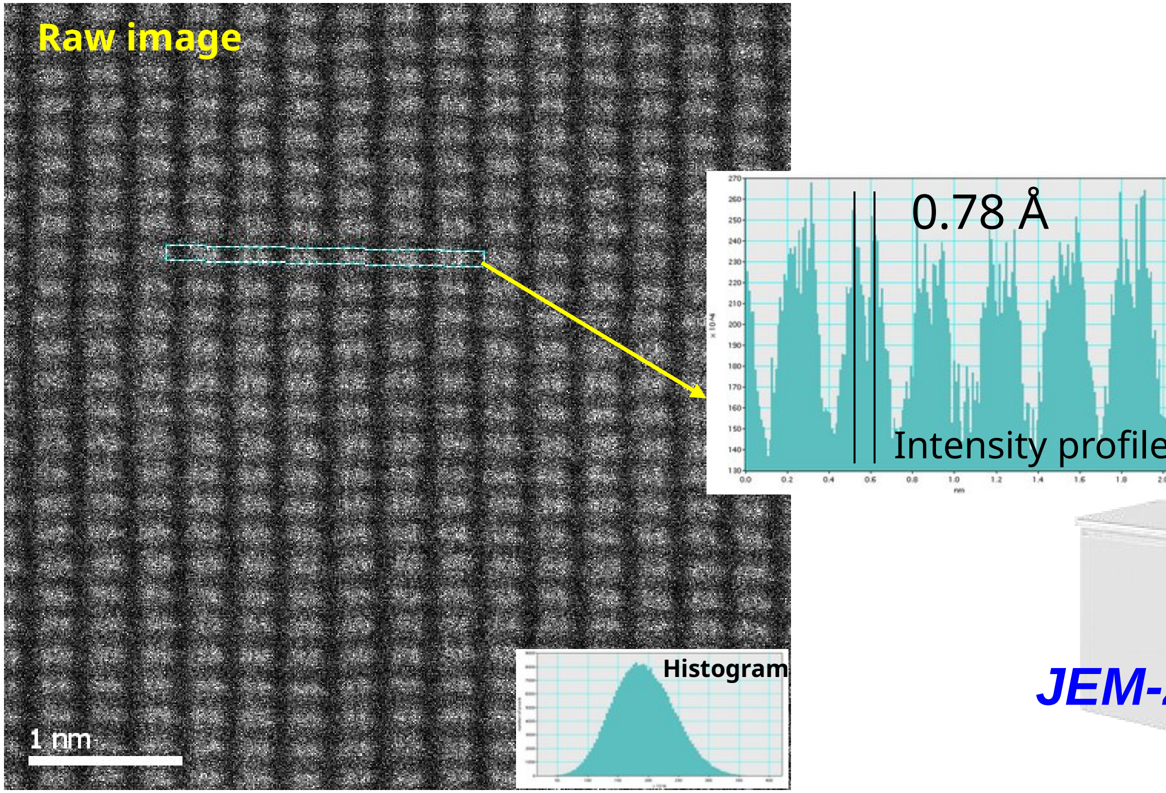


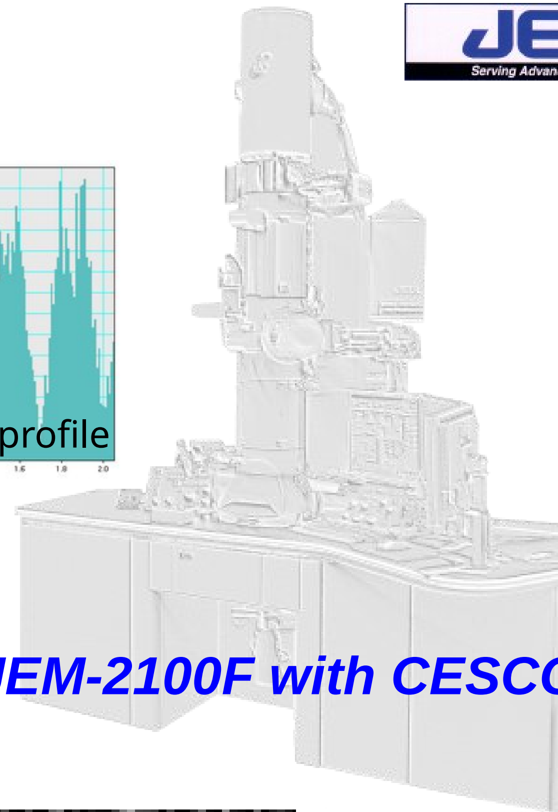
Nion's Cs-corrector at 100keV
Dellby et al. JEM 50(3): 177-185 (2001)

Direct observation of 0.78 Å resolution in STEM

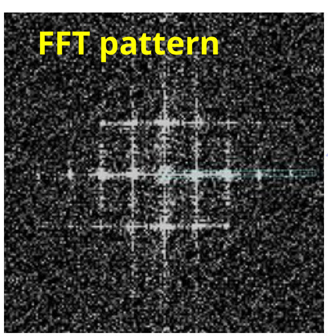
Si[112] sample, C_s-corrected HAADF imaging

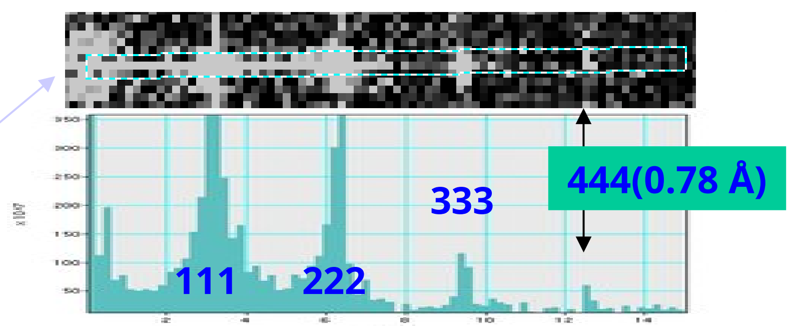
CESCOR in 2008





JEM-2100F with CESCOR





CEOS aberration-correctors for TEM and STEM

FEI
ThermoFisher SCIENTIFIC

CETCOR(+)
CESCOR
DCOR(+)
SCORR
(BCOR, CCOR)

JEOL

2100F
ARM200
NEOARM200

CETCOR
CESCOR
ASCOR
LASCOR
ATCOR

Zeiss
Libra200

CETCOR
CESCOR

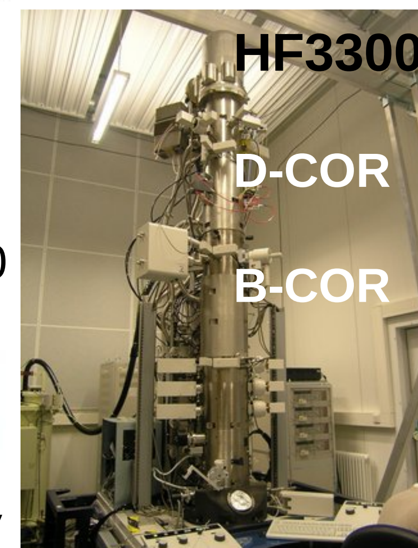
HITACHI

HD2700

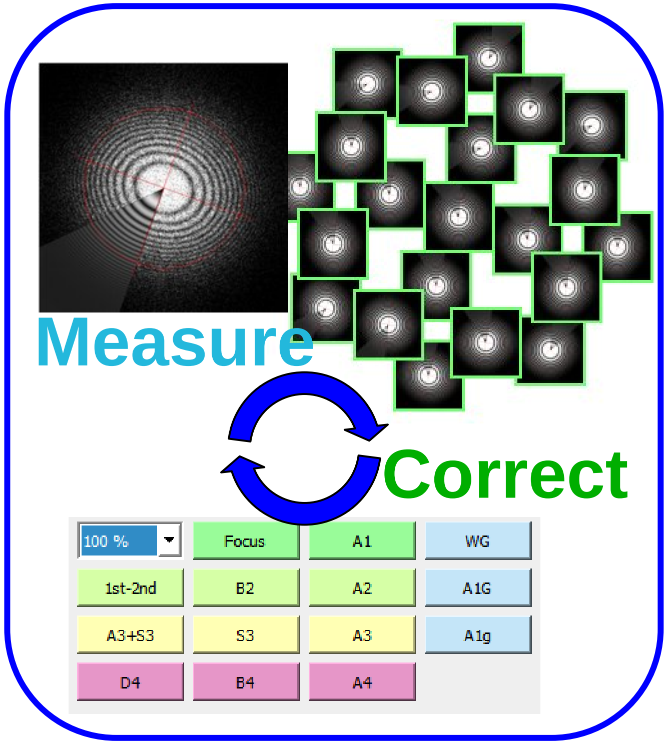
CESCOR

HF5000

BCOR
CETCOR-UHV



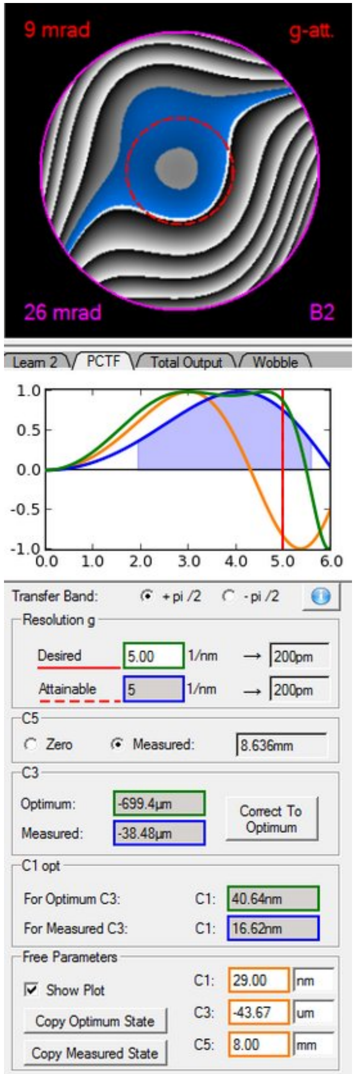
Daily corrector-tuning

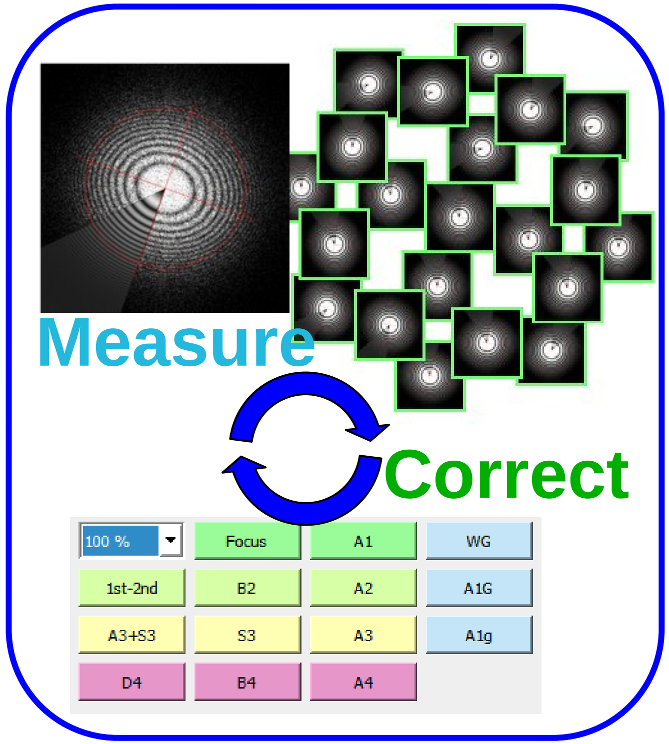


Desired optical state ≠ zero aberrations

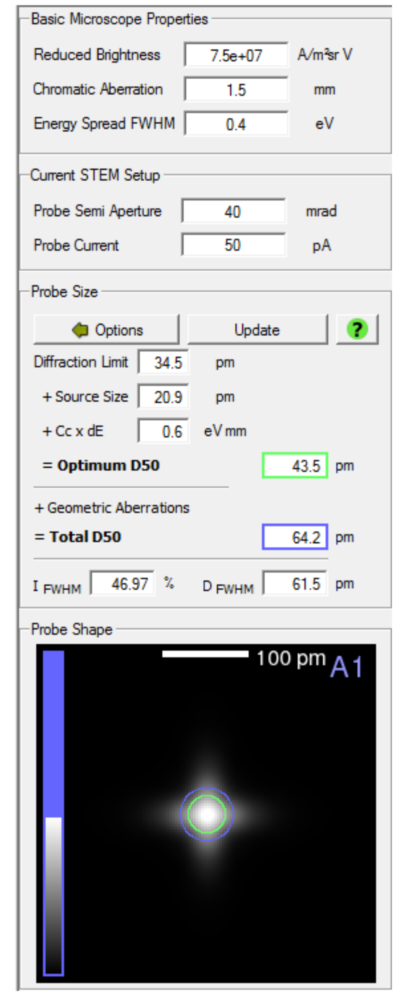
- TEM: Phase Contrast Transfer Function
- STEM: (sometimes) tailored probe

TEM: PCTF





STEM: probe shape



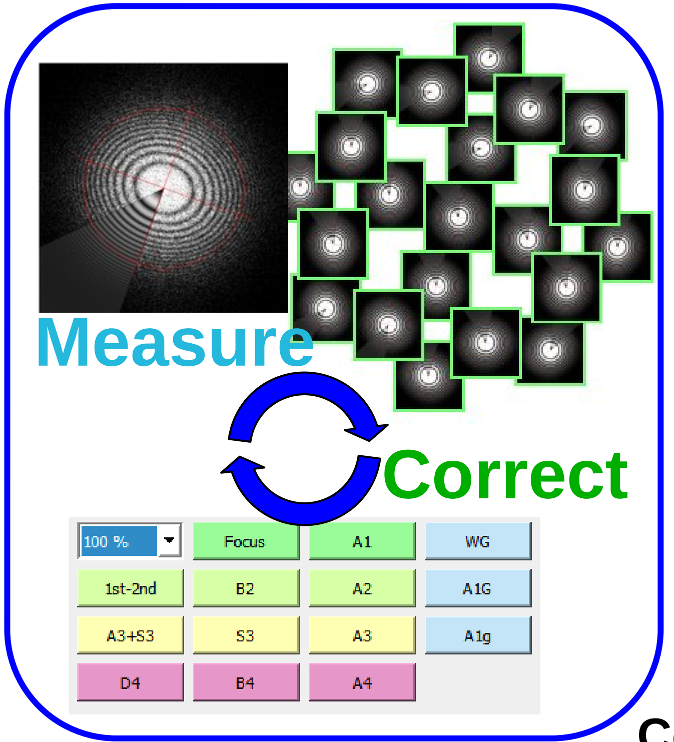
Important feedback:

Good enough for desired experiment?

Auto-tuning developments

Desired optical state ≠ zero aberrations

- **TEM: Phase Contrast Transfer Function**
- **STEM: (sometimes) tailored probe**



Automatic

Measurement settings

- *magnification*
- *fraction and binning, defocus*
- *outer tilt angle, tableau type*
- *fit parameters*
- *aberrations to be corrected*

Error recognition

- *wrong magnification*
- *messed-up illumination*
- *bad image quality (Thon rings / deconvolution)*

Stop criteria

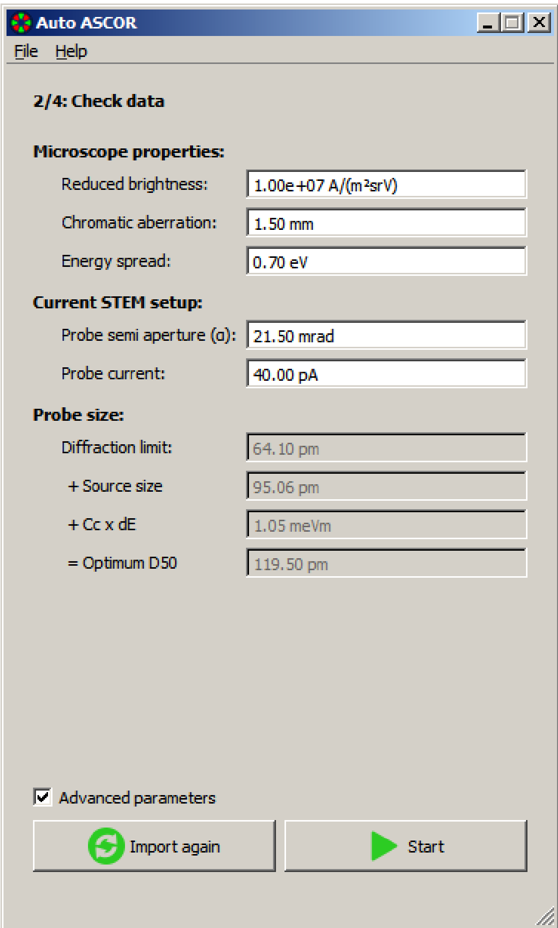
- *confidence of measurement*
- *further correction not meaningful*
- *measurement failed*

Correction criteria

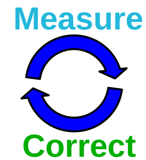
- *confidence of measurement*
- *compensation schemes (different orders of same multiplicity)*

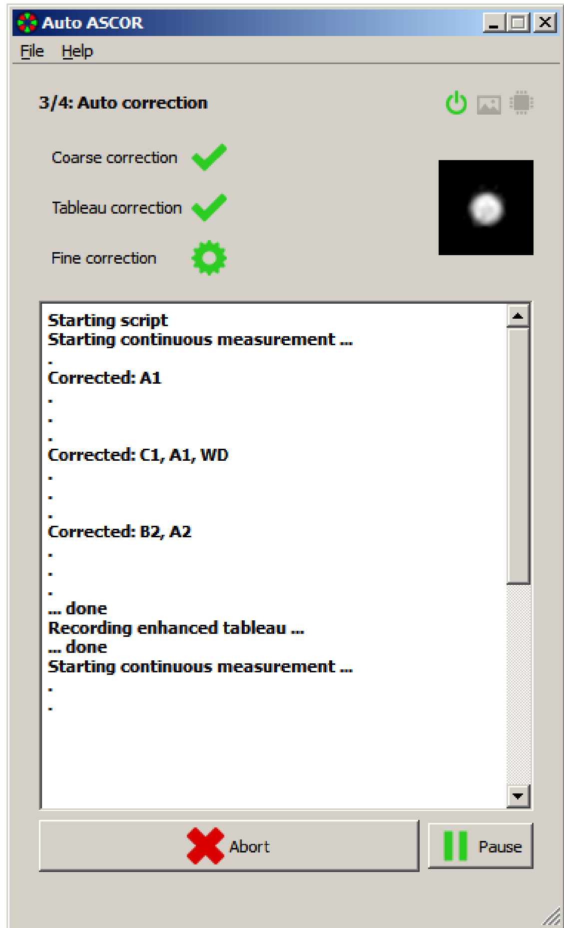
STEM Auto-tune

Microscope configuration and STEM setup

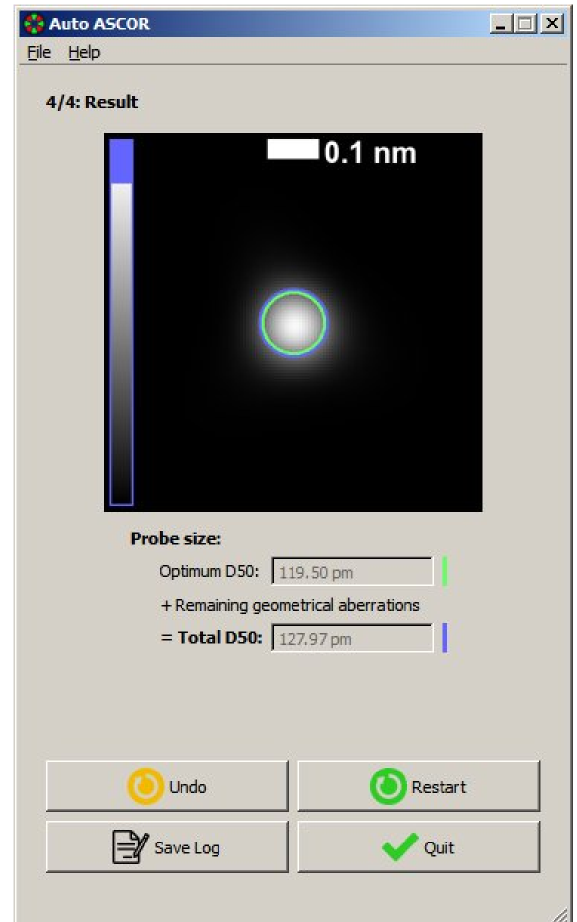


Auto correction in progress



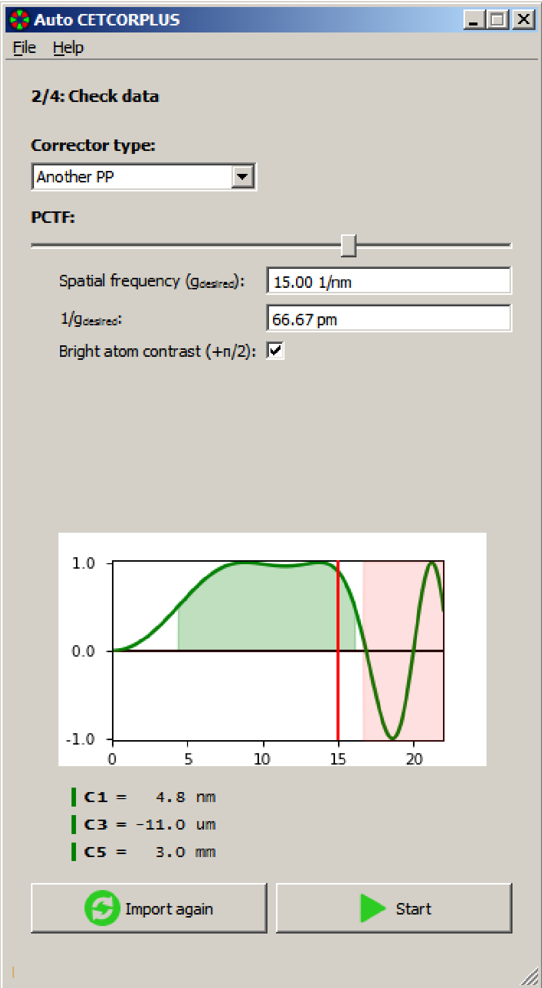


Probe simulation with attainable probe size

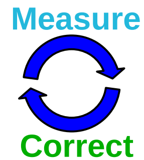


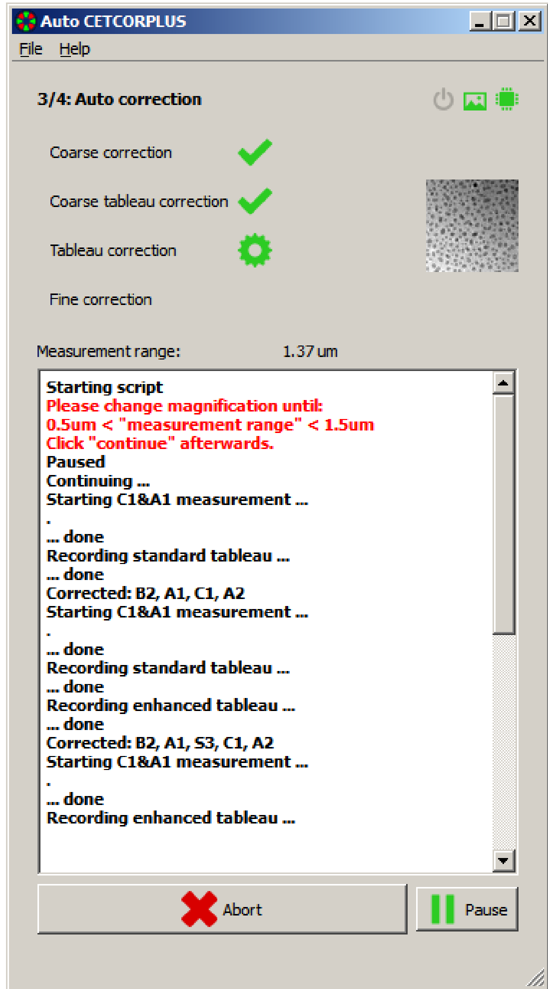
TEM Auto-tune

Microscope configuration and PCTF requirements

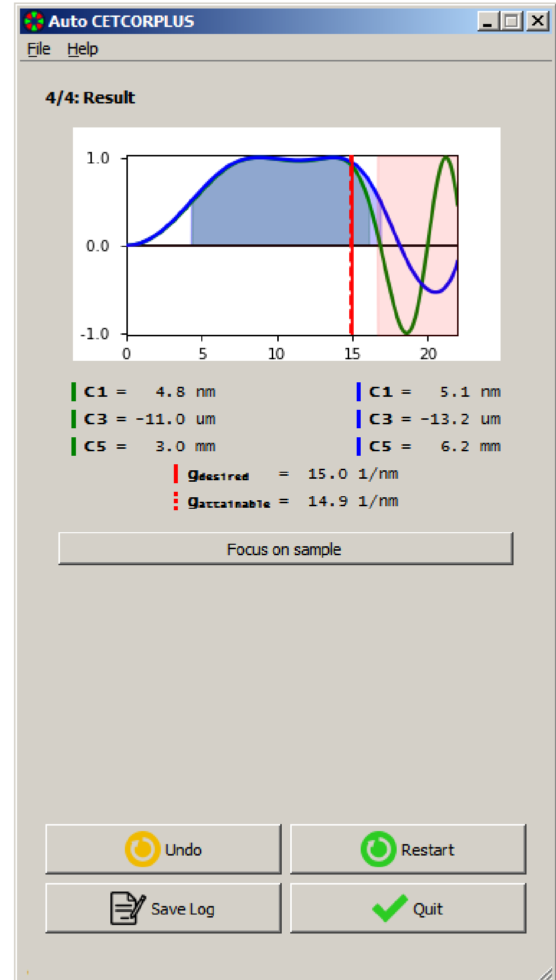


Auto correction in progress

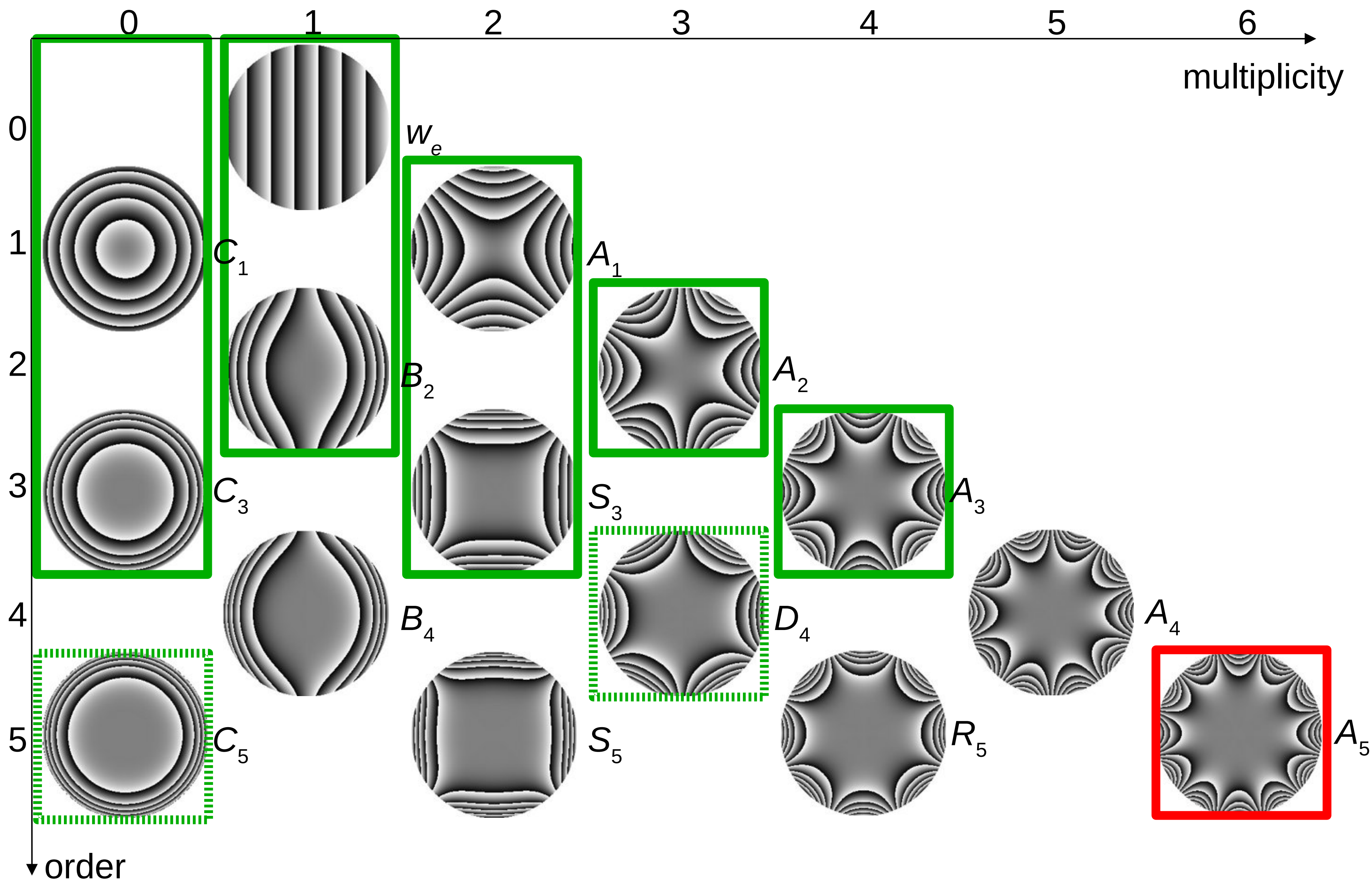




Final PCTF with attainable resolution



Axial aberrations: CETCOR/CESCOR



2008: DCOR/ASCOR for STEM

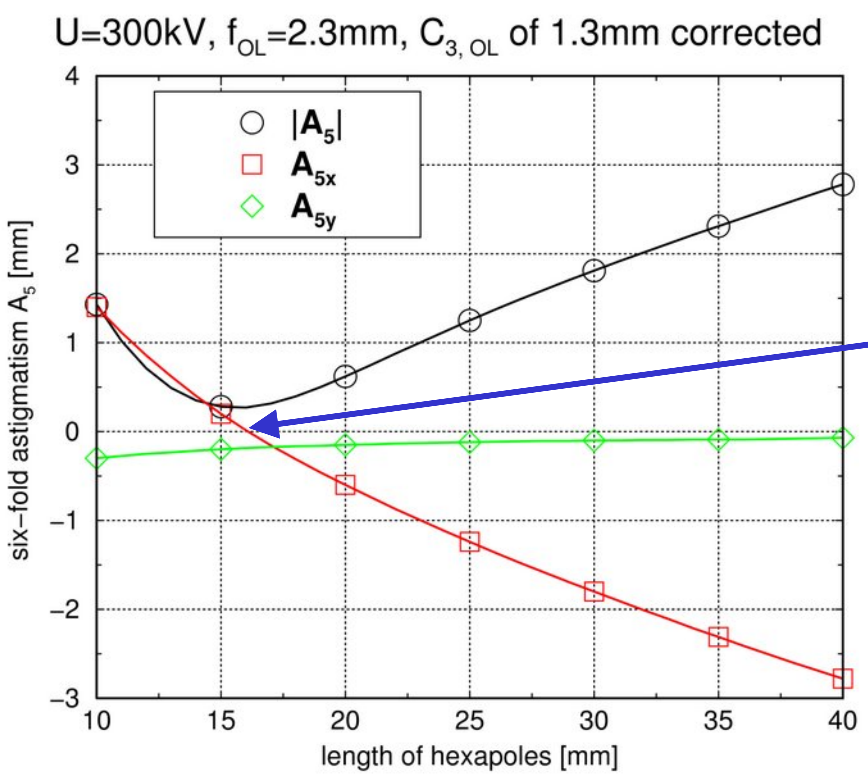
Advancing the Hexapole C_s-Corrector for the Scanning Transmission Electron Microscope

Heiko Müller,* Stephan Uhlemann, Peter Hartel, and Maximilian Haider

Corrected Electron Optical Systems GmbH, Englerstr. 28, D-69126 Heidelberg, Germany

Microsc. Microanal. 12, 442–455, 2006
DOI: 10.1017/S1431927606060600

Microscopy AND Microanalysis



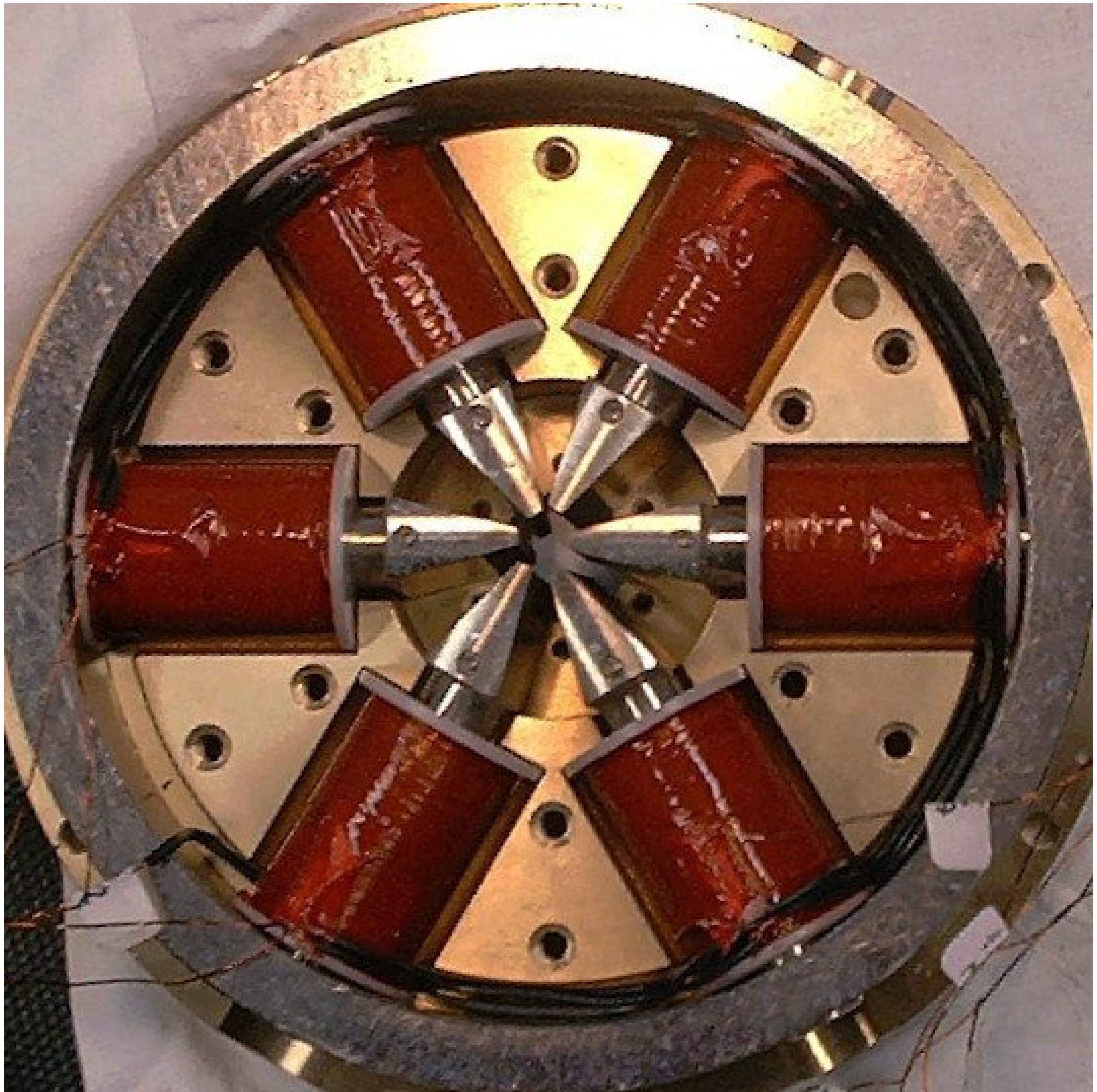
Six-fold astigmatism A_5 is a function of hexapole length.

Shorter & stronger hexapoles allow minimization of A_5.

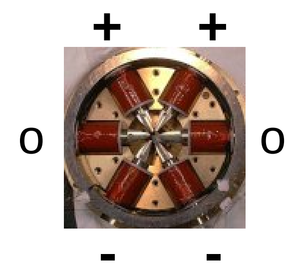
DCOR/ASCOR:

- A_{5x} corrected
- complete 4th order axial aberration correction

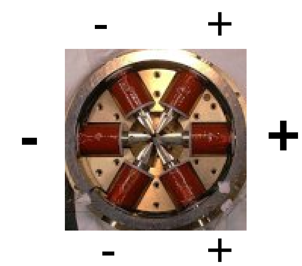
Hexapole with deflectors and quadrupoles



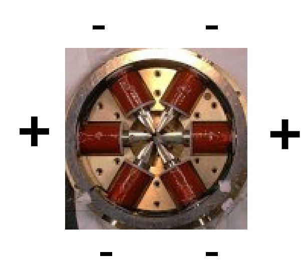
dipole x



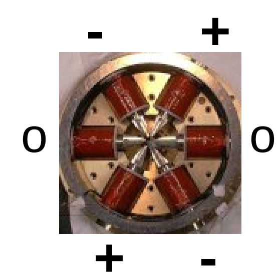
dipole y



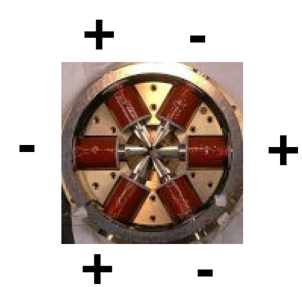
quadrupole x



quadrupole y



main hexapole



PRL **102,** 096101 (2009) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2009

Atomic-Resolution Imaging with a Sub-50-pm Electron Probe

Rolf Erni, Marta D. Rossell, Christian Kisielowski, and Ulrich Dahmen

National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 17 June 2008; published 2 March 2009)

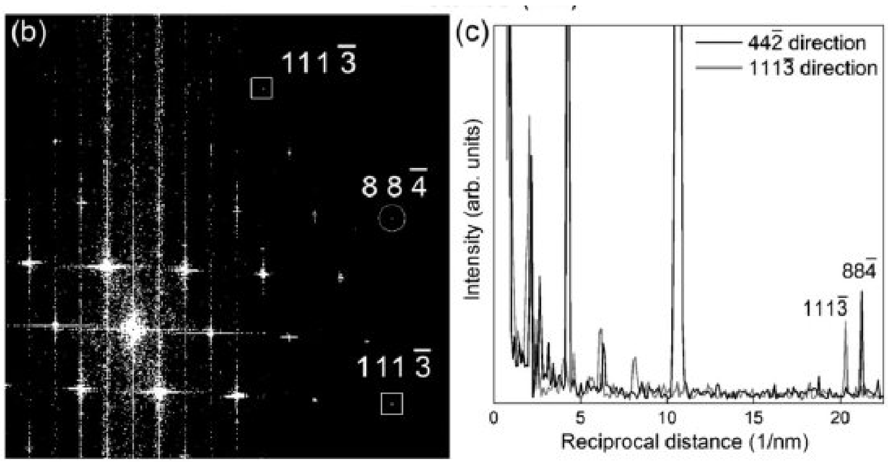
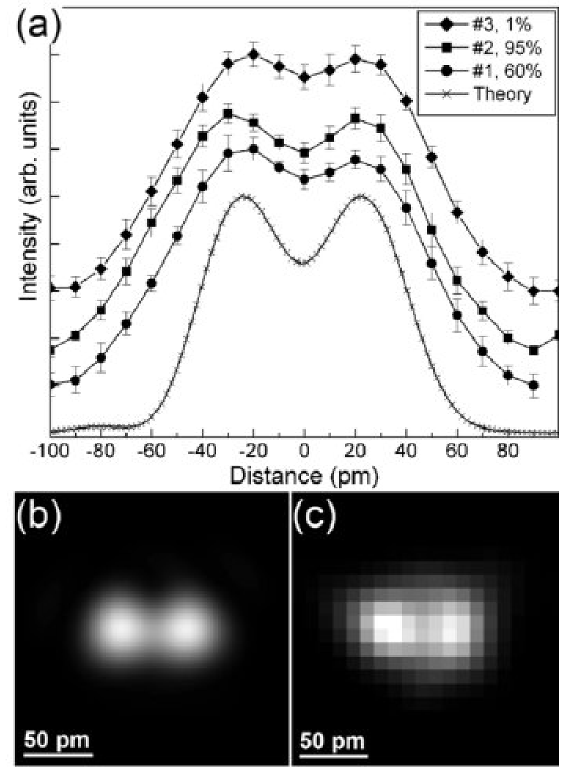


FIG. 2. (a) Line profiles across the atom row of RoI 1 in Fig. 1(a) (gray) and Fig. 1(b) (black). (b) Detail of the power spectrum of the Ge ⟨114⟩ micrograph and (c) line profiles through the power spectrum. The $88\bar{4}$ image frequency (47 pm) and both $111\bar{3}$-type reflections (49 pm) are present, confirming the sub-50-pm information transfer.

~ 40 mrad

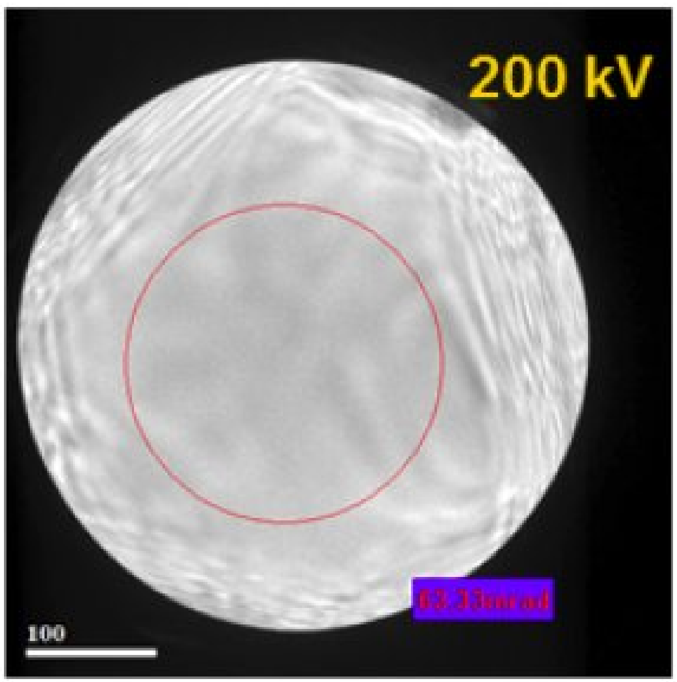


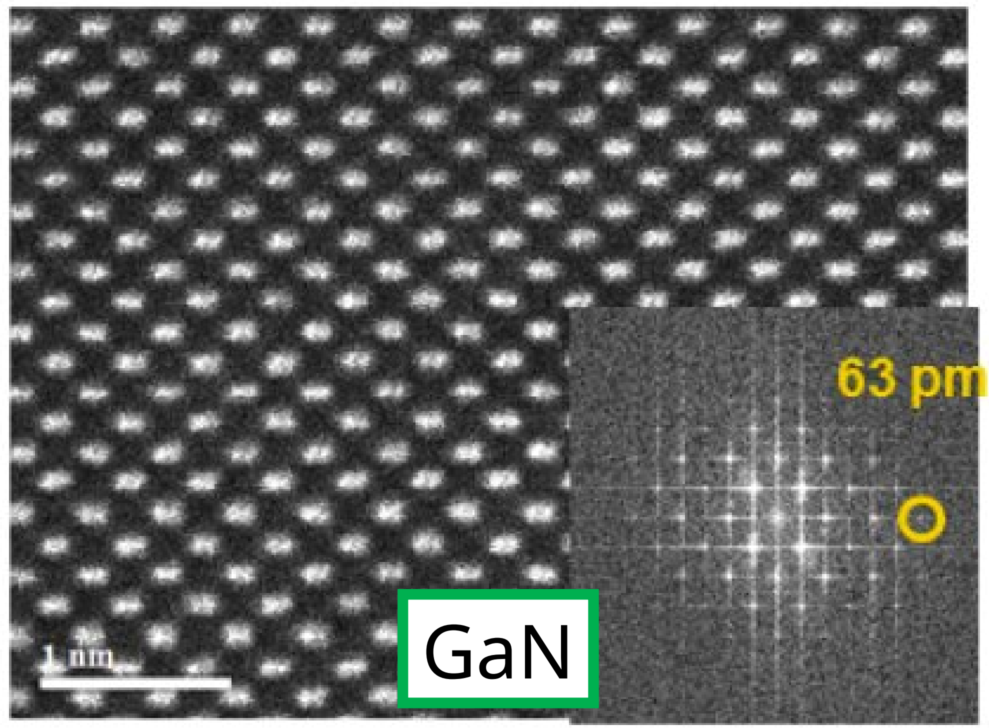
ASCOR @200kV: JEOL ARM200, cold FEG

Improvement of Imaging Performance with a New ASCOR Probe-Corrector in a 200 kV JEM-ARM200CF

Microsc. Microanal. 22 (Suppl 3), 2016

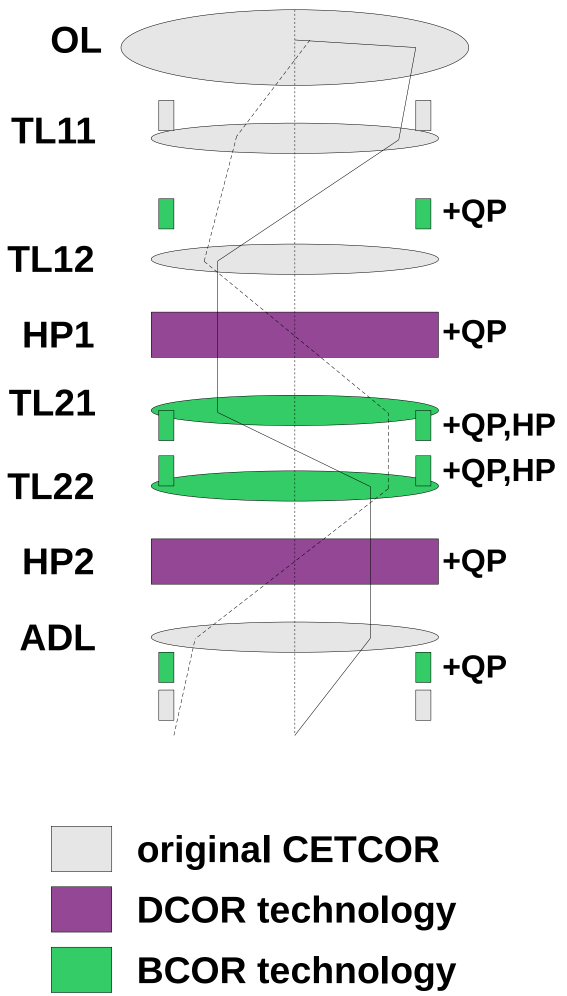
M. Watanabe*, T. Nakamura**, T. Ishikawa***
* Dept of Materials Science and Engineering, Lehigh University, Bethlehem. PA 18015.
** JEOL USA Inc.. Peabody, MA 01960.
*** JEOL Ltd., 3-1-2 Musashino, Akishima, Tokyo, 196-8558, Japan.

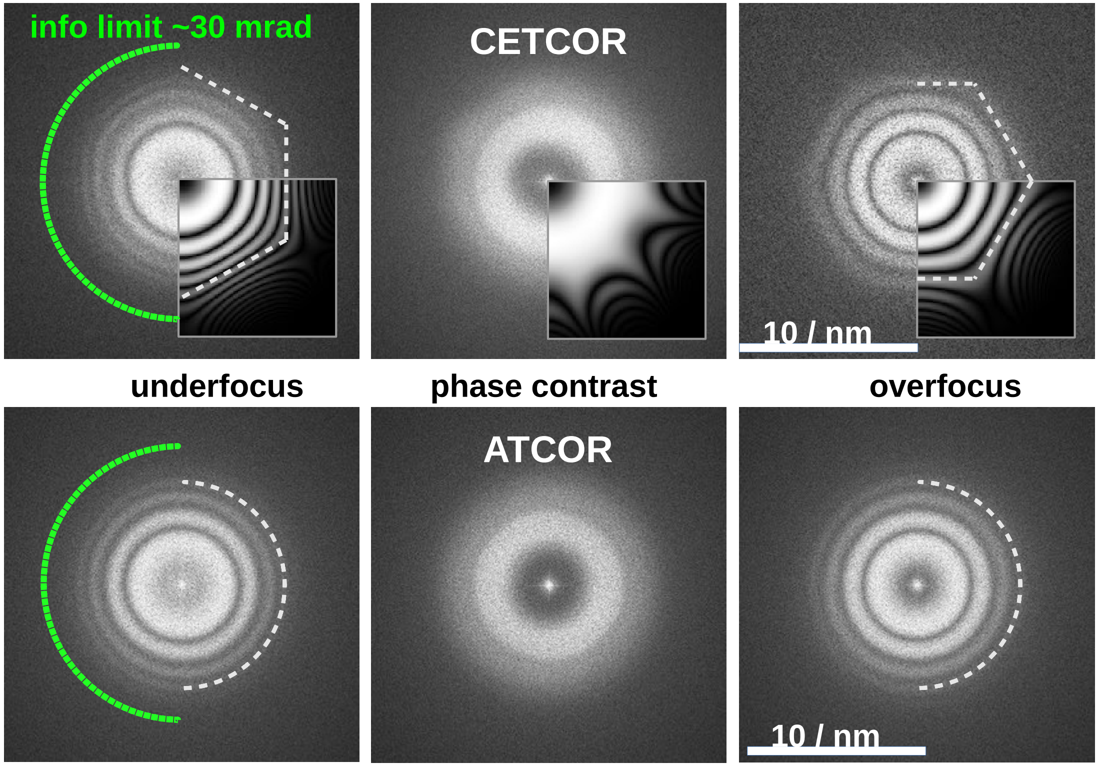


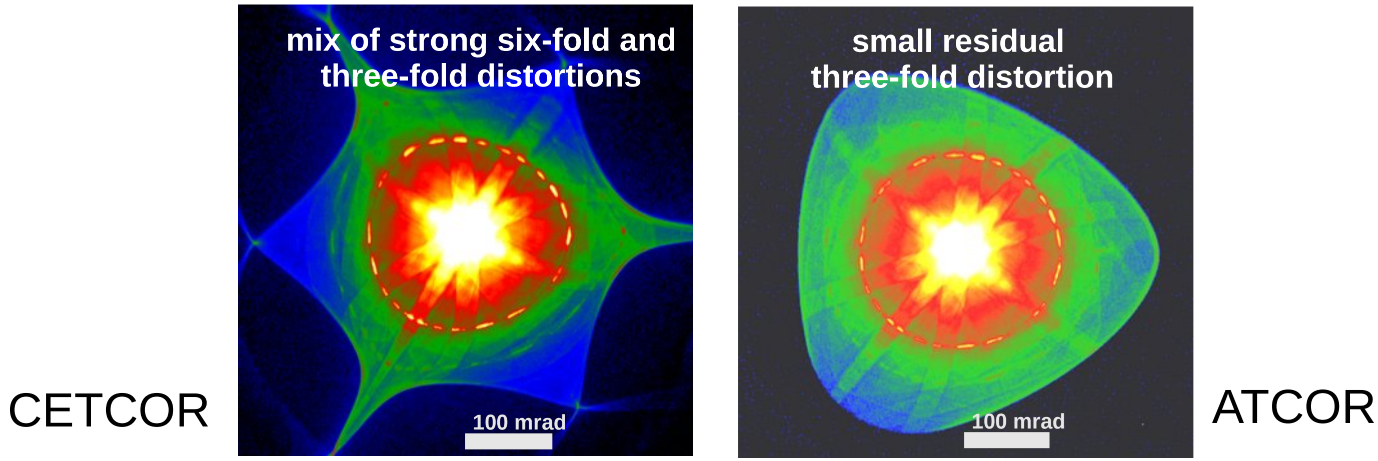


ATCOR – Advanced HP-corrector for TEM (2020)

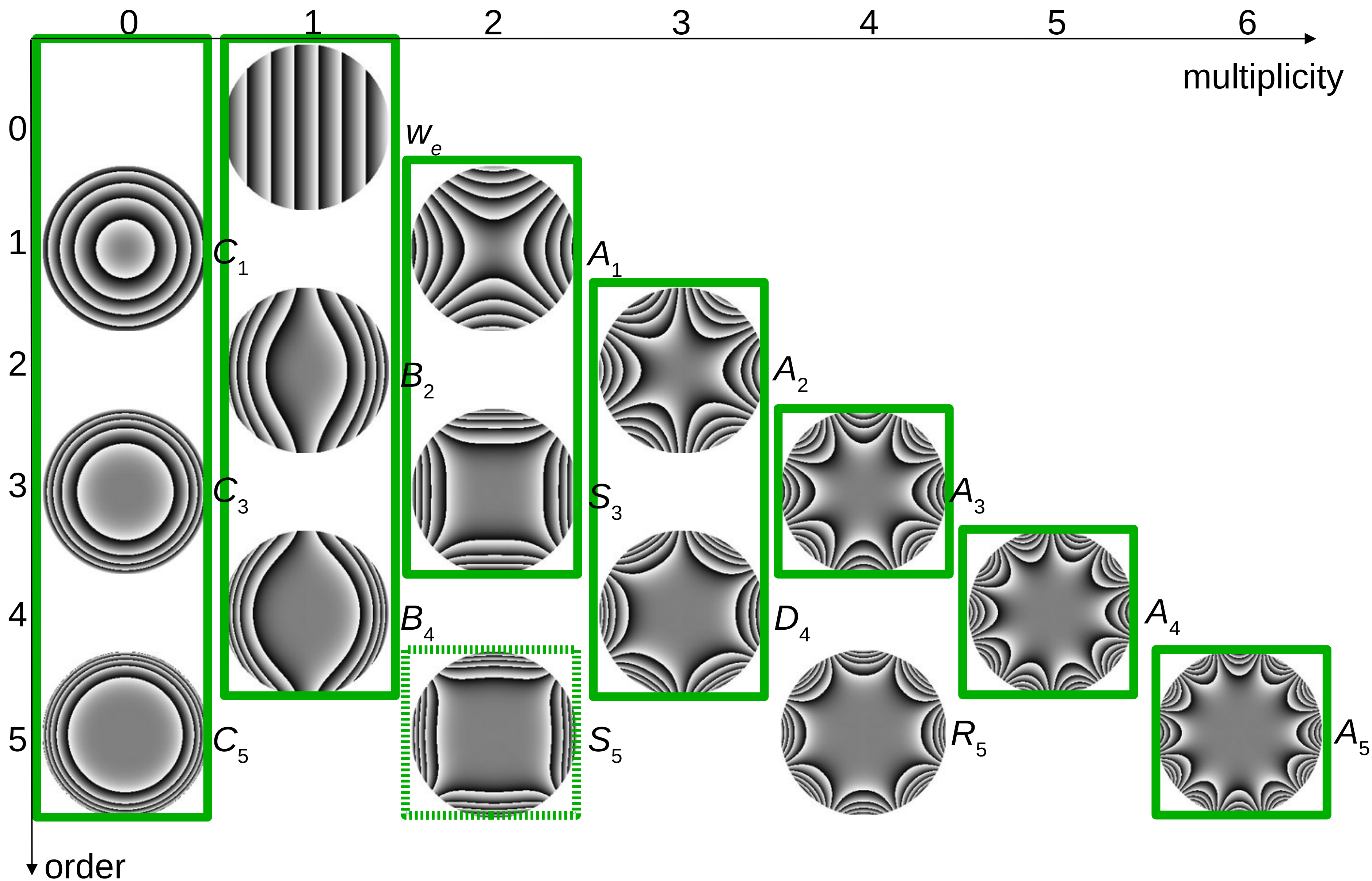
CEOS
Corrected Electron Optical Systems GmbH





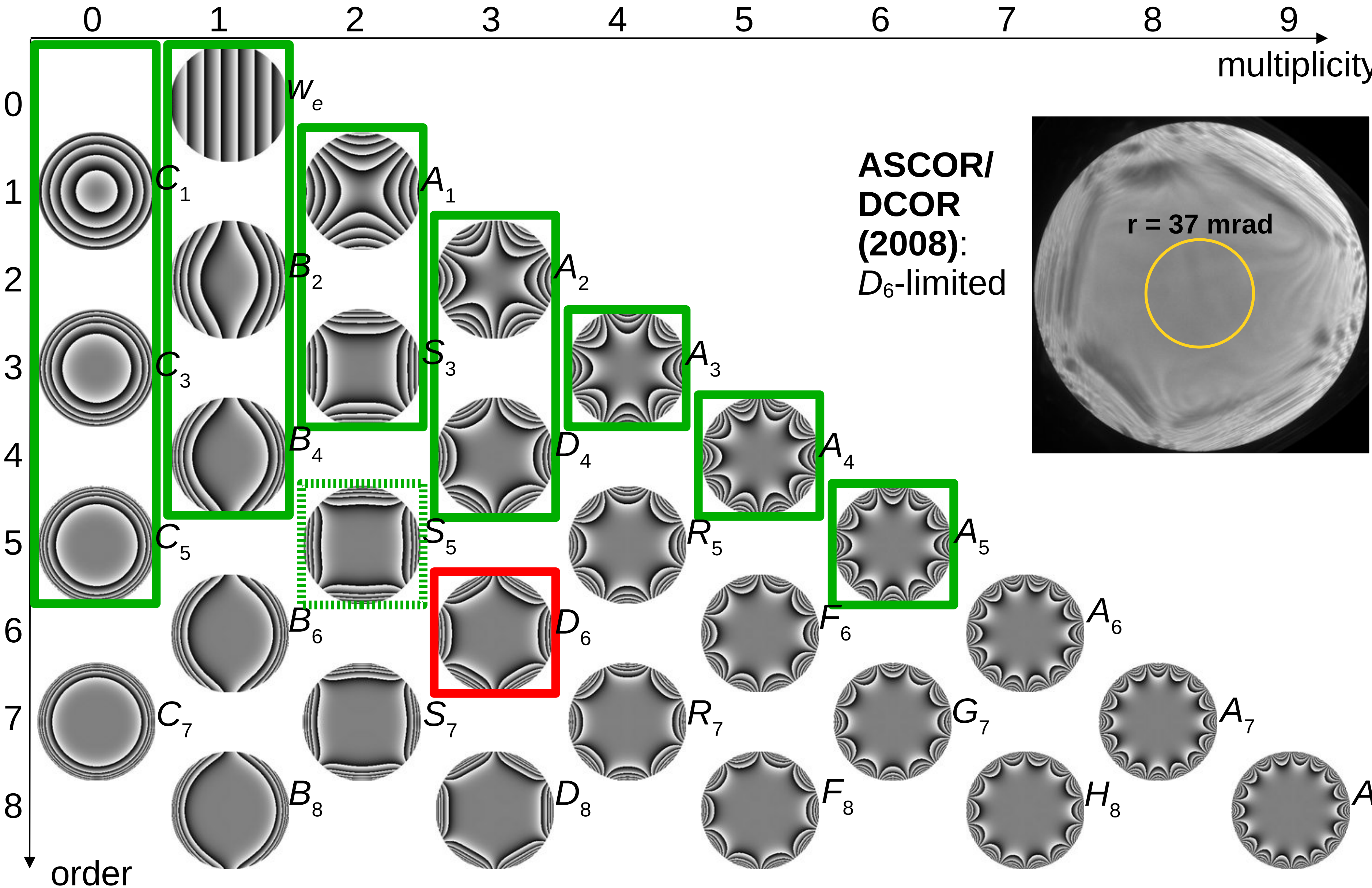


Axial aberrations: advanced two-HP correctors



Axial aberrations: advanced two-HP correctors

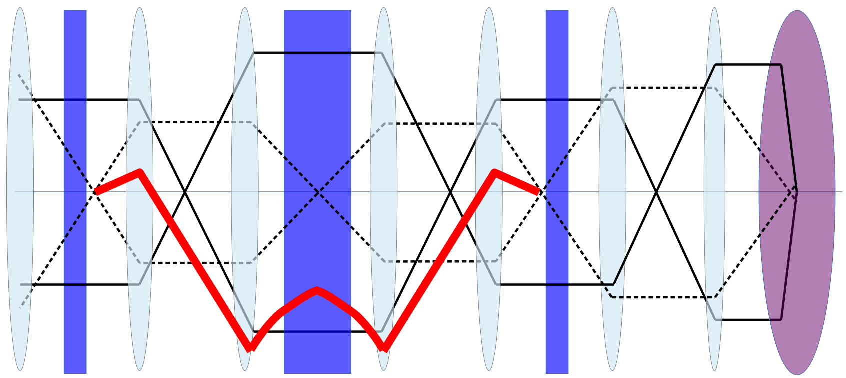
CEOS
Corrected Electron Optical Systems GmbH



ASCOR/ DCOR (2008): D_6-limited

D_6-correction principle with three hexapoles

$$D_6 \sim \int_{HP\,1,2,3} \Psi_{3S} \cdot u_{\langle A_2 \rangle} \cdot u_{\langle D_4 \rangle} \cdot u_{\alpha}\, dz$$



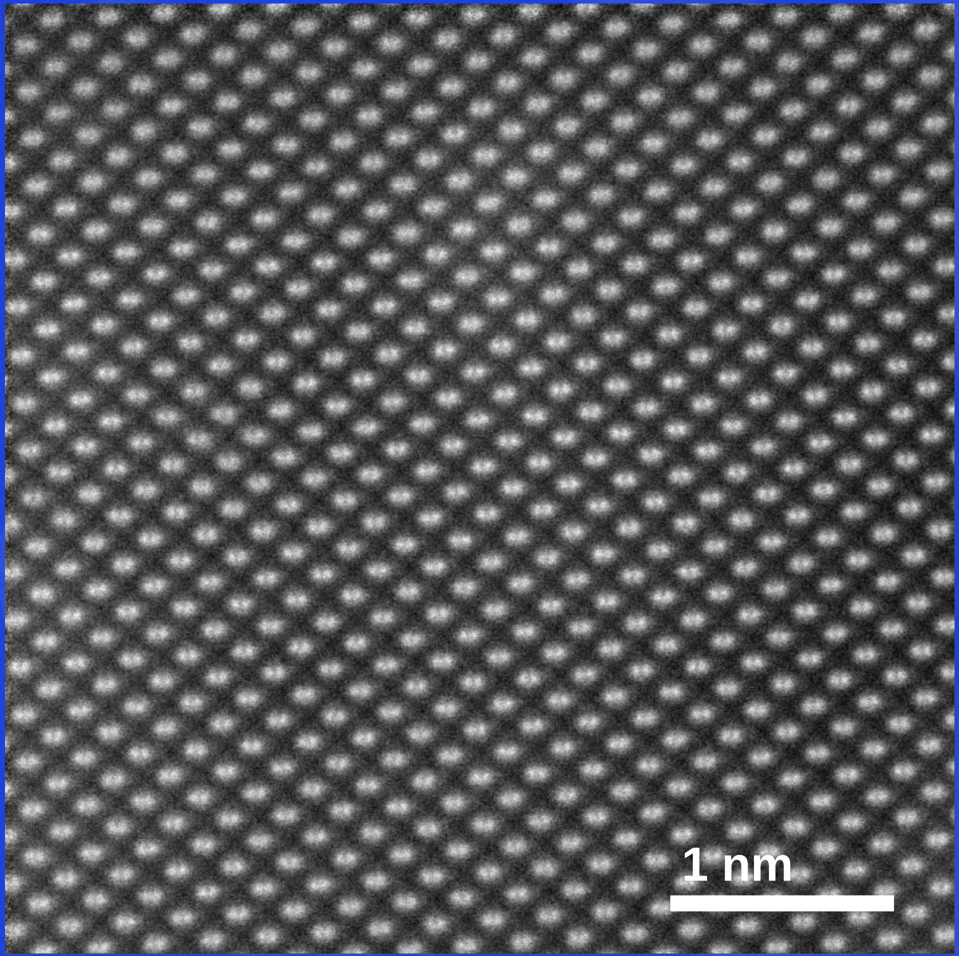
$$D_6 \sim -\int_{HP\,1,2,3} \Psi_{3S} \cdot u_{\langle A_5 \rangle} \cdot u_{\alpha}^2\, dz$$

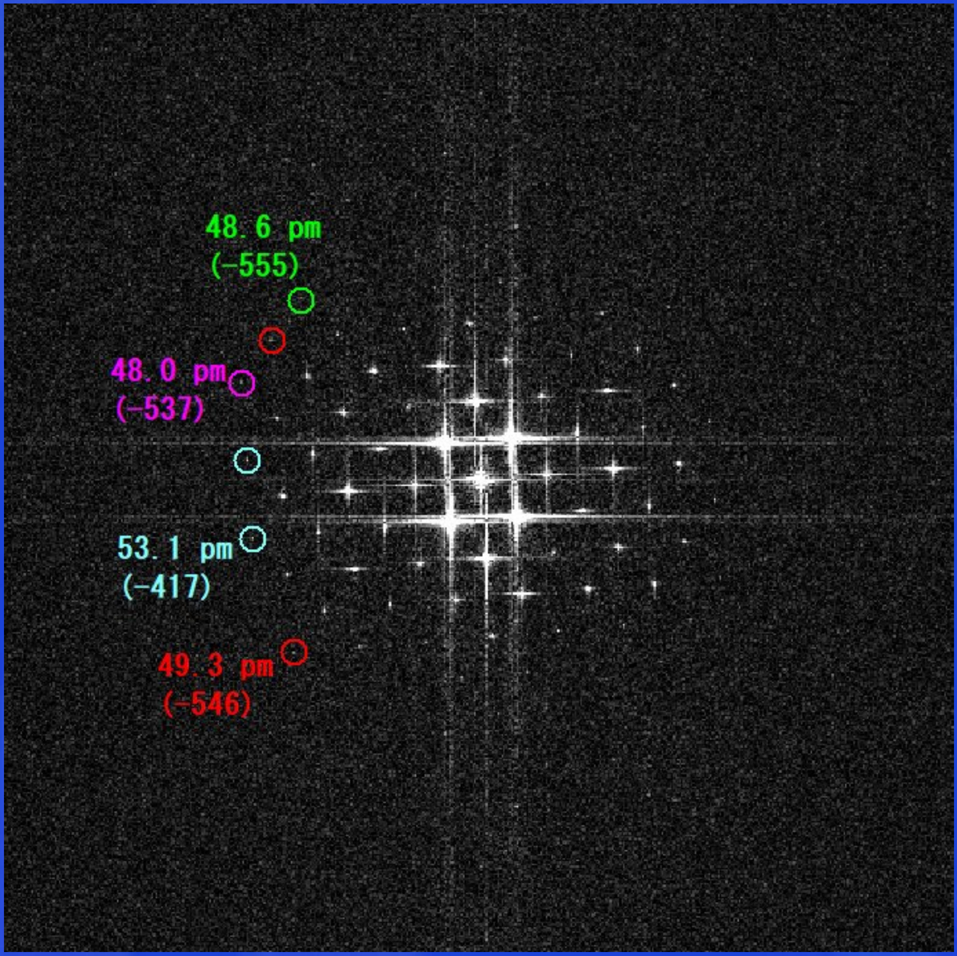
A_5 aberration ray is large in center hexapole

D_6 correction part is considerable and can be used for compensation.
(Not possible for two-HP-correctors.)

LASCOR: Three-hexapole corrector for STEM

STEM HAADF GaN [211]: HR-STEM experiments at 200 keV with oversized aperture



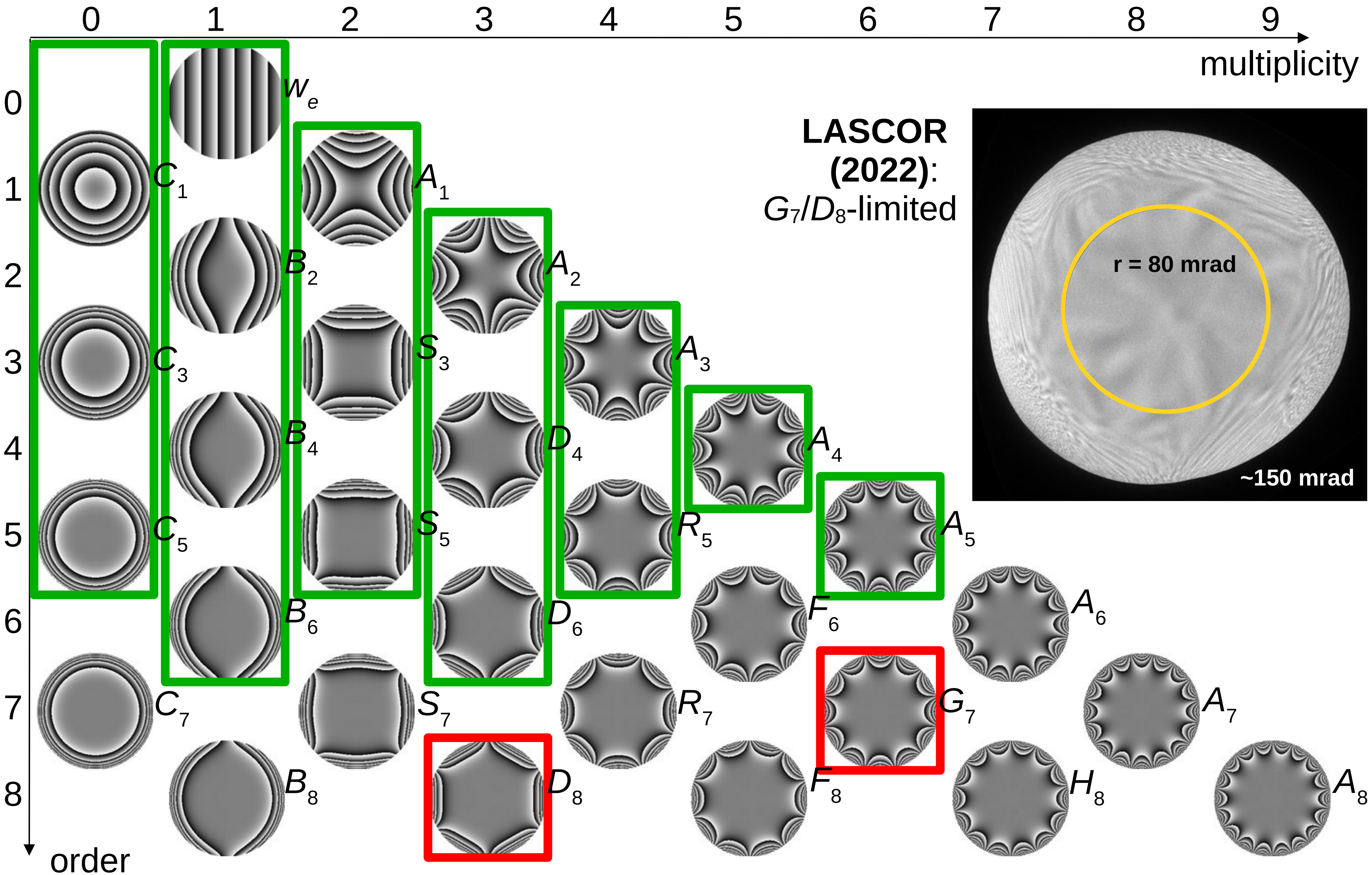


10 aligned images, pixel time 2 us

CFEG (0.34 eV), **α = 48 mrad**

Axial aberrations: three-HP-STEM corrector

CEOS
Corrected Electron Optical Systems GmbH

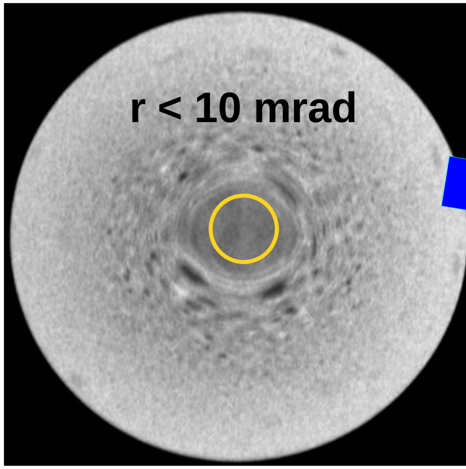


LASCOR (2022):
G_7/D_8-limited

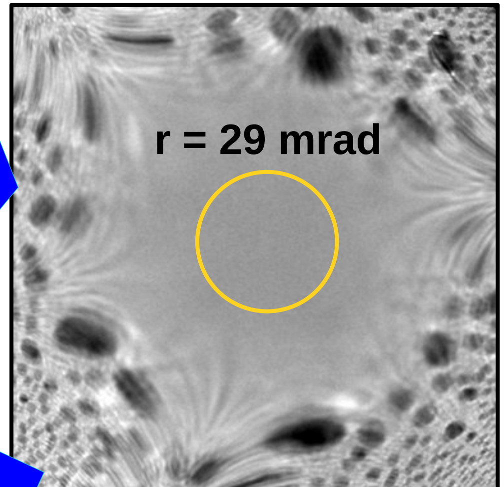
LASCOR: Three-hexapole corrector for STEM

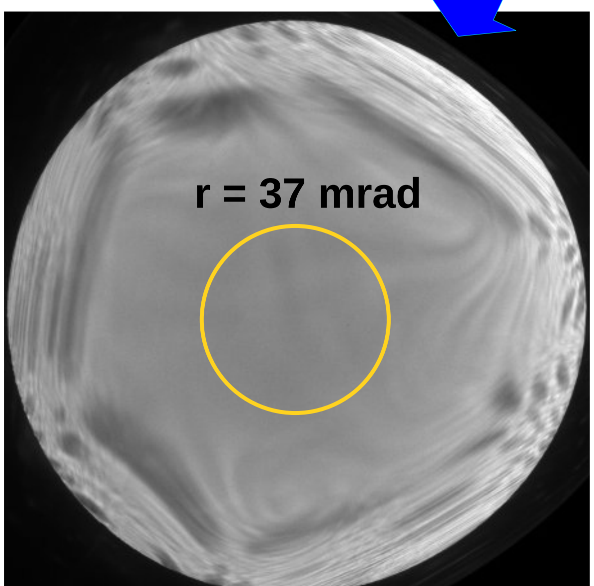
CEOS
Corrected Electron Optical Systems GmbH

uncorrected: C_S-limited



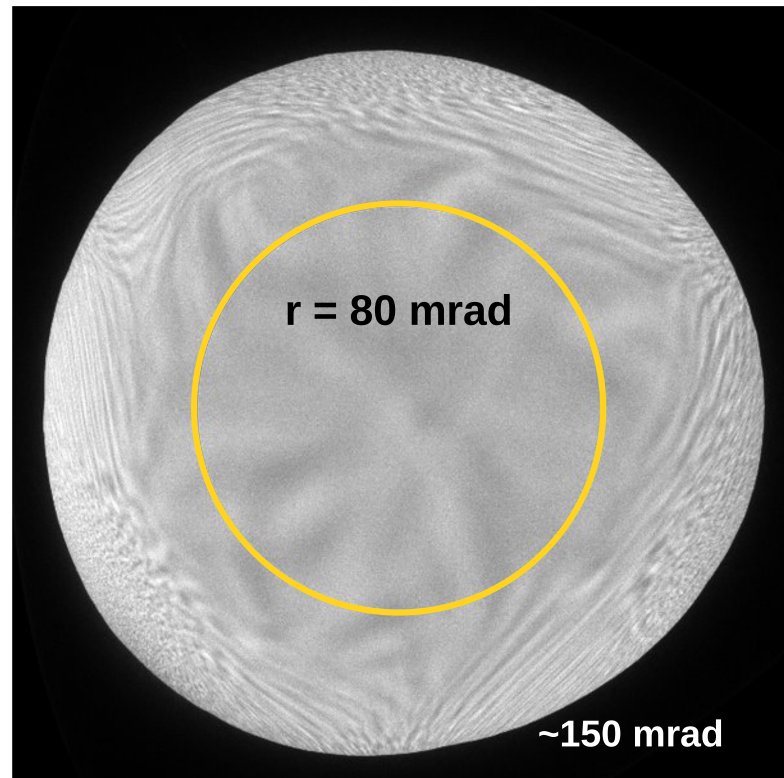
CESCOR (2001): A_5-limited





ASCOR/ DCOR (2008): D_6-limited

Large **A**perture **S**TEM **COR**rector

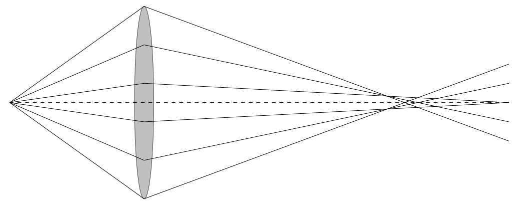


LASCOR (2022): G_7/D_8-limited

Off-axial aberration correction

Unavoidable aberrations of magnetic lenses

Spherical Aberration: C3 ~ r^0, α^3



Off-axial Coma: B3 ~ r^1, α^2

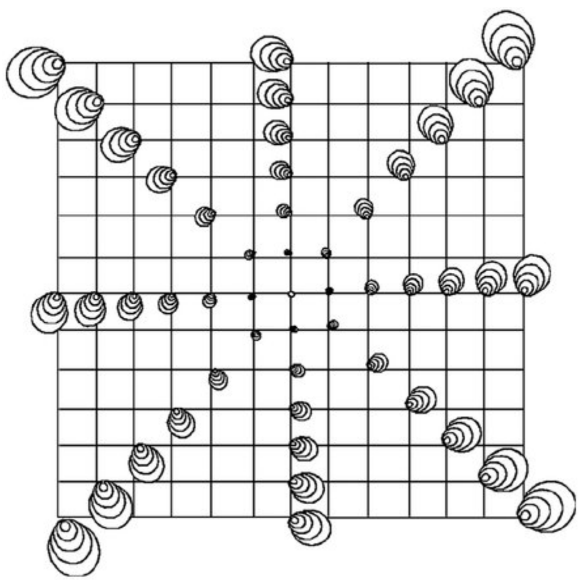
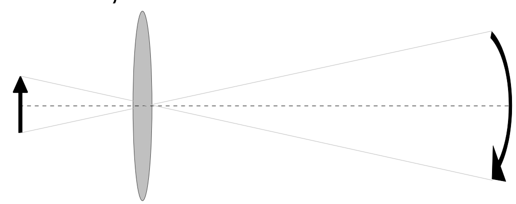
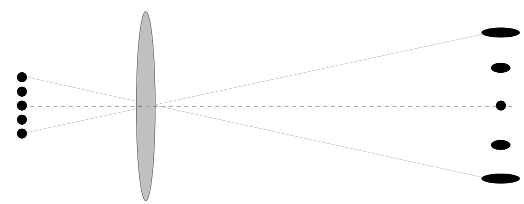


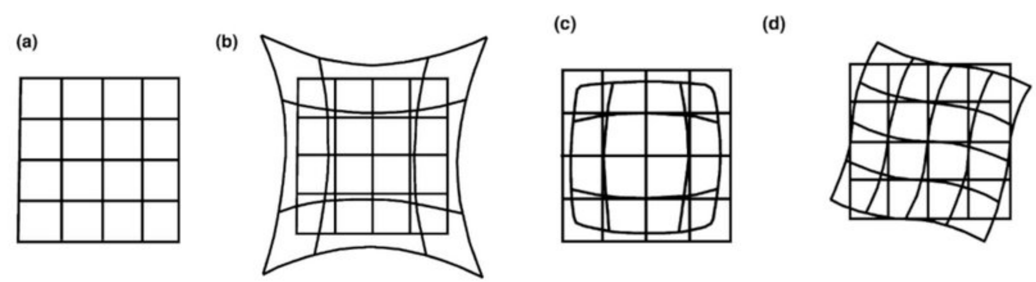
Image curvature: F3 ~ r^2, α^1



Field astigmatism: Af3 ~ r^2, α^1



Pincushion/barrel distortion and spiral distortion:
D3 ~ r^3, α^0

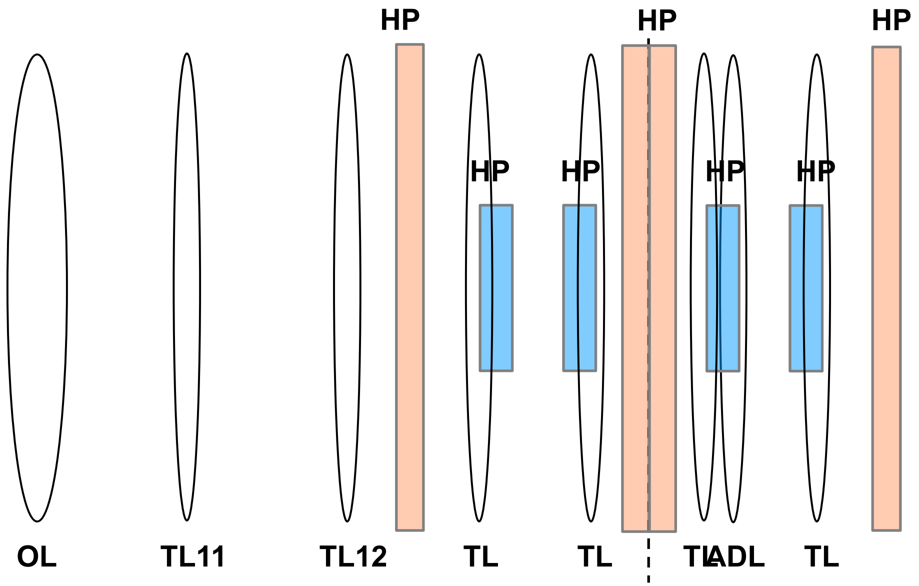


von H. Rose: Geometrical Charged Particle Optics, Springer-Verlag

BCOR: off-axial coma correction

main HPs: strong and symmetric → C_s-correction

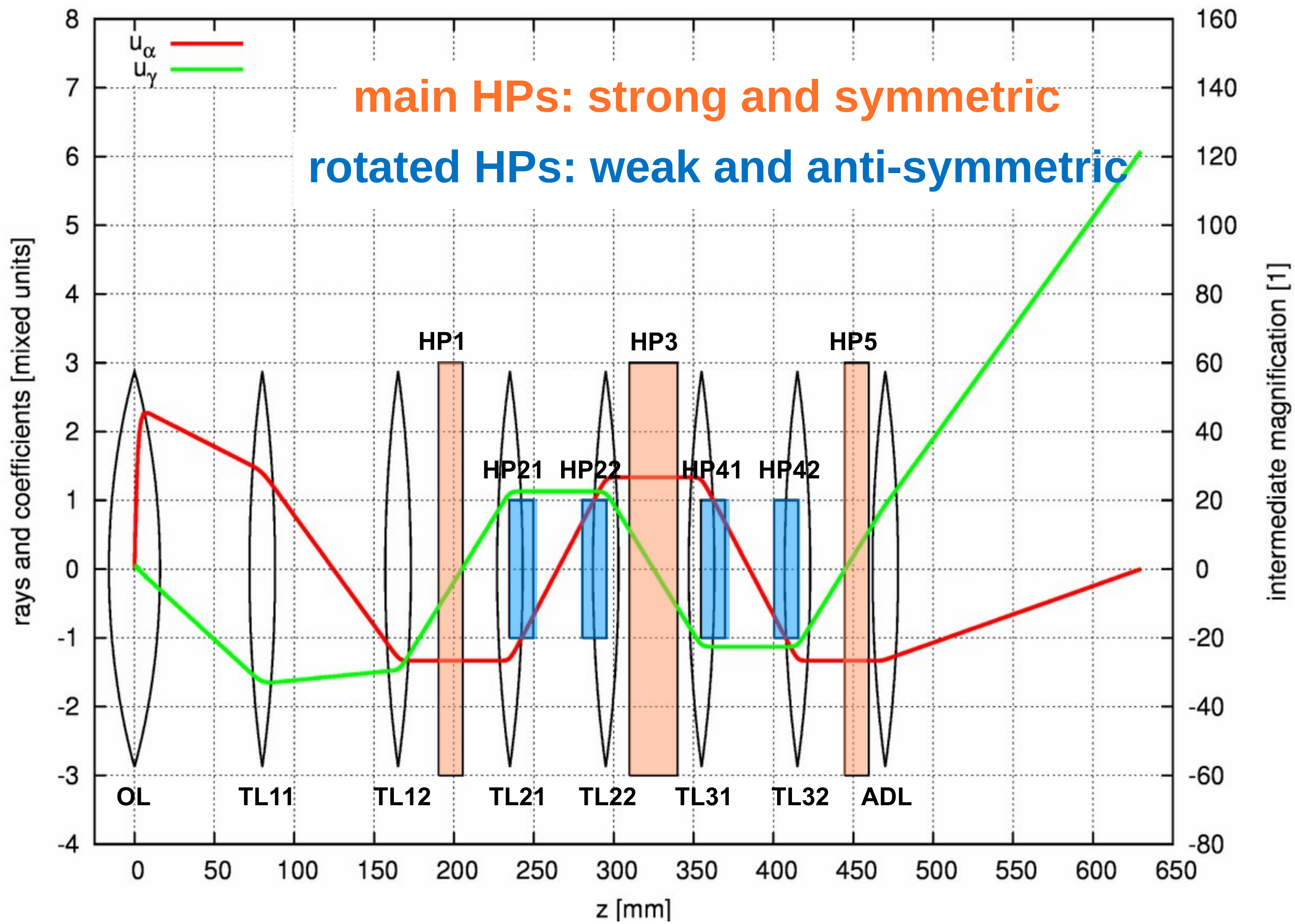
rotated HPs: weak and anti-symmetric → huge D_4 and some B_3



H. Müller, et al.: "*Aplanatic imaging systems for the transmission electron microscope*",
Nuclear Instruments and Methods in Physics Research Section A, Volume 645, Issue 1, p. 20-27, 2011.

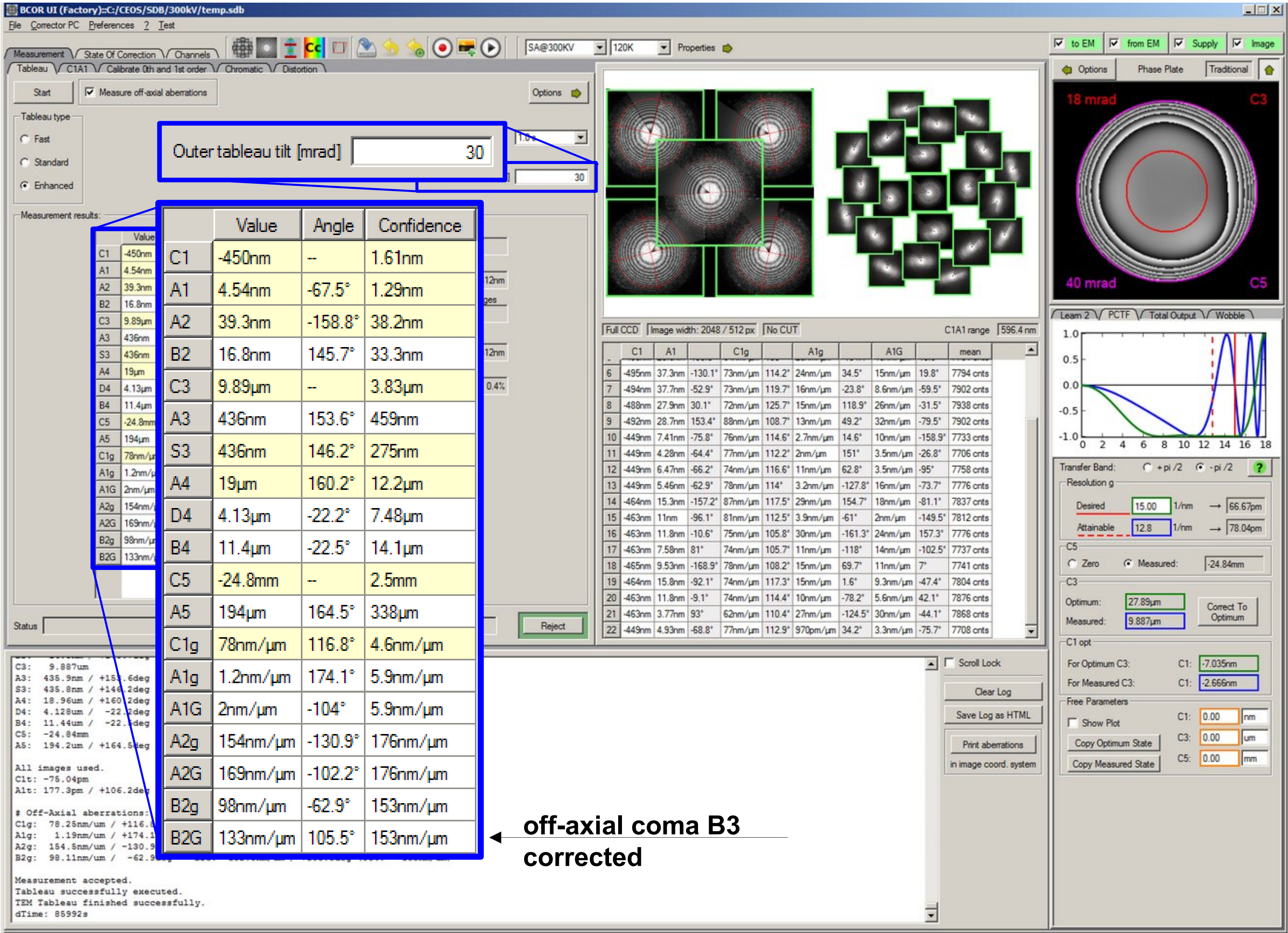
BCOR: off-axial coma correction

CEOS
Corrected Electron Optical Systems GmbH



H. Müller, et al.: "*Aplanatic imaging systems for the transmission electron microscope*", Nuclear Instruments and Methods in Physics Research Section A, Volume 645, Issue 1, p. 20-27, 2011.

BCOR: off-axial coma correction



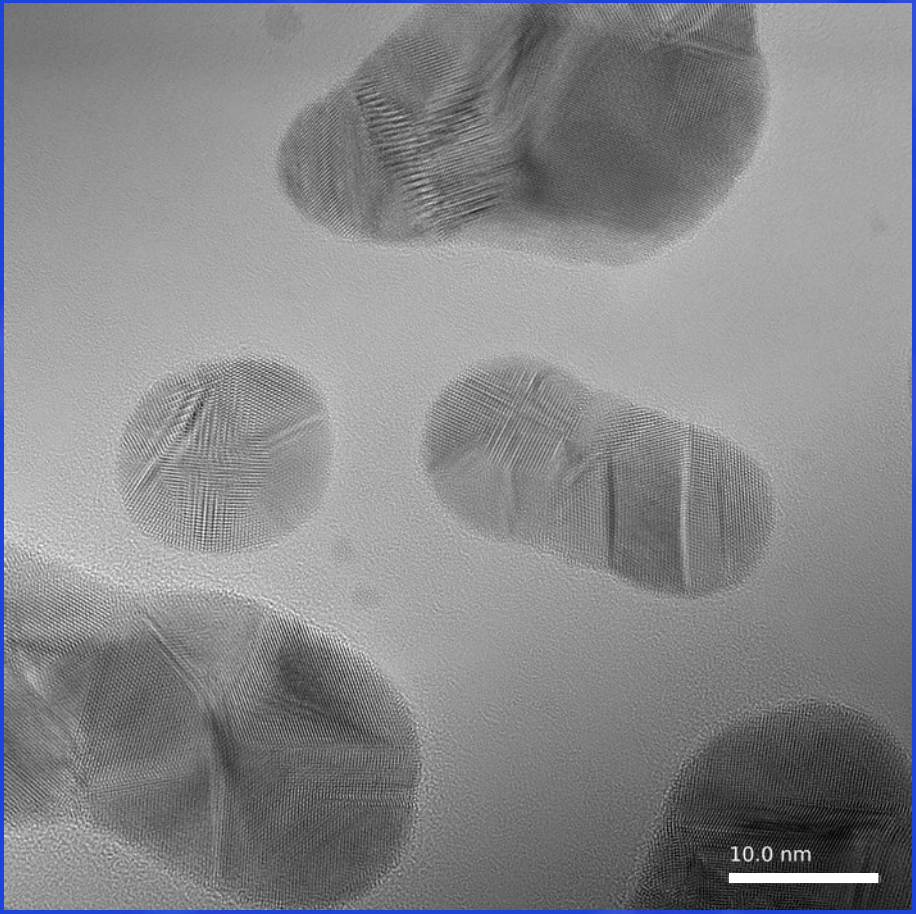
	Value	Angle	Confidence
C1	-450nm	--	1.61nm
A1	4.54nm	-67.5°	1.29nm
A2	39.3nm	-158.8°	38.2nm
B2	16.8nm	145.7°	33.3nm
C3	9.89µm	--	3.83µm
A3	436nm	153.6°	459nm
S3	436nm	146.2°	275nm
A4	19µm	160.2°	12.2µm
D4	4.13µm	-22.2°	7.48µm
B4	11.4µm	-22.5°	14.1µm
C5	-24.8mm	--	2.5mm
A5	194µm	164.5°	338µm
C1g	78nm/µm	116.8°	4.6nm/µm
A1g	1.2nm/µm	174.1°	5.9nm/µm
A1G	2nm/µm	-104°	5.9nm/µm
A2g	154nm/µm	-130.9°	176nm/µm
A2G	169nm/µm	-102.2°	176nm/µm
B2g	98nm/µm	-62.9°	153nm/µm
B2G	133nm/µm	105.5°	153nm/µm

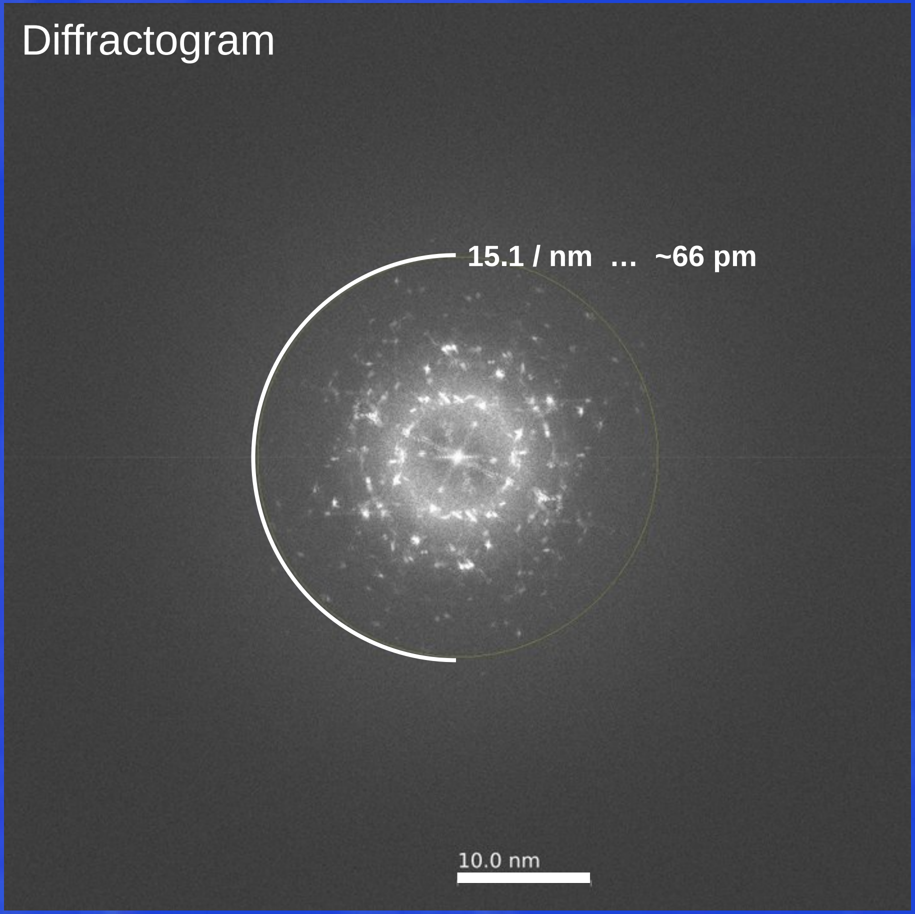
off-axial coma B3 corrected

Titan Krios with BCOR: Performance at 300kV

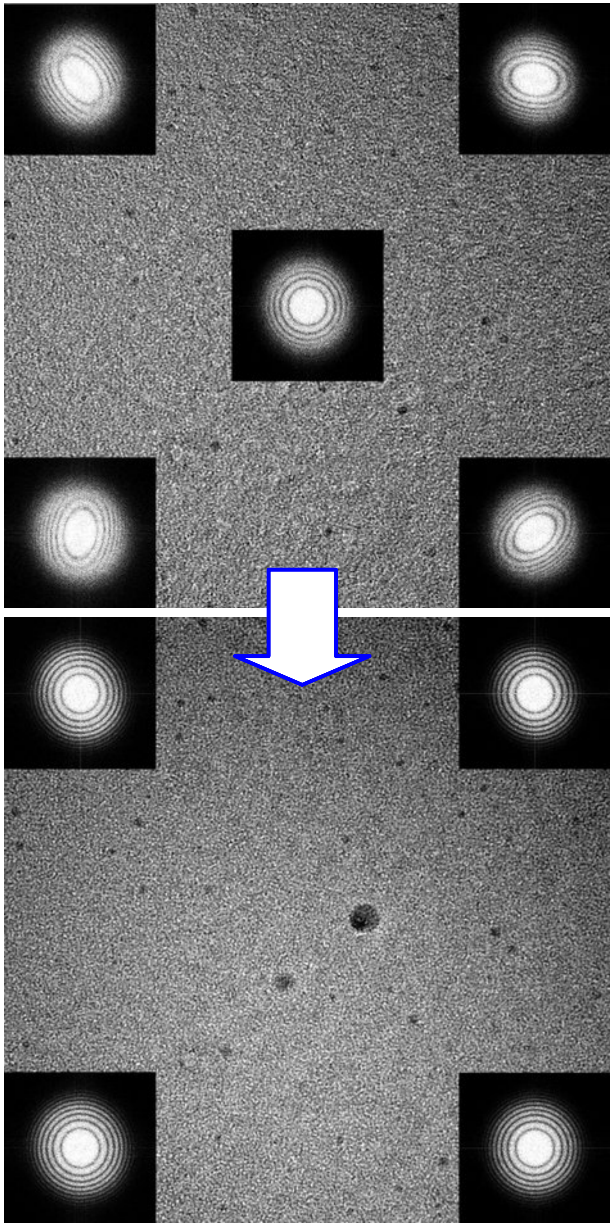
CEOS
Corrected Electron Optical Systems GmbH

- Cryo-lens, total Cc at 300kV ~ 3.9mm
- monochromated illumination (unknown energy witdh, no spectrometer on the system)
- indicated magnification: MH380kx … Nyquist = 34.1 / nm … pixel size = 14.7 pm
- Gold particles on ultrathin Carbon
- 2 sec exposures on 4096x4096 CETA camera





BCOR applications



tuning the off-axial astigmatism with BCOR

sample:
amorphous tungsten

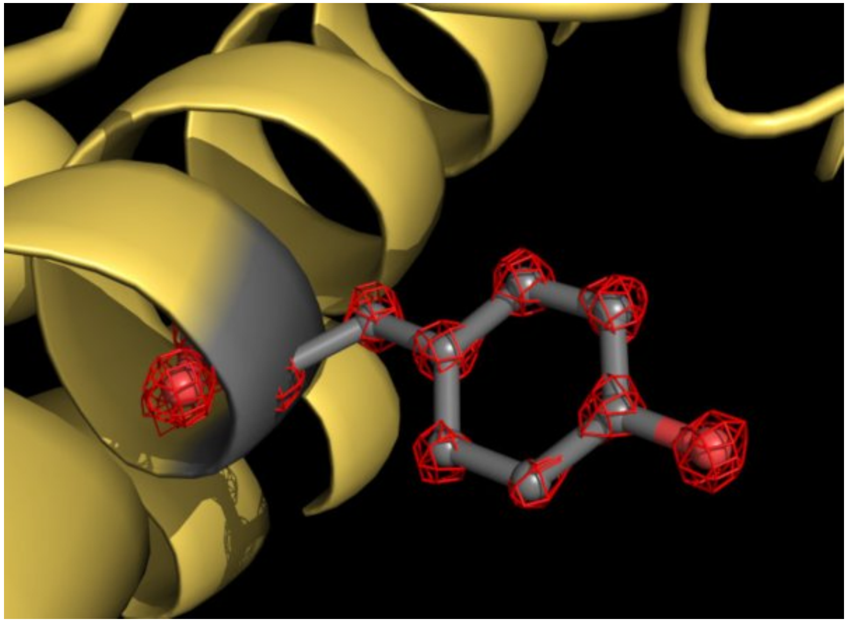
field of view:
~ 191 nm x 191 nm

BCOR in Life Sciences:

First time resolving individual atoms in a proteine structure using cryo electron microscopy.

yellow: part of an Apoferritin proteine
grey: Tyrosin side-chain consisting of several atoms
red: individual resolved atoms in Tyrosin structure

Data was collected in a TFS Krios operated at 300kV with BCOR and monochromator.



Ka Man Yip, Niels Fischer, Elham Paknia, Ashwin Chari, Holger Stark:
Atomic-resolution protein structure determination by cryo-EM.
Nature 587, 157-161, October 21, 2020.

Aberration correction for electron lenses using quadrupoles and octupoles

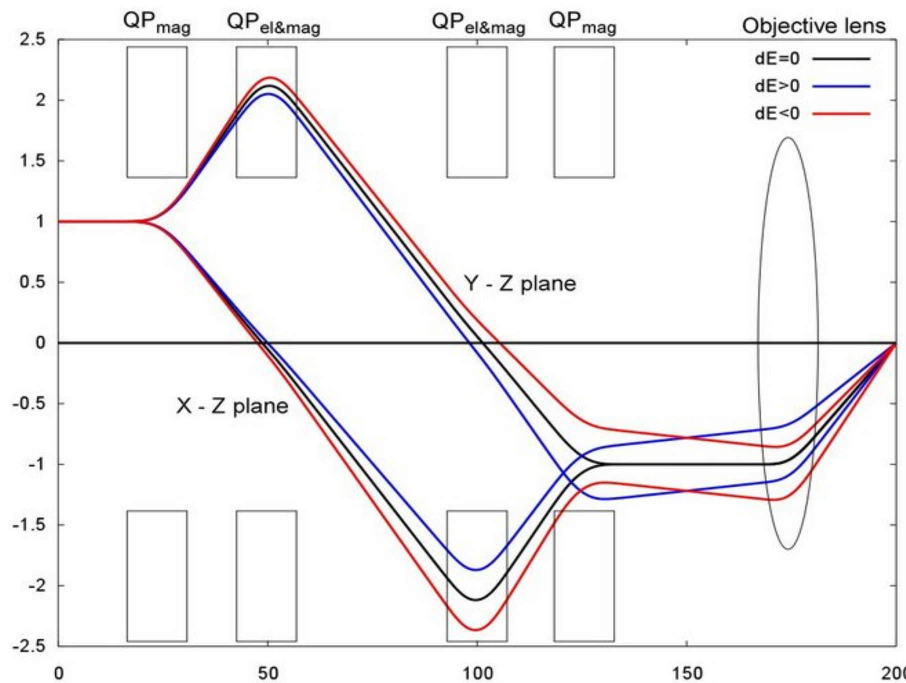
CEOS
Corrected Electron Optical Systems GmbH

1995: First ever working and resolution improving corrector

Optik 98, No. 3 (1995) 112–118 © Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart

Correction of spherical and chromatic aberration in a low voltage SEM

J. Zach, M. Haider

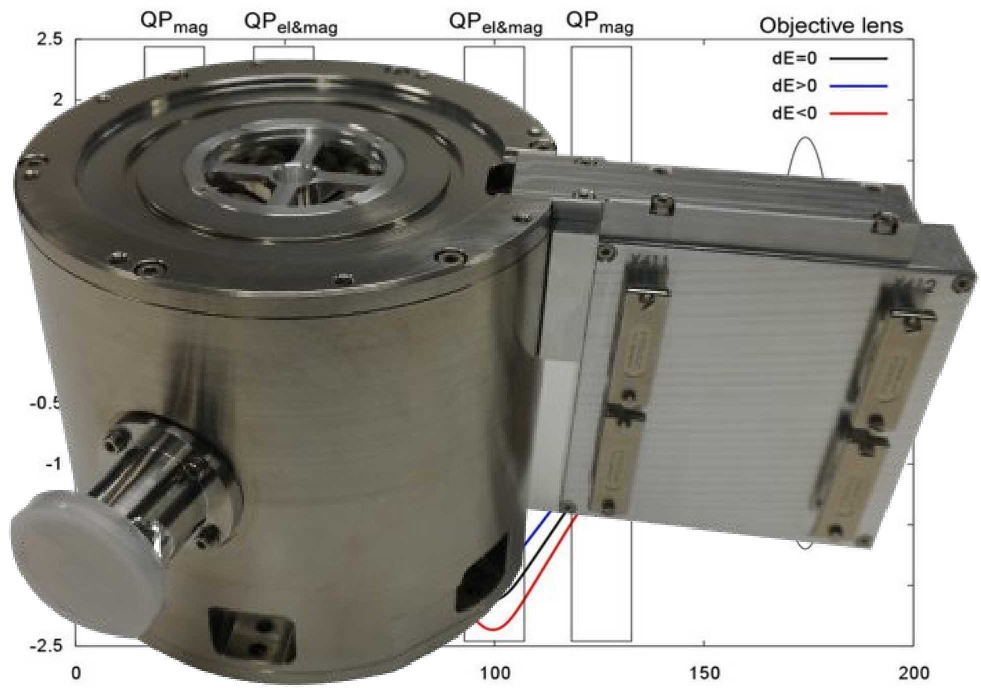


1995: First ever working and resolution improving corrector

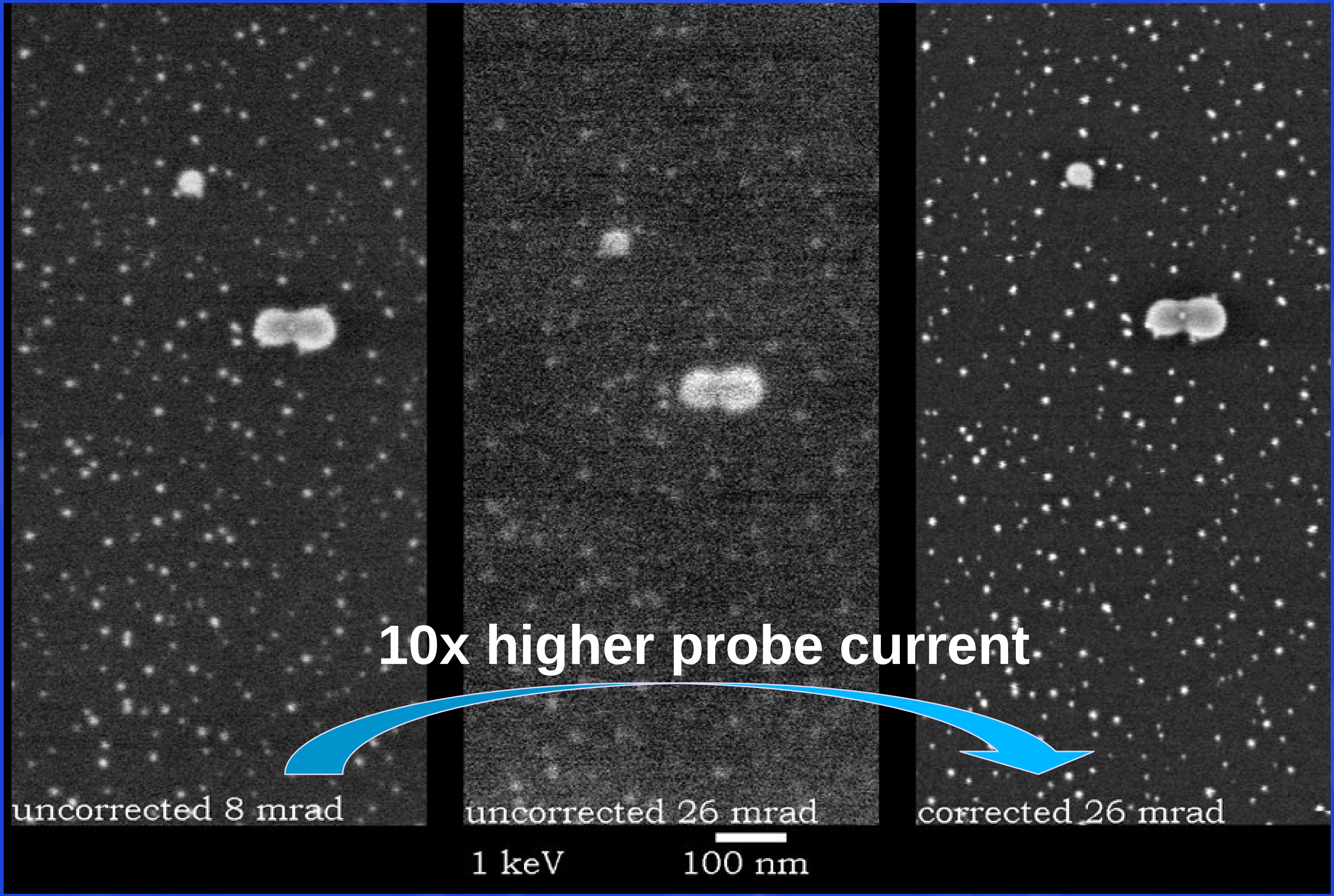
Optik 98, No. 3 (1995) 112–118 © Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart

Correction of spherical and chromatic aberration in a low voltage SEM

J. Zach, M. Haider

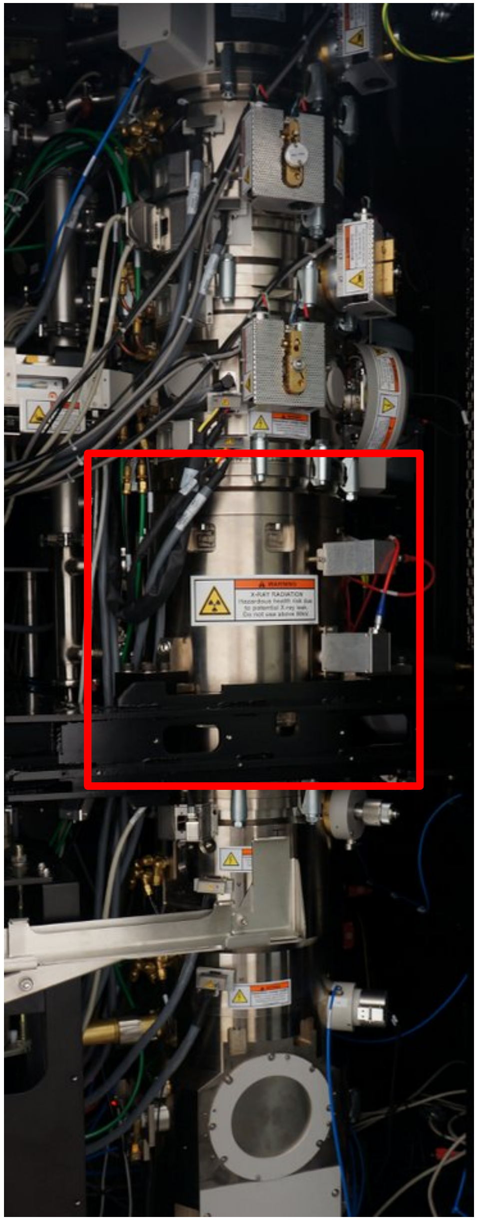


C_c- and C_s-correction for a low-voltage SEM

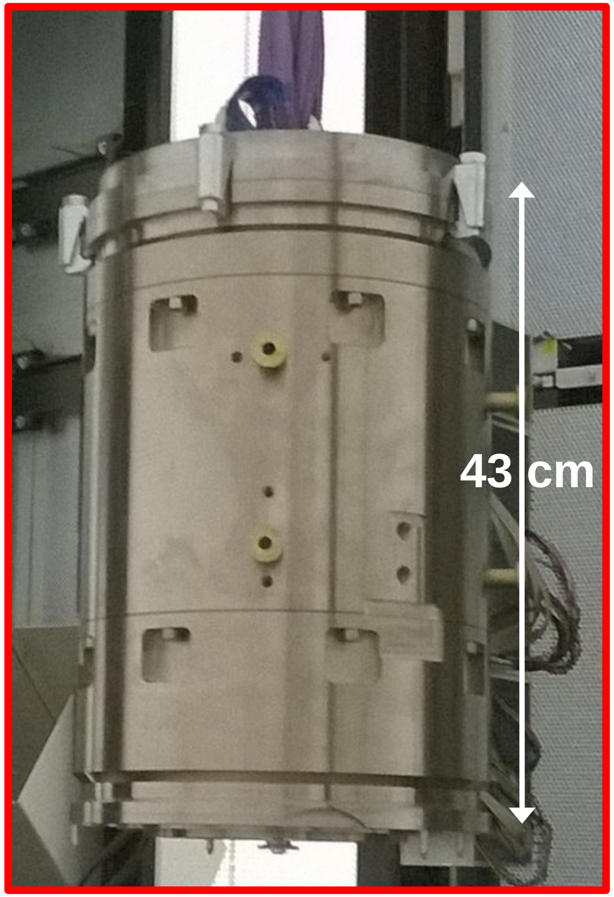


SALVE – Instrument Overview

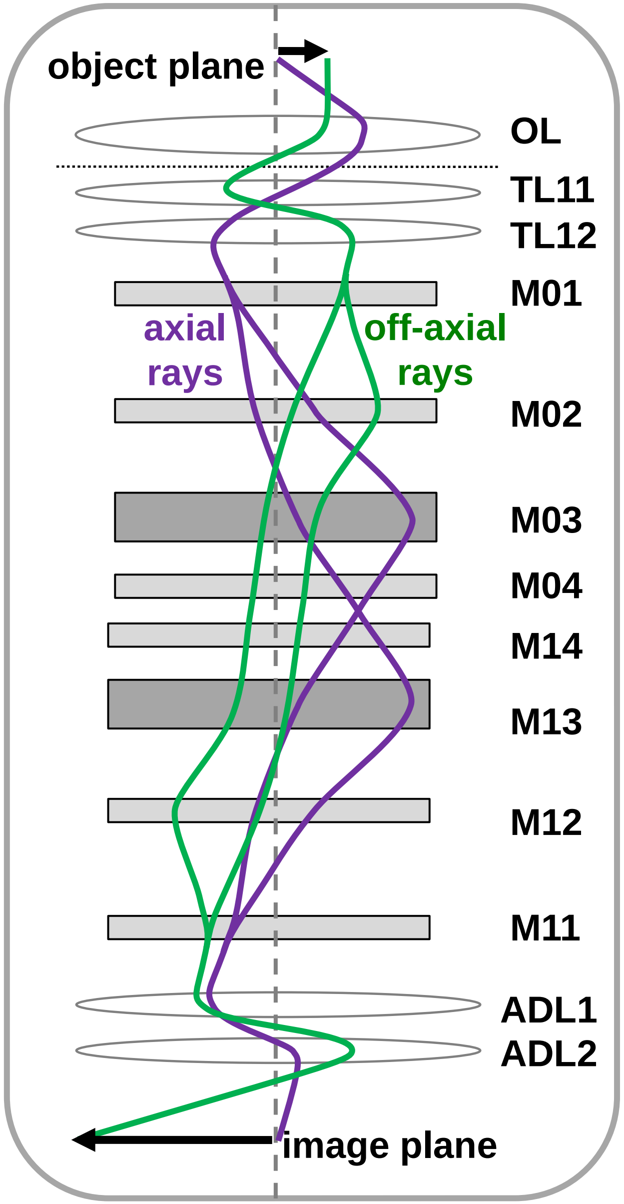
CEOS
Corrected Electron Optical Systems GmbH



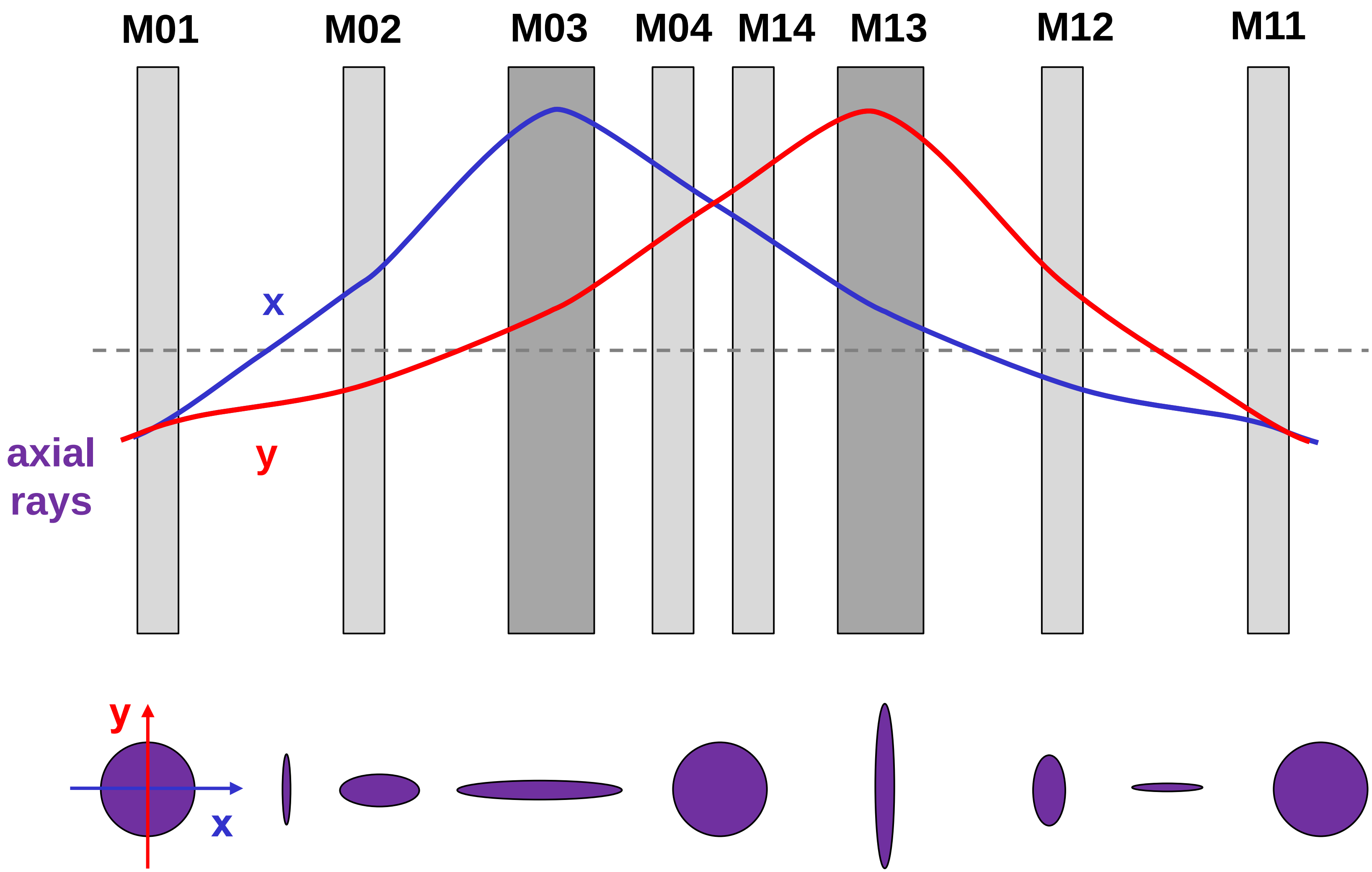
SALVE-C_c-C_s-corrector



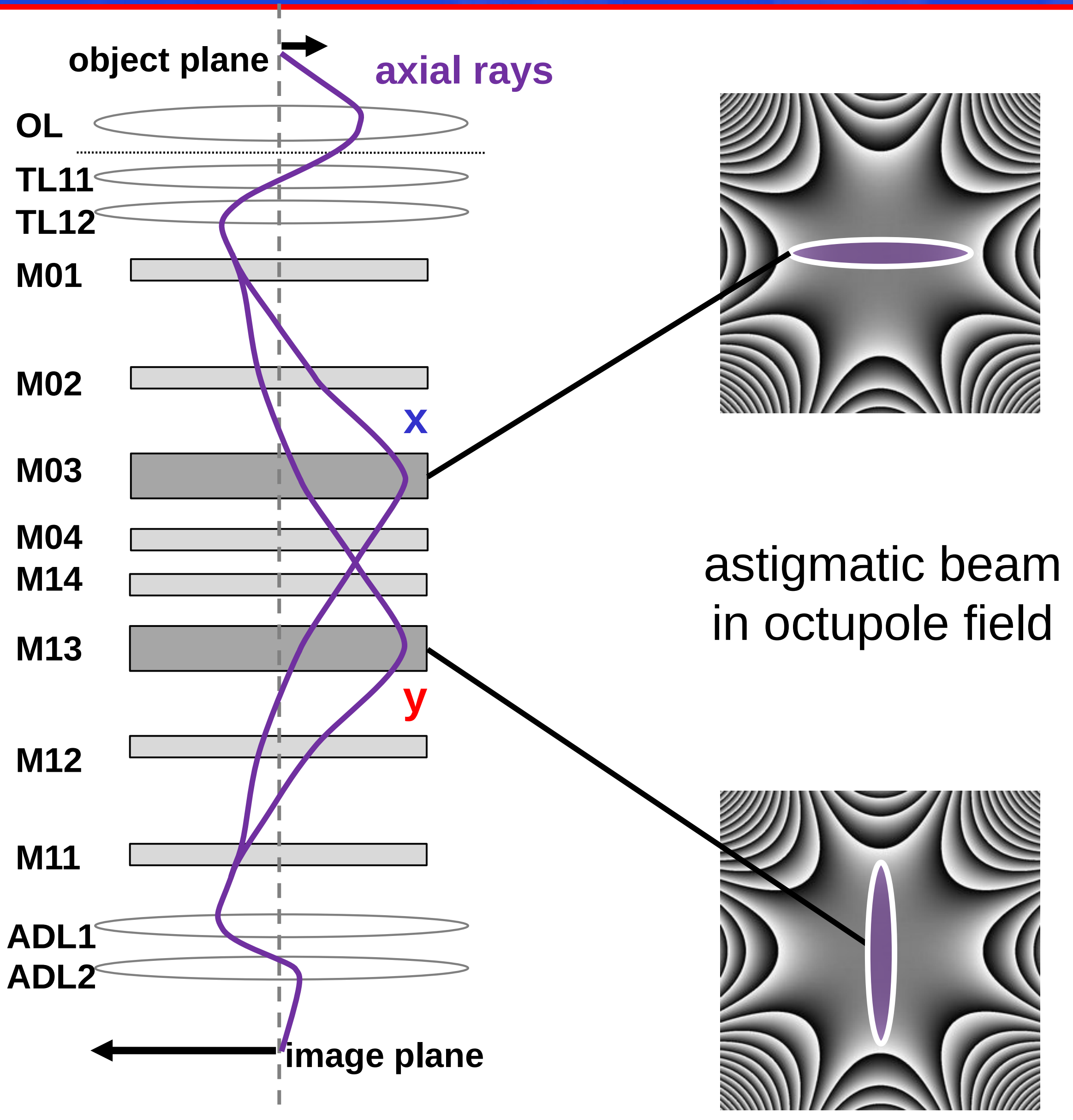
~ 185 kg



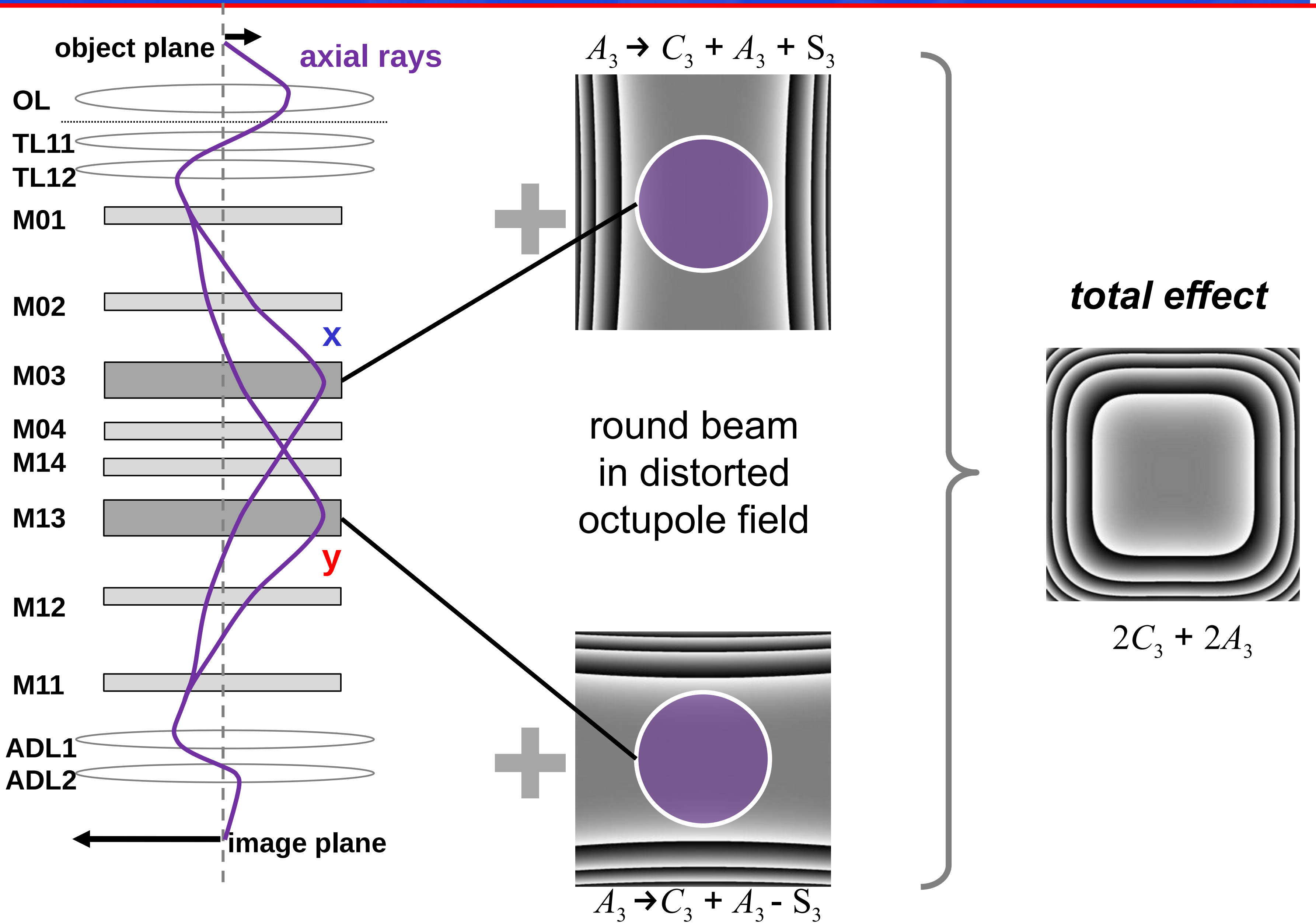
SALVE – Basic Ray Path



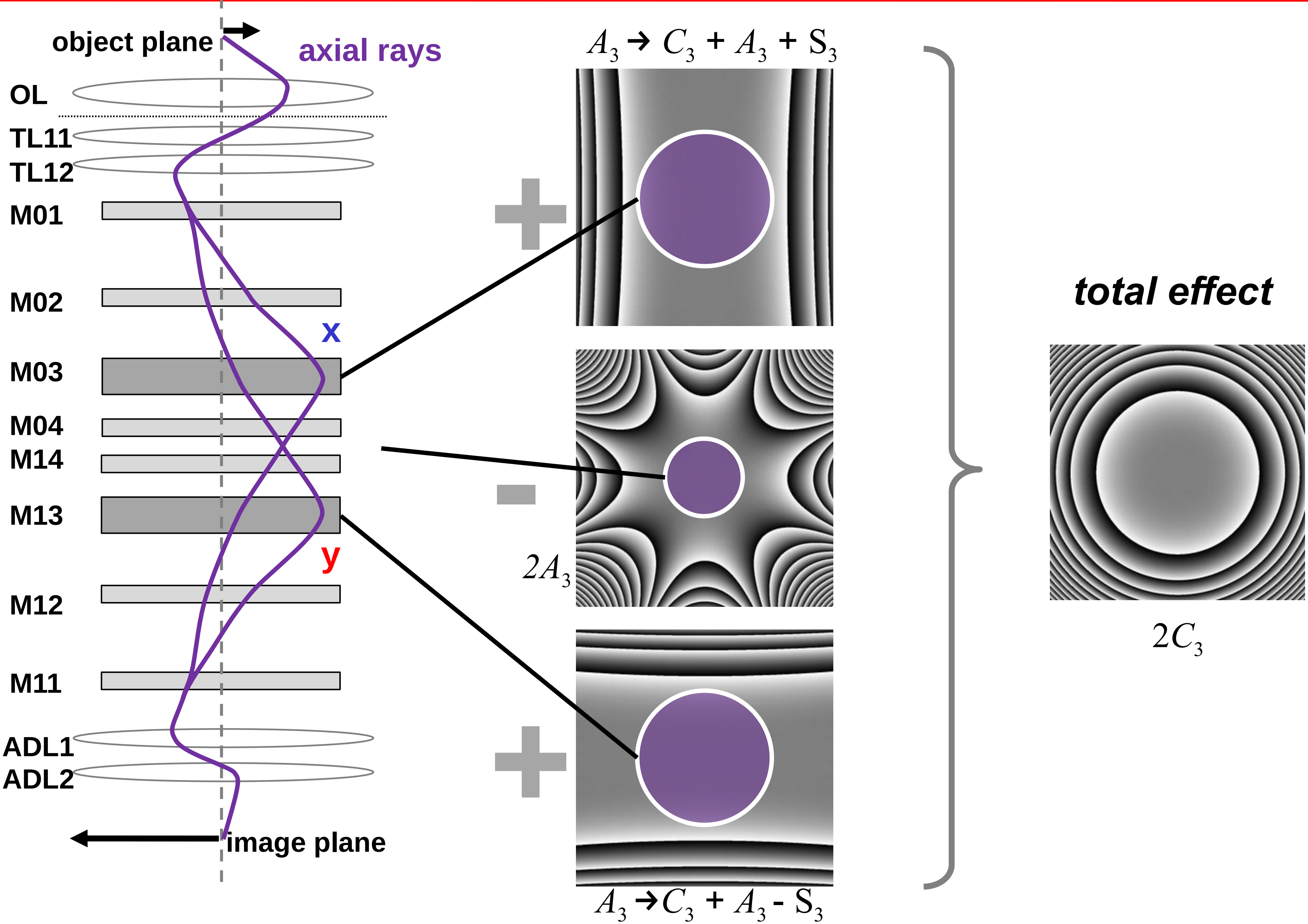
SALVE – Correction of spherical aberration



SALVE – Correction of spherical aberration



SALVE – Correction of spherical aberration



nion: C_s-correction in a dedicated STEM

NIklas Dellby and **ON**drey Krivanek

kavliprize.org

wikipedia.org

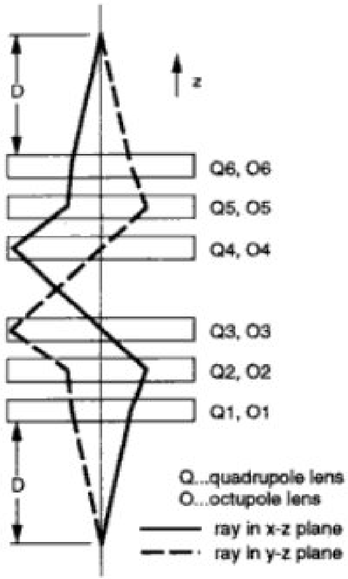
check **www.nion.com**

now part of BRUKER

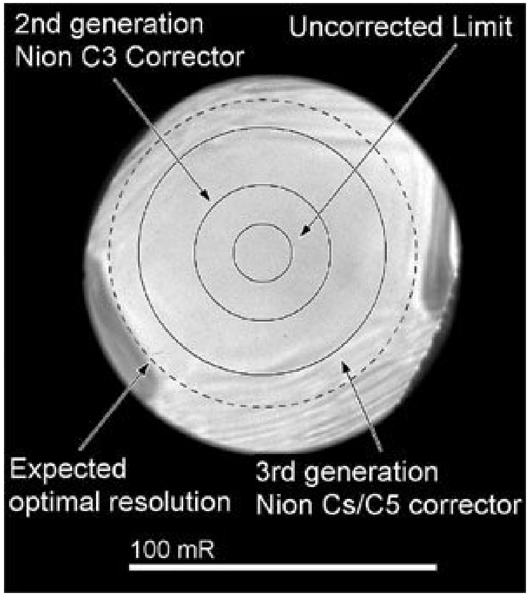
Nion UltraSTEM 100

http://www.nion.com

- resolution improvement by Cs-correction in a VG HB5 STEM (1997)
  based on a 1964 concept from J. Deltrap, Cavendish labs (UK)
- today: complete nion STEM column with monochromator and spectrometer

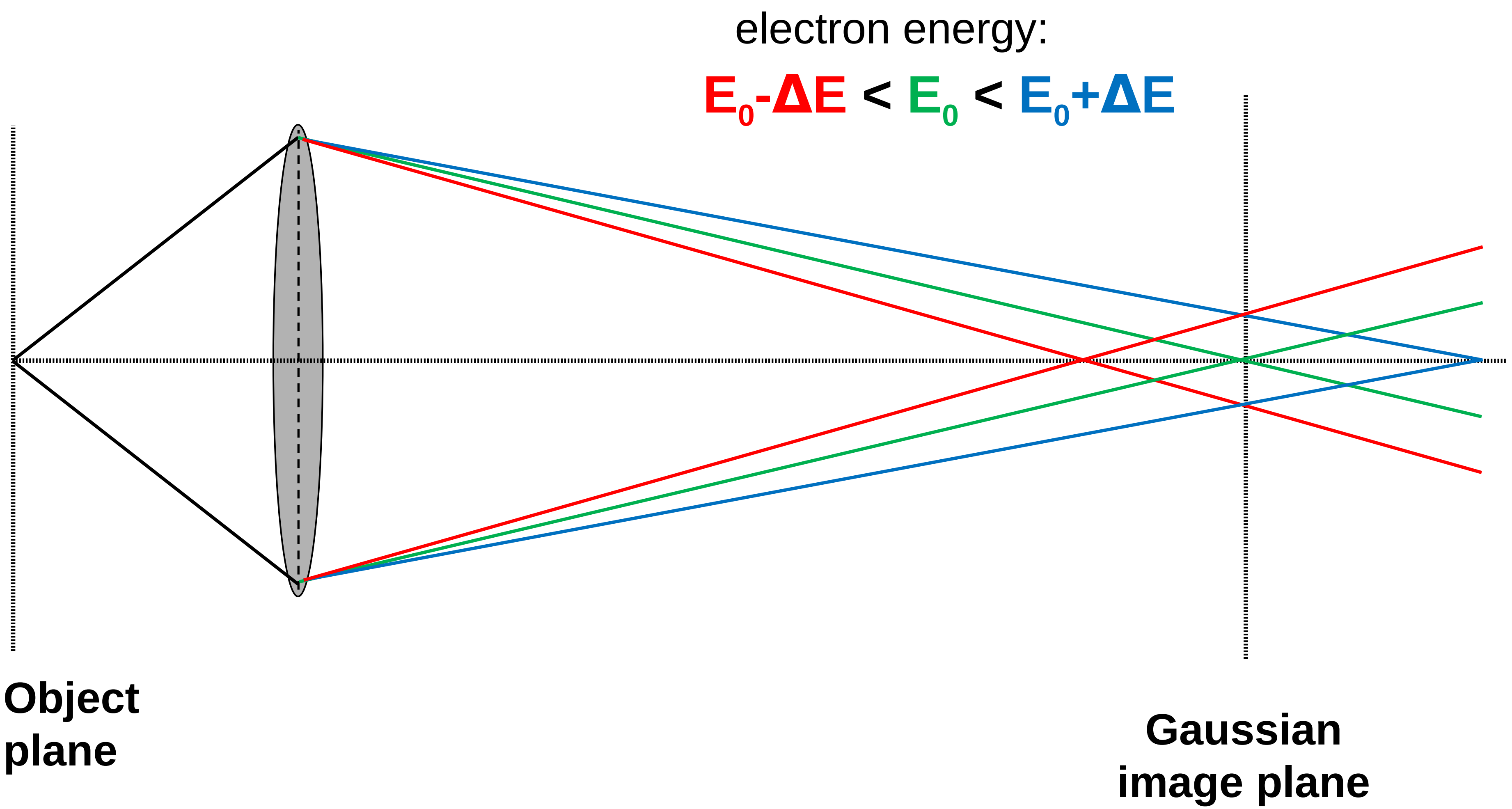


from: Krivanek et al. Inst. Phys. Conf.Ser.153 (Proc. 1997 EMAG)

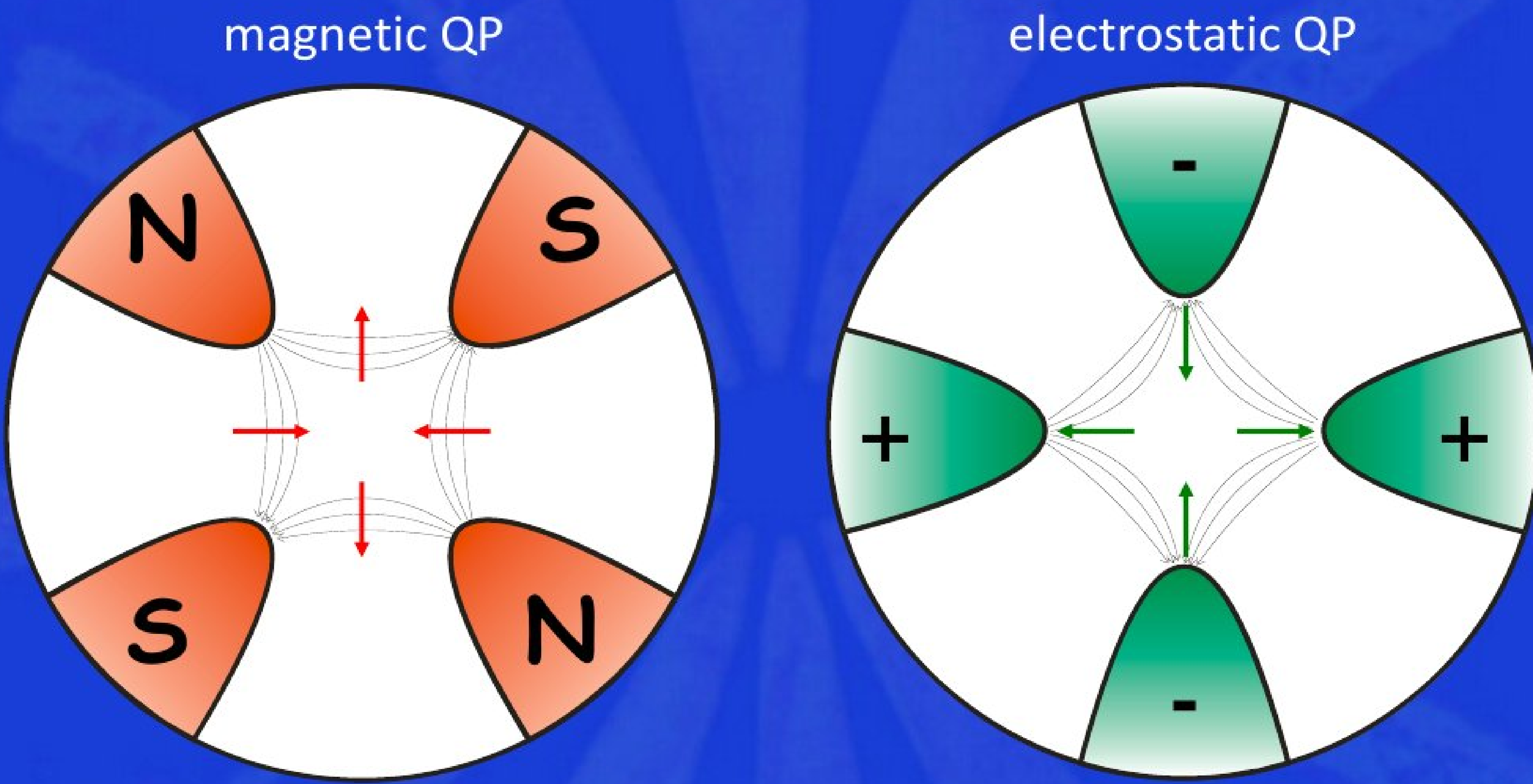


http://www.nion.com

Chromatic aberration correction



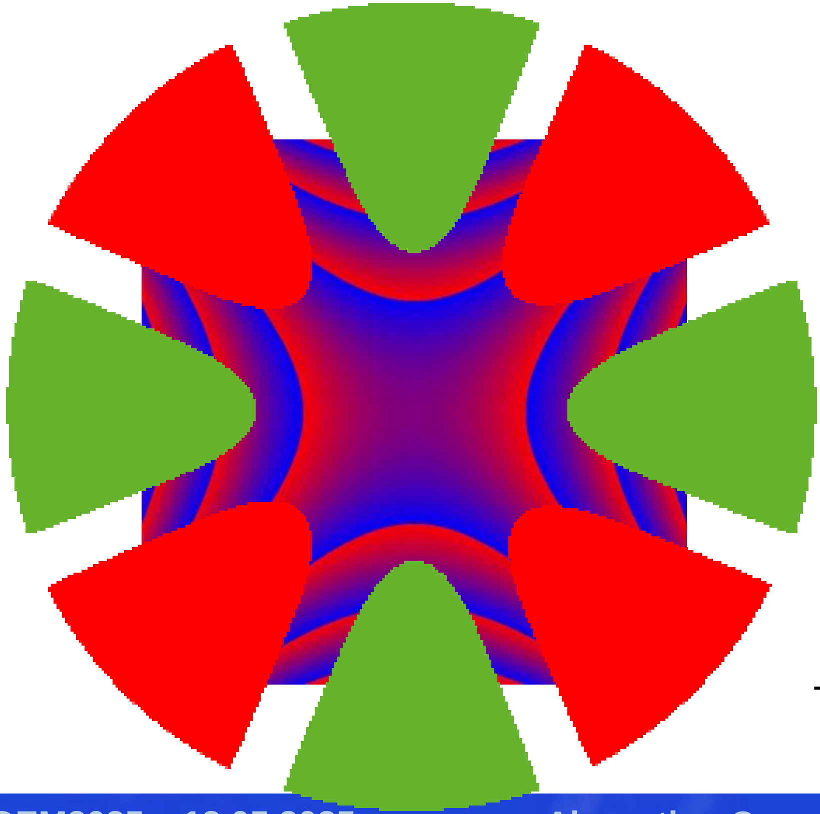
Chromatic aberration correction



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Crossed electric and magnetic fields:

equation of motion $$\frac{d}{dt}(m\vec{v}) = -e(\vec{E} + \vec{v} \times \vec{B})$$



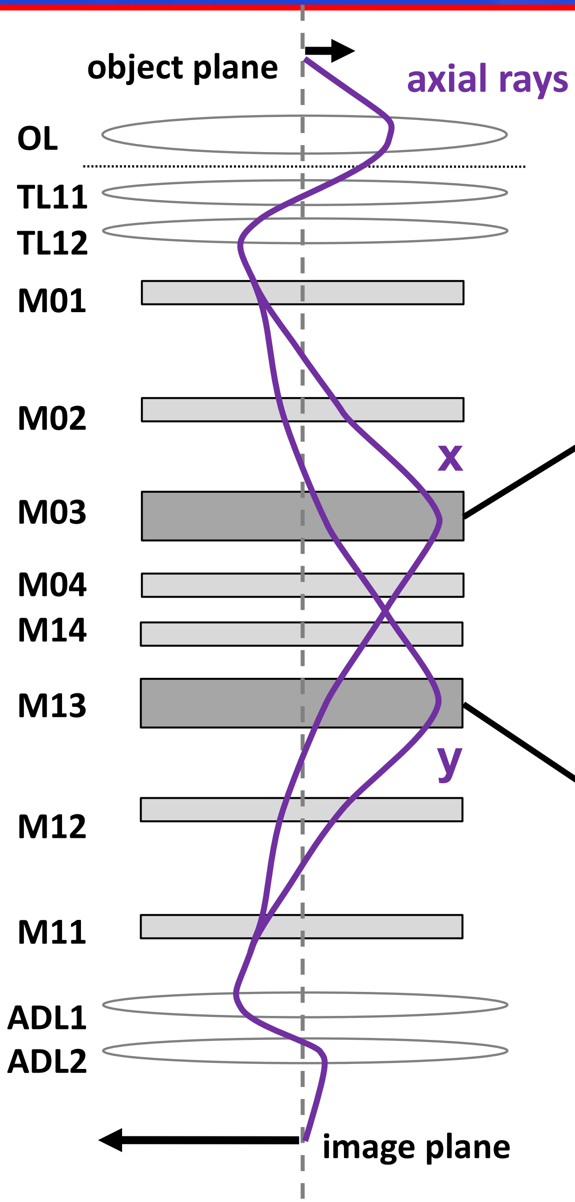
Wien filter: = 0
for exact energy E_0

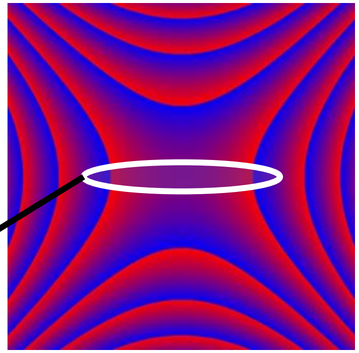
$E < E_0$: quadrupole effect

$E > E_0$: opposite QP effect

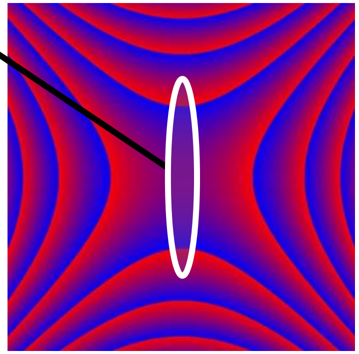
→ **"chromatic quadrupole"** A_{1c}

SALVE - Correction of chromatic aberration

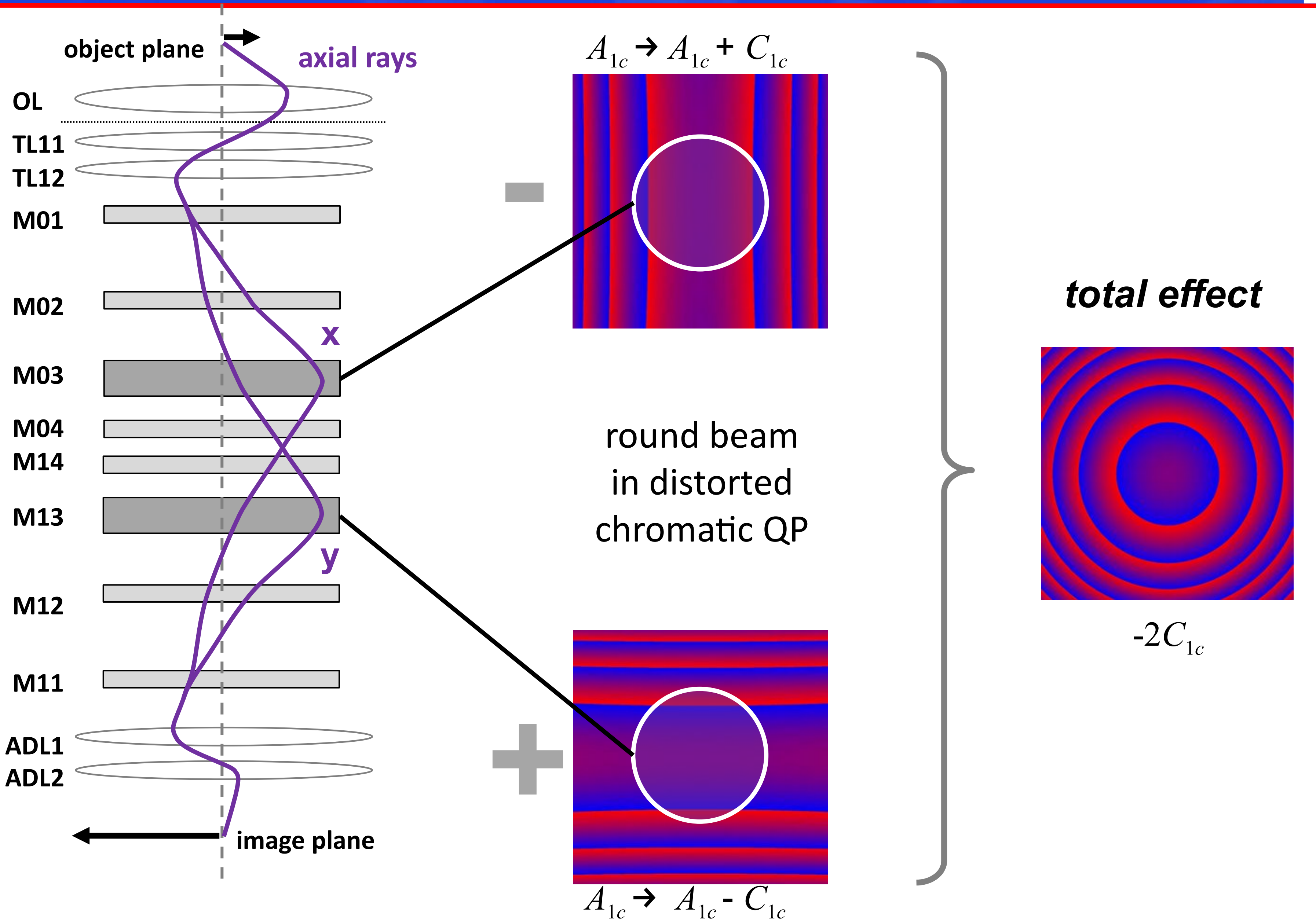




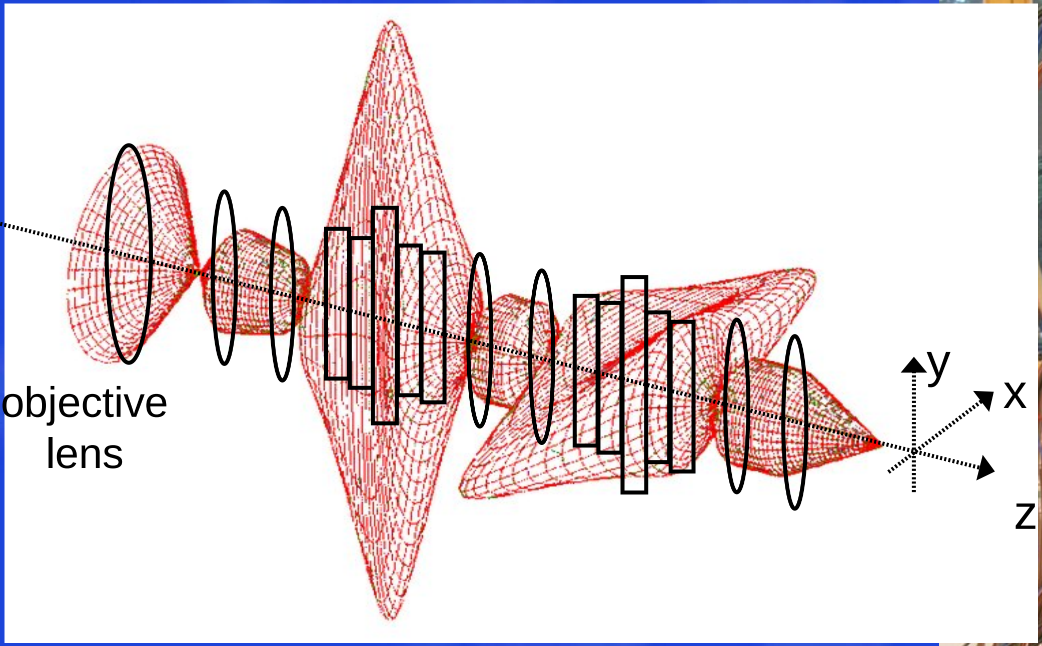
astigmatic beam
in chromatic QP

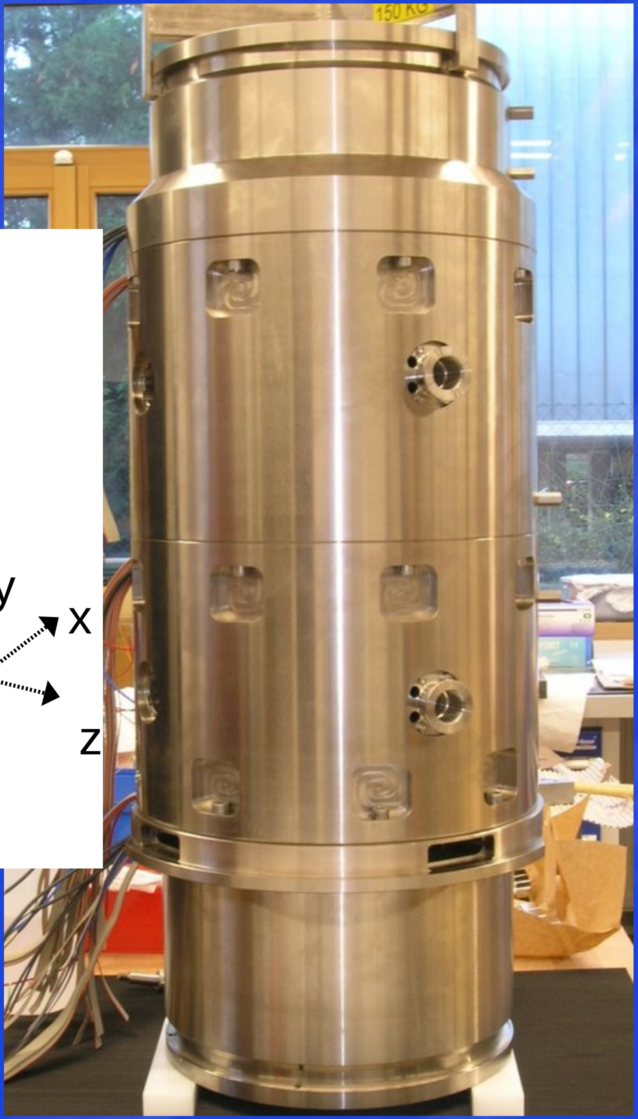


SALVE - Correction of chromatic aberration



Chromatic aberration correction: CCOR



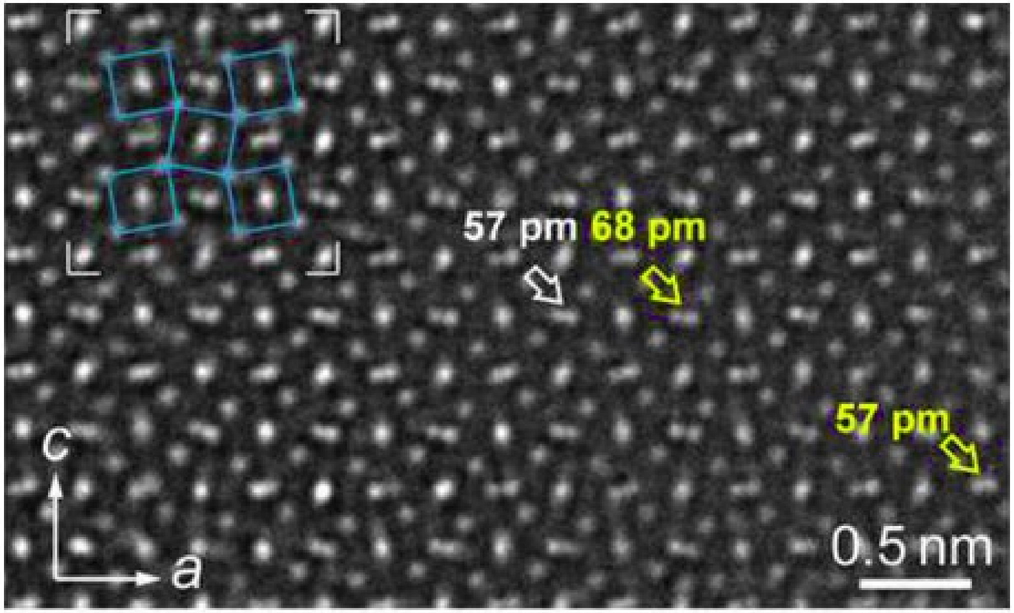


828 mm

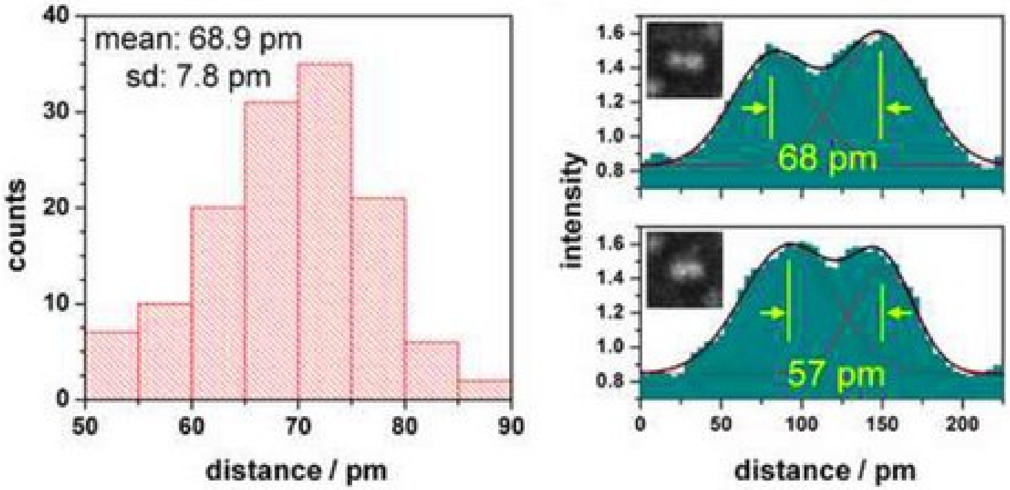
470 kg,
160 channels

PICO: application with 50pm at 200kV

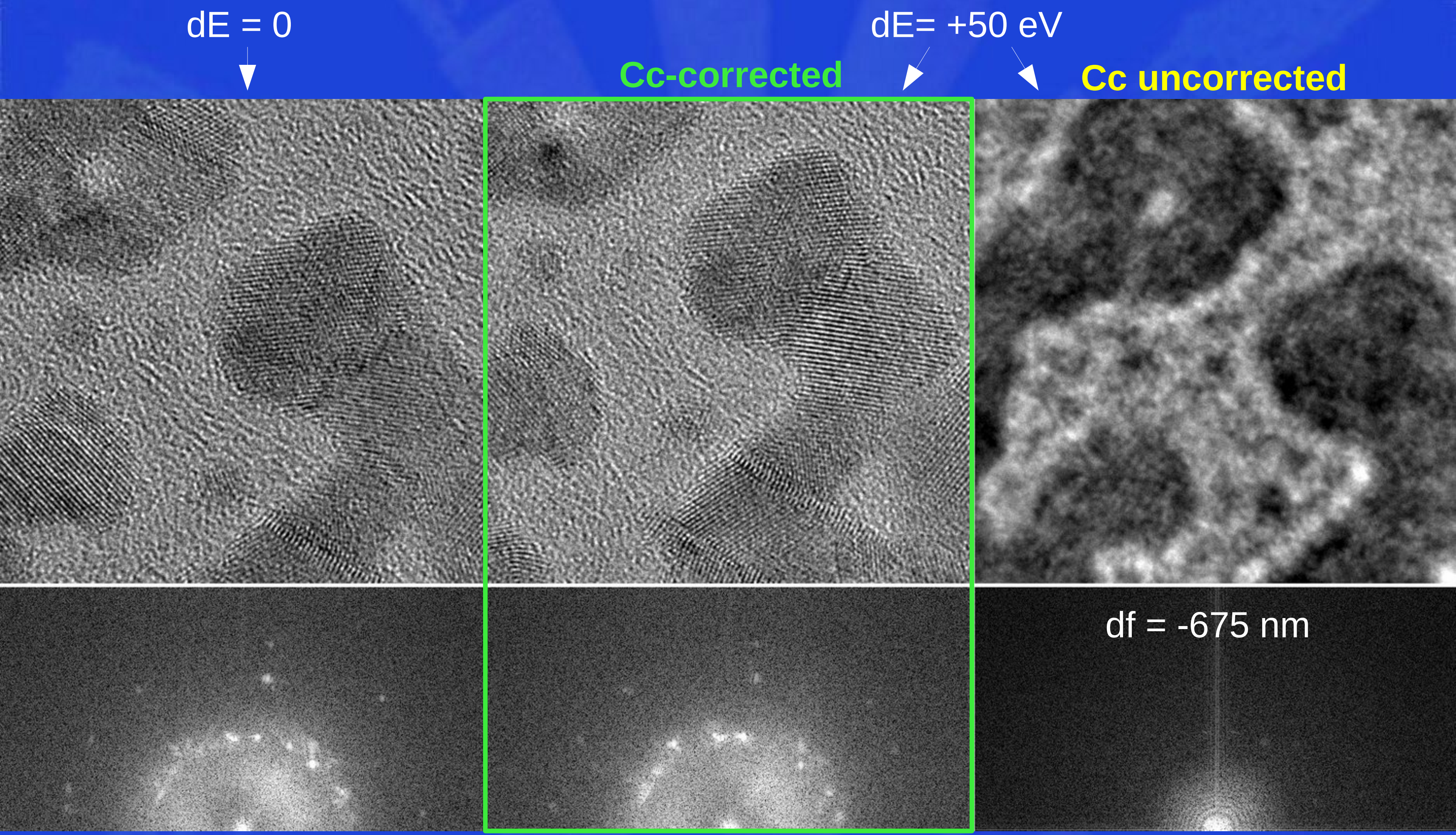
Lei Jin, Juri Barthel, Chinlin Jia and Knut W. Urban, Ultramicroscopy 176 (2017) 99-107.



Atomic resolution imaging of $YAlO_3$:Ce in the chromatic and spherical aberration corrected PICO electron microscope.

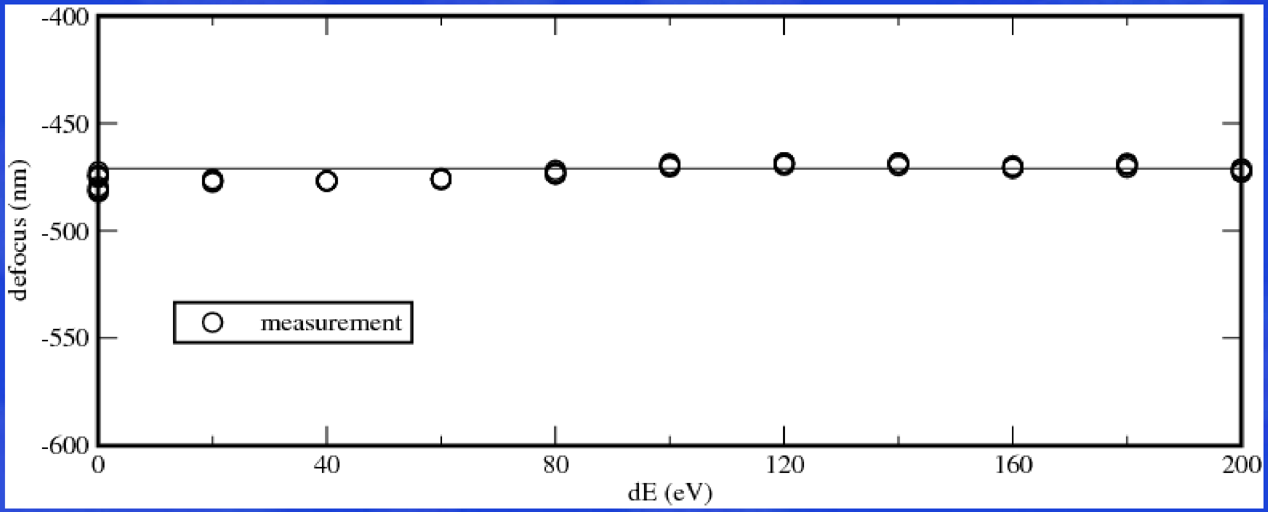


CCOR: achromatic imaging



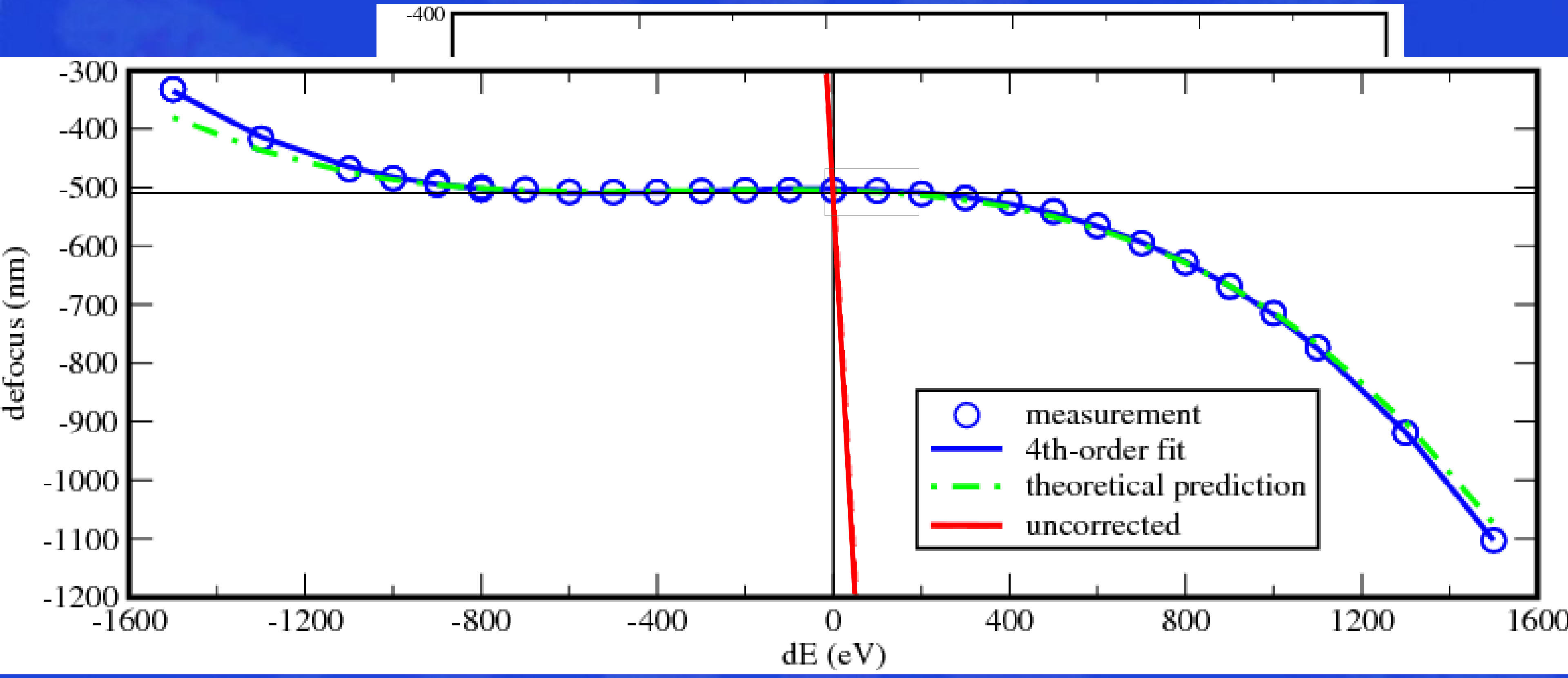
CCOR: achromatic imaging

defocus vs. energy shift at 200 keV



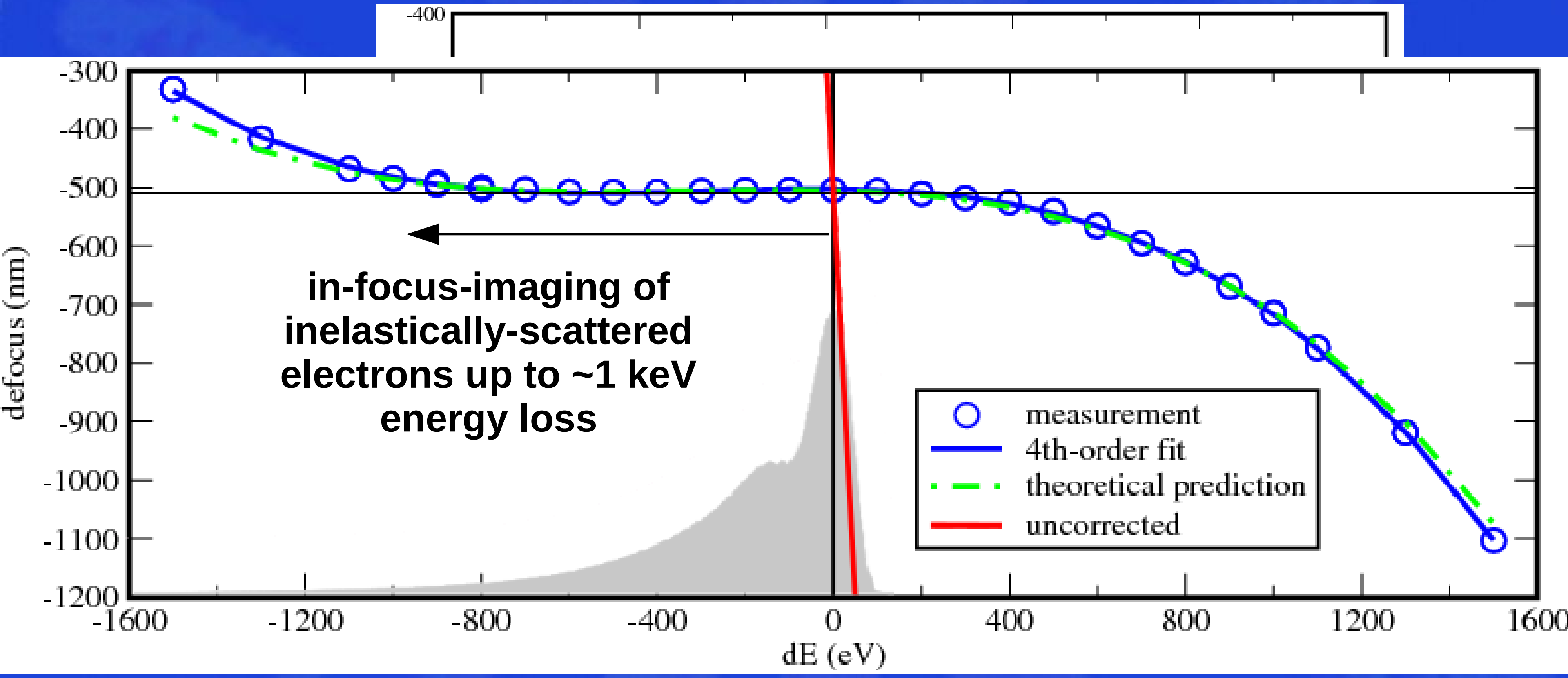
CCOR: achromatic imaging

defocus vs. energy shift at 200 keV



CCOR: achromatic imaging

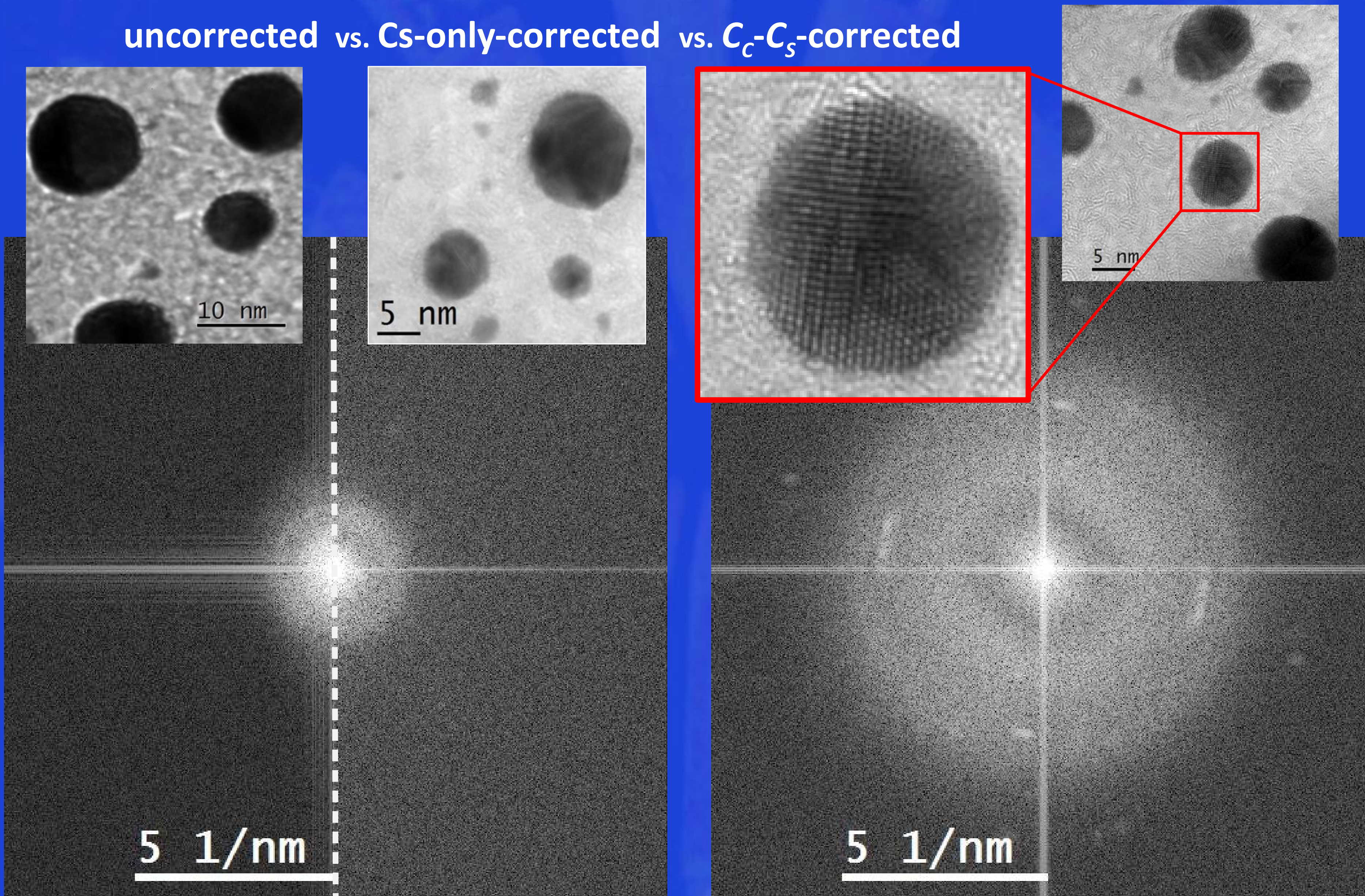
defocus vs. energy shift at 200 keV



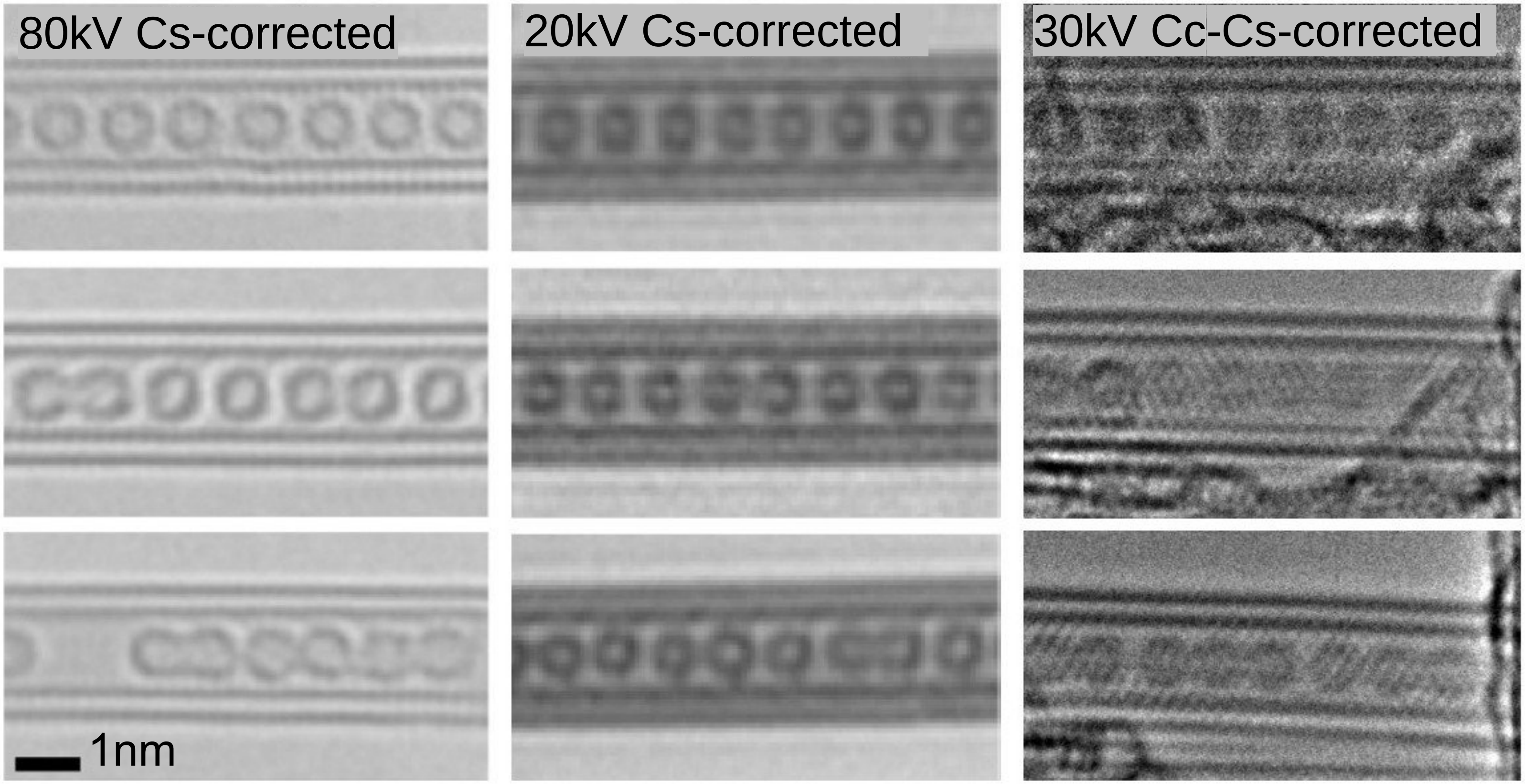
→ **unprecedented EFTEM experiments**

HRTEM imaging at 20kV

uncorrected vs. Cs-only-corrected vs. C_c-C_s-corrected



C60 molecules in double-walled CNTs: dose-dependent experiments



5×10^6 e$^-$/nm^2

2×10^7 e$^-$/nm^2

1×10^9 e$^-$/nm^2

Summary: Aberration correctors

- **Aberration correction improves the resolution by increasing the usable aperture**

  from **d ≈ 100 λ** (10 mrad) to **d ≈ 25…15 λ** (40...65 mrad)

  for example: d = 50 pm @ 200kV and 300kV (CCOR+/TEAM)
  d = 90 pm @ 50kV and 40kV (CCOR+/SALVE)

- **Delocalisation vanishes with Cs-correction in TEM**

- **Higher probe currents and smaller probes in STEM, and better depth resolution**

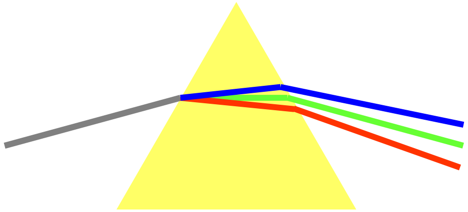
- **Beyond ultimate resolution:**

  Cc- and Cs-correction open up new applications
  in biology, in-situ, dynamic EM, Lorentz EM (large pole piece gaps),
  low voltage (S)TEM, energy selective imaging (large ΔE)

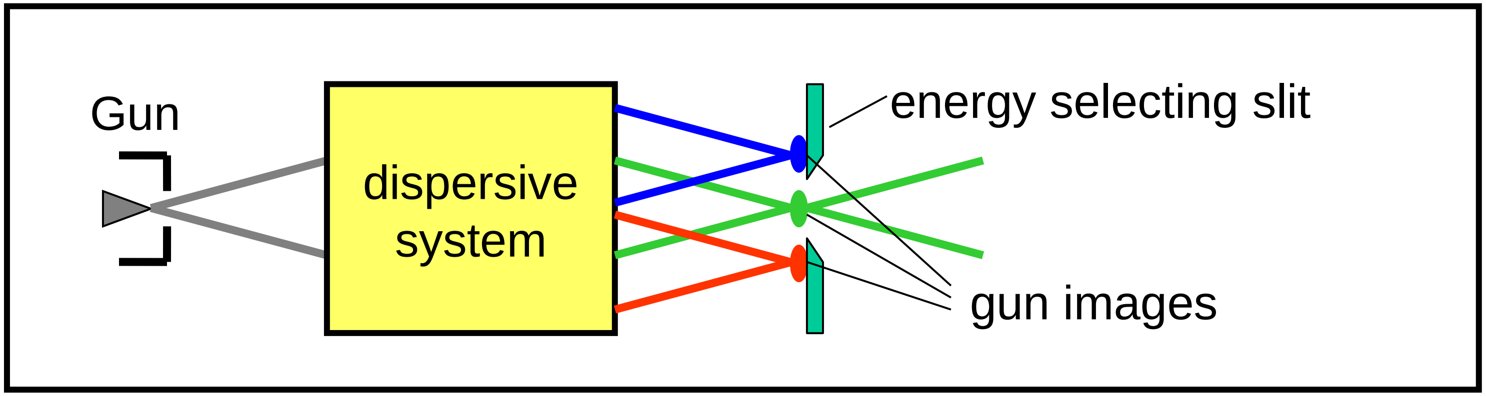
Monochromators

CEOS
Corrected Electron Optical
Systems GmbH

Monochromators: Basic principles



Two main applications:
- improve lateral resolution in imaging
- improve energy resolution in spectroscopy



Challenges:

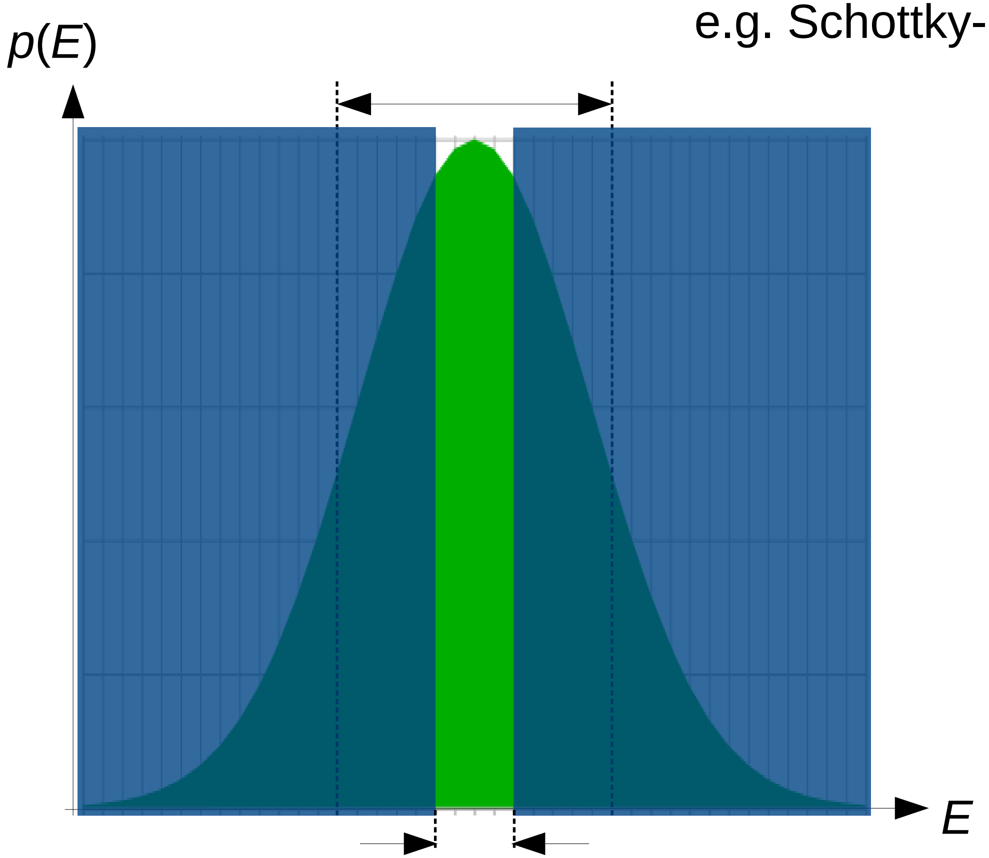
- large dispersion

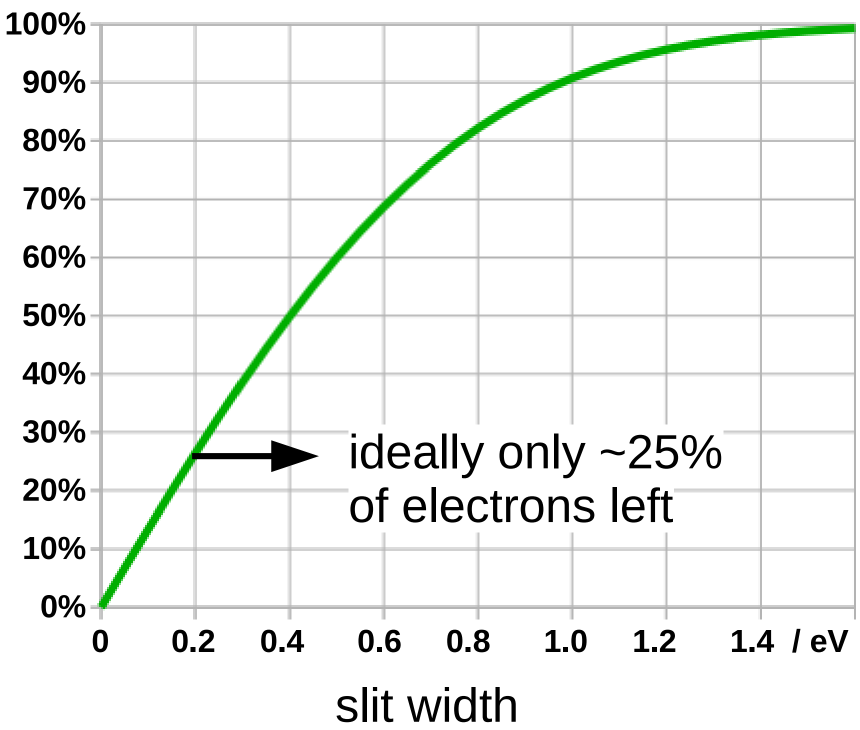
- small selection windows (narrow and clean slit)

- proper imaging conditions from source to selection plane

Cut out the "right" electrons!

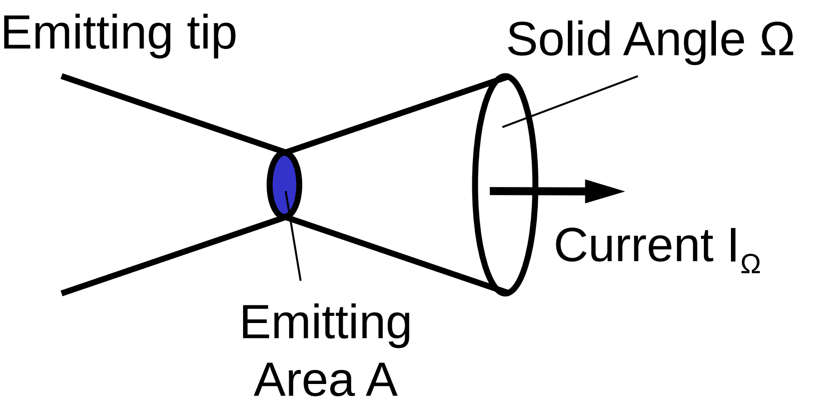
e.g. Schottky-FEG





Monochromators: Brightness conservation

$$\text{Brightness} = \frac{\text{Current } I_\Omega}{\text{Solid Angle } \Omega \times \text{Emitting Area } A}$$



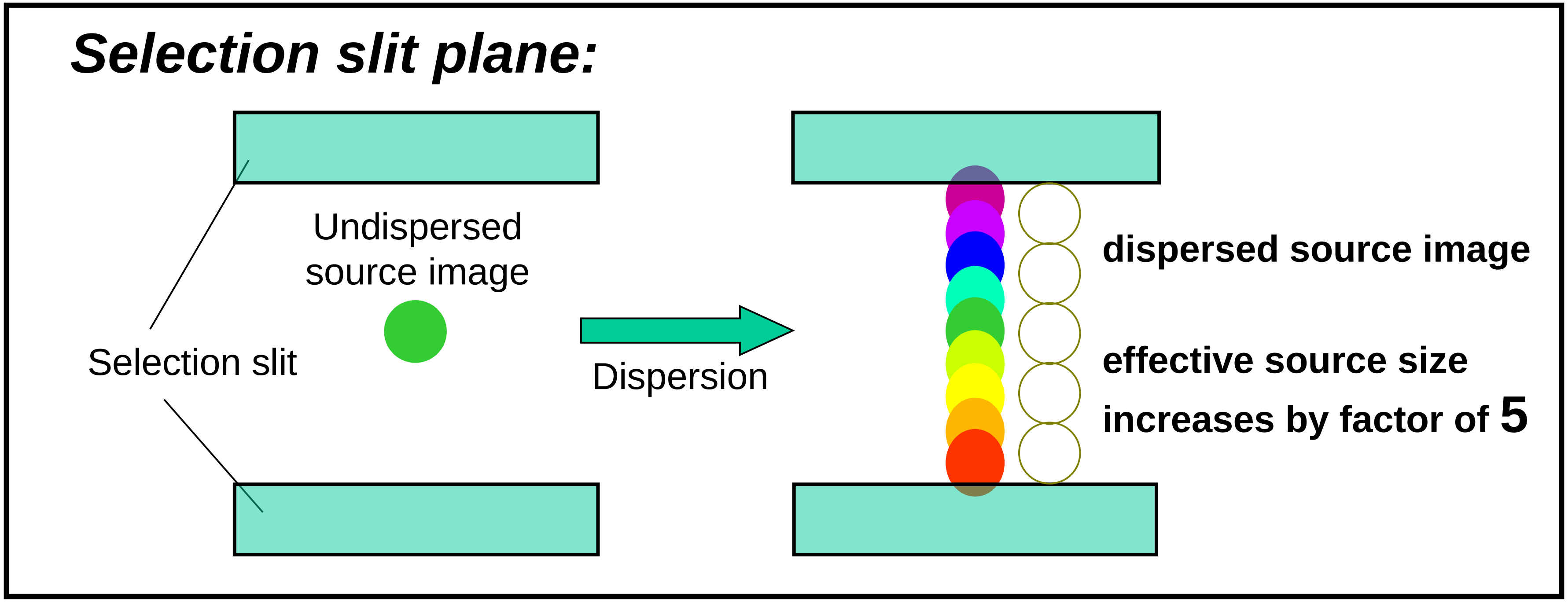
example: STEM probe

probe current ~ Brightness, probe angle ($\rightarrow \Omega$), demagnification ($\rightarrow A$)

Brightness cannot be increased but reduced by:

- beam limiting apertures (e.g., selection slits)
- increase of source size due to dispersion
- aberrations in slit plane

Monochromators: Brightness conservation



$$\text{Brightness} = \frac{\text{Current } I_\Omega}{\text{Solid Angle } \Omega \times \text{Emitting Area } A}$$

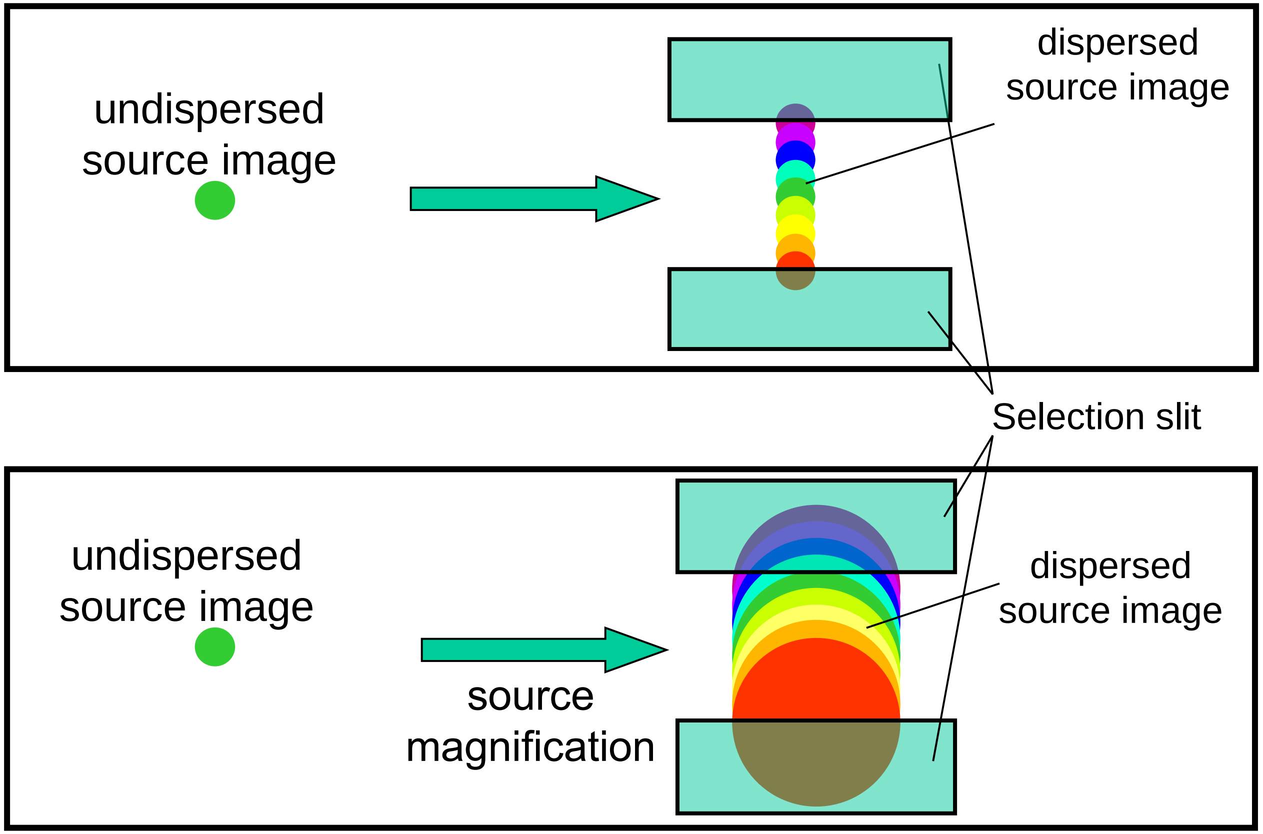
Brightness reduced additionally by a factor of 1/5

Example for 0.2eV (filter factor 25%):

25% / **5** = **5%** (loss of original brightness by factor 20)

Monochromators: Brightness conservation

- Size of source image should be equal to slit width
- aberration discs should be much smaller than that



Source size grows by factor of 5

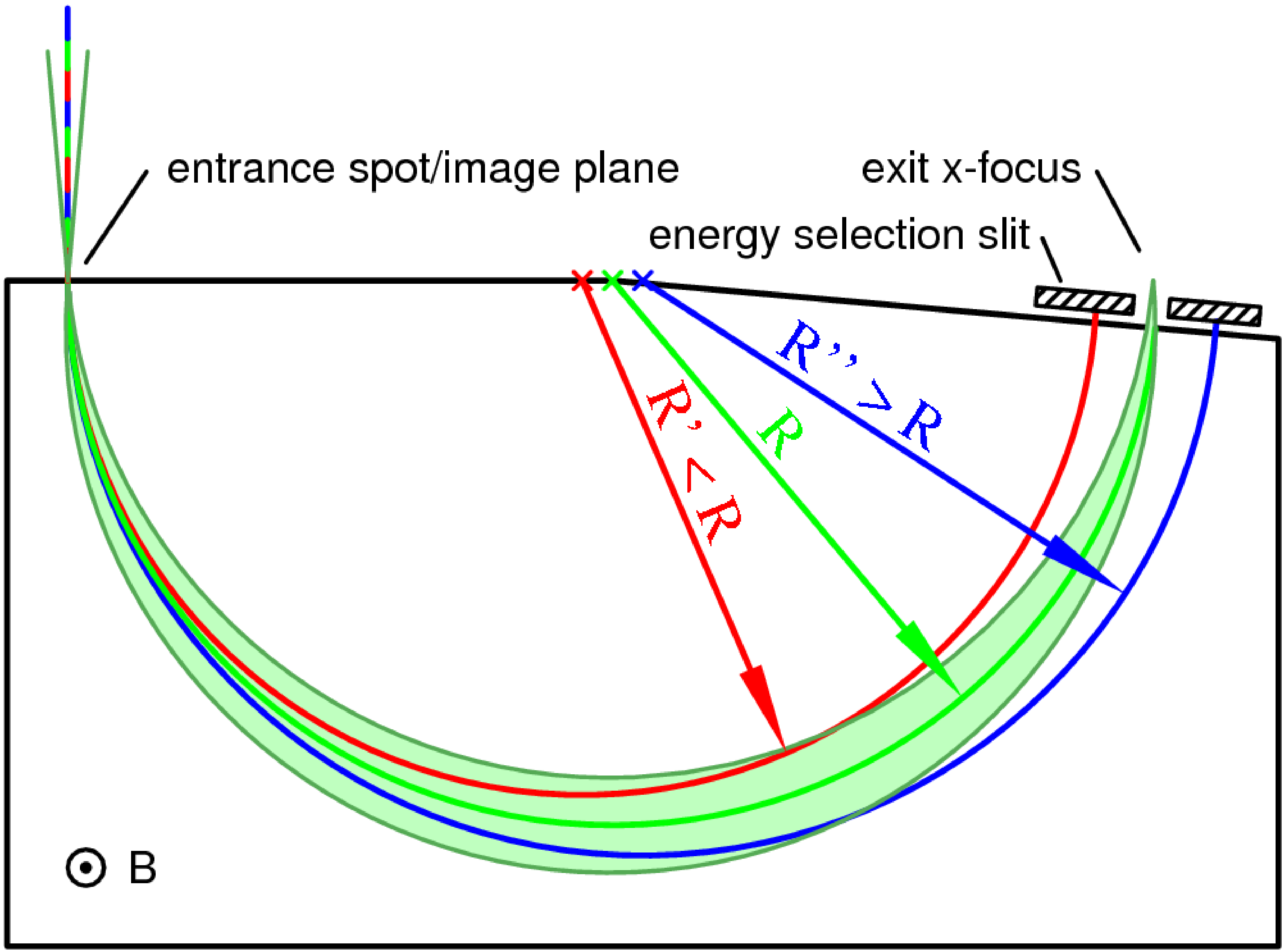
→ **high brightness loss**

Source size remains roughly as is

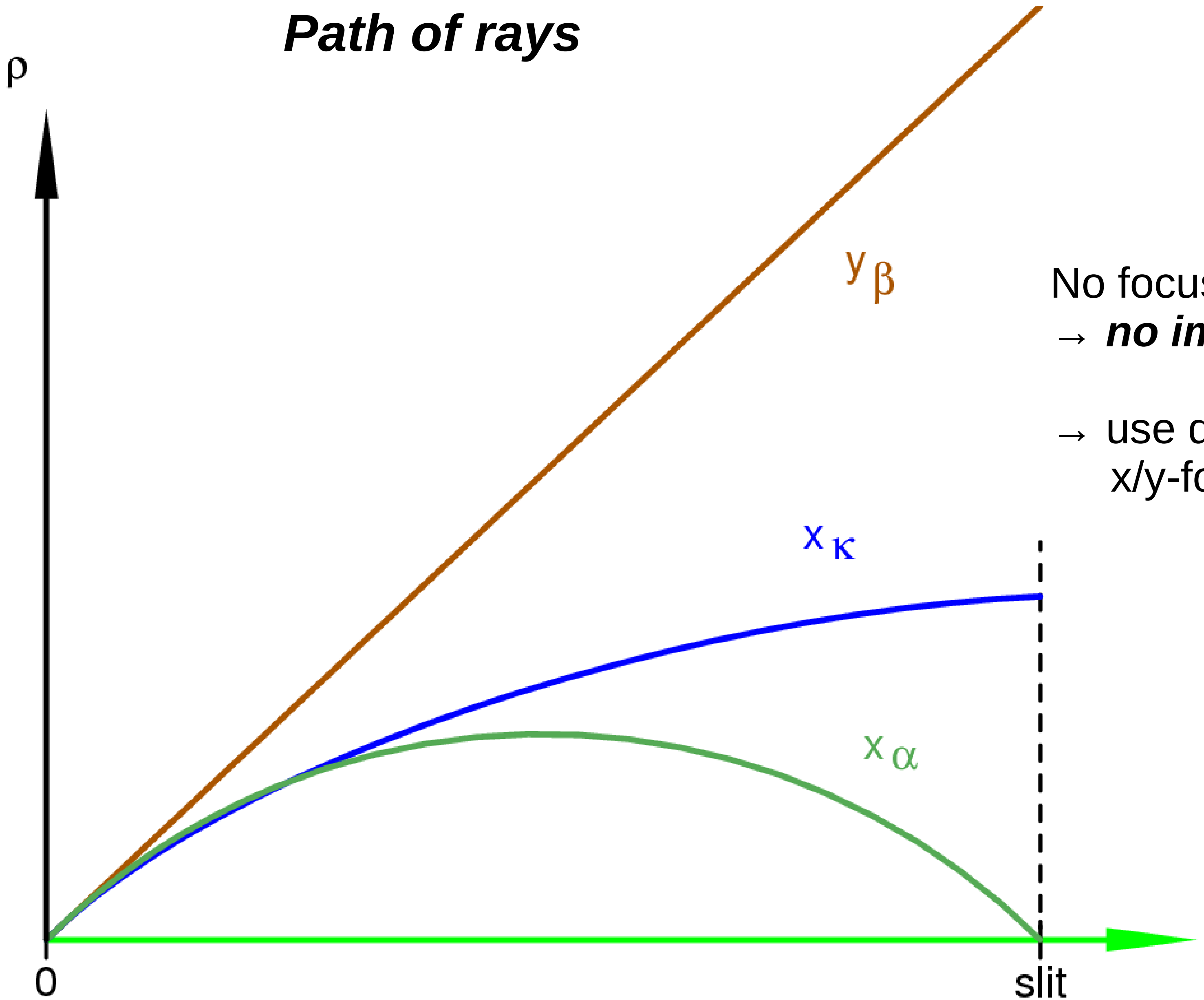
→ **low brightness loss**

→ **additional requirements on gun and condensor optics**

Simple monochromator: homogenious field



Simple monochromator: homogenious field



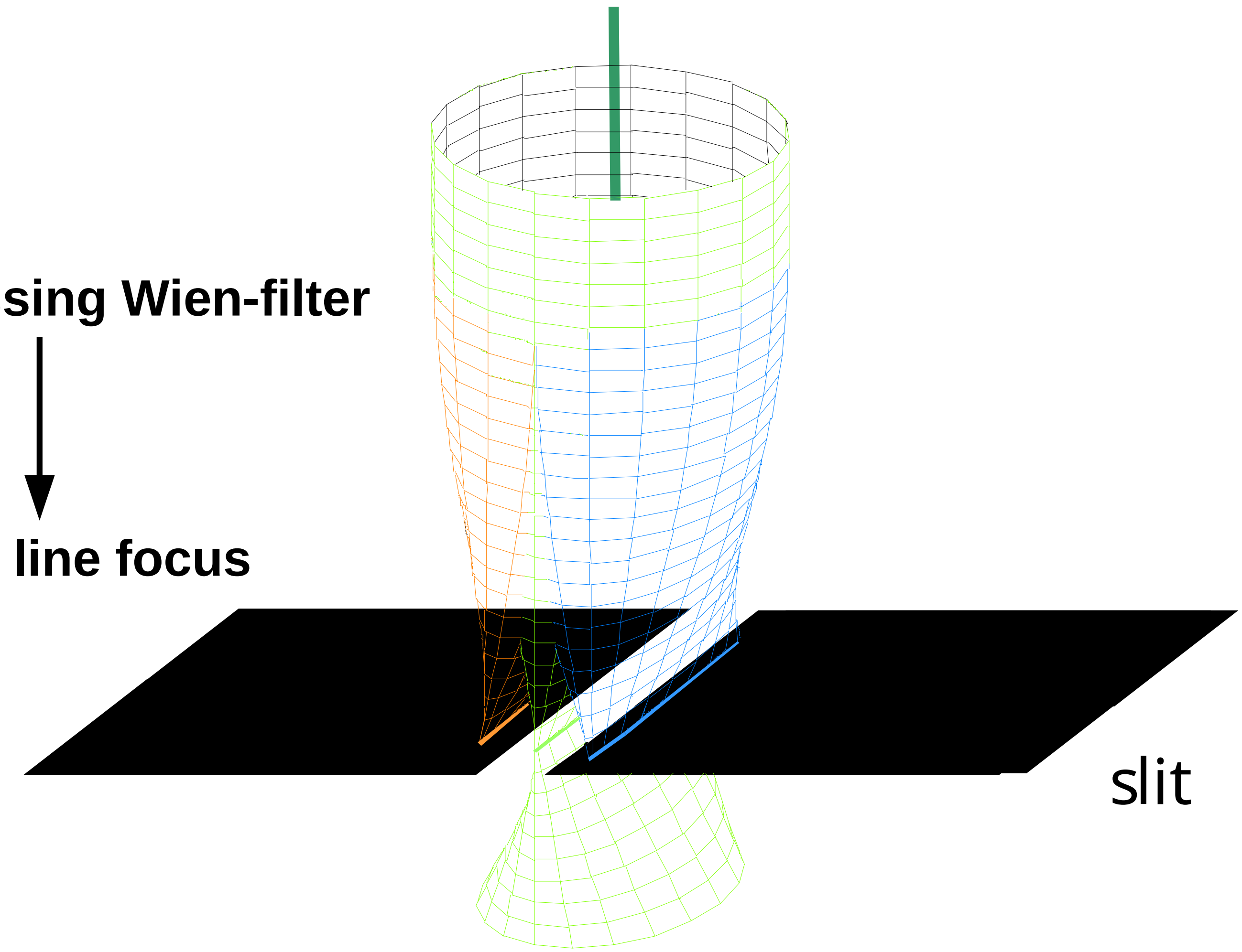
No focus in y-direction
→ ***no image of source***

→ use quadrupoles for x/y-focus in exit plane

Monochromator without quadrupoles

“single” focussing Wien-filter

simple line focus



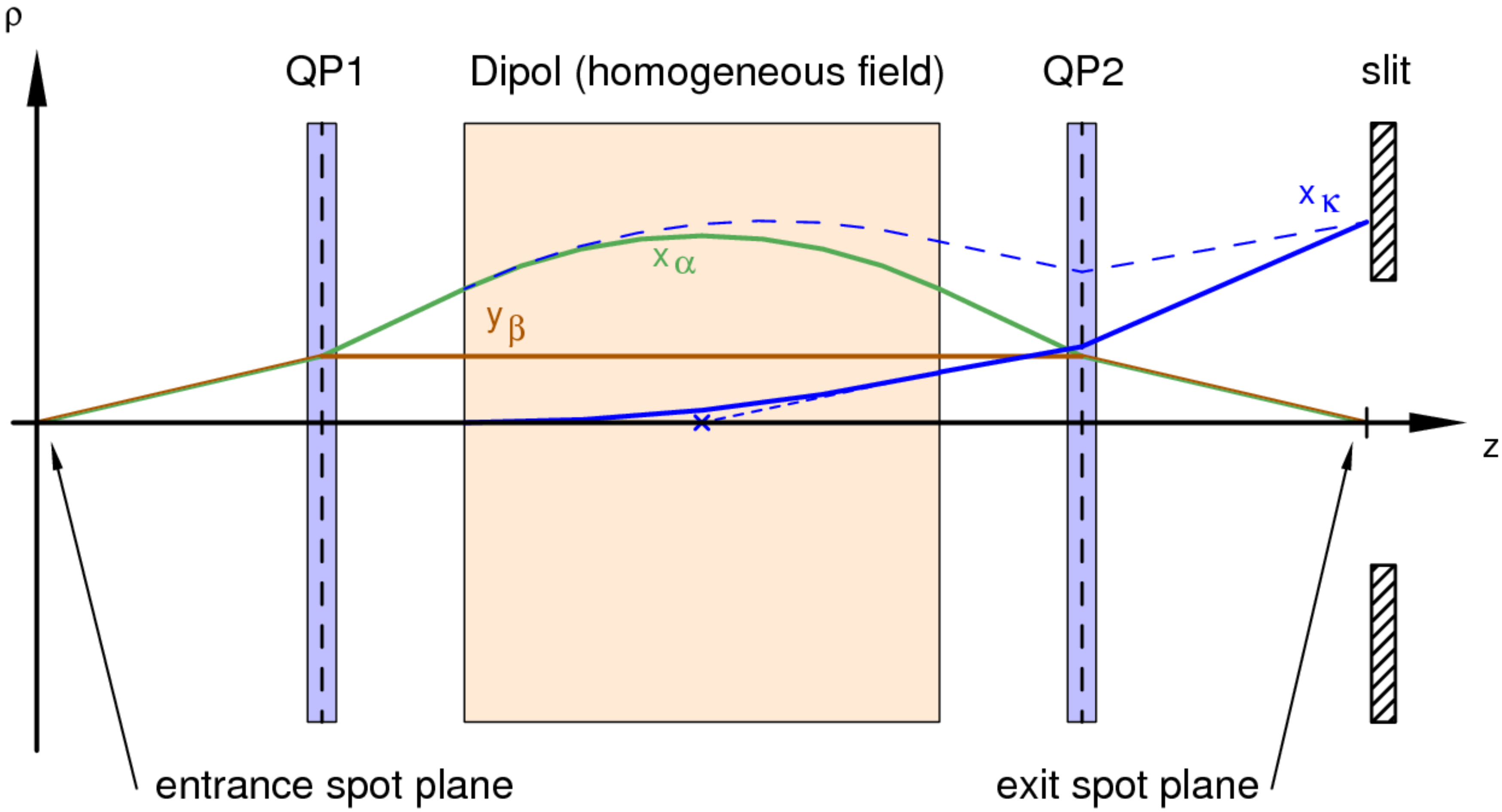
P. Tiemeijer

FEI™

Simple monochromator with quadrupoles

CEOS
Corrected Electron Optical Systems GmbH

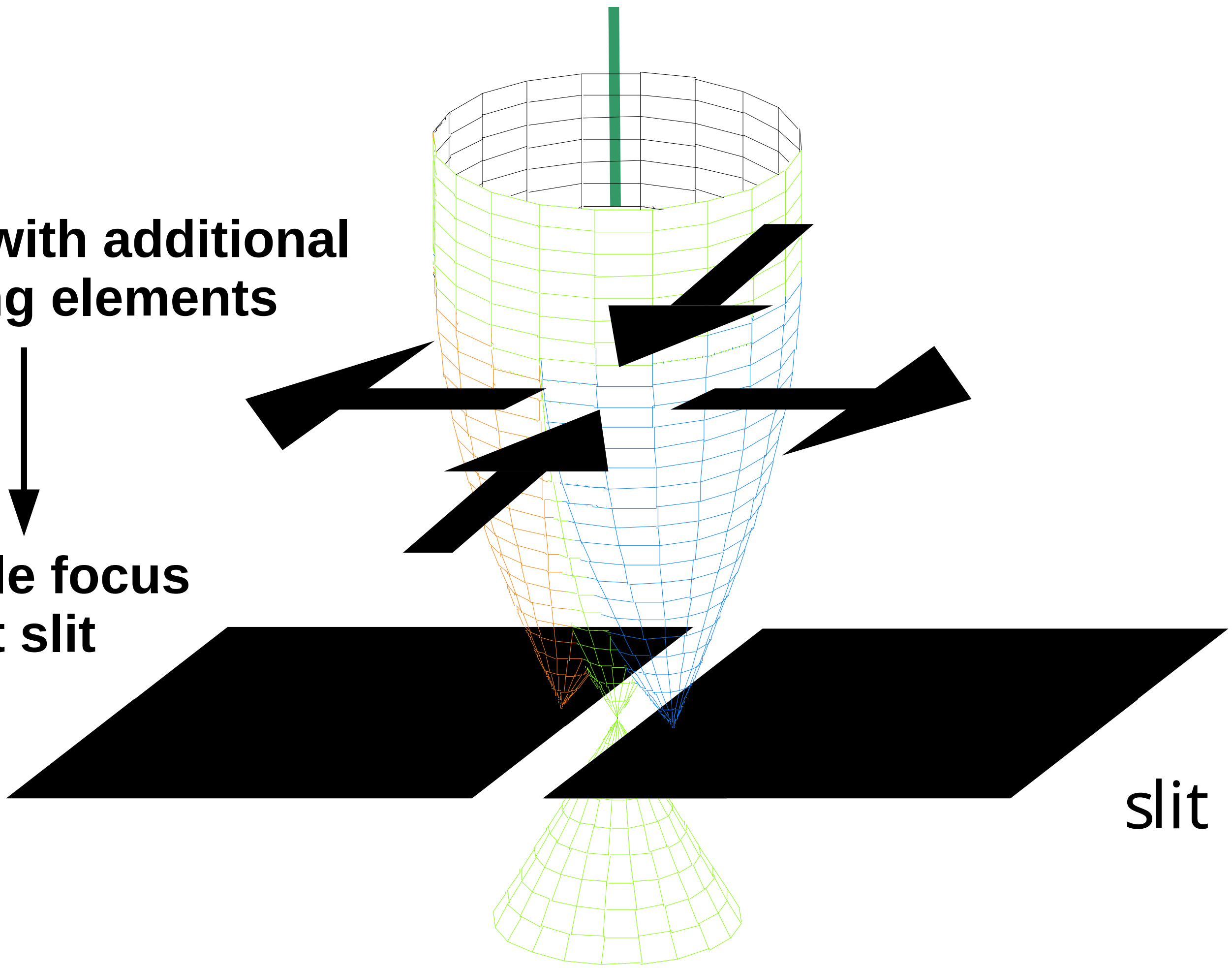
x- and y-focus at the same exit plane



Monochromator with quadrupoles

Wien filter with additional focussing elements

double focus at slit



P. Tiemeijer

FEI

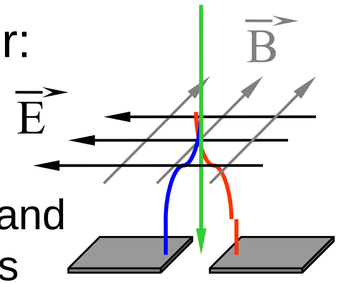
Different flavours of monochromation

Axis

Straight (TFS, JEOL)

Wien–filter:

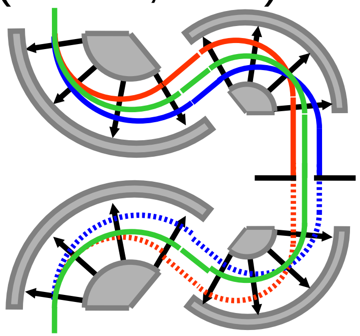
crossed electric and magnetic fields



Curved (CEOS, nion)

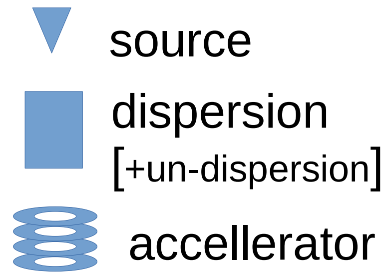
e.g. Ω–filter:

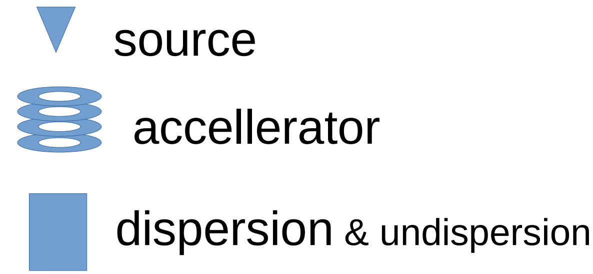
pure electric or magnetic fields



Different flavours of monochromation

Axis	**Straight** (TFS, JEOL)	**Curved** (CEOS, nion)
Potential	**at high-voltage level** (CEOS, TFS, JEOL)	**at ground potential** (nion, CEOS)





At high-voltage level:

- inside the gun, before acceleration stage
- high sensitivity to Boersch effect
- easy to produce high dispersion
- high vacuum requirements (UHV)
- additional electronics on the HV level

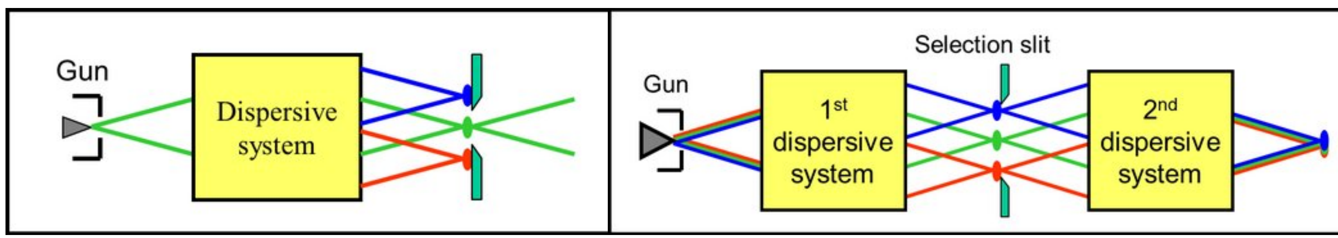
At ground potential:

- below accelerator
- insensitive to HT instabilities
- very strong fields required
- complicated optics (requires correction elements)

Different flavours of monochromation

Axis	**Straight** (TFS, JEOL)	**Curved** (CEOS, nion)
Potential	**at high-voltage level** (CEOS, TFS, JEOL)	**at ground potential** (nion, CEOS)

Dispersion management



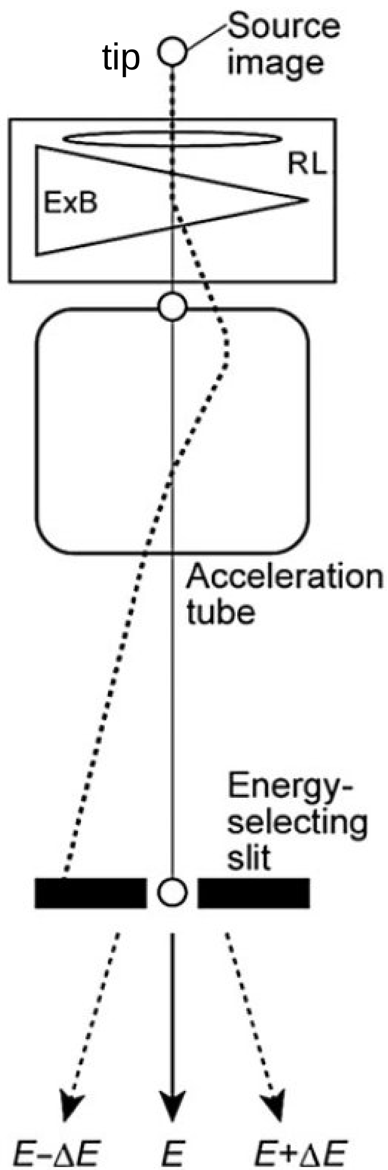
(TFS) (CEOS, JEOL, nion)

"Rainbow" illumination:

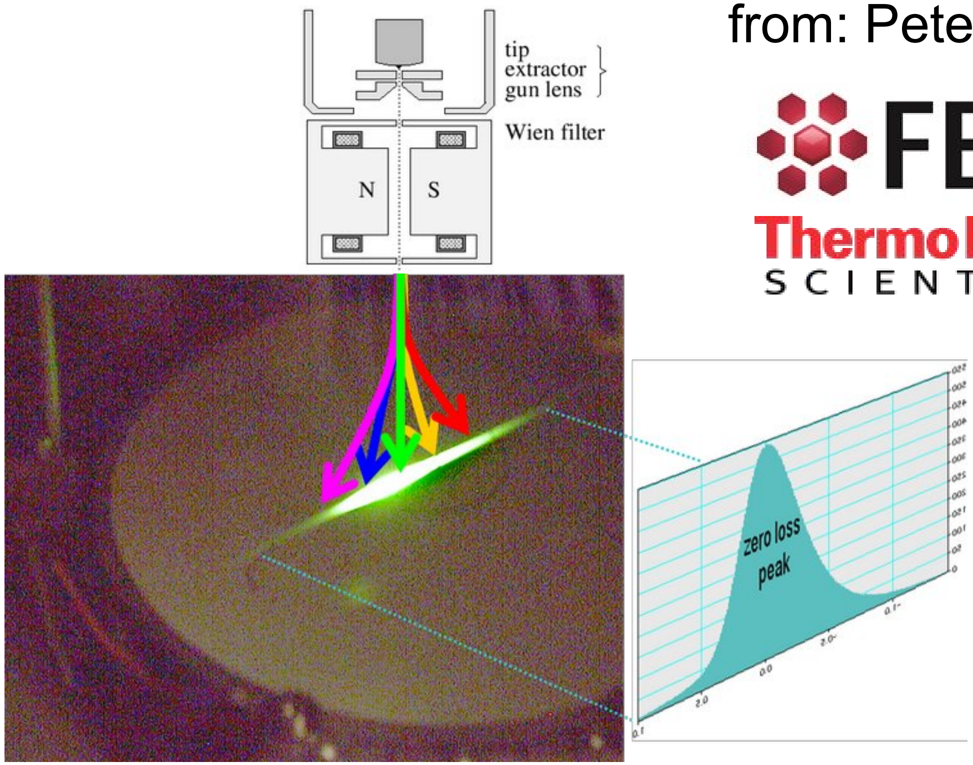
- dispersion remains in whole beam path
- source images for different energies at different positions → emission in different directions

- dispersion removed in illumination
- no brightness loss due to dispersion
- source image looks as usual
- source images for different energies might emit in different directions

monochromator: single Wien filter



from: Koji Kimoto, Microscopy, 2014, 1–8.



from: Peter Tiemeijer

Advantages:

- TEM + STEM
- simple design
- continuously adjustable dispersion

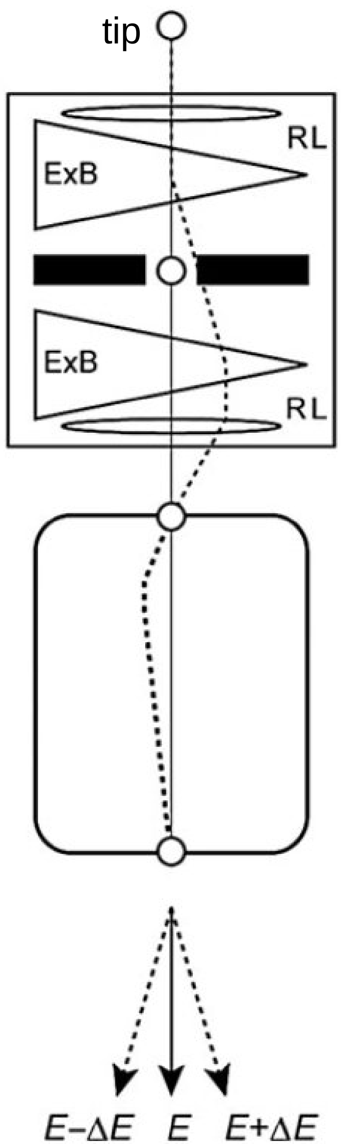
Disadvantages:

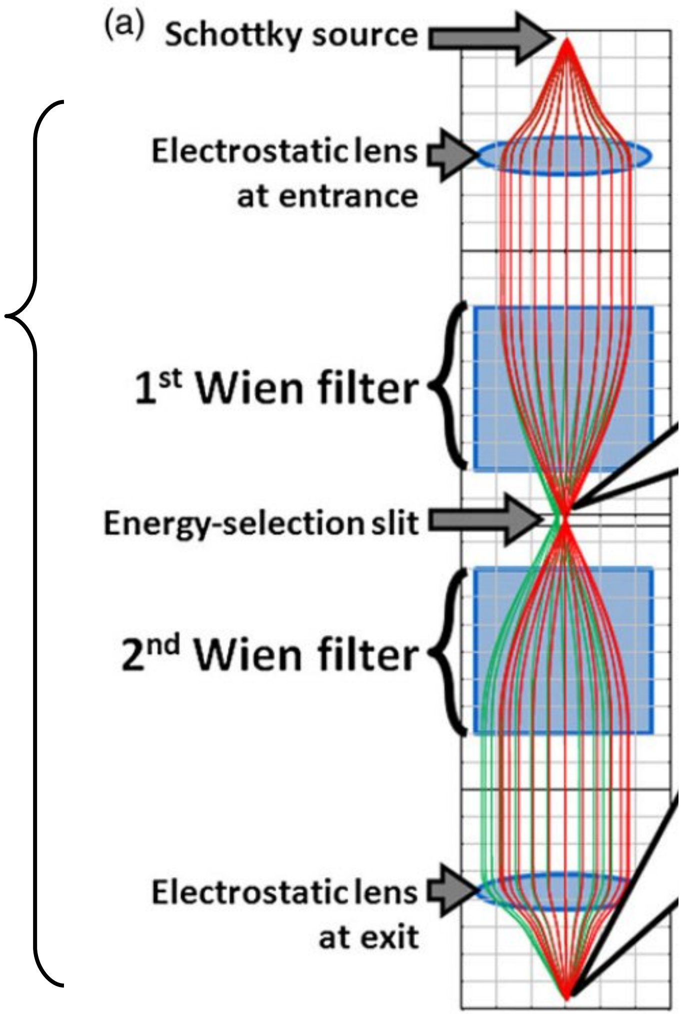
- dispersed spot (“rainbow illu”)

→ **special usage of condenser**

- drift after excitation changes (magnetic elements)

monochromator: double Wien filter





from: Masaki Mukai, Microscopy, 2015, 1–8.

Advantages:

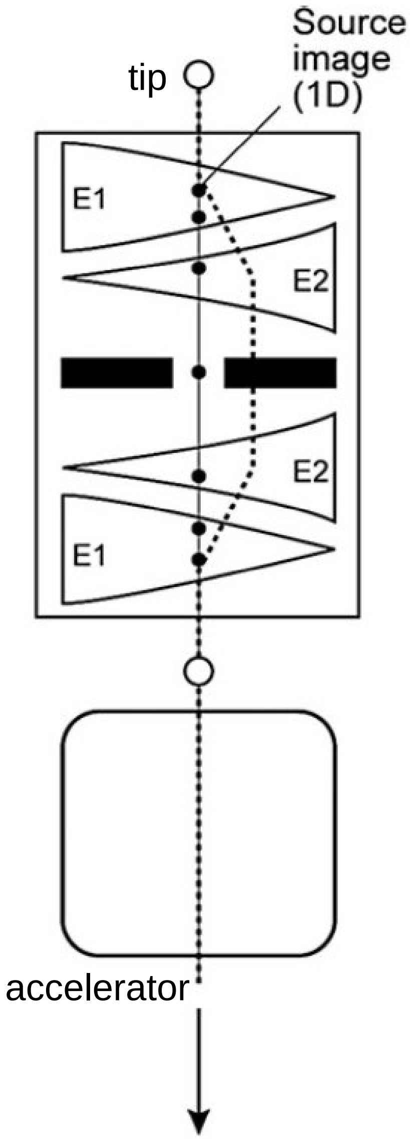
- TEM + STEM
- achromatic spot

Disadvantages:

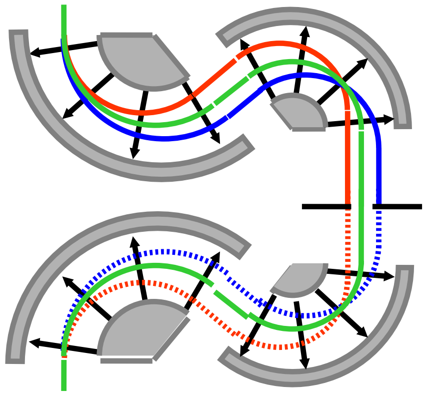
- many voltages and currents on high-tension level
- residual angular dispersion

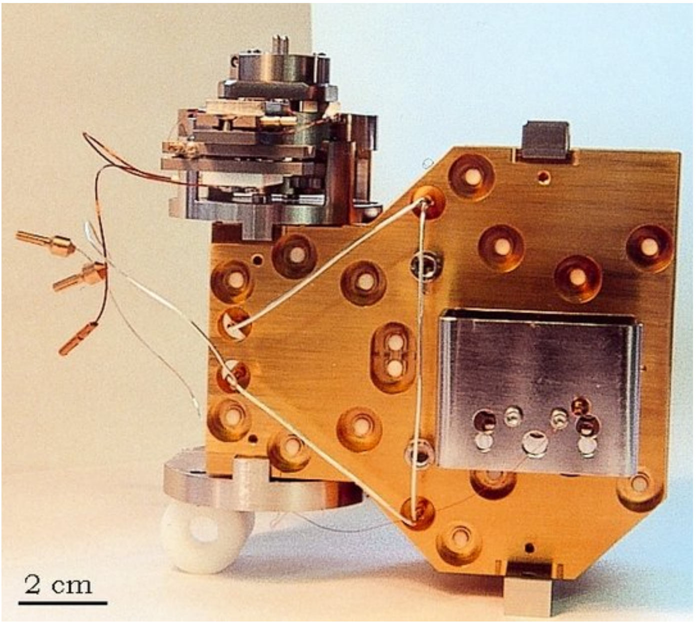
from: Koji Kimoto, Microscopy, 2014, 1–8.

CEOS monochromator: electrostatic Omega



from: Koji Kimoto Microscopy, 2014, 1–8.



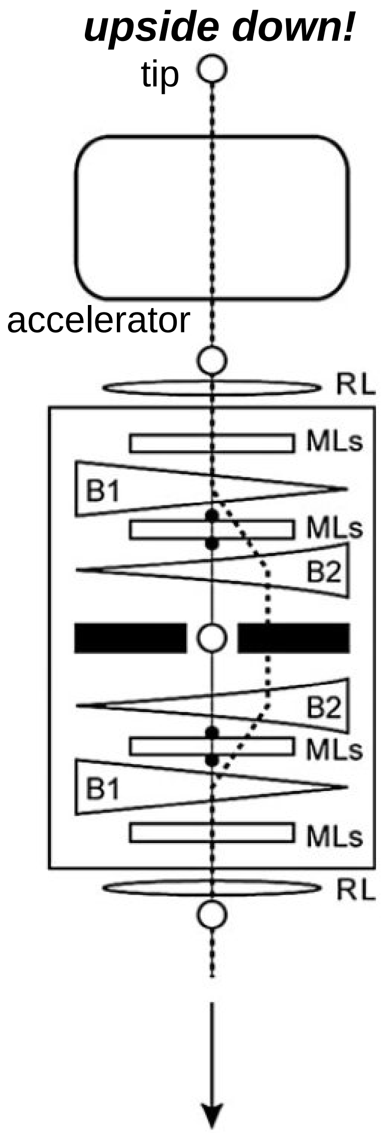


Advantages:

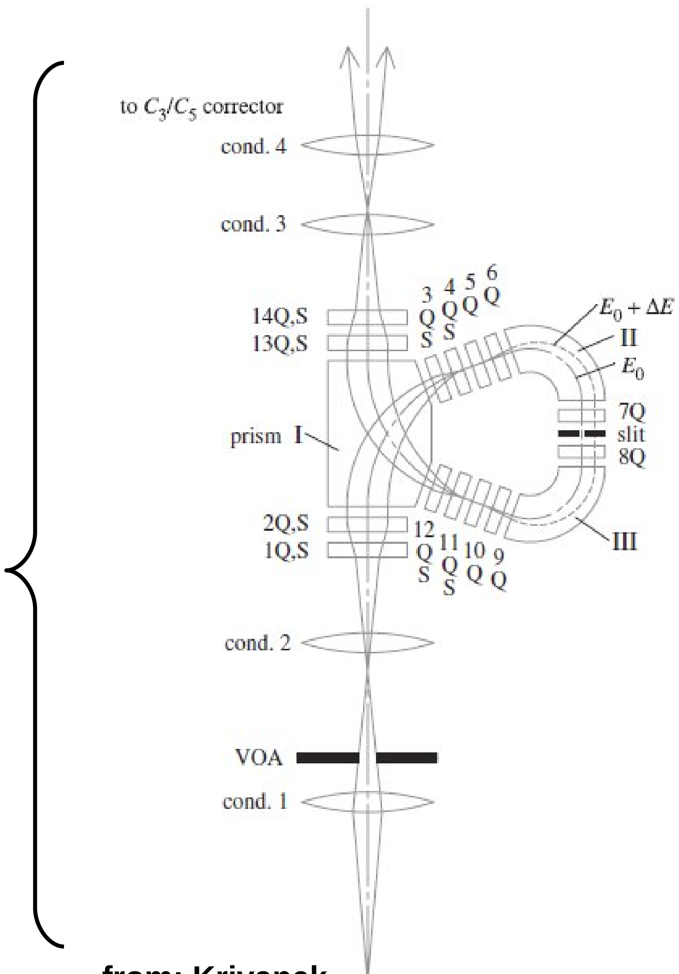
- TEM + STEM
- purely electrostatic: no drift, no hysteresis
- achromatic spot

Disadvantages:

- moveable slit on HT-level
- **currently not available**: *ZEISS has quit TEM business*



from: Koji Kimoto,
Microscopy, 2014, 1–8.



from: Krivanek,
Phil. Trans. R. Soc. A (2009) 367, 3683–3697.

Advantages:

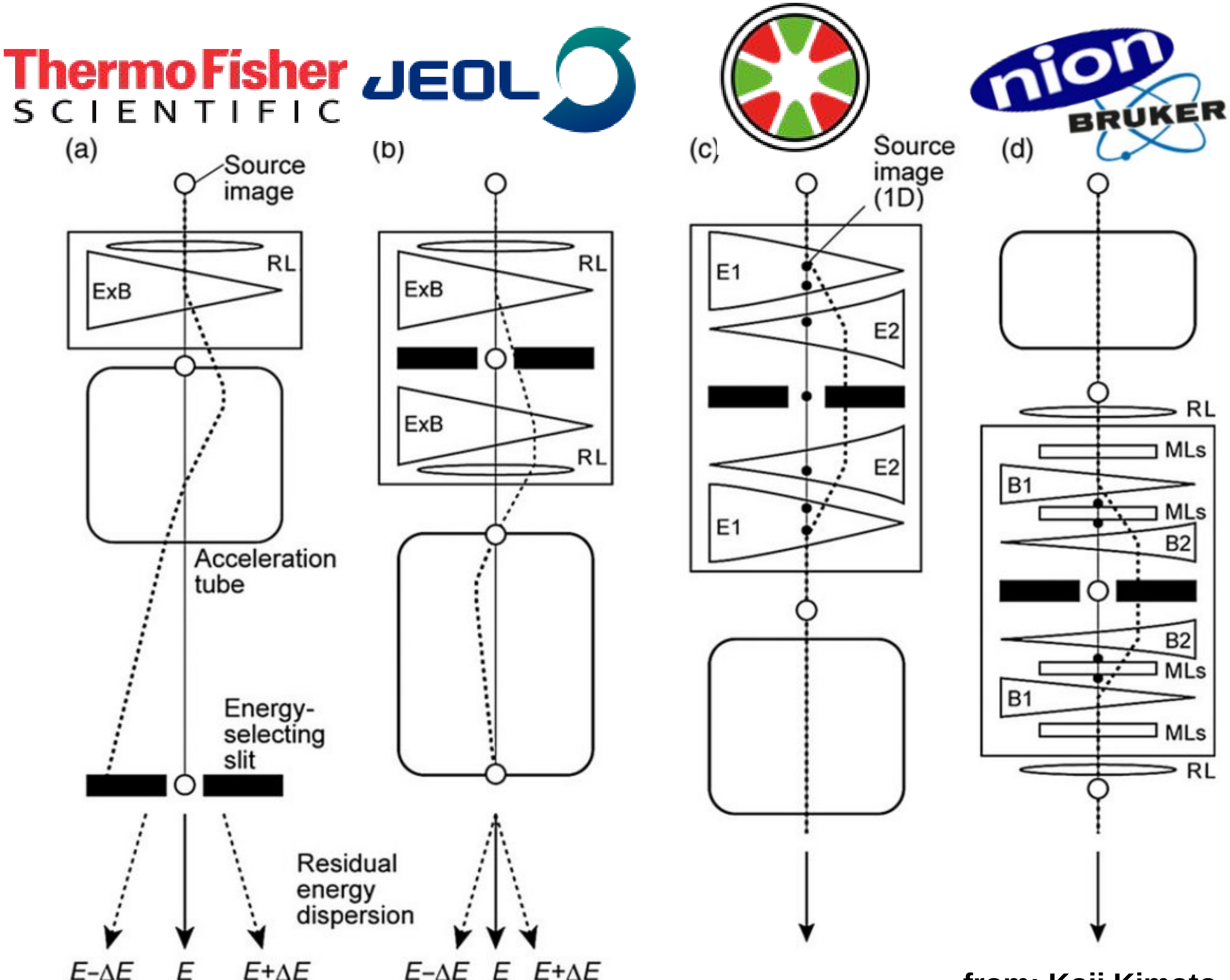
- less sensitive for HT instabilities
- coupling of main filter current and monochromator current
- achromatic spot

Disadvantages:

- large effort to create dispersion
- many current supplies
- STEM only

Summary: Monochromators

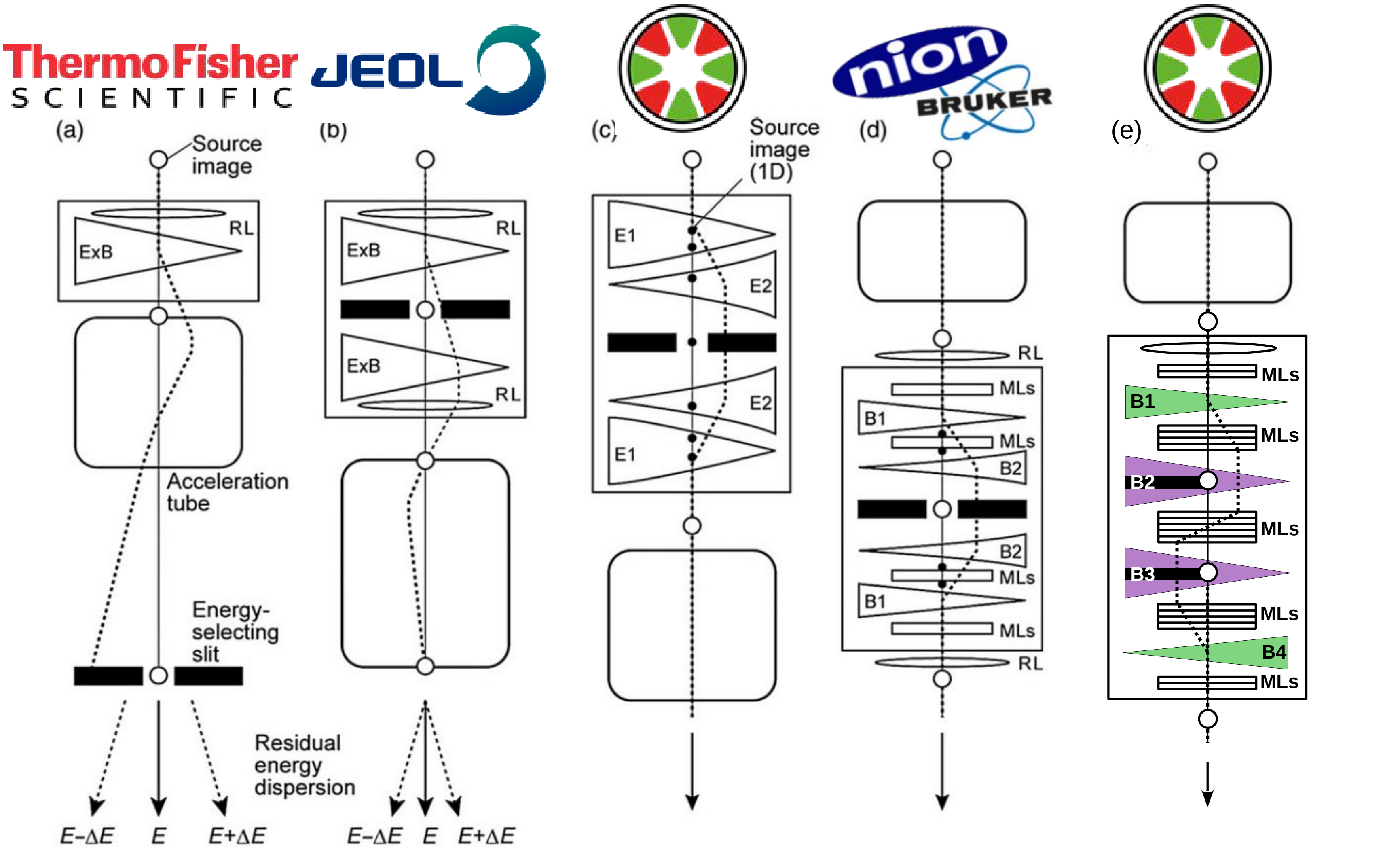
- Only one single choice of monochromator for each microscope manufacturer.
- Remember the strengths and weaknesses of the monochromator you have to live with!



from: Koji Kimoto, Microscopy, 2014, 1–8.

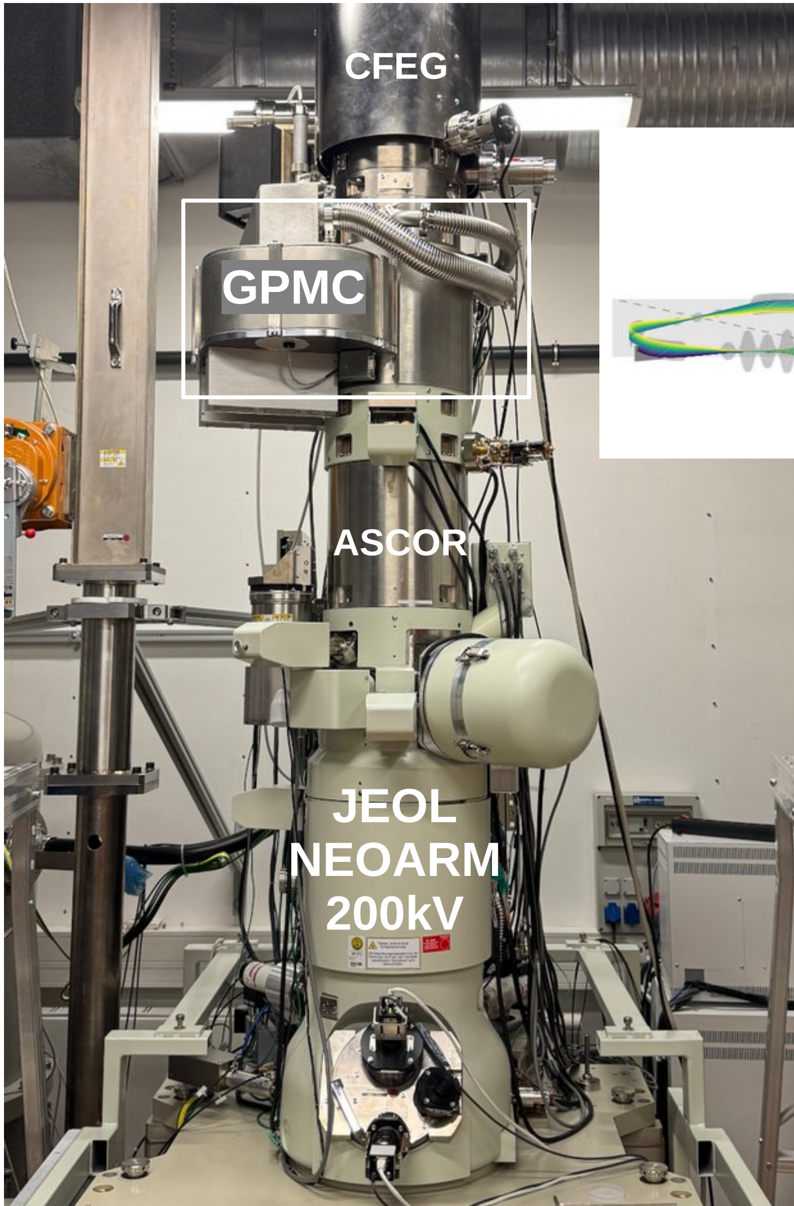
Summary: Monochromators

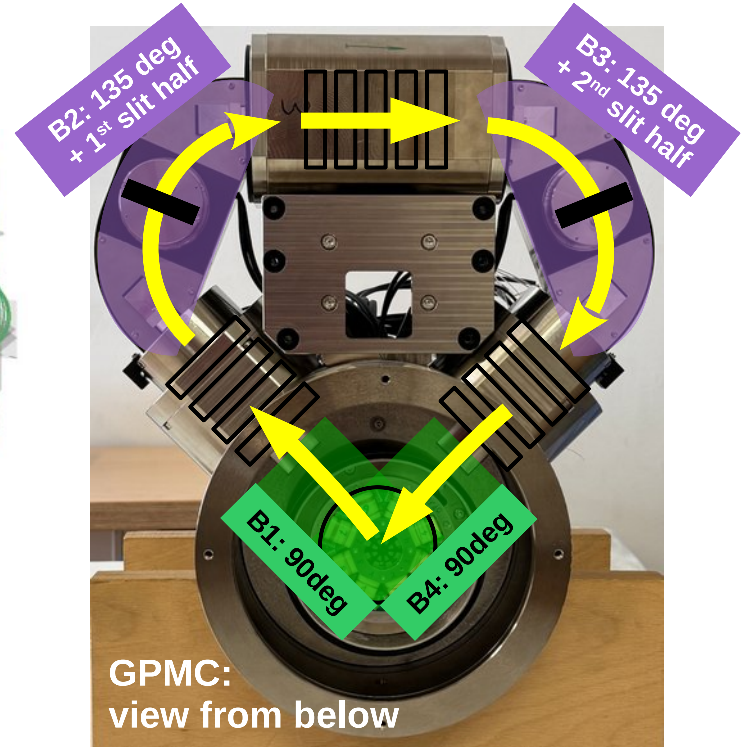
- Only one single choice of monochromator for each microscope manufacturer.
- Remember the strengths and weaknesses of the monochromator you have to live with!

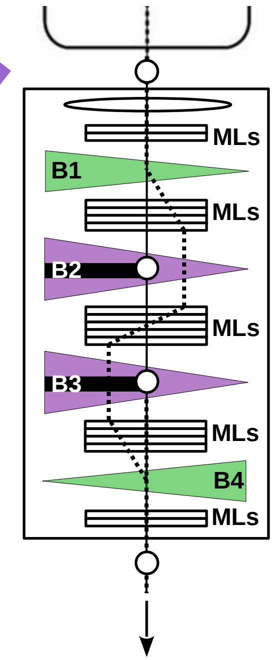


CEOS ground-potential monochromator

CEOS
Corrected Electron Optical Systems GmbH

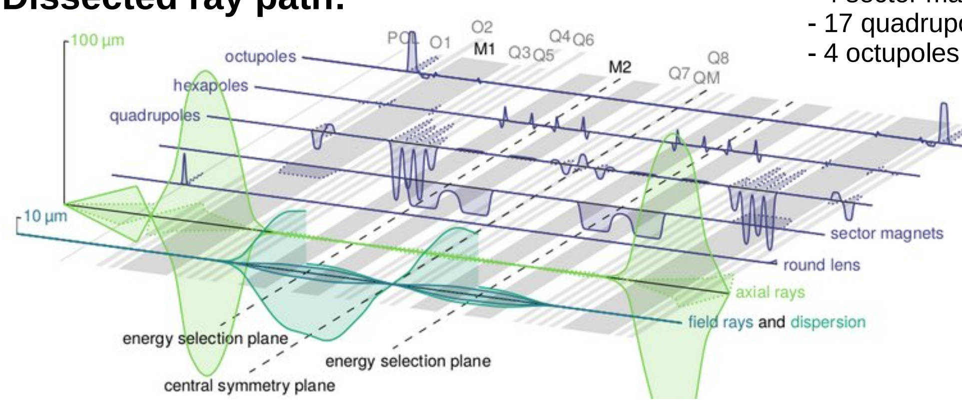






- 1 lens
- 4 sector magnets
- 17 quadrupoles
- 4 octupoles

Dissected ray path:



Börrnert et al., Ultramicroscopy 253 (2023), 113805. https://doi.org/10.1016/j.ultramic.2023.113805

Acknowledgements

Thanks to QEM organizers!

Thanks to all collegues at CEOS!

Thanks to the colleages at JEOL and TFS for sharing content.

Thanks to QEM audience for listening!

Further resources

P.W. Hawkes: “The correction of electron lens aberrations”, Ultramicroscopy 156 (2015), A1-A64.

M. Haider et al.: “Present and Future Hexapole Aberration Correctors for High-Resolution Electron Microscopy”, Advances in Imaging and Electron Physics, Volume 153, 43-119, ISSN 1076-5670.

H. Müller et al.: “Aberration-corrected optics: from an idea to a device”,
Physics Physics Procedia Procedia 1 (2008), 167–178.

Learn how to get the most out of your aberration-corrected electron microscope!

Join an intense half-day workshop with renowned invited speakers …

Prof.Dr. Rolf Erni
Empa Dübendorf, CH

Dr. Lothar Houben
Weizmann Institute, IL

Dr. Penghan Lu
ER-C Jülich, D

"Practical aspects of aberration correction in TEM and STEM"

pre-conference workshop WS 3