How do aberration correctors work?

Martin Linck

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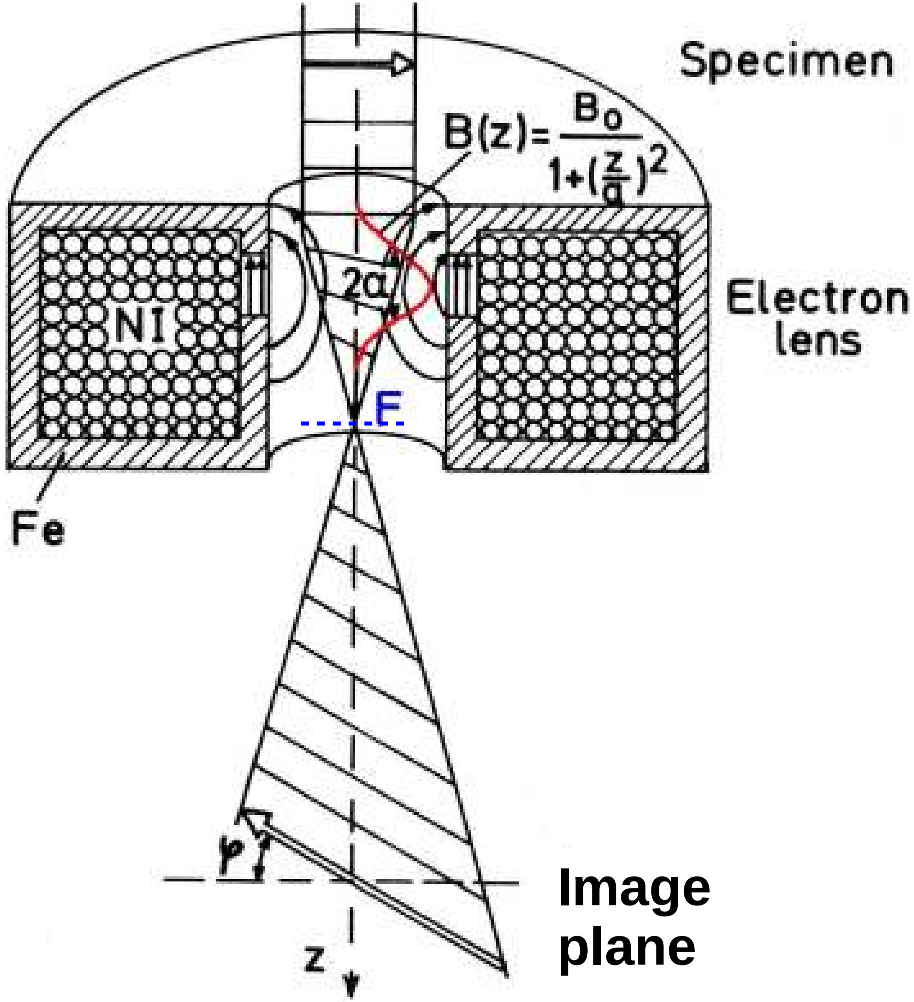
CEOS
Corrected Electron Optical
Systems GmbH

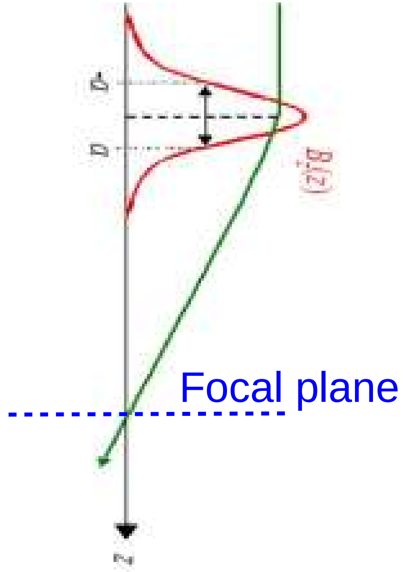
Invention of the Transmission Electron Microscope

Magnetic Lens for Electrons



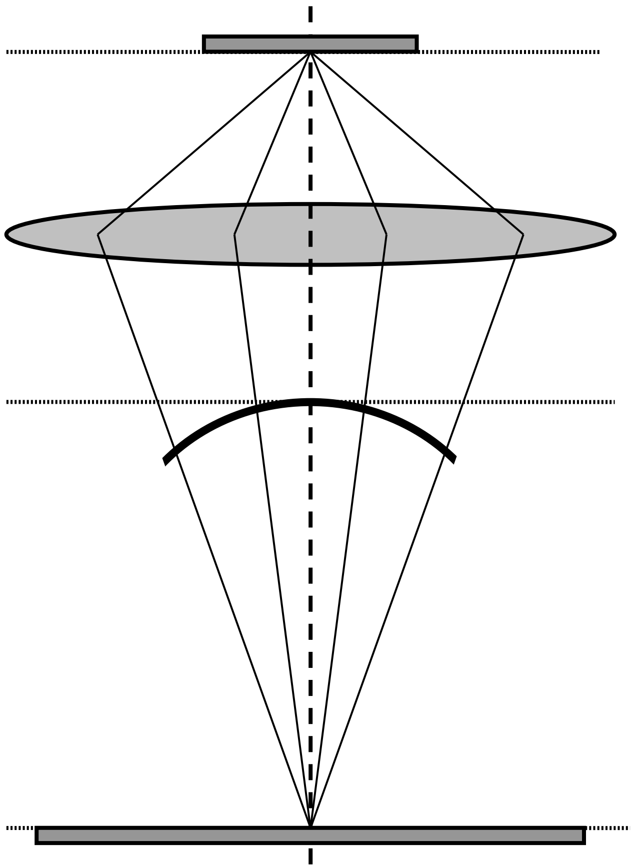
Glaser's "Glockenfeld"

bell-shaped,
axial magnetic field

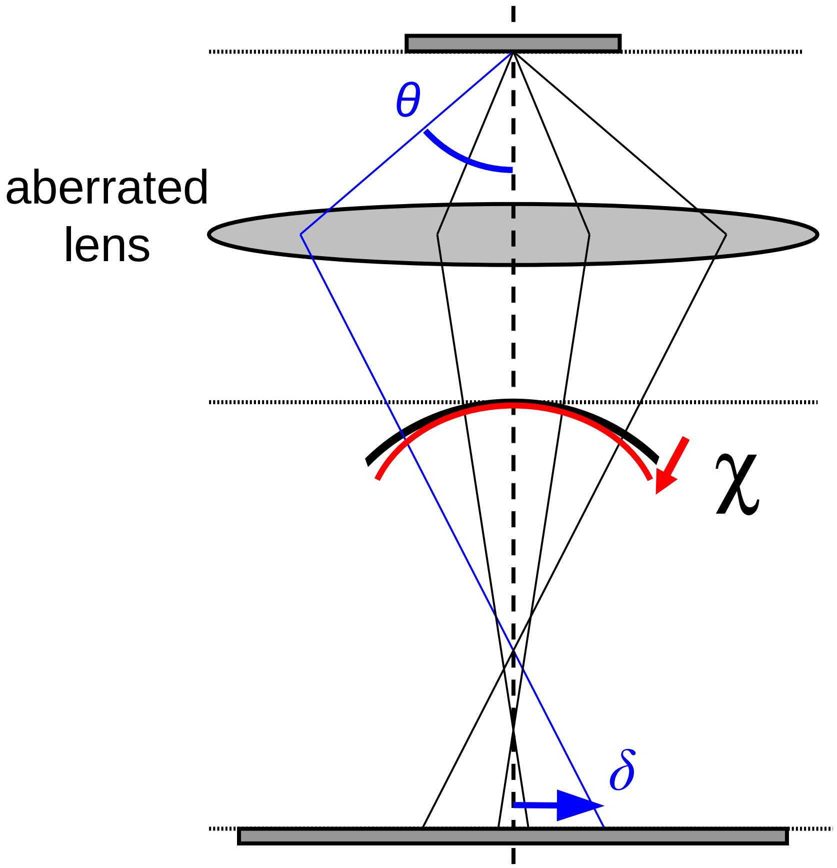


Lens aberrations

ideal lens



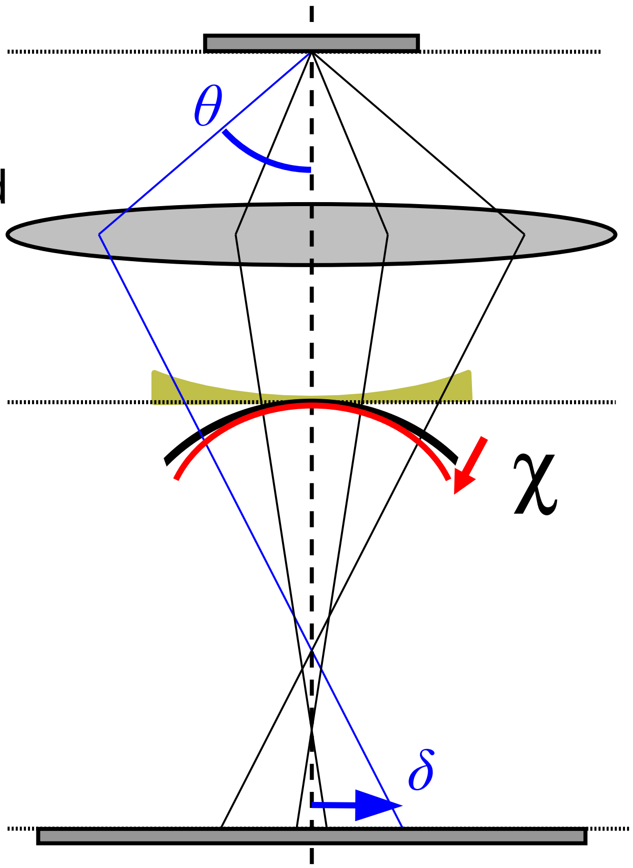
Lens aberrations: Spherical aberration

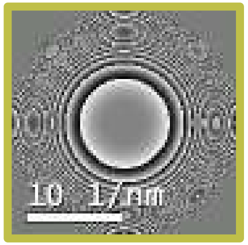


delocalization

Lens aberrations: Spherical aberration

aberrated lens





phase plate

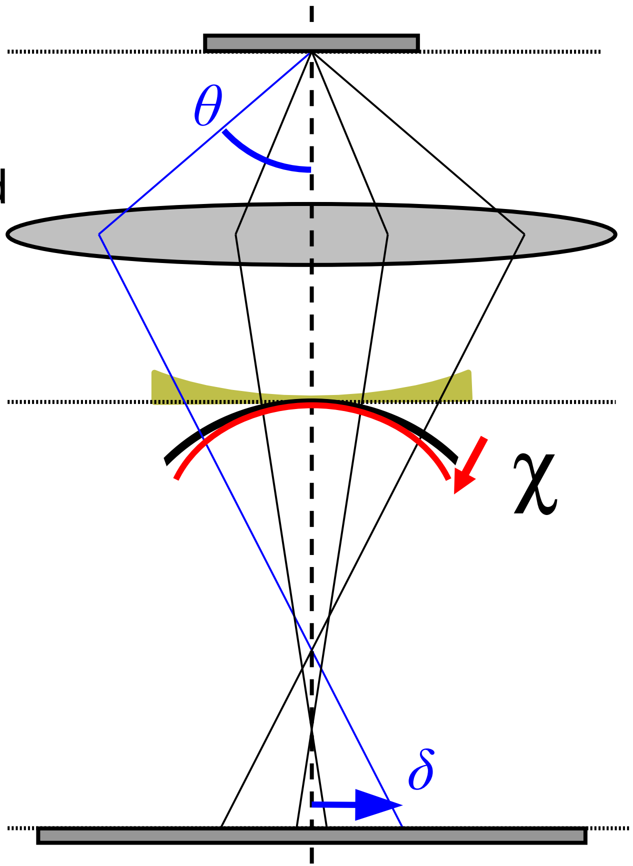
$$\exp\{-i\chi\} \quad \text{with} \quad \chi = \frac{2\pi}{\lambda} \cdot \frac{C_3}{4} \theta^4$$

⇕

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

Spherical aberration : Scherzer's Theorem

aberrated lens

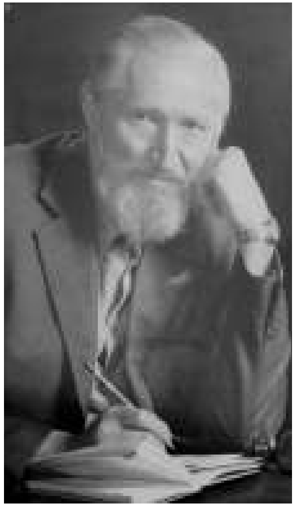


Über einige Fehler von Elektronenlinsen.

Von **O. Scherzer** in Darmstadt.

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

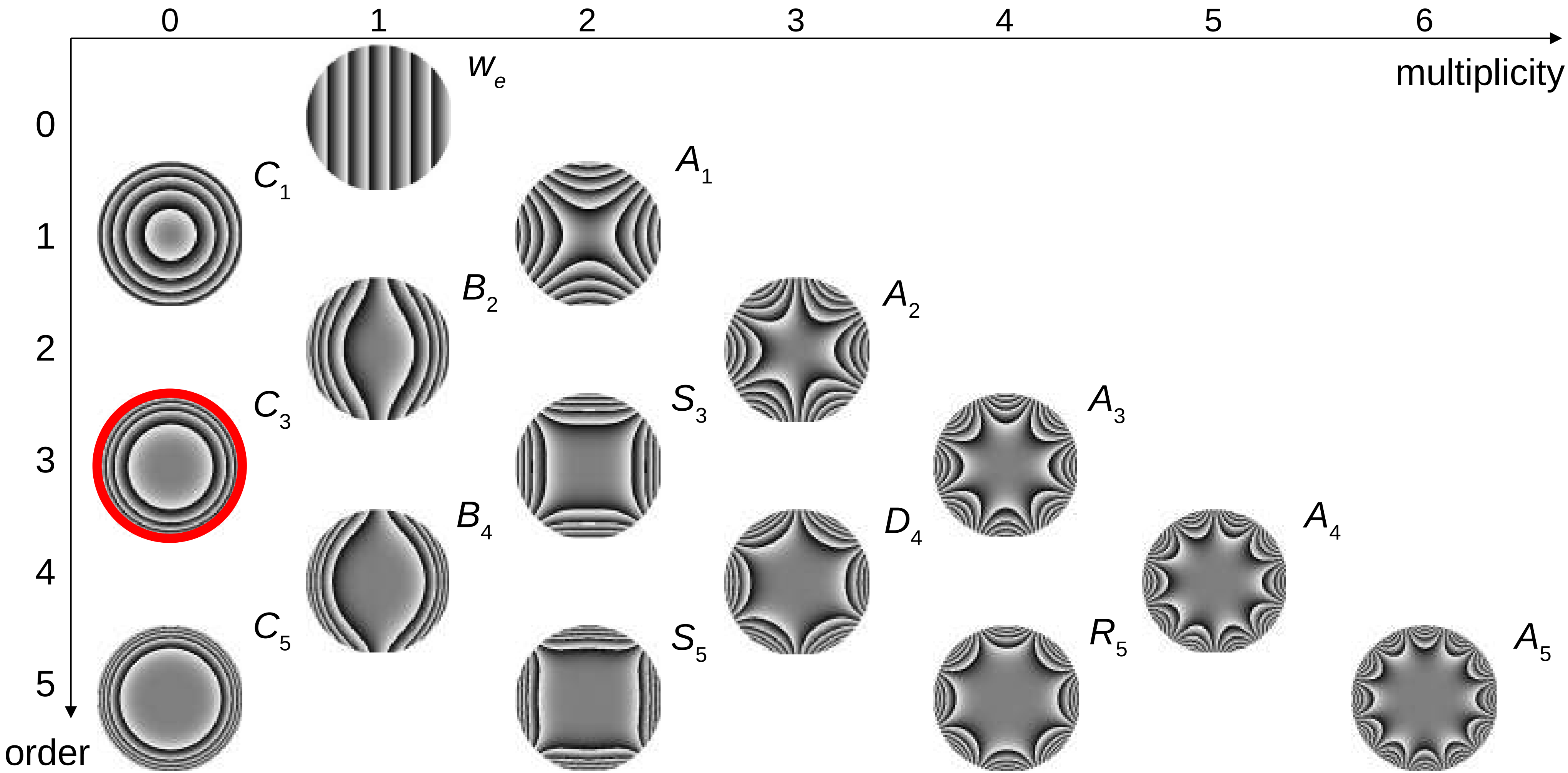
Unmöglichkeit des Achromaten. Die Bildfehler dritter Ordnung. Unvermeidbarkeit der sphärischen Aberration.



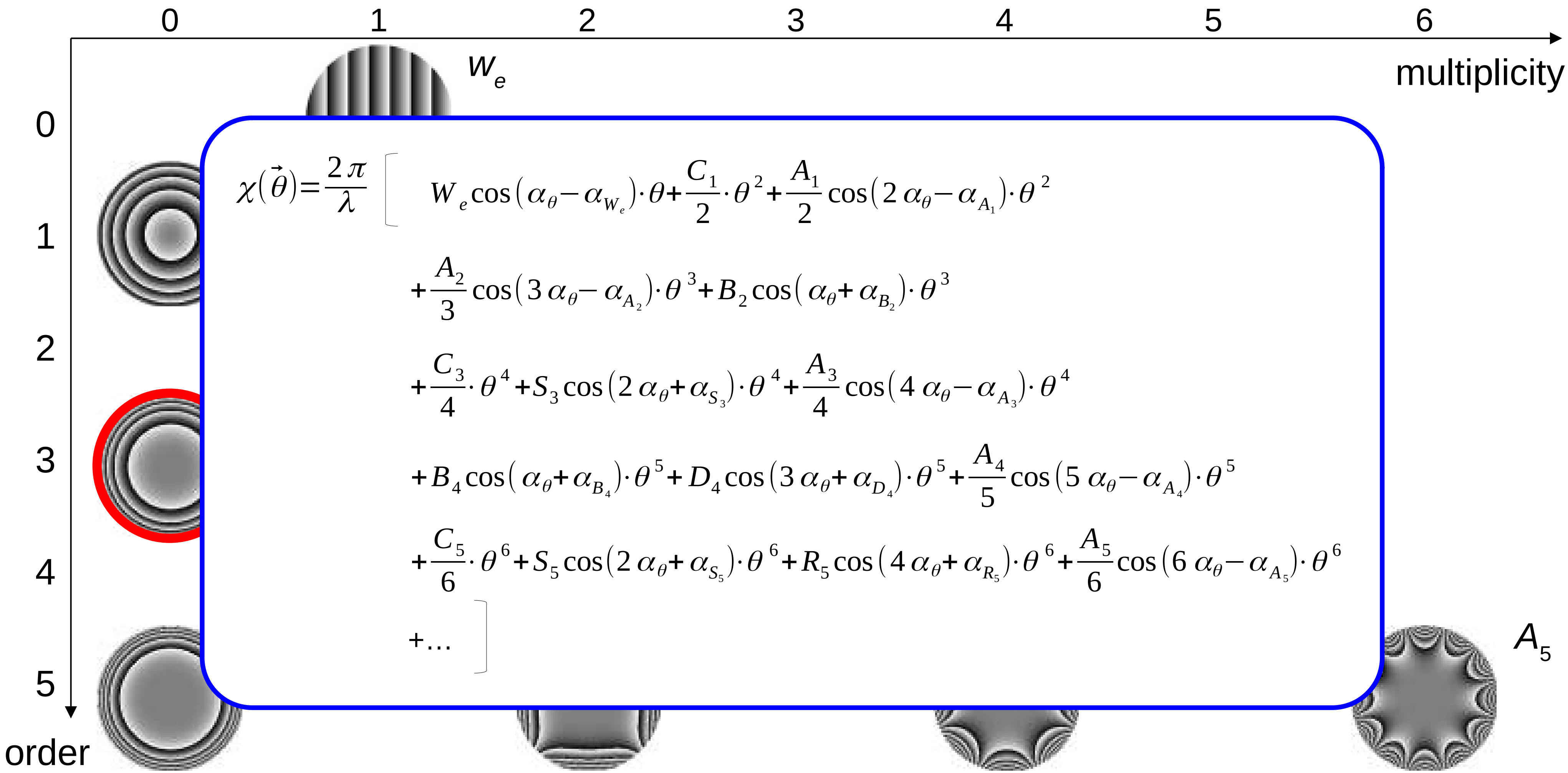
Unavoidable positive spherical aberration for stationary, space-charge-free, round electron lenses!

Prof. Otto Scherzer
(TU Darmstadt)

Wave aberration χ



Wave aberration χ



$$\chi(\vec{\theta}) = \frac{2\pi}{\lambda}\Big[W_e \cos(\alpha_\theta - \alpha_{W_e})\cdot\theta + \frac{C_1}{2}\cdot\theta^2 + \frac{A_1}{2}\cos(2\alpha_\theta - \alpha_{A_1})\cdot\theta^2$$

$$+ \frac{A_2}{3}\cos(3\alpha_\theta - \alpha_{A_2})\cdot\theta^3 + B_2\cos(\alpha_\theta + \alpha_{B_2})\cdot\theta^3$$

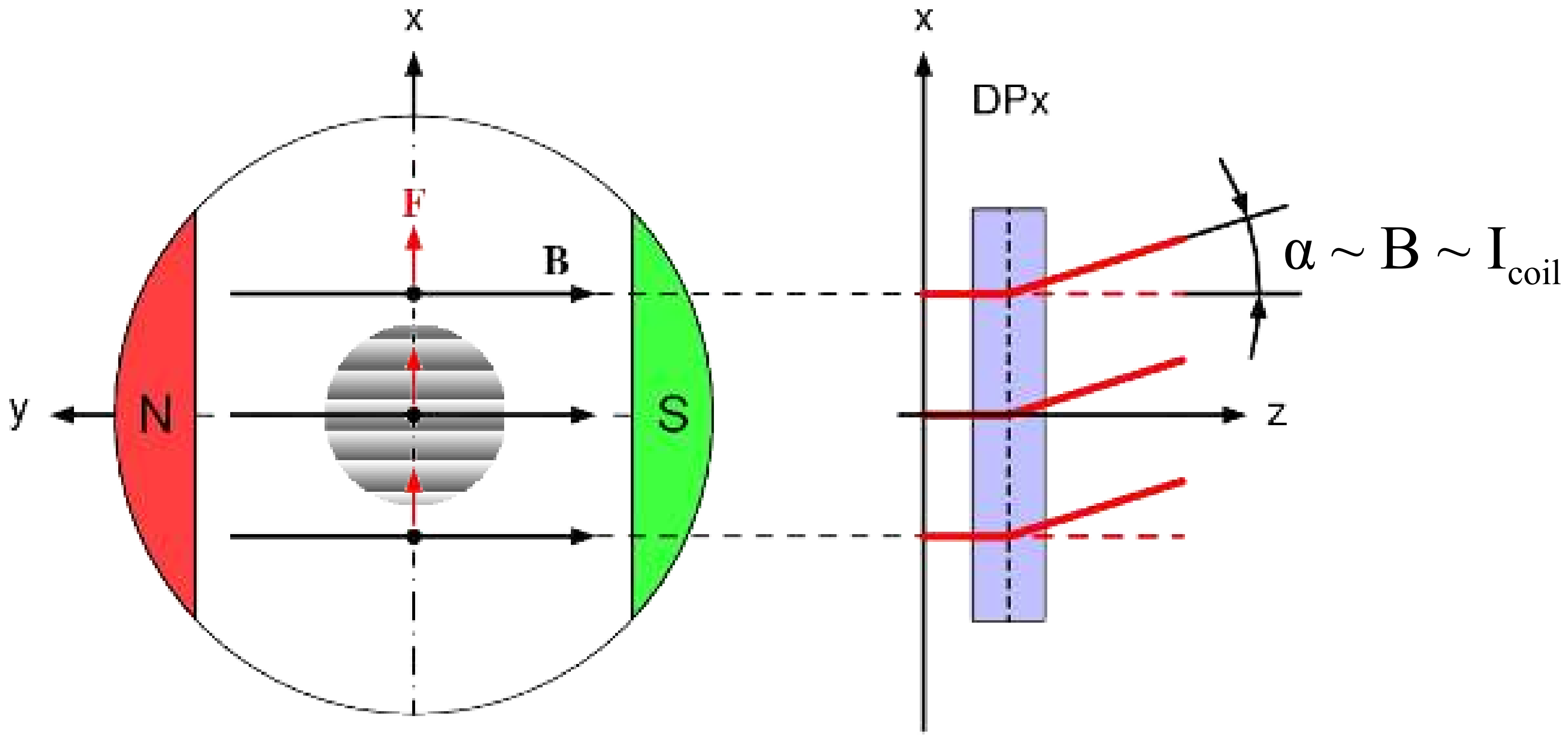
$$+ \frac{C_3}{4}\cdot\theta^4 + S_3\cos(2\alpha_\theta + \alpha_{S_3})\cdot\theta^4 + \frac{A_3}{4}\cos(4\alpha_\theta - \alpha_{A_3})\cdot\theta^4$$

$$+ B_4\cos(\alpha_\theta + \alpha_{B_4})\cdot\theta^5 + D_4\cos(3\alpha_\theta + \alpha_{D_4})\cdot\theta^5 + \frac{A_4}{5}\cos(5\alpha_\theta - \alpha_{A_4})\cdot\theta^5$$

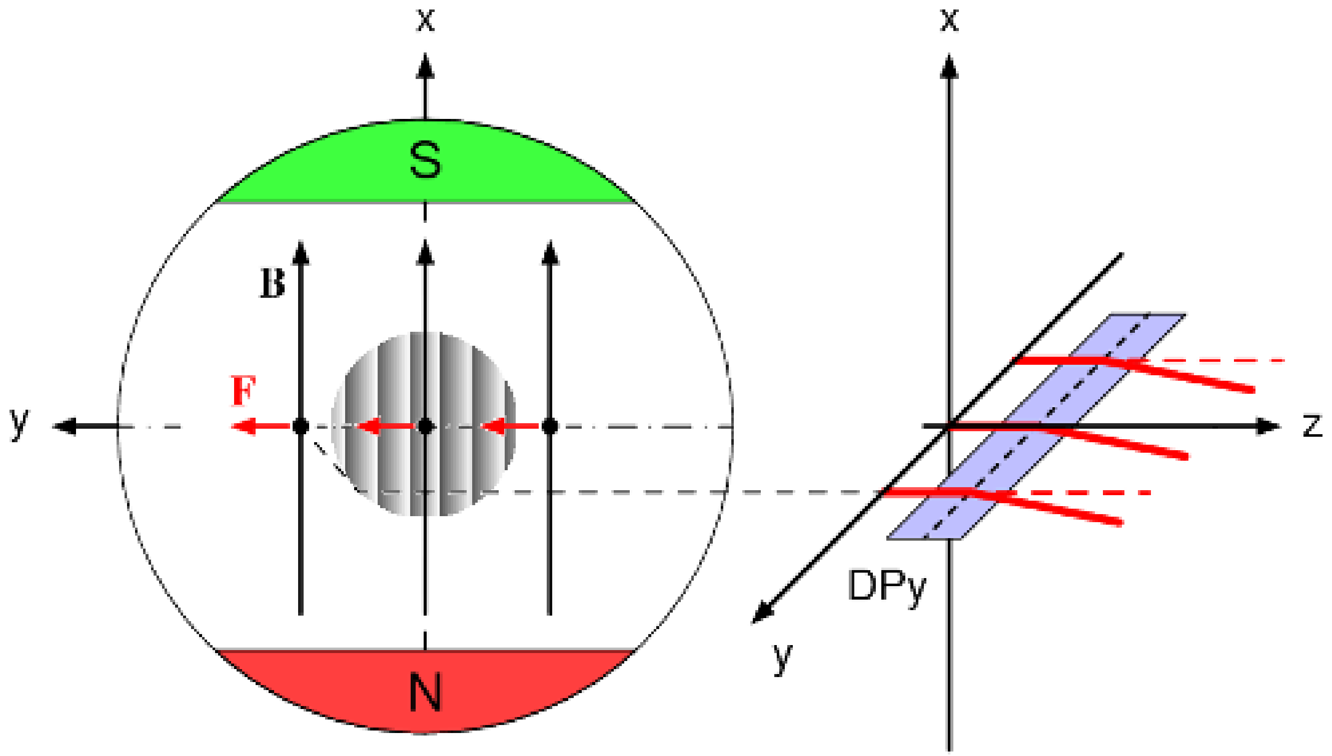
$$+ \frac{C_5}{6}\cdot\theta^6 + S_5\cos(2\alpha_\theta + \alpha_{S_5})\cdot\theta^6 + R_5\cos(4\alpha_\theta + \alpha_{R_5})\cdot\theta^6 + \frac{A_5}{6}\cos(6\alpha_\theta - \alpha_{A_5})\cdot\theta^6$$

$$+ \ldots \Big]$$

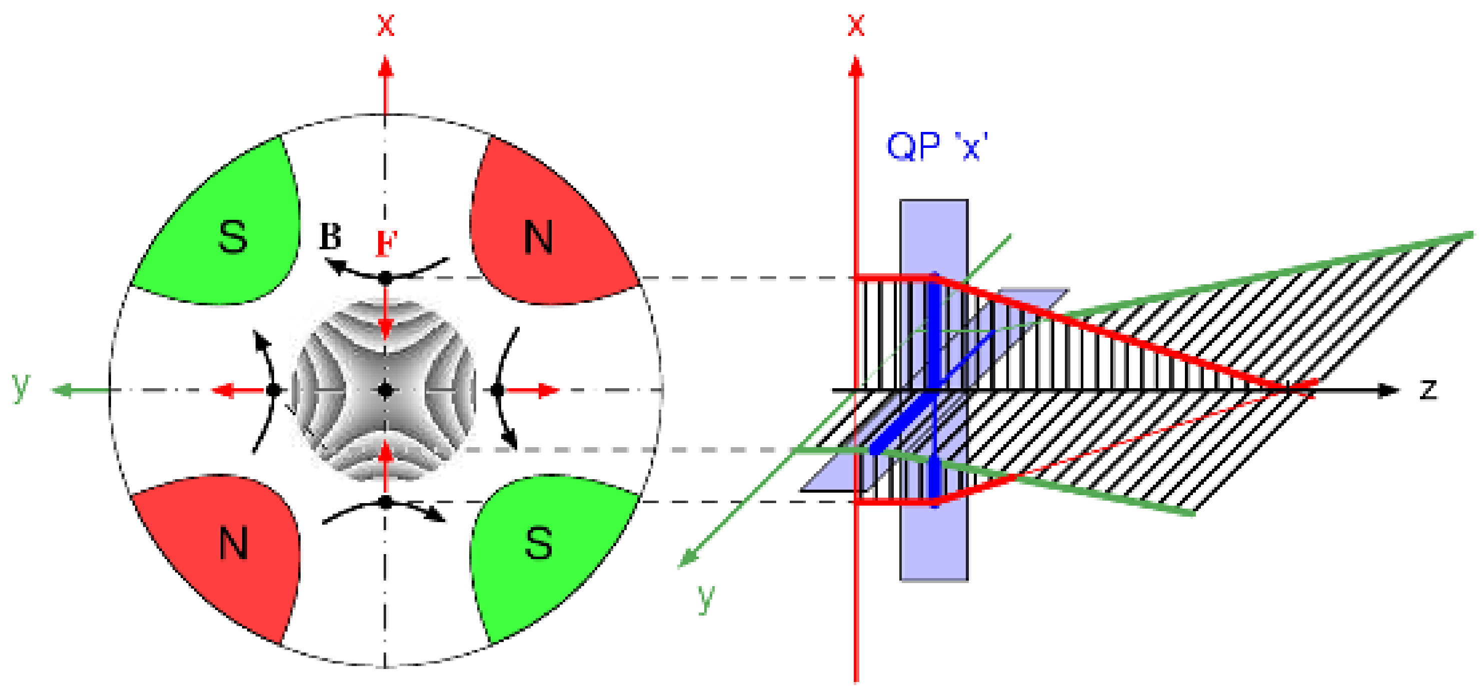
Dipoles – beam deflection in x-section



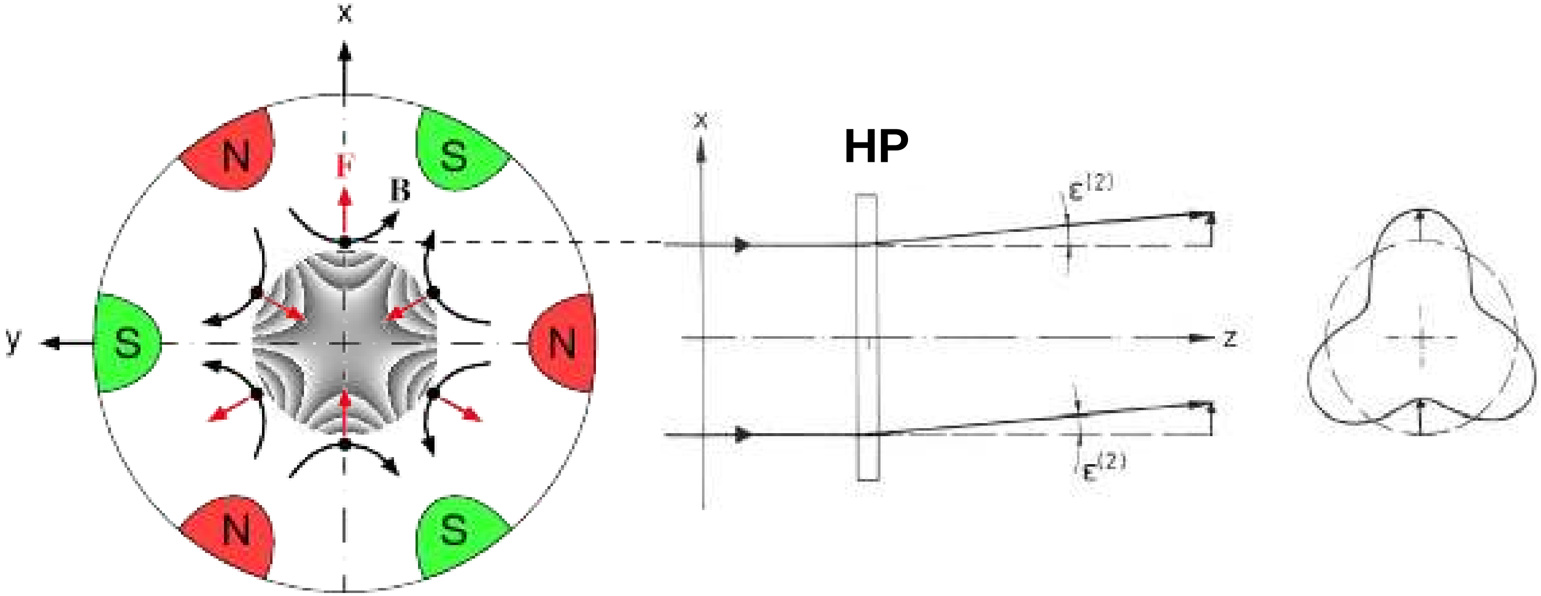
Dipoles – beam deflection in y-section



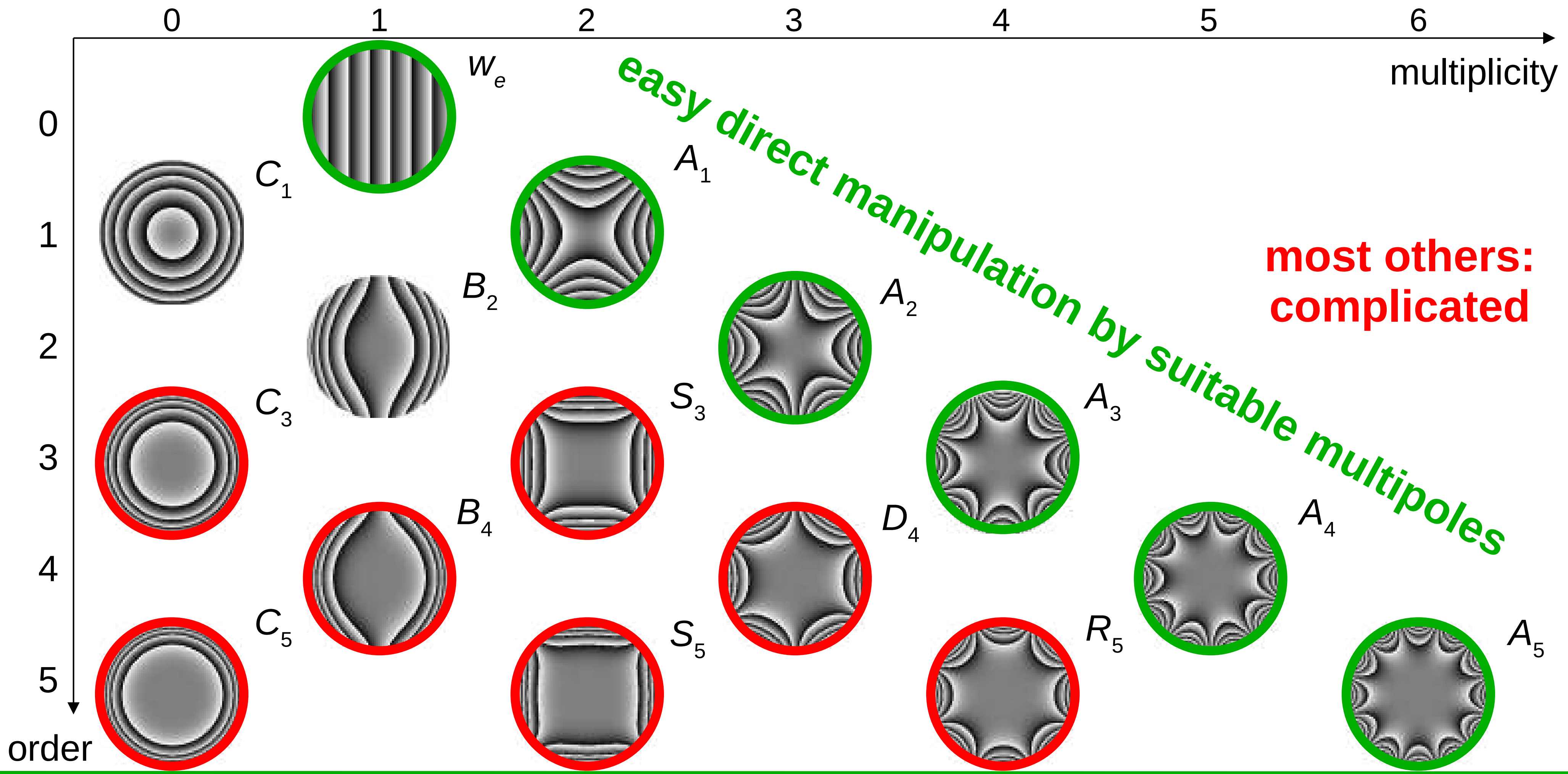
Quadrupoles – 2-fold Stigmators



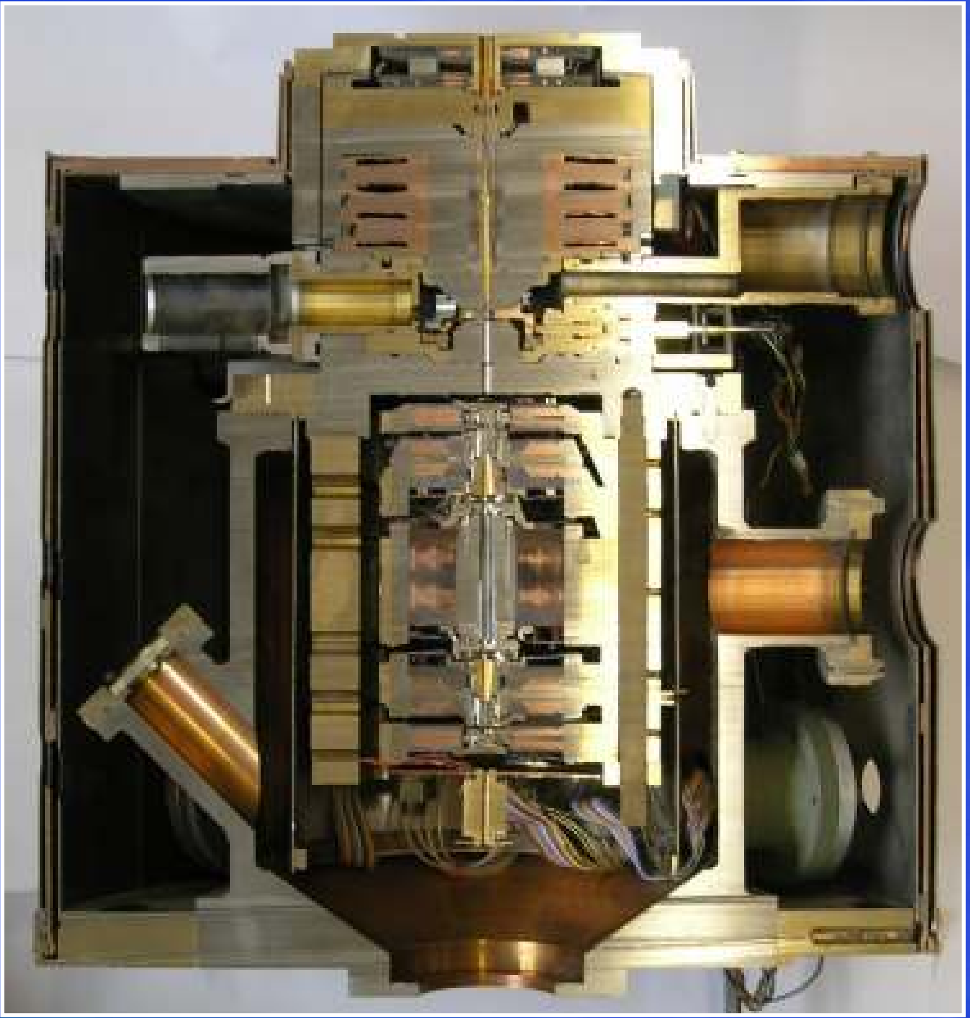
Hexapoles – 3-fold Stigmators



Wave aberration χ



Long history of aberration correction



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 ...**

same outcome world-wide
e.g. in Chicago and Cambridge

Aberration correction using hexapoles

Prof. Harald Rose in 1990 …

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

Institut für Angewandte Physik Technische Hochschule Darmstadt, FRG

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.

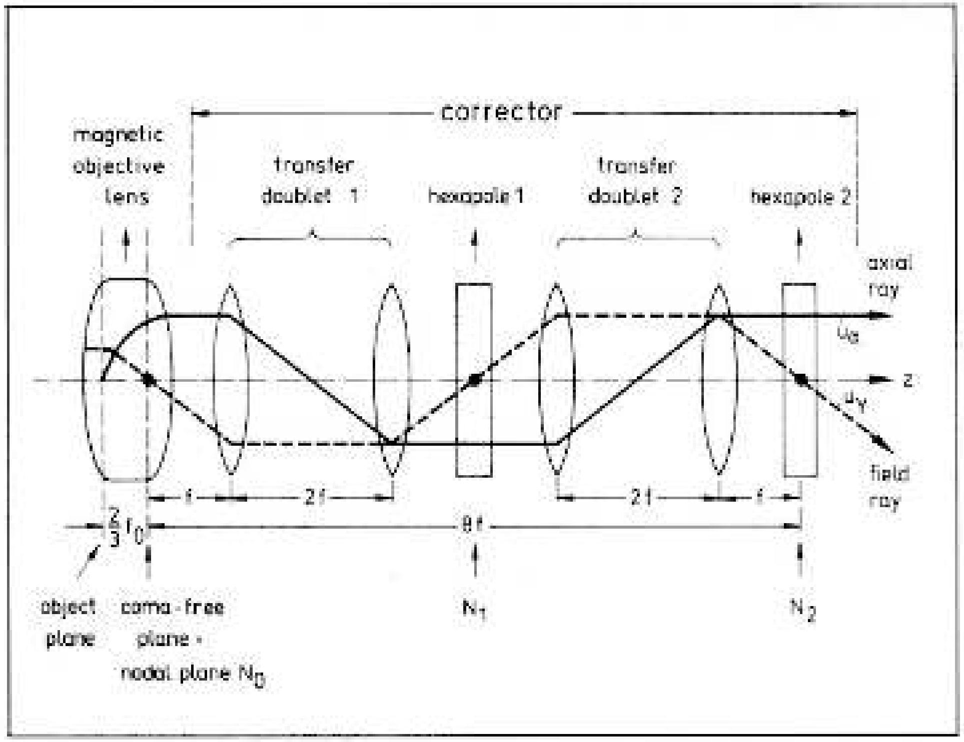


Fig. 2. Schematic arrangement of the elements of the spherically corrected semiaplanatic objective lens.

Aberration correction by means of hexapoles

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

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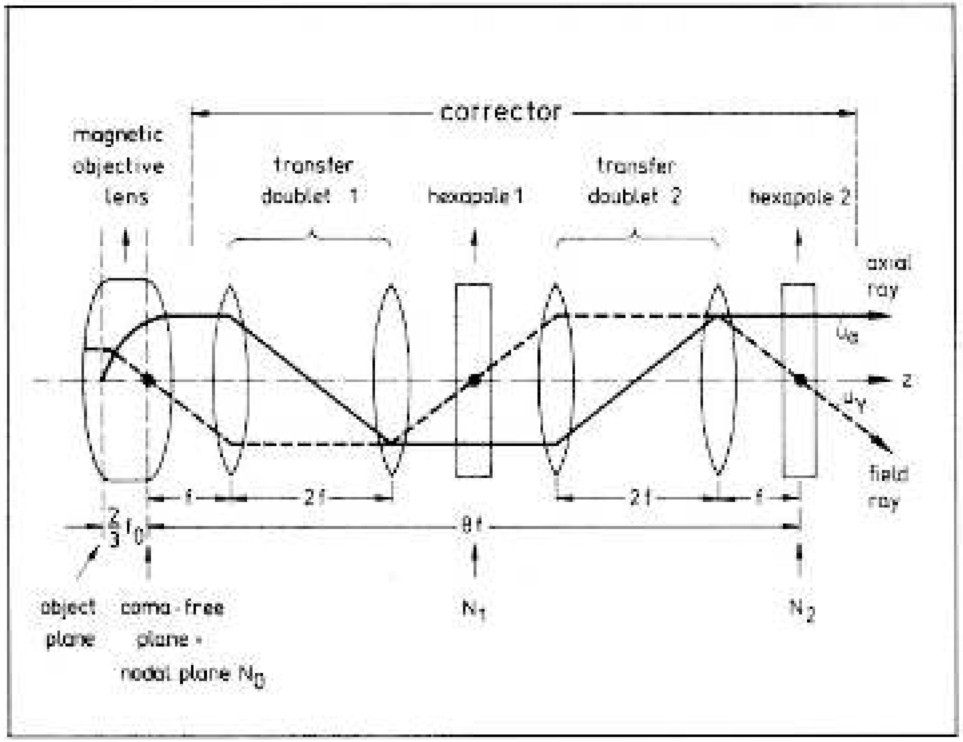
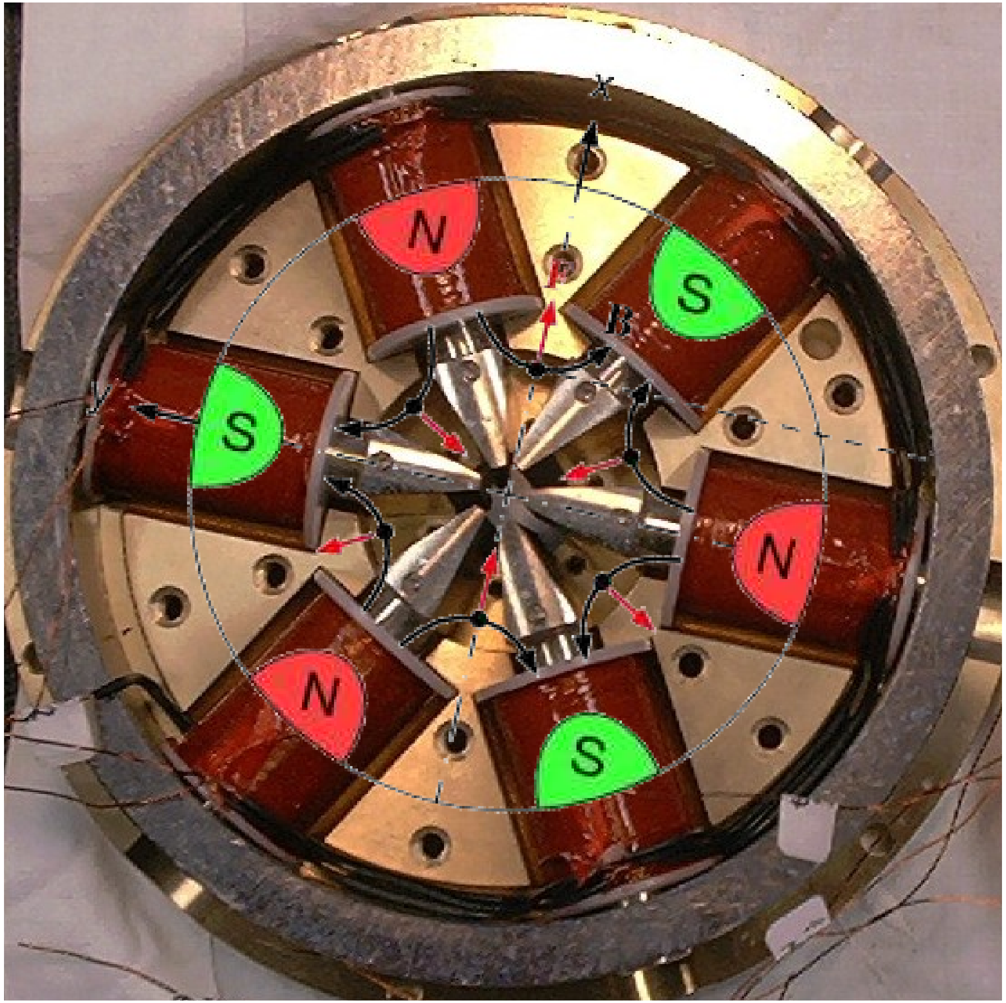
Institut für Angewandte Physik Technische Hochschule Darmstadt, FRG





Aberration correction by means of hexapoles

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

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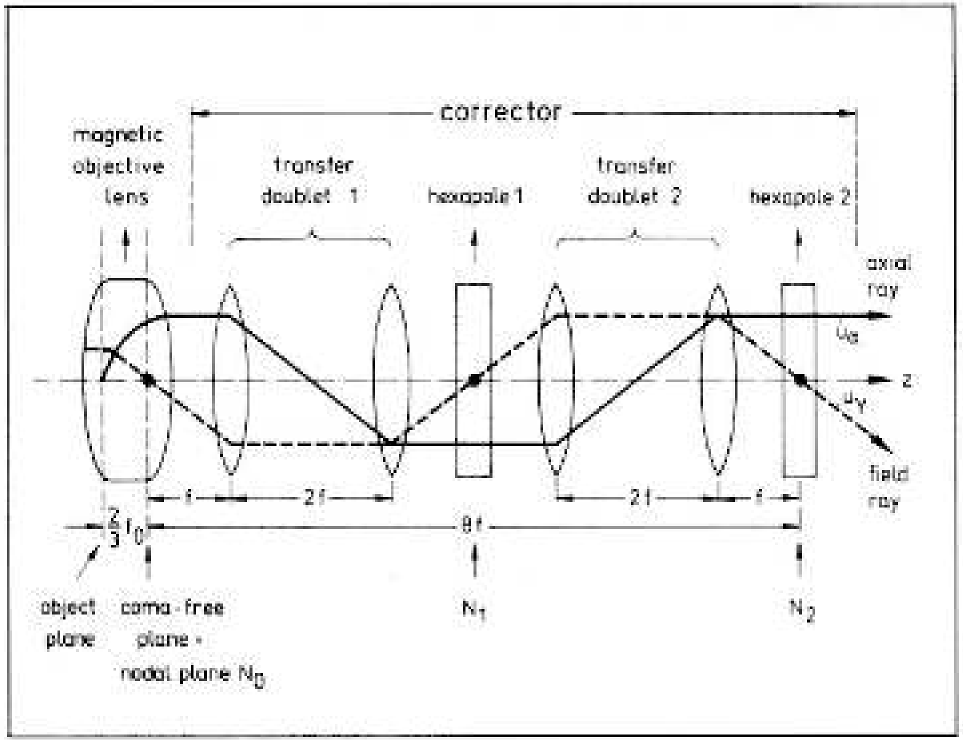
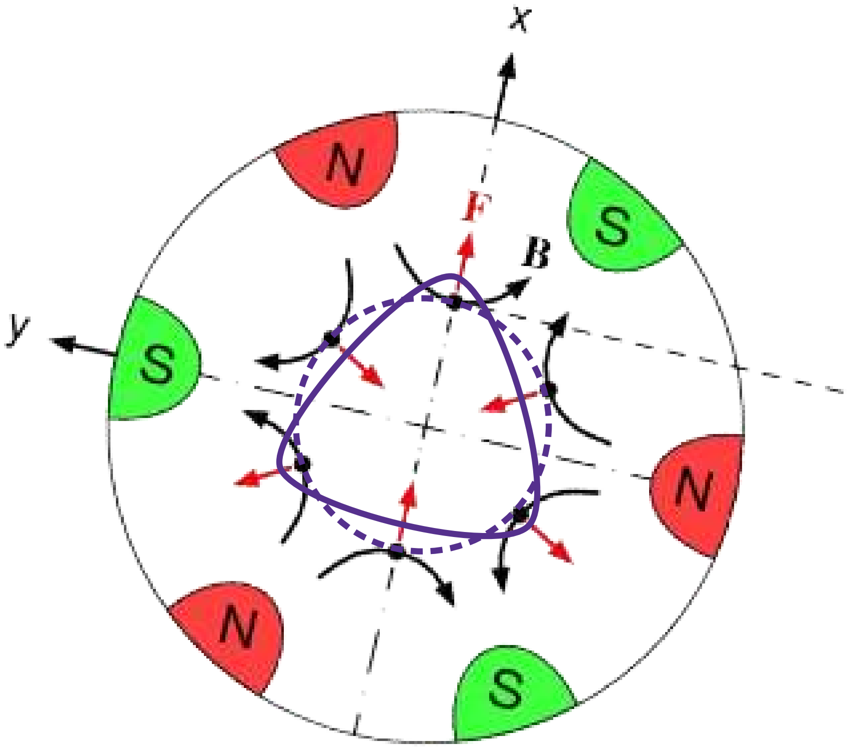
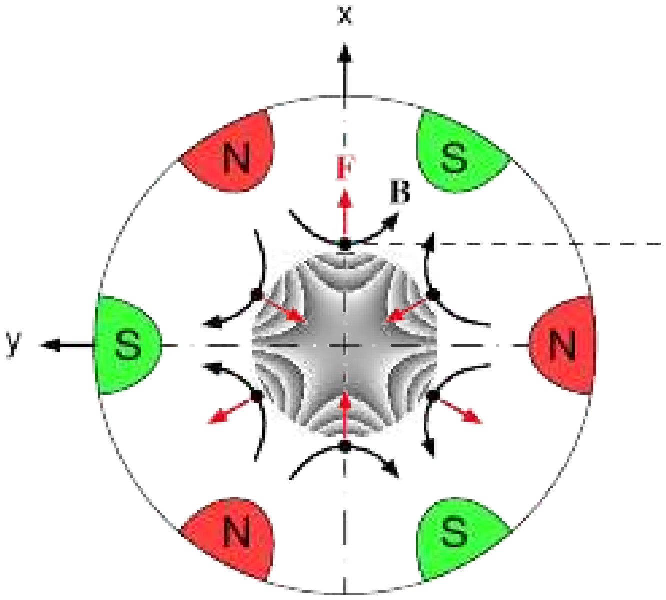
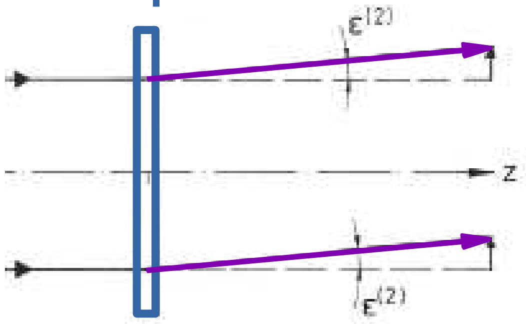


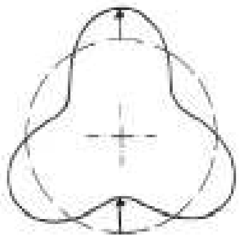


Aberration correction by means of hexapoles



short hexapole

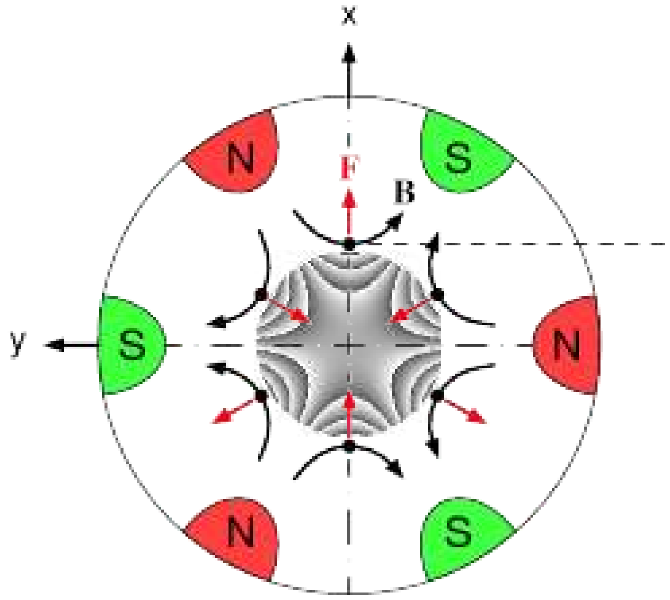


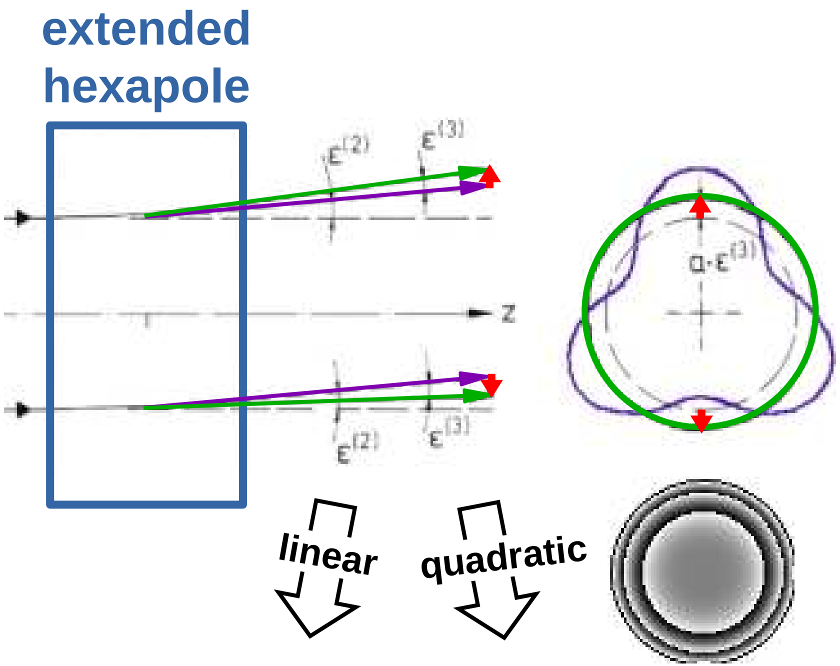


linear

2nd order aberration
(three-fold astigmatism)

Aberration correction by means of hexapoles



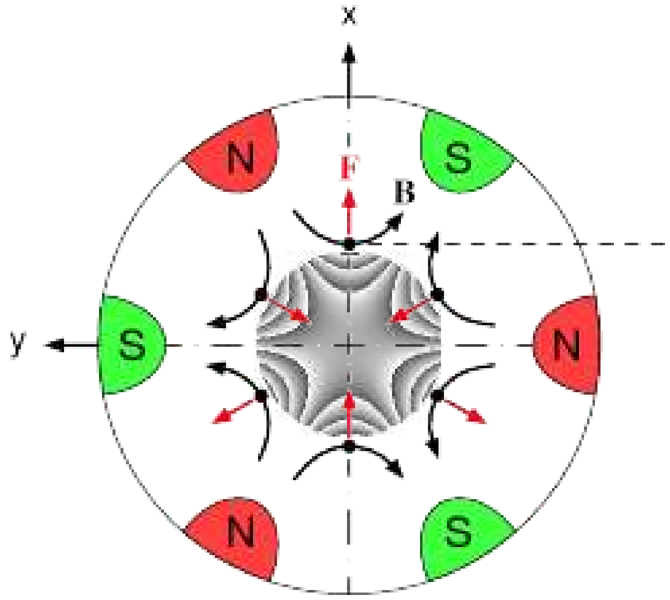


2nd order aberration
(three-fold astigmatism)

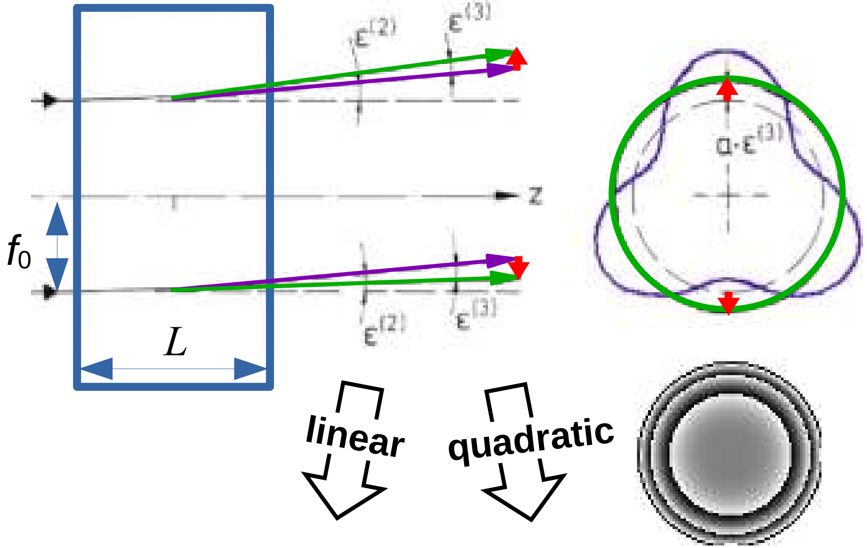
3rd order aberration
(negative spherical aberration)

Peter W. Hawkes: "The geometrical aberrations of general electron optical systems", Philos. Trans. R. Soc. Lond. A, 257 (1965), 479-552.
Vernon D. Beck: “A hexapole spherical aberration corrector”, Optik. 53 (1979), 241–255.

Aberration correction by means of hexapoles



extended hexapole



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

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

2nd order aberration
(three-fold astigmatism)

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

linear

3rd order aberration
(negative spherical aberration)

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

quadratic

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

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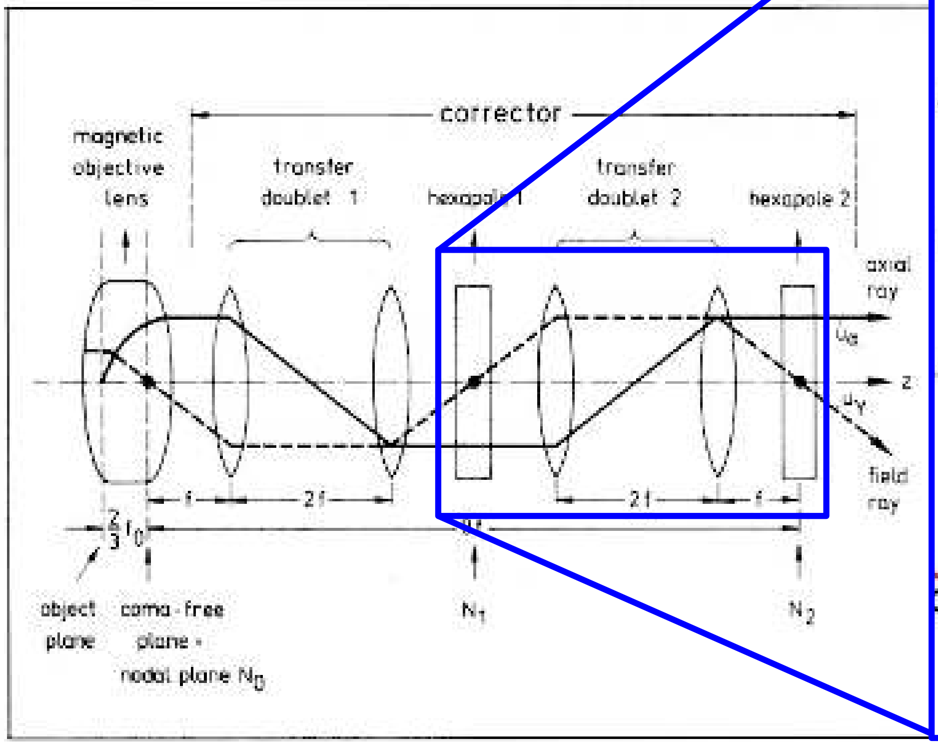
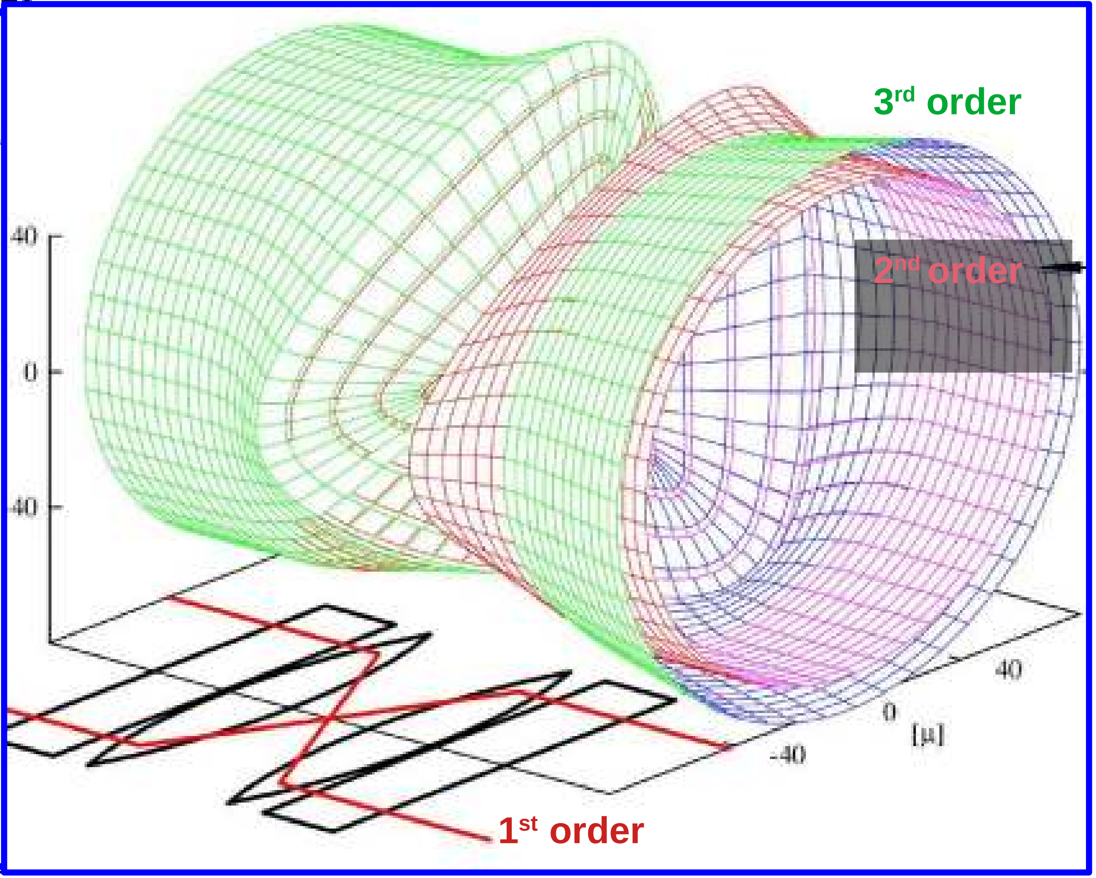
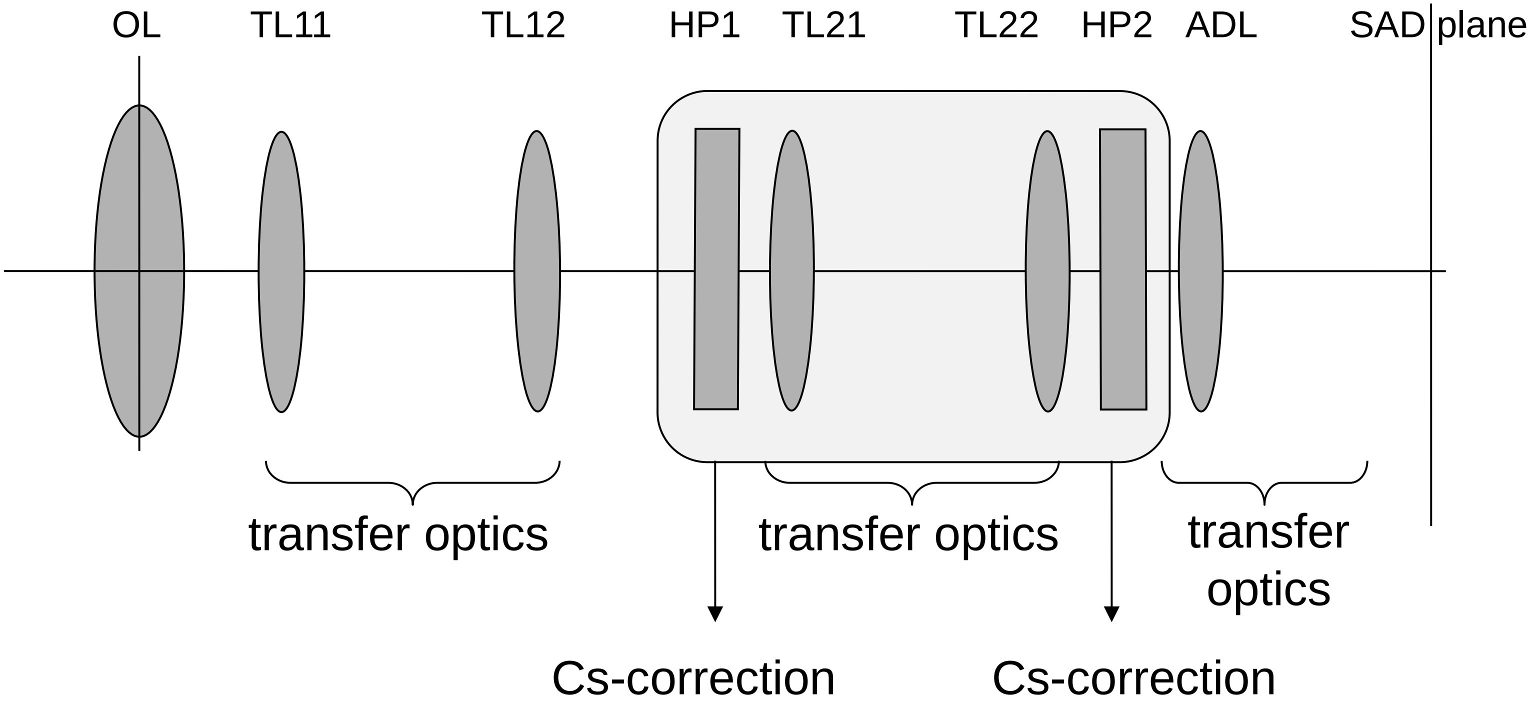




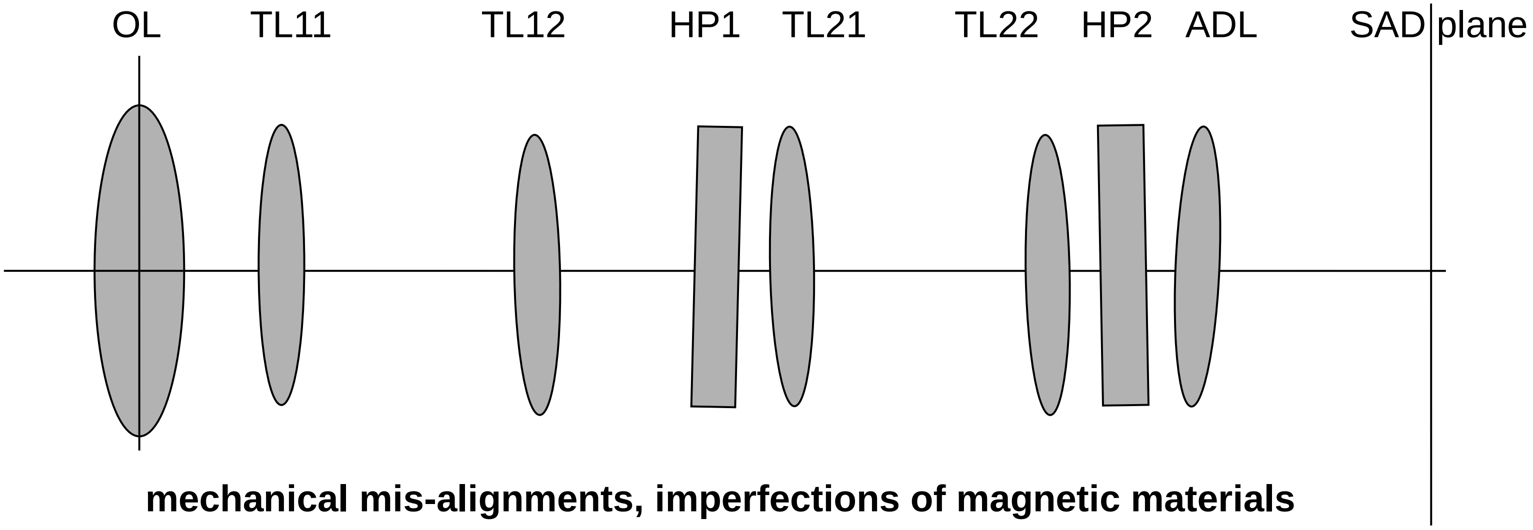
Aberration correction by means of hexapoles

Ideal system:



Aberration correction by means of hexapoles

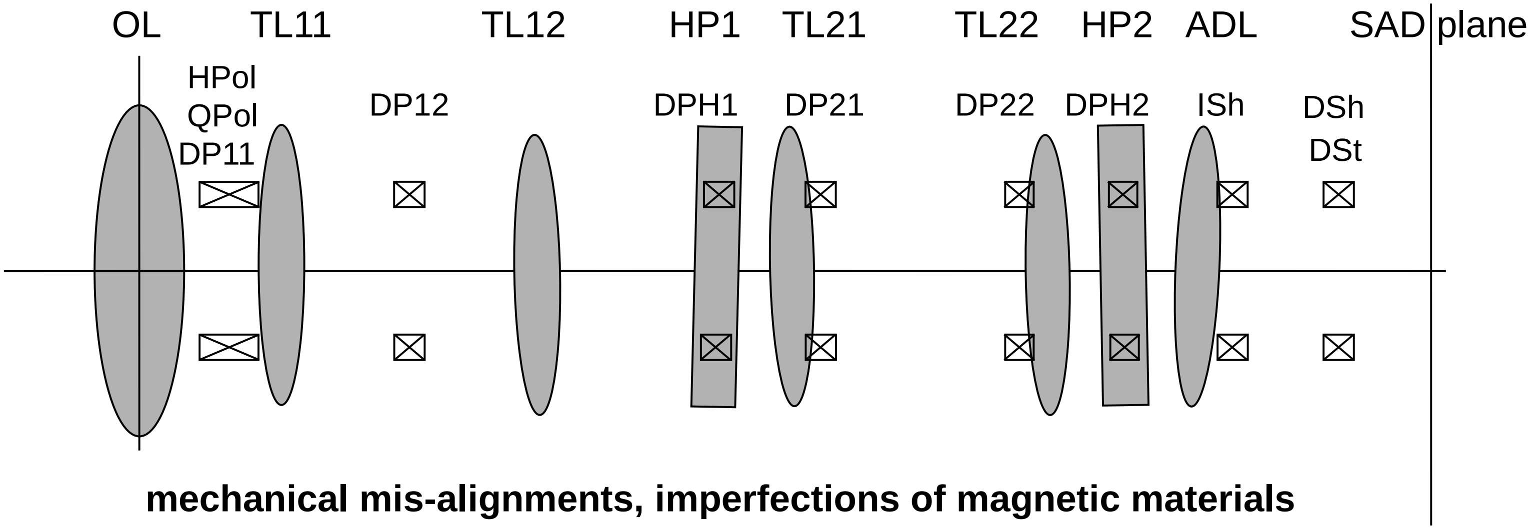
Ideal system vs. real system: small imperfections due to limited manufacturing precision



mechanical mis-alignments, imperfections of magnetic materials

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

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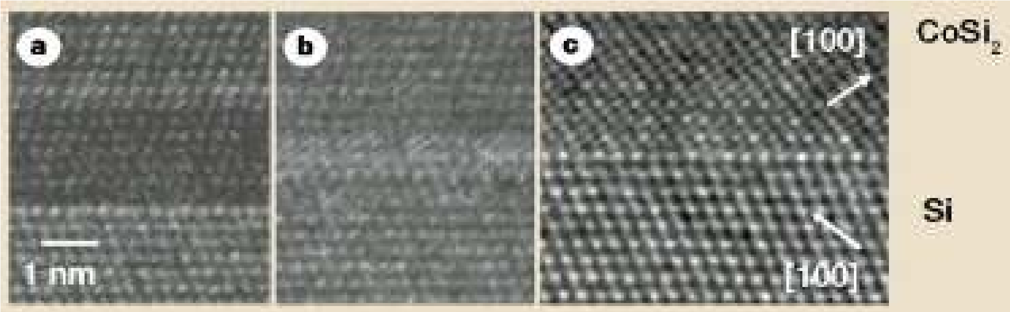
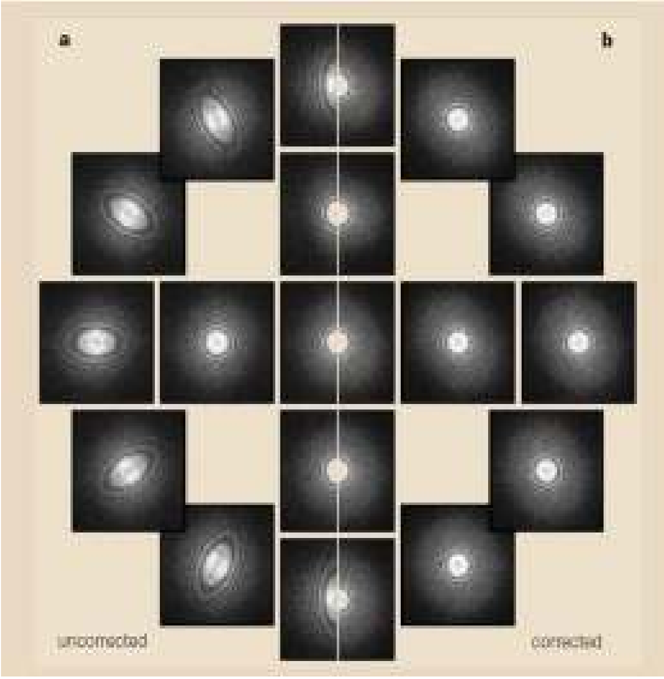
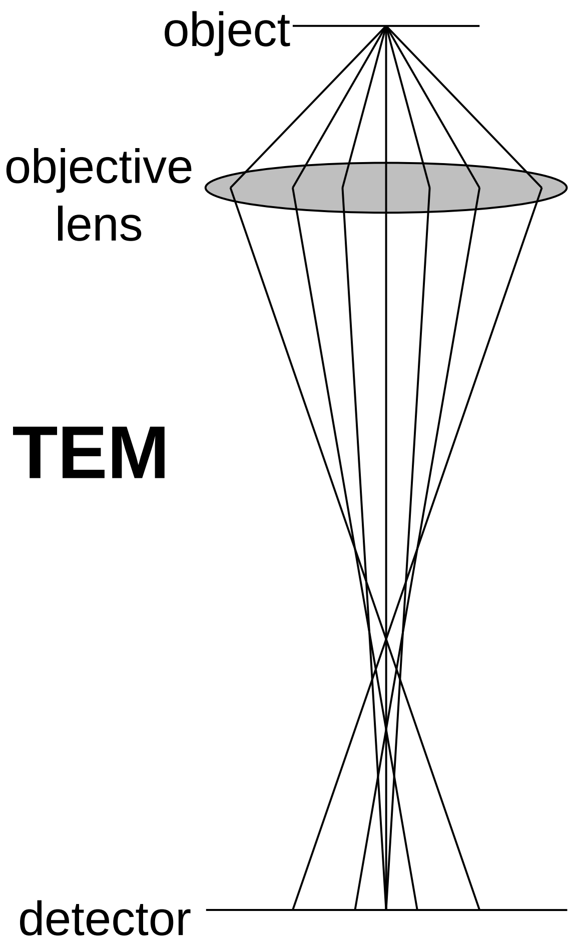
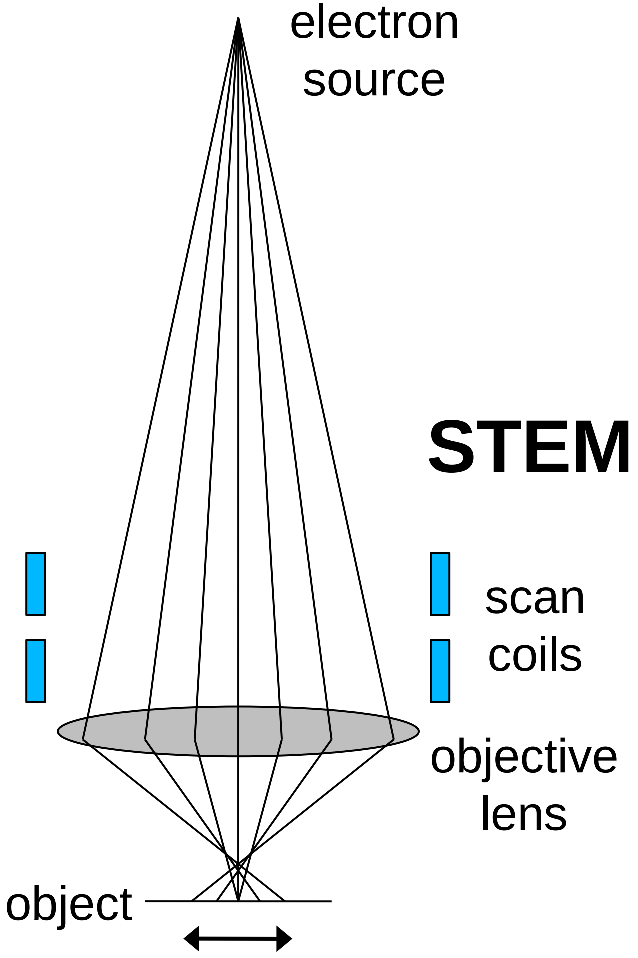




Aberration-correction for TEM and STEM





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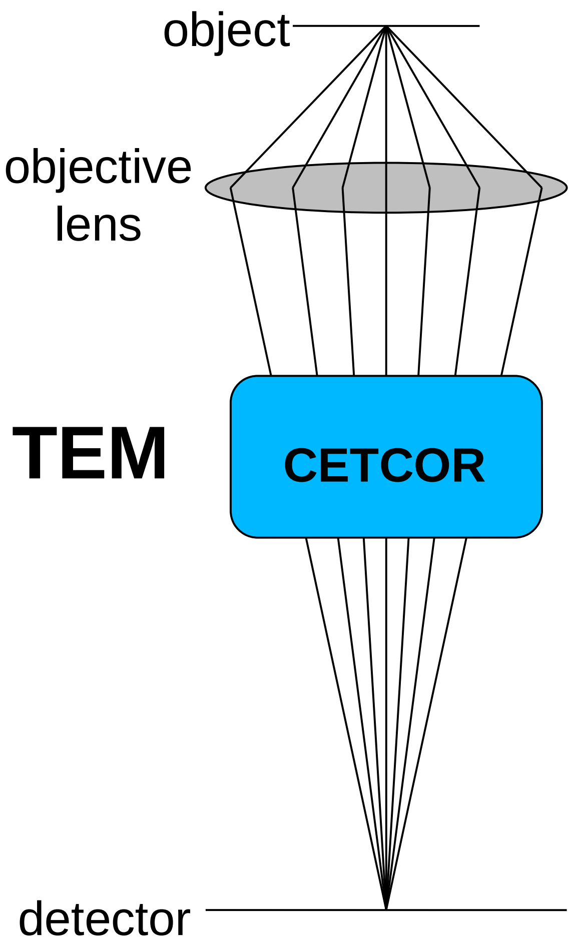
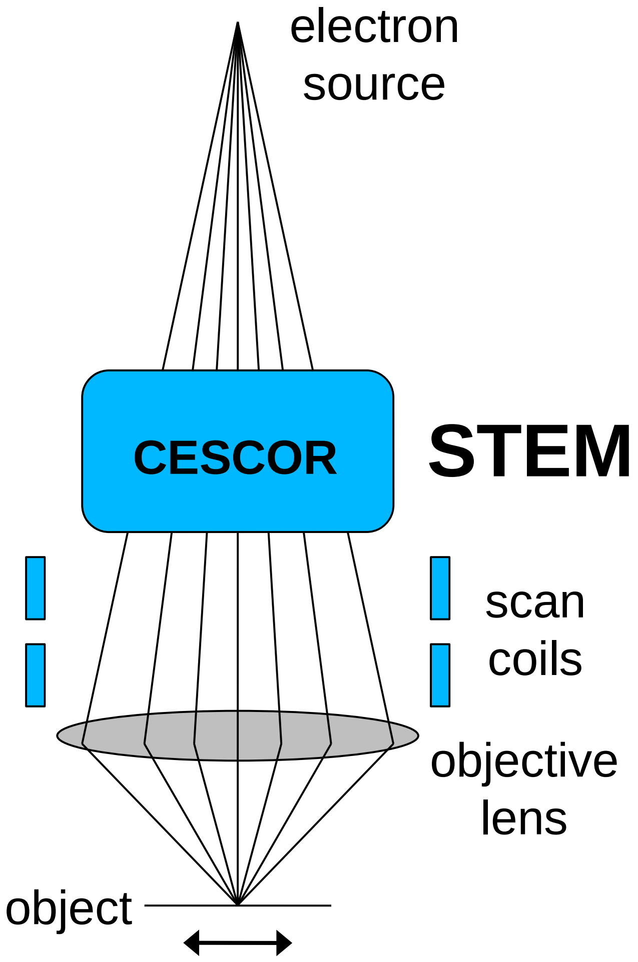
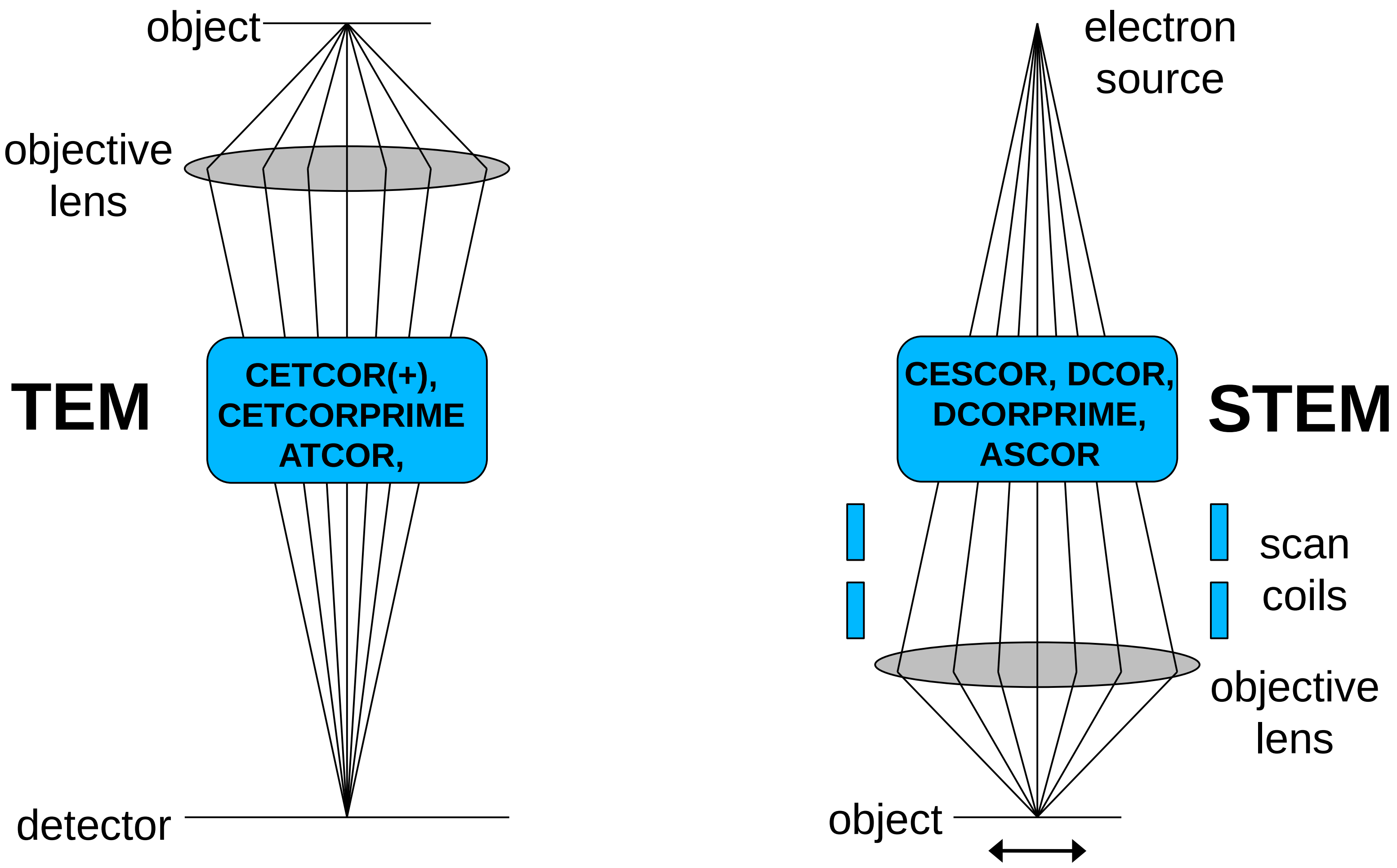


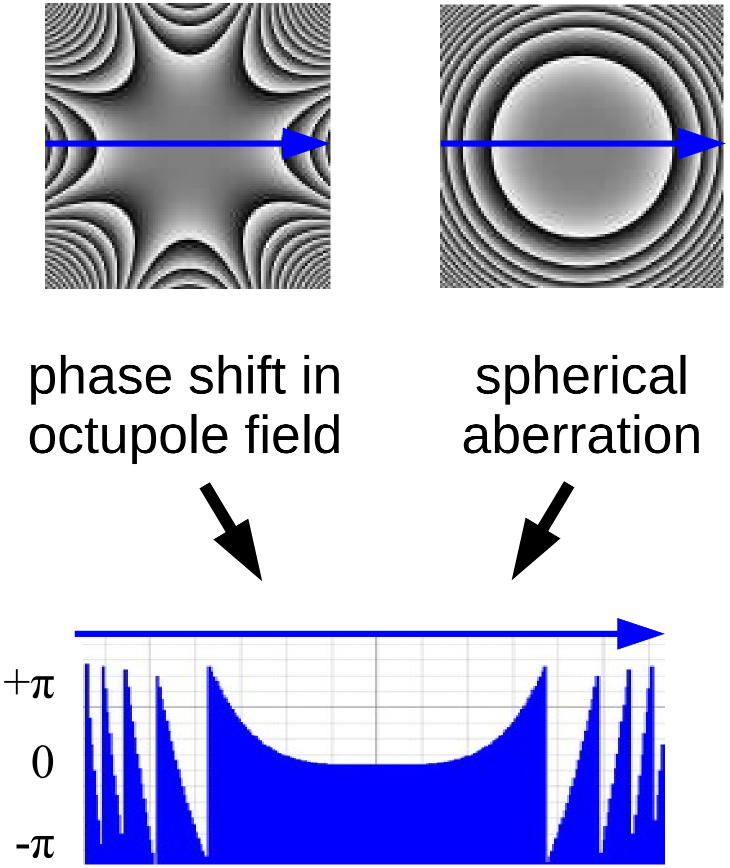


Aberration-correction for TEM and STEM



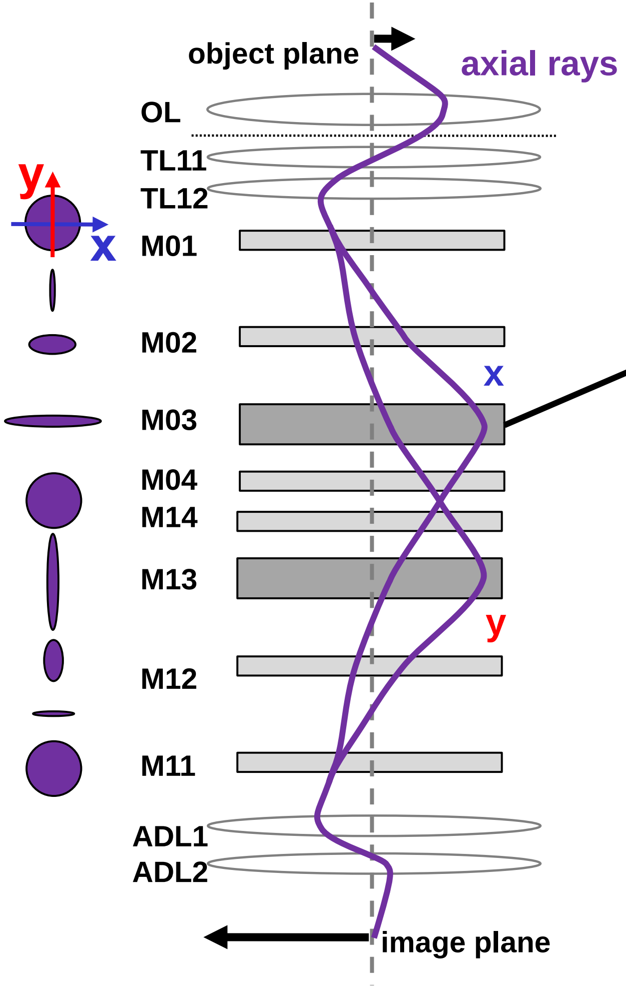
Aberration correction using quadrupoles and octupoles

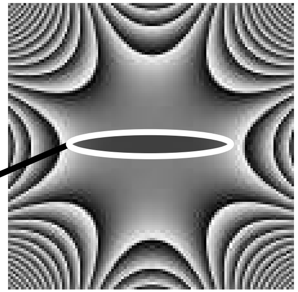
C_S-correction by means of octupoles



phase shift lineprofiles

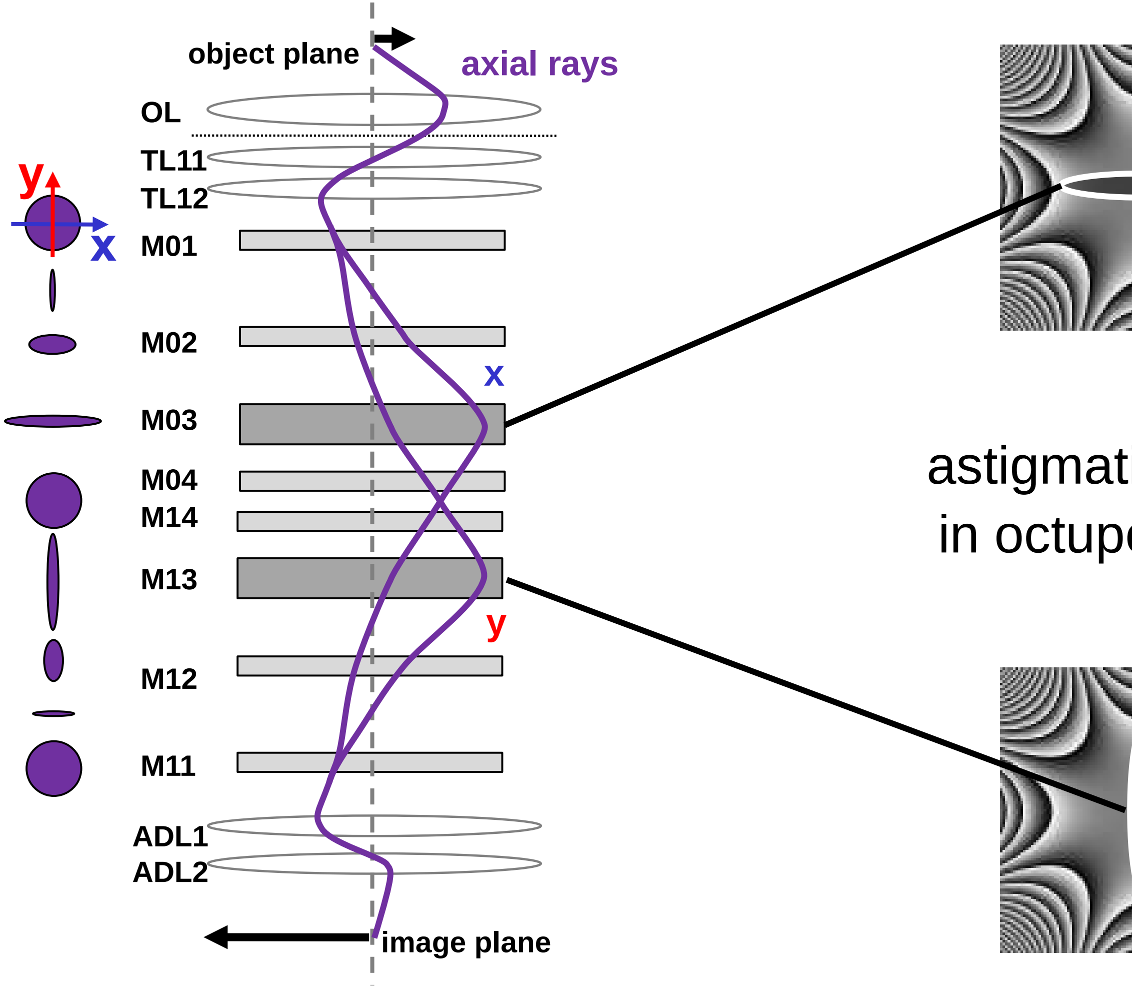
C_S-correction by means of octupoles

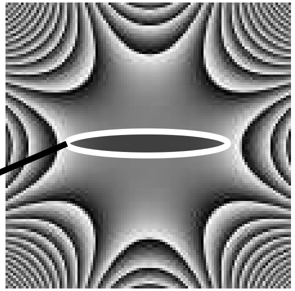




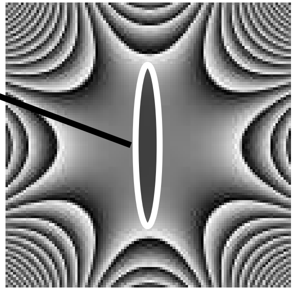
astigmatic beam
in octupole field

C_S-correction by means of octupoles

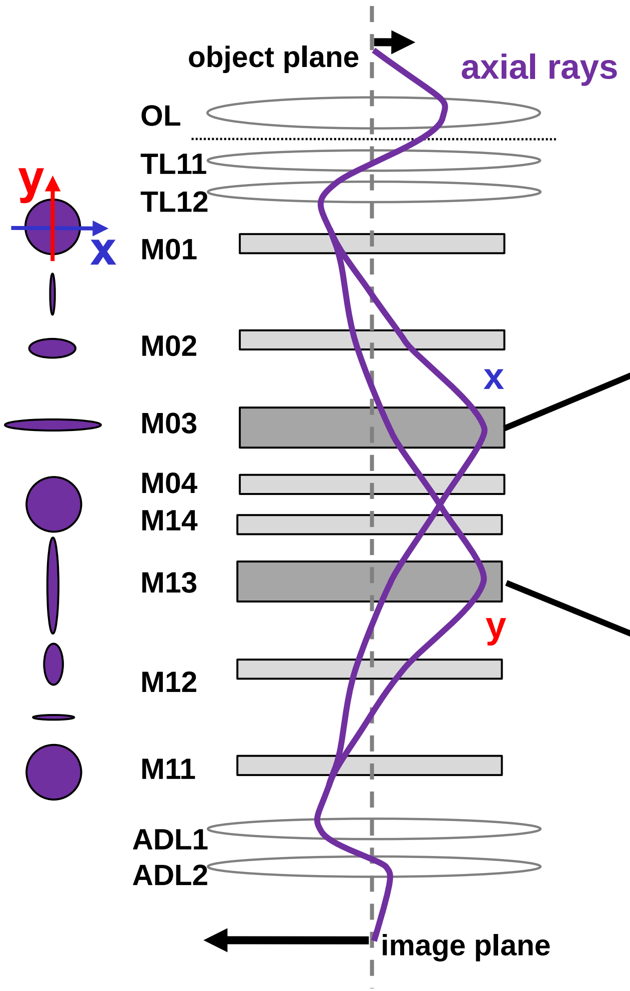




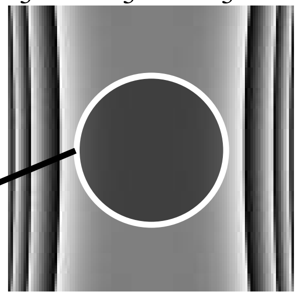
astigmatic beams
in octupole fields



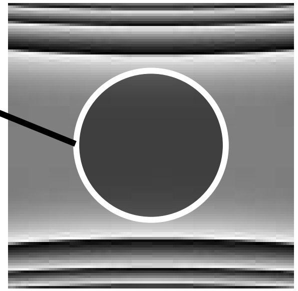
C_S-correction by means of octupoles



$A_3 \rightarrow C_3 + A_3 + S_3$

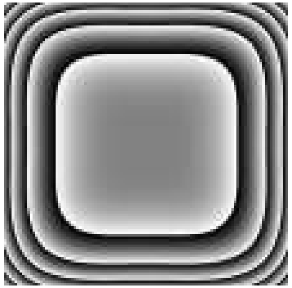


round beams in distorted octupole fields



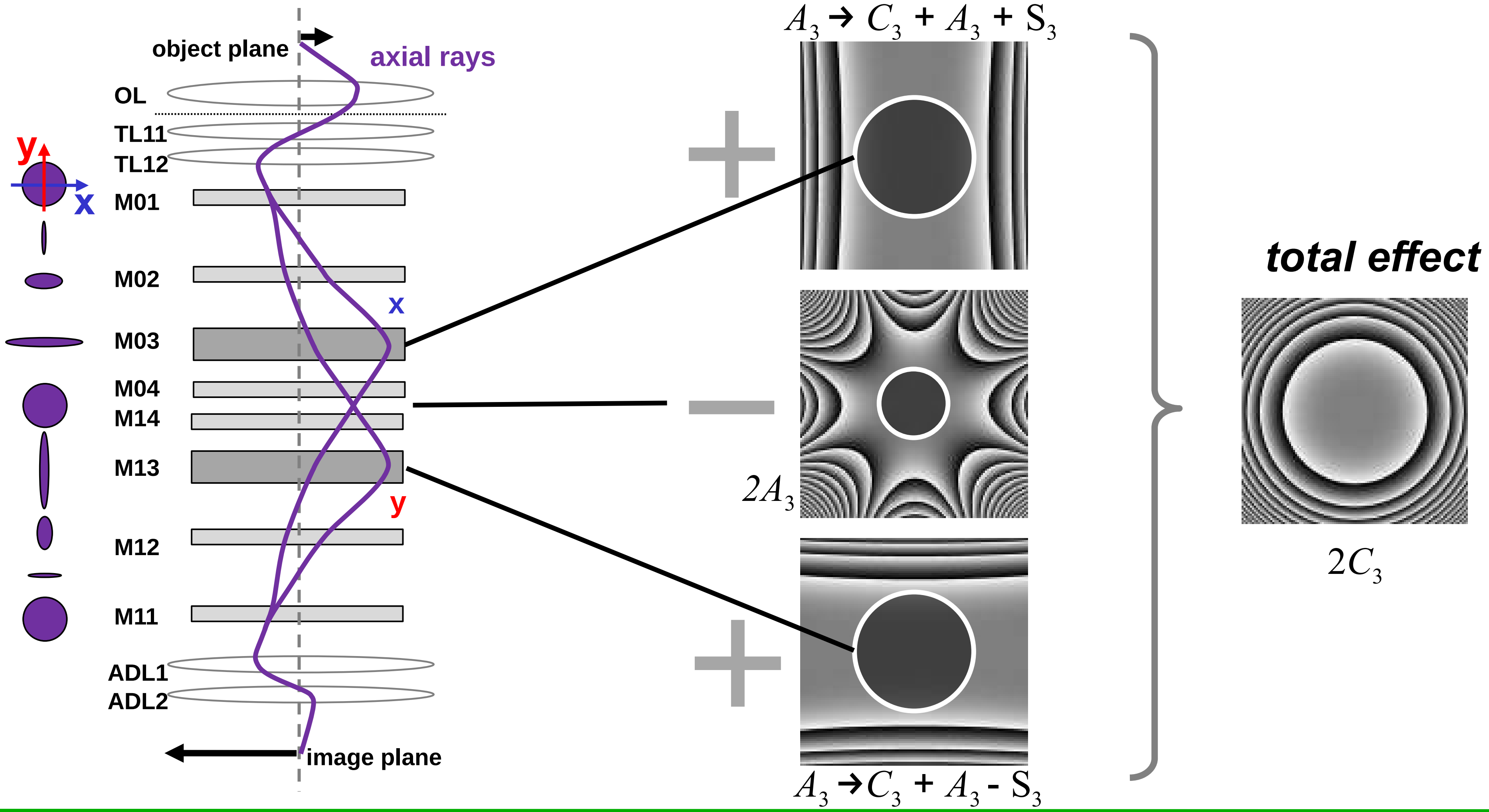
$A_3 \rightarrow C_3 + A_3 - S_3$

total effect



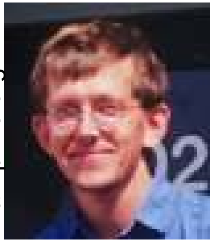
$2C_3 + 2A_3$

C_S-correction by means of octupoles



nion : C_S-correction in a dedicated STEM

NIklas Dellby and **ON**drey Krivanek


kavliprize.org

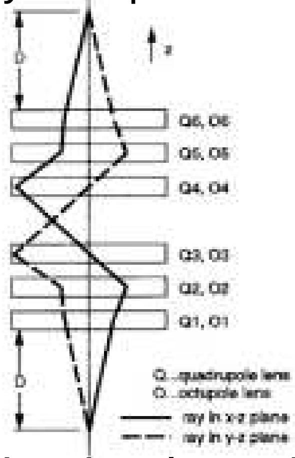

wikipedia.org

nion now part of BRUKER

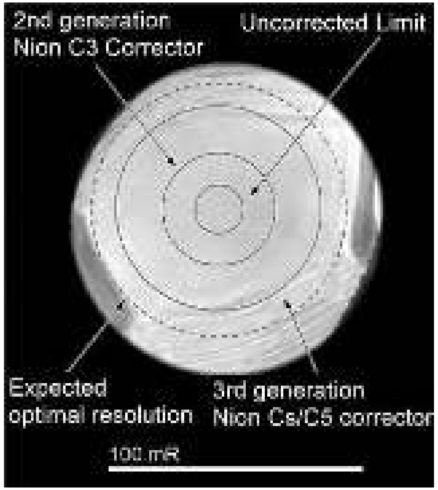
Nion UltraSTEM 100


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



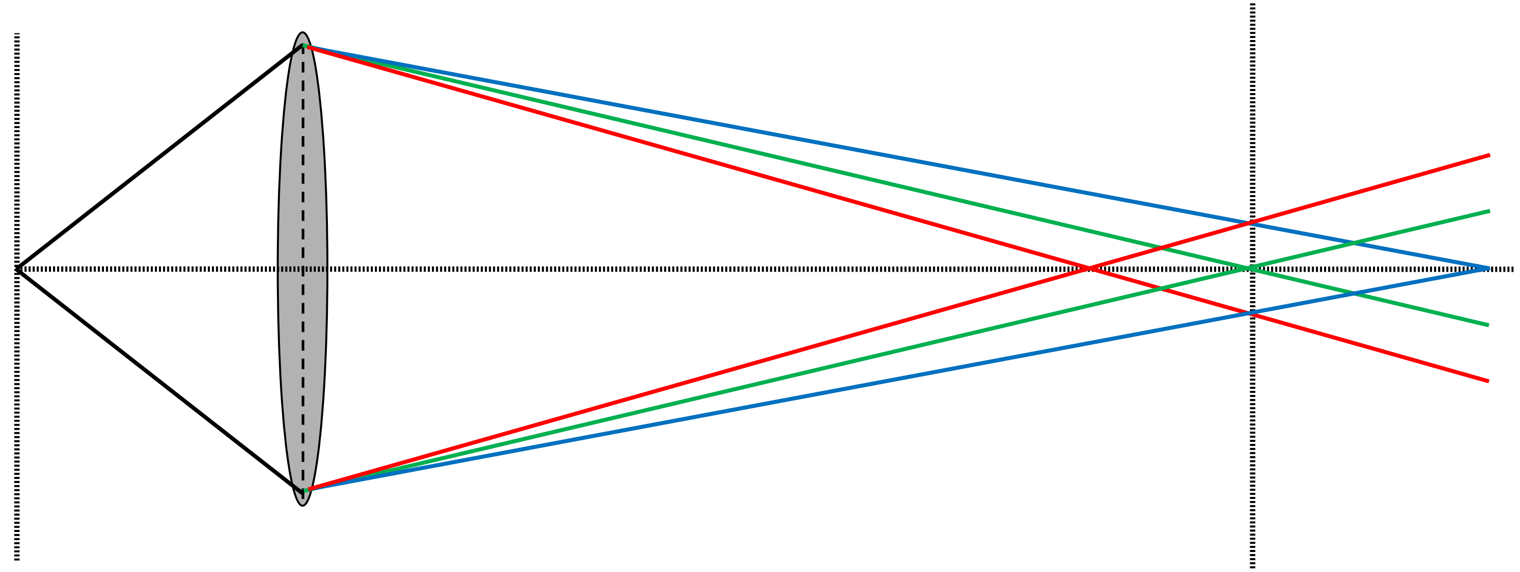
from: Krivanek et al. Inst. Phys. Conf.Ser.153 (Proc. 1997 EMAG)



http://www.nion.com

Chromatic aberration

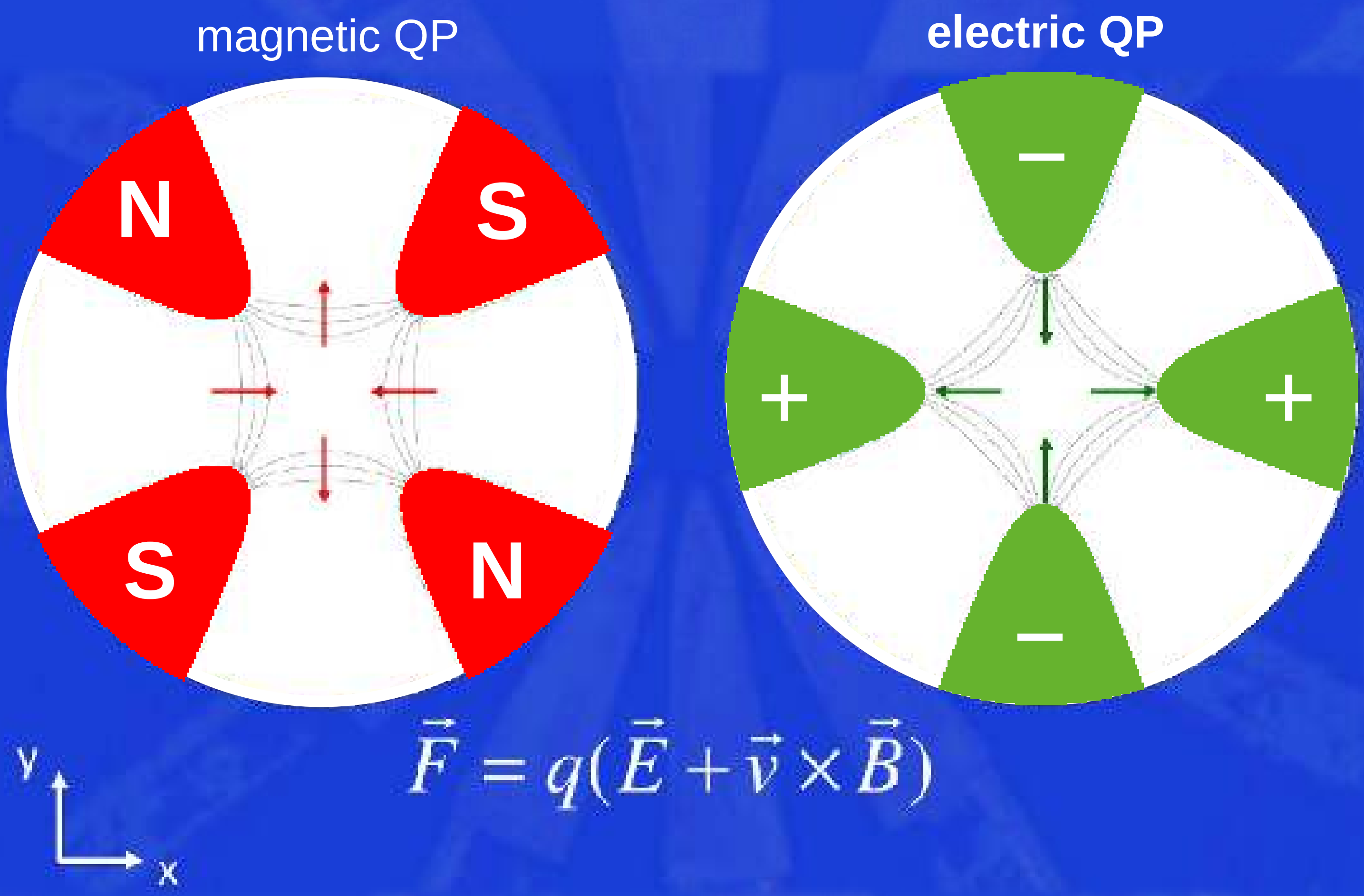
Electron energy: $E_0 - \Delta E < E_0 < E_0 + \Delta E$



Object plane

Gaussian image plane

Chromatic aberration correction



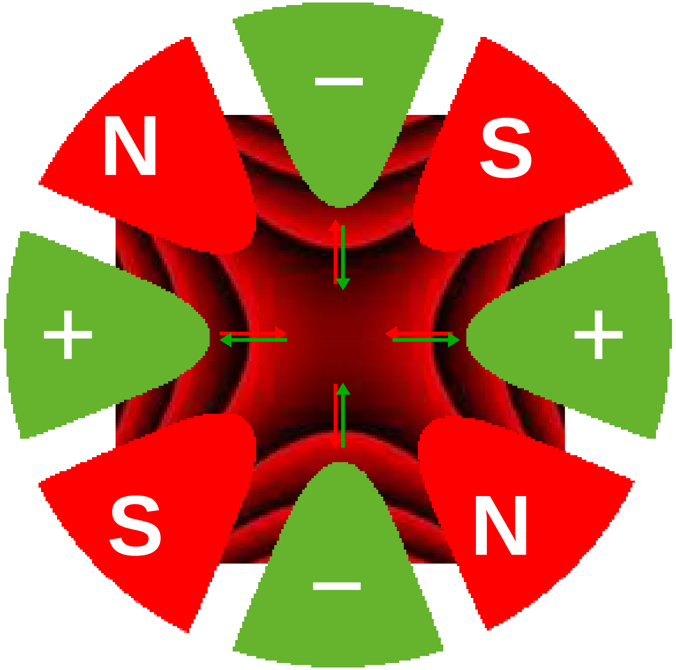
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

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

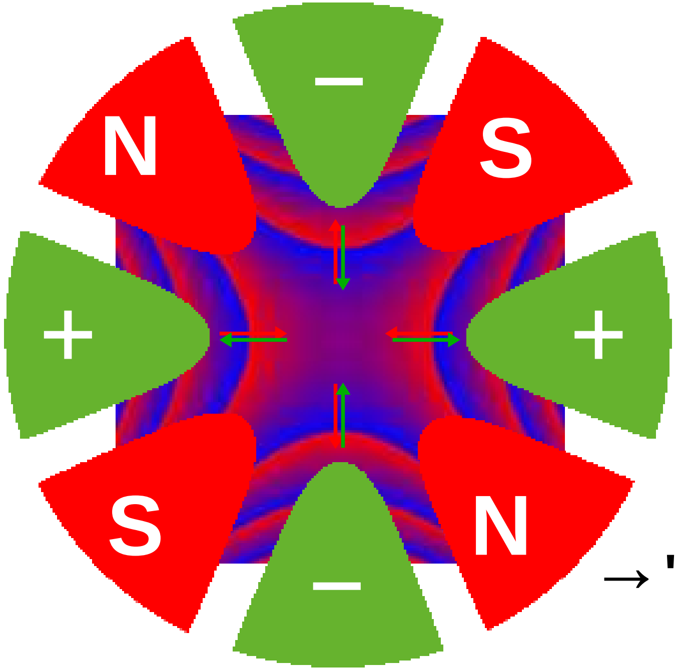


$E < E_0$: quadrupole effect

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

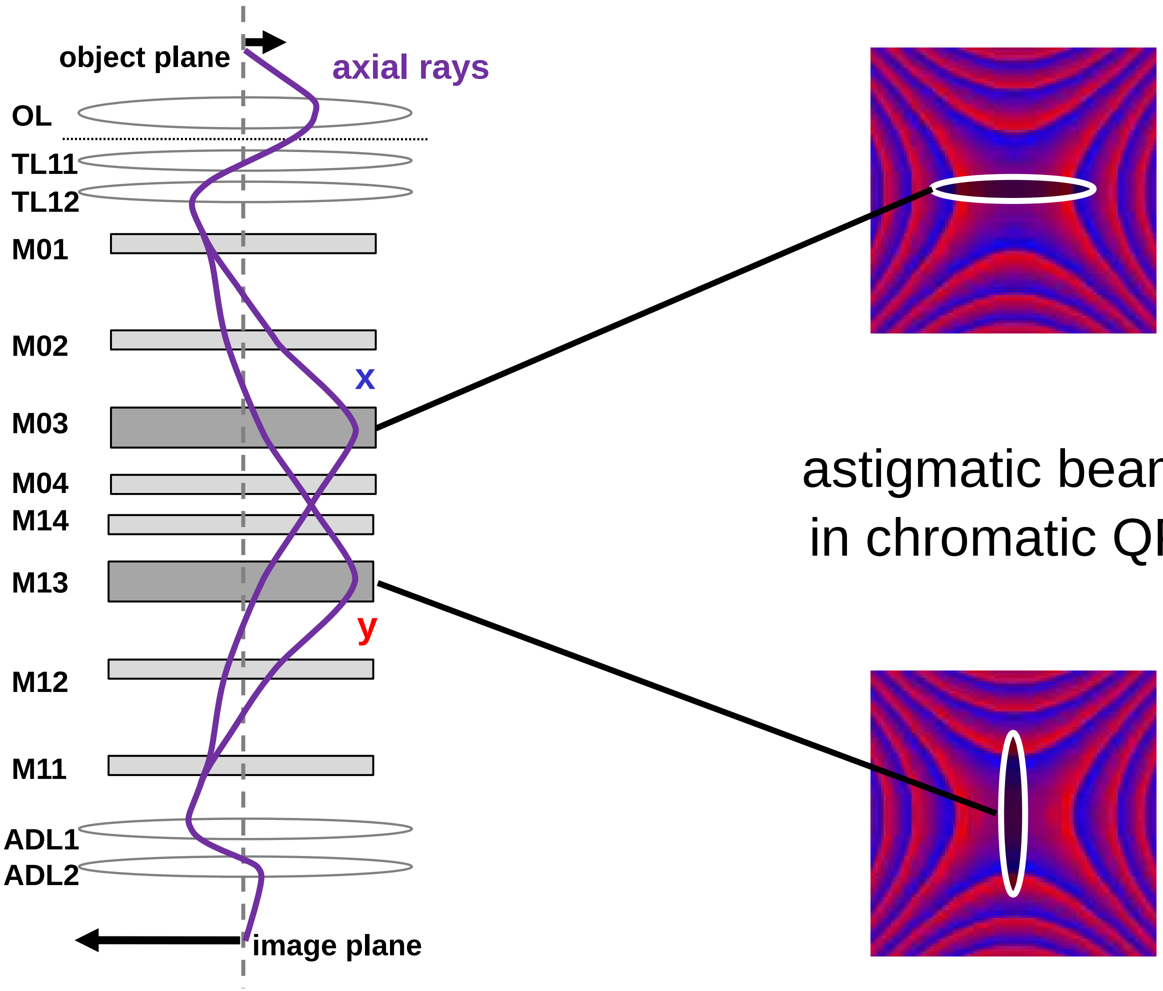


$E < E_0$: quadrupole effect

$E > E_0$: opposite QP effect

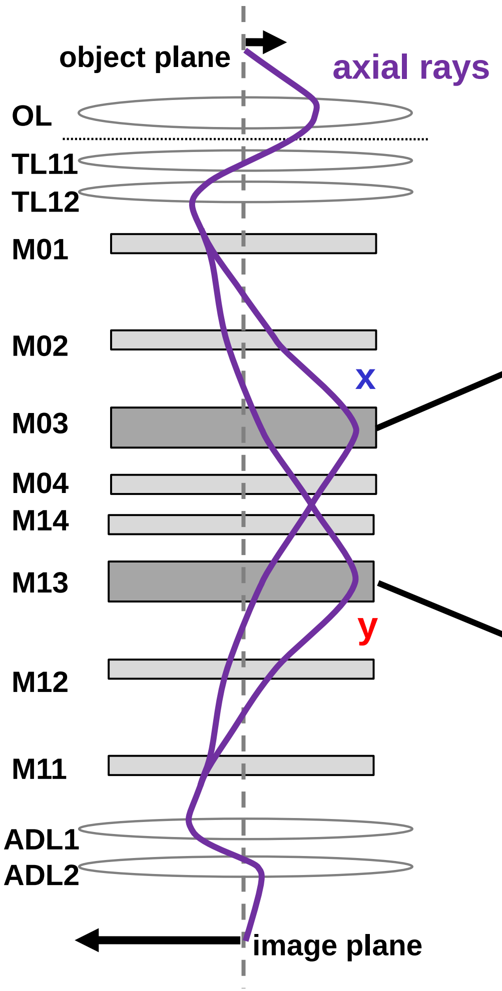
→ **"chromatic quadrupole"** A_{1c}

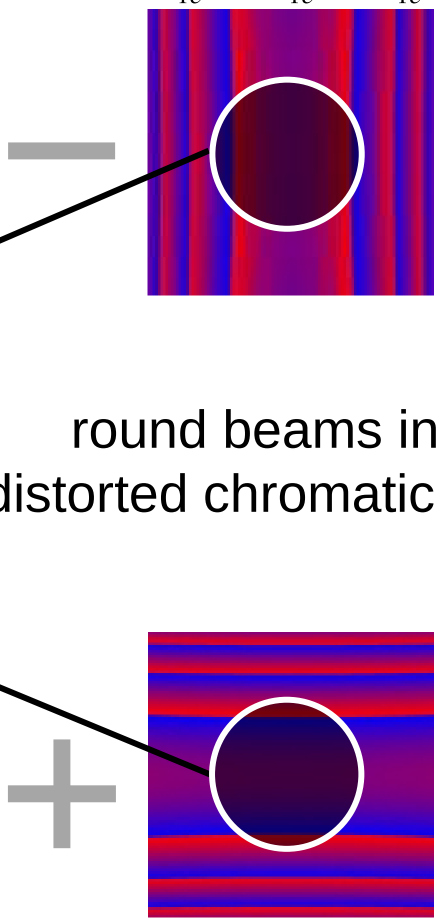
Chromatic aberration correction



astigmatic beams
in chromatic QP

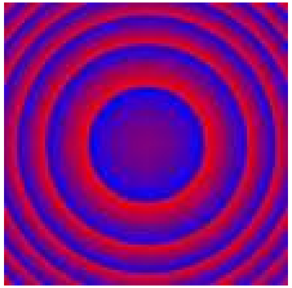
Chromatic aberration correction





round beams in
distorted chromatic QP

total effect



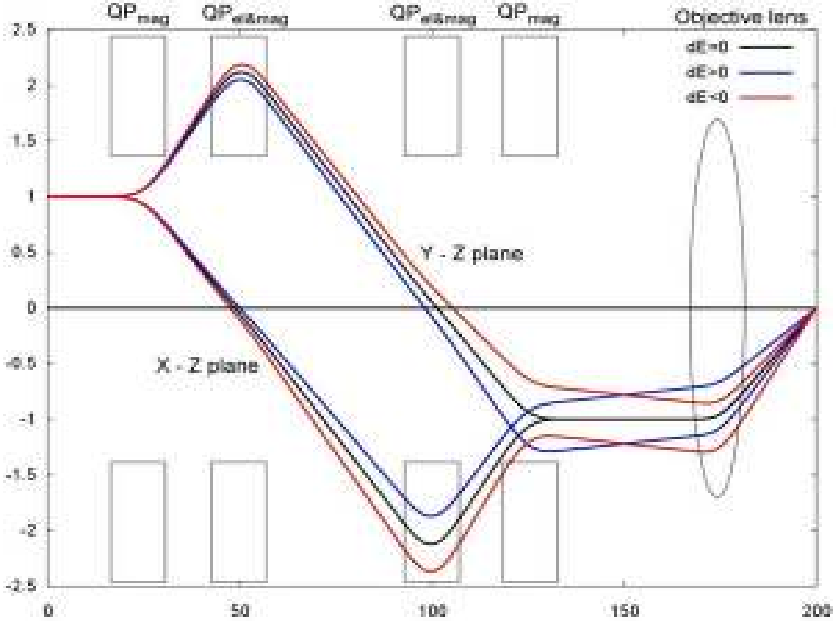
$-2C_{1c}$

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



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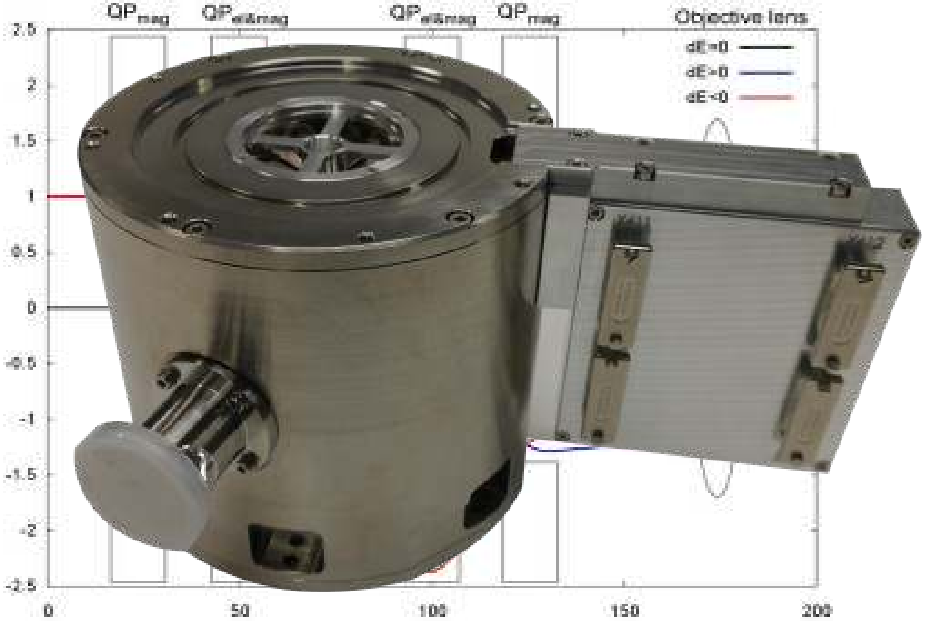


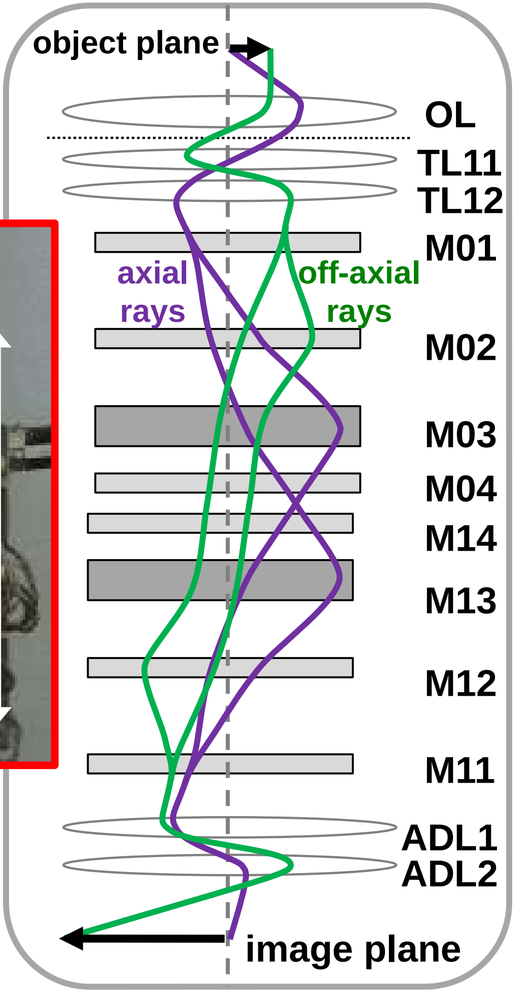
C_C- and C_S-correction for TEM

CCOR 30-300kV 160 channels

SALVE Project
Sub-Angstrom Low-Voltage Electron Microscopy

20-80kV

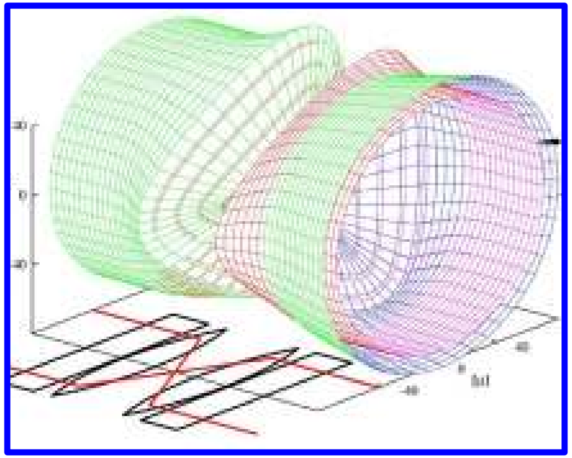
~ 185 kg



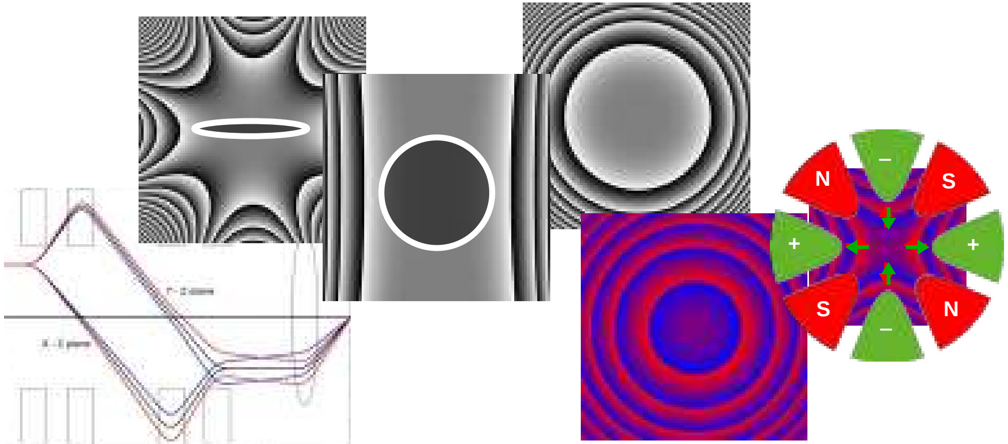
Thanks for your attention!

CEOS
Corrected Electron Optical Systems GmbH

C_S-correction with hexapoles



C_C-C_S-correction with quadrupoles and octupoles



Further resources

R. Erni: “Aberration-Corrected Imagingin TEM” (second edition 2015).

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.