Preface

The resolution of any imaging microscope is ultimately limited by diffraction and can never be significantly smaller than the wavelength λ of the image-forming wave, as realized by Abbe [1] in 1870. In a visionary statement, he argued that there might be some yet unknown radiation with a shorter wavelength than that of light enabling a higher resolution at some time in the future. The discovery of the electron provided such a radiation because its wavelength at accelerating voltages above 1 kV is smaller than the radius of the hydrogen atom. The wave property of the electron was postulated in 1924 by de Broglie [2]. Geometrical electron optics started in 1926 when Busch [3] demonstrated that the magnetic field of a rotationally symmetric coil acts as a converging lens for electrons. The importance of this discovery was subsequently conceived by Knoll and Ruska [4] who had the idea to build an electron microscope by combining a sequence of such lenses. Within a short period of time, the resolution of the electron microscope surpassed that of the light microscope, as depicted in Fig. 1. This success resulted primarily from the extremely small wavelength of the electrons rather than from the quality of standard electron lenses which limit the attainable resolution to about 100λ. Therefore, shortening the wavelength by increasing the voltage was the most convenient method for improving the resolution. However, radiation damage by knock-on displacement of atoms limits severely the application of high-voltage electron microscopes. In addition, the so-called *delocalization* caused by spherical aberration prevents an unambiguous interpretation of images of nonperiodic objects such as interfaces and grain boundaries. The correction of the spherical aberration eliminates this deleterious effect.

The successful correction of the spherical aberration can be considered as a quantum step in the development of the electron microscope because it enables one to obtain sub-Å resolution at voltages below the threshold for atom displacement. The threshold voltage depends on the composition of the object and lies in the region between 60 and 300 kV for most materials.

At about the same time as Knoll and Ruska developed the first electron microscope with magnetic lenses, Ernst Brueche at the research department

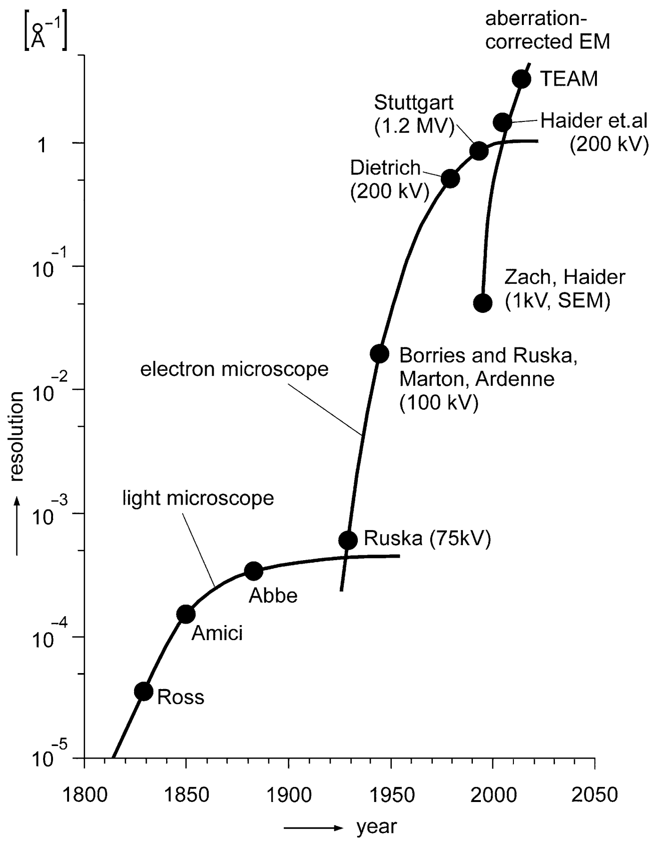

Fig. 1 Increase in resolution of transmission microscopy as a function of time

of the AEG in Berlin investigated with his collaborators A. Recknagel and H. Mahl the properties of electrostatic round lenses. To obtain theoretical assistance, Brueche invited the young Scherzer in 1932 to join his group. Within the short period of 2 years, Scherzer established the theoretical basis of geometrical electron optics. In 1934, he published his results together with Brueche in the first book on the subject entitled "Geometrische Elektronenoptik" [5]. Scherzer [6] employed for his calculations the so-called *trajectory method*, which starts from the Newton equation of motion and the Lorentz force, whereas Glaser [7] applied the *Hamiltonian formalism* to electron optics to determine the motion of electrons in rotationally symmetric static electromagnetic fields. This method is based on the ideas of Hamilton who showed that the properties of an optical system can be derived from a single characteristic function or eikonal. Because the two calculation procedures differ from each other, they give seemingly different integral expressions for the aberration coefficients. However, the integrals can be transformed in identical forms by partial integrations. Using this method, Scherzer [8] transformed, in 1936, the integral expressions for the coefficients of the spherical and axial chromatic aberrations in such a form that the integrands consist of sums of positive quadratic terms, proving that these coefficients can never change sign. The physical origin for this behavior is due to the fact that the static electromagnetic potentials satisfy the Laplace equation in the domain of the electron trajectories. As a consequence, the spatial distribution of the index of refraction of electron lenses cannot be formed arbitrarily. Because the potential adopts an extremum at the boundary surfaces, the outer zones of rotationally symmetric electron lenses always focus the rays more strongly than the inner zones, causing unavoidable spherical aberration. Owing to its importance, this property has been named "Scherzer theorem."

Scherzer and Glaser are recognized as the founders of theoretical electron optics. The subject up to 1952 was fully summarized in Glaser's book *Grundlagen der Elektronenoptik*, which served as the standard textbook for several decades [9]. The Hamiltonian approach to electron optics was developed further by Sturrock [10]. Several other books on the subject appeared in the following years [11, 12]. In particular, the treatise *Electron Optics and the Electron Microscope* by Zworykin et al. [13] and Grivet's excellent *Electron Optics* [14] are milestones of the subject. The last approach covering all fields of electron optics was performed by Hawkes and Kasper [15] with their three-volume treatise *Principles of Electron Optics* published in 1995.

The history of electron optics is to a large extent the struggle to overcome the limitations of the resolution of electron microscopes imposed by the unavoidable spherical and chromatic aberrations of round lenses. In 1947, Scherzer [16] demonstrated in another fundamental paper that correction of aberrations is possible by lifting any of the constraints of his theorem, either by abandoning rotational symmetry or by introducing time-varying fields or space charges. In the following decades, intensive experimental efforts to compensate for the resolution-limiting aberrations by means of multipole correctors have been pursued by several groups in Germany [17], England [18], and the USA [19] with disappointing results. The attempts came to an end in the 1980s primarily due to severe problems of precisely aligning the many elements of the correctors during a period of time which is shorter than the overall stability period of the microscope. Moreover, digital processing of through-focus series provided a successful alternative solution for eliminating the spherical aberration of images a posteriori.

As a result, work on electron optics shrank and was limited to theoretical investigations and to applications in electron lithography and to the design of electron-beam devices for the inspection of wafers [20, 21]. Owing to the advancement in technology and computer-assisted alignment, correction of the resolution-limiting aberrations became very promising again at the beginning of the 1990s. In 1992, experimental work started by M. Haider at the EMBL in Heidelberg within the frame of the Volkswagen project aimed to compensate for the spherical aberration of a transmission electron microscope (TEM) by means of a novel hexapole corrector [22]. One of the main tasks concerned the reduction of the information limit in order that the resolution was limited by the spherical aberration rather than by the incoherent aberrations resulting from instabilities. At about the same time, high-performance imaging energy filters became available in commercial electron microscopes leading to a rapid growth of analytical electron microscopy [23]. The successful correction of the spherical aberration in a commercial 200-kV TEM by Haider et al. [24] and Krivanek et al. [25] in a 100-kV scanning transmission electron microscope (STEM) induced a revival of electron optics. In the following years, numerous new correctors compensating for chromatic and spherical aberrations were proposed as well as novel high-performance imaging energy filters and monochromators [26, 27]. The revival of electron optics culminated in the TEAM project of the US Department of Energy (DOE) aimed to realize a chromatic and spherically corrected TEM with a resolution limit of 0.5 Å.

Geometrical electron optics provides the appropriate tool for designing a large variety of other charged-particle instruments such as electron mirrors, spectrometers, time-of-flight analyzers, electron guns, accelerators, and storage rings. Owing to the large progress in electron optics, electron holography, image formation, and design of charged-particle instruments made during the last 15 years, it is impossible to treat all subjects in a single book. Therefore, we confine the content of this book to geometrical electron optics with the impetus on analytical methods for calculating the properties of charged-particle systems and methods for designing optimum electron optical instruments and elements. Diffraction effects resulting from the wave nature of the elementary particles and interactions between electrons within the beam will not be covered. Therefore, the content of this book may properly be referred to as a single particle description. Because the effect of the spin on the motion of the electron is very small, it is only treated in Chap. 14 at the end of the book.

The content of this book originated from lectures taught by the author for many years at the Technical University Darmstadt and from courses in charged-particle optics given at the Lawrence Berkeley National Laboratory (BNL) during the period 2003–2005. Therefore, particular attention has been given to the presentation of techniques which would enable the reader not only to "follow the literature" but also to perform electron optical design and calculations on his own. The degree of emphasis which each topic has is a matter of personal judgment. We have not attempted to present an encyclopedia on the subject because it is not possible to include all topics of geometrical electron optics in a single book. For example, model fields providing analytical solutions for the paraxial trajectories of electron lenses have been omitted. They are discussed in great detail in the second volume of *Principles of Electron Optics* by Hawkes and Kasper [15]. Moreover, many computer programs are nowadays available which provide solutions of the paraxial path equations for arbitrary field distributions. Most of the presented material on aberrations, systems with curved axis, and aberration correctors is based on research work performed at the University of Darmstadt over a period of several decades. No attempt has been made to provide a complete bibliography. The references have been confined to those which treat specific topics in greater detail. Hence, this selection should not be judged as a ranking and I offer my apologies to the many contributors to the subject whose excellent papers have not been cited. An extensive list of references can be found in Hawkes and Kasper [15].

The book is intended as a textbook for graduate students with good mathematical background and for anyone involved in the design of charged-particle devices ranging from electron lenses to spectrometers. Practical applications of electron optics serve as illustrations of the principles under discussion. Due to the recent progress in aberration correction, the properties of various corrector types are discussed in detail. The book contains some unpublished material on multipole systems and provides a novel analytical calculation procedure for determining the Gaussian optics and the aberrations of electron guns in the absence of space charge effects. In the last chapter, we consider spin precession and radiation effects in the context of relativistic electron motion in electromagnetic fields by employing a novel covariant treatment [28]. By introducing the Lorentz-invariant universal time as independent variable, we extend the Hamilton–Jacobi formalism of classical mechanics from three to four spatial dimensions. This approach allows one to construct a proper four-dimensional covariant Lagrangian, which considers charge, gravitation, and spin interactions [28].

I want to thank Dr. Weishi Wan, BNL, for numerical calculations of trajectories and Mrs. Anna Zilch for the skilful making of many drawings. Thanks are due to the members of CEOS (Heidelberg) for helpful discussions and editorial support and to Prof. E. Plies and Dr. Essers for allowance to publish drawings.

Darmstadt *Harald Rose*
August 2008

Springer

http://www.springer.com/978-3-540-85915-4

Geometrical Charged-Particle Optics
Rose, H.
2009, XVI, 414 p. 137 illus., 5 illus. in color., Hardcover
ISBN: 978-3-540-85915-4