Otto Scherzer
The father of aberration correction

Biography

Otto Scherzer was born 9 March, 1909 in Passau. He studied physics from 1927 to 1931 at the Munich Technical University and the Ludwig Maximilians University (LMU) of Munich, where his thesis advisor was the renowned Arnold Sommerfeld. His PhD thesis in 1931 was on x-ray Bremsstrahlung. From 1932 to 1933, he worked on electron optics at the AEG Research Institute in Berlin, where Ernst Brüche was head of the Physics Department. He returned in 1934 to LMU, where he completed is his Habilitation, as an assistant to Sommerfeld. In 1935, Scherzer moved to the Technische Hochschule in Darmstadt, and in 1936 he became Professor of Theoretical Physics. At age 26, he was the youngest Professor in Germany. From 1939 to 1945 he remained at Darmstadt and worked on radar for the German Navy. In 1947 and 1948, he spent a brief period doing similar work for the US signal Corps in New Jersey. On the condition that he have his own workshop to construct experimental instruments, he returned to the Technische Hochschule in Darmstadt, where he became a senior Professor in 1954. He remained there until his death, November 15, 1982. In 1983, he received the Distinguished Scientist Award from EMSA.

Electron optical foundations

Scherzer spent his two years at AEG designing electron lenses, deflection elements and other electron optical components used in oscilloscopes and image converter tubes. This led to the first comprehensive book on electron optics published together with Ernst Brüche (Brüche and Scherzer, 1934; Figs 1,2).

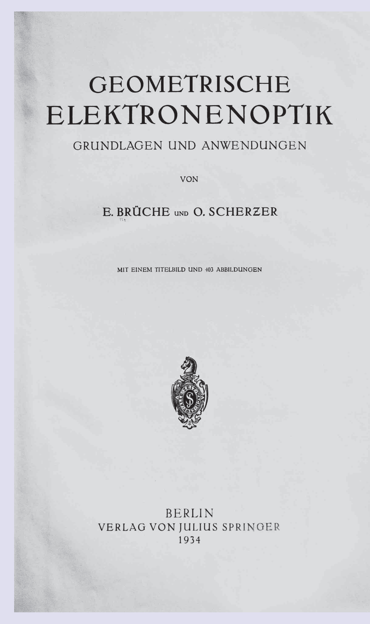
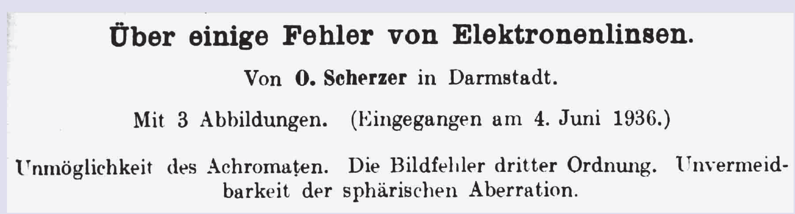

GEOMETRISCHE
ELEKTRONENOPTIK
GRUNDLAGEN UND ANWENDUNGEN
VON
E. BRÜCHE UND O. SCHERZER
BERLIN
VERLAG VON JULIUS SPRINGER
1934

Fig. 1. Title page of the 1934 book.

Fig. 2. Left to right: Brüche, Scherzer's wife, unidentified, Scherzer. Courtesy of Dieter Typke.

The Scherzer Theorem

Improving the performance of the electron microscope was always Scherzer's main interest, and he soon discovered that this would not be easy. The strong positive spherical aberration of round electron lenses is unavoidable, and limits resolution to 50 to 100 times the electrons' wavelength. However, unlike the case with light-optical lenses, it is not possible make a round lens with negative spherical aberration. This finding (Scherzer, 1936; Fig. 3), became known as the Scherzer Theorem, still the only theorem in electron optics.


Über einige Fehler von Elektronenlinsen.

Von **O. Scherzer** in Darmstadt.

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

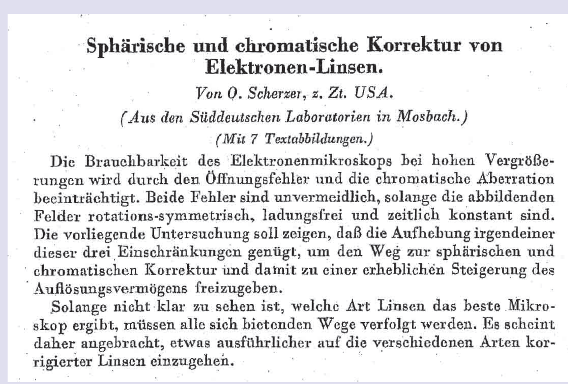
Unmöglichkeit des Achromaten. Die Bildfehler dritter Ordnung. Unvermeidbarkeit der sphärischen Aberration.

Fig. 3. The 1936 "Scherzer Theorem" paper in *Zeitschrift für Physik*. "Impossibility of an achromat. Third-order image artifacts. Unavoidability of spherical aberration."

The way forward

Since he realized that an attempt to increase resolution by decreasing the electron wavelength meant that the high accelerating voltage would damage specimens, especially those consisting of light elements, he spent most of his effort on devising innovative ways to bypass the conditions for which correction was not possible.

In 1947, he discussed several ways to avoid these conditions and to correct the aberrations (Scherzer, 1947, 1949a,b; Fig. 4,5): (1) An arrangement of non-rotationally symmetric lenses (Fig. 6), which he eventually implemented as a plan of four quadrupoles and three octopoles; (2) A lens containing a space charge (such as a charged foil, see below); (3) A dynamic lens, operating at high frequency; (4) A lens–mirror combination (which suffers because of the sensitivity to stray fields of the low-velocity electrons at the mirror).


Sphärische und chromatische Korrektur von Elektronen-Linsen.

Von O. Scherzer, z. Zt. USA.

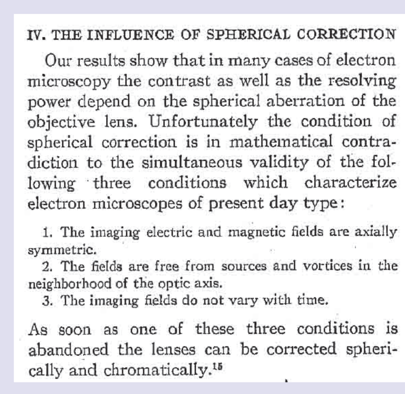
(Aus den Süddeutschen Laboratorien in Mosbach.)

(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.

Fig. 4. "Spherical and chromatic correction of electron lenses" (*Optik*, 1947).


IV. THE INFLUENCE OF SPHERICAL CORRECTION

Our results show that in many cases of electron microscopy the contrast as well as the resolving power depend on the spherical aberration of the objective lens. Unfortunately the condition of spherical correction is in mathematical contradiction to the simultaneous validity of the following three conditions which characterize electron microscopes of present day type:

1. The imaging electric and magnetic fields are axially symmetric.
2. The fields are free from sources and vortices in the neighborhood of the optic axis.
3. The imaging fields do not vary with time.

As soon as one of these three conditions is abandoned the lenses can be corrected spherically and chromatically.[15]

Fig. 5. Essentially the same statement as Fig. 4 (from *J. Appl. Phys.*, 1949).

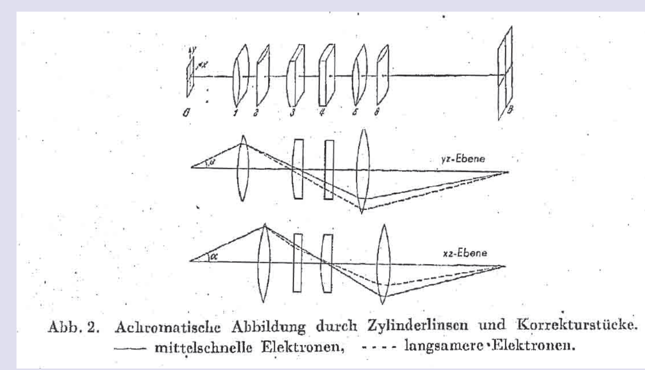


Fig. 6. Aberration correction by cylindrical lenses and correcting elements. (*Optik*, 1947)

The design he would put into practice was implemented by his student (Seeliger, 1951; Fig. 7). It was tested again by Möllenstedt (1956). This device was successful as proof of principle, in that it could correct aberrations that were intentionally made quite high. However, because mechanical and electrical instability of the microscopes of the time had a greater effect on resolution than spherical aberration, and sufficiently precise alignment of the corrector was impractical, the early correctors did not increase the resolution of the electron microscopes available at that time. Later, a similar quadrupole-octopole-based system was used by Deltrap (1964), with more success, but the ultimate TEM resolution was still not improved.

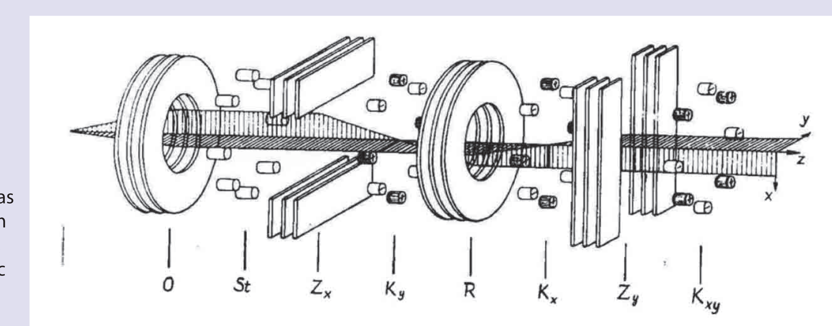
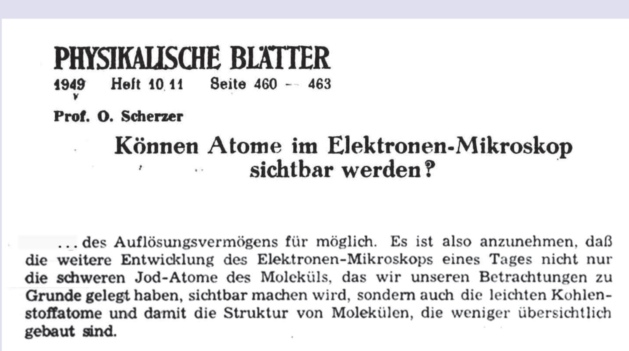


Fig. 7. The Scherzer corrector, as constructed in the 1950s (from Seeliger, 1951): Objective lens (O), stigmator (St), electrostatic cylinder lenses (Z), round lens (R), octopoles (K).

Can we see atoms?

Scherzer always hoped that the electron microscope would some day enable quantitative atomic resolution, and he carefully considered the possibility and the means to this end (Scherzer, 1949a,b; Figs 8,9). In this context, he identified the optimal high-resolution imaging conditions ("Scherzer focus"; Scherzer, 1949b; Fig. 10). He was convinced that sub-Ångström atomic resolution would one day be possible.


PHYSIKALISCHE BLÄTTER
1949 Heft 10 11 Seite 460 – 463

Prof. O. Scherzer

Können Atome im Elektronen-Mikroskop sichtbar werden?

. . . des Auflösungsvermögens für möglich. Es ist also anzunehmen, daß die weitere Entwicklung des Elektronen-Mikroskops eines Tages nicht nur die schweren Jod-Atome des Moleküls, das wir unseren Betrachtungen zu Grunde gelegt haben, sichtbar machen wird, sondern auch die leichten Kohlenstoffatome und damit die Struktur von Molekülen, die weniger übersichtlich gebaut sind.

Fig. 8. "Can atoms be visible in the electron microscope?" He suggests that the EM will eventually be developed such that even light elements making up molecular structure will be clearly visible.

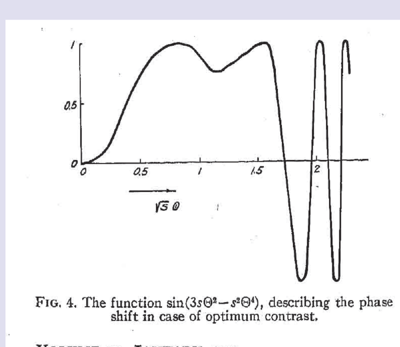
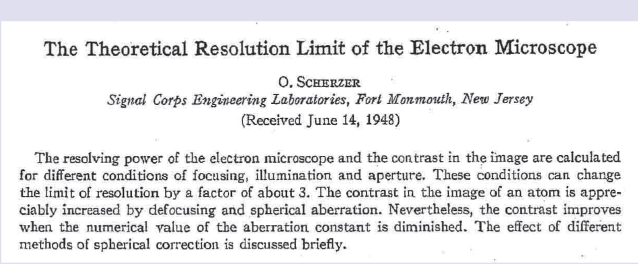


Fig. 10. What we now call the phase-contrast transfer function, at "Scherzer focus".


The Theoretical Resolution Limit of the Electron Microscope

O. Scherzer

Signal Corps Engineering Laboratories, Fort Monmouth, New Jersey

(Received June 14, 1948)

The resolving power of the electron microscope and the contrast in the image are calculated for different conditions of focusing, illumination and aperture. These conditions can change the limit of resolution by a factor of about 3. The contrast in the image of an atom is appreciably increased by defocusing and spherical aberration. Nevertheless, the contrast improves when the numerical value of the aberration constant is diminished. The effect of different methods of spherical correction is discussed briefly.

Fig. 9. From J. Appl. Phys., 1949.

The "Darmstadt Project"

Scherzer was the academic father (Fig. 11) of several accomplished physicists, the most famous of them being Harald Rose, who continued the aberration-correction quest, in turn through Rose's student Max. Haider, with eventual success at increasing the resolution of TEM with correction of both spherical and chromatic aberration, as first reported in 2009 (Kabius *et al.*).

Harald Rose showed in 1971 that the correctors used to date suffered from off-axial coma, and Scherzer started the "Darmstadt Project" to try other corrector designs, to improve the mechanical and electrical stability, and to address higher-order aberrations. A foil corrector was considered (Scherzer, 1980; Fig. 12), suitable for thin specimens and EMs that have a small energy spread. The foil would have a central hole for the unscattered beam (like a Zernike phase plate), and a correcting charge pattern would be induced on the film by electrostatic electrodes below it. A novel aplanatic corrector utilizing multipoles and symmetry properties was built. It demonstrated for the first time the simultaneous correction of chromatic and spherical aberration (Bernhard, 1980). Although good progress was made, the "Darmstadt Project" ended with Scherzer's death in 1982.

Fig. 11. In class at Darmstadt. Courtesy of Dieter Typke.

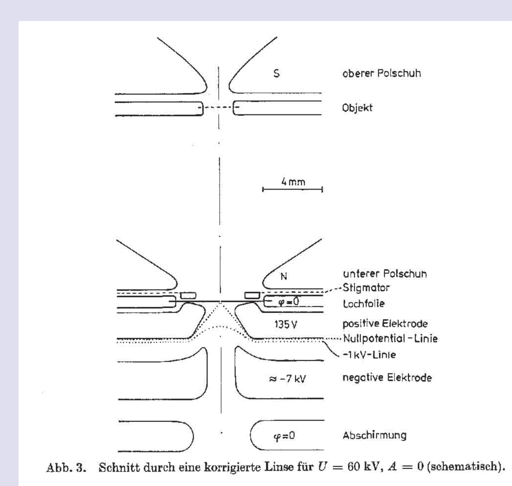


Fig. 12. The foil corrector (Scherzer, 1980). Lochfolie = foil with central hole.

Scherzer's legacy

In 1978, at the International Congress on Electron Microscopy in Toronto, Scherzer pointed out the prime reason for not yet being able to improve the resolution of the best uncorrected TEMs: "resolution is clearly limited by the unavailability of the necessary funds" (Scherzer, 1978). The Darmstadt lab continued, with the help of the Volkswagen Foundation, and under Harald Rose, a sextupole-based system with additional multipole elements, was designed (Rose, 1990). It was demonstrated in a practical instrument with excellent results, the first time TEM resolution was increased beyond what was possible with an uncorrected microscope (Haider *et al.*, 1998). Independently, Ondrej Krivanek demonstrated an advanced quadrupole/octopole design, which was the first corrector for STEM mode that increased resolution beyond the best obtainable without correction (Krivanek *et al.*, 2003).

With funding from the US Department of Energy, the current chapter in the aberration-correction story is now being written, in the context of the TEAM project. Harald Rose was given the goal of a combined spherical and chromatic aberration corrector that would increase the resolution of the best uncorrected TEMs. For this, there was a return to the quadrupole–octopole system, by replacing each sextupole element of his previous corrector with a telescopic quadrupole-octopole quintuplet employing mixed electric and magnetic quadrupole fields

This does not reach the end of the story, or the ultimate goal of Otto Scherzer. In order to image the light atoms in biological molecules, aberration correction at low accelerating voltage will be needed. For this to succeed, further improvements in electrical and mechanical stability will be required. Indeed, this represents the repeating pattern in the quest for ever-higher resolution: a new electron-optical design is at first unhelpful, until the available technology becomes able to support it (Rose, 2009). Success with this corrector was first reported in 2009 (Kabius *et al.*; Fig. 13), finally reaching Scherzer's goal of TEM aberration correction that enables heretofore unobtainable resolution.

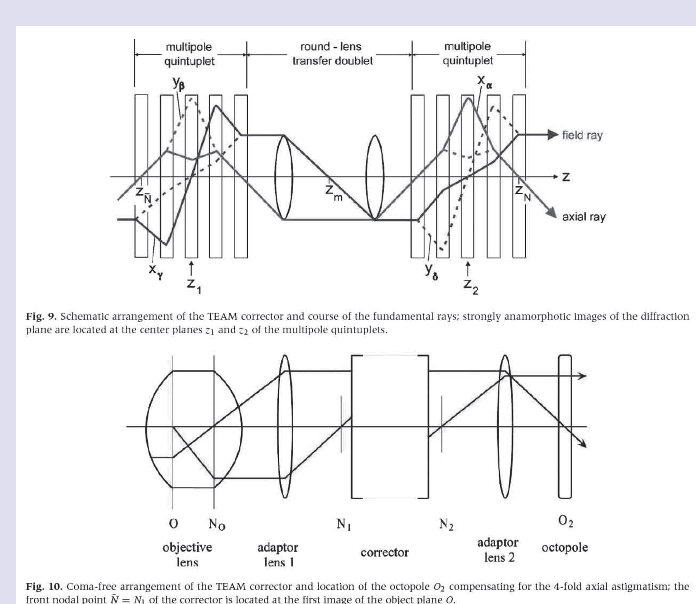


Fig. 13. The TEAM corrector (from Rose, 2009)

Acknowledgements

Many thanks to Dieter Typke (LBNL), whose mentor was Otto Scherzer, for supplying images and material, and to Harald Rose for verifying the accuracy of this poster.

The following sources of information were also used:

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