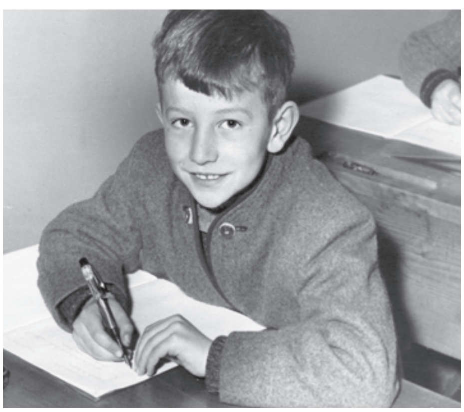
autobiography

by Maximilian Haider



At primary school in 1960, age 10

In 1950, I was born in a small historic town in Austria, where my parents Maximilian Haider and Anna Haider owned a watchmaker shop. My father had taken over his father´s shop, and my eldest brother stepped into their footsteps and became a watchmaker, too. To expand the business, it was agreed early in my childhood that I should become an optician. Therefore, I started working as an optician´s apprentice in Linz, Austria, when I was 14 years old. After the first optician certification exam I realized that the prospect of working as an optician for my whole life did not satisfy me. Hence, in the following years, I passed several exams to be admitted to university and finally, at the age of 26, started studying physics at the University of Kiel and the Technical University of Darmstadt, Germany. For my diploma thesis I got in touch with the group of Harald Rose that worked in the field of theoretical particle optics. I was attracted by the ongoing aberration correction project due to familiar aberrations in electron optics I knew from my time as an optician. The task I had to carry out was the development of a novel twelve-pole element for an aberration corrector with which the required strong quadrupole and octopole fields could be generated. At the Institute of Applied Physics of TU Darmstadt two groups led by Otto Scherzer and Harald Rose were carrying out a long time project on the correction of the spherical (Cs) and chromatic (Cc) aberration of a conventional Transmission Electron Microscope (TEM) by means of a quadrupole-octopole correction system. The development of such a corrector was

Max Haider is the last person on the right side - when he worked as apprentice in Linz/Austria

Together with Joachim Zach at the European Conference in Budapest, 1984

At the end of the seventies, this was state of the art of aberration correction, however, it could not be demonstrated that this would indeed improve the resolution. Rather than being limited by the aberrations, the proof failed because of the instabilities of the homemade TEM. As the last scientist capable of handling this instrument had left for a position in industry, I had to learn how to operate the complex instrument – the very first functioning aberration corrected TEM – before I could finish my diploma work. A large number of power supplies had to be controlled and, at the same time, the mechanical adjusters of the various lenses had to be kept stable. The alignment of the whole system had to be carried out manually without the help of computers or CCD cameras. In the end, the project was successful in its proof to compensate the two aberrations, but it had failed to show an improvement of resolution. Nevertheless, the project convinced me that aberration correction was the future of resolution improvement, but it was also clear to me that one should only go ahead with enough money to buy a state-of-the-art TEM and to first investigate this TEM to ensure the resolution to be aberration limited. Otherwise one would run into the same problem again.

After my diploma, I continued to work in the Rose group, planning improvements of the existing aberration corrected TEM. Unfortunately, a German Research Foundation (DFG) grant proposal was

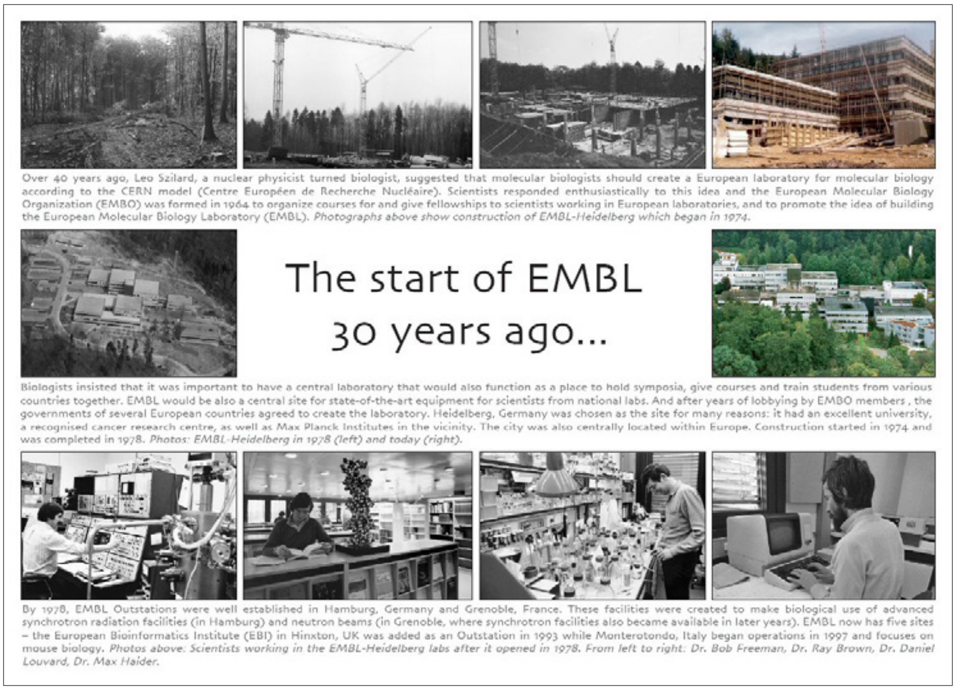
PhD celebration in 1987 with his youngest daughter

rejected because Harald Rose was a theoretician and the project he applied for was an experimentally challenging task. Shortly afterwards, Otto Scherzer, the second "father" of the Darmstadt aberration correction project, died and it seemed impossible to get funding. So I took on a position at the European Molecular Biology Laboratory (EMBL) in Heidelberg with the task to develop an electron spectrometer for a Scanning Transmission Electron Microscope (STEM). Also for this device, the compensation of aberrations was indispensable, and in 1987, with the successful development of a highly dispersive electron spectrometer for a dedicated STEM and in close cooperation with the Rose group I finished my PhD. I then continued the application of the two existing dedicated STEMs for biological applications in the group of Arthur Jones at the European Molecular Biology Laboratory.

The initial experimental work experience with the Darmstadt corrector had inspired my long-standing interest in this field of science. When working in the EMBL environment for biological structure research – knowing that the resolution of biological structures within a TEM is by far not limited by the resolving power of a

EMBL-TEM installation in 1993

TEM – the idea of realizing an aberration correction system to improve the available resolution did not let go of me. However, globally, electron optics lost attraction in physics at that time, and several groups had to close because emeriti were replaced by scientists from other fields. Likewise, the funding agencies lost interest because several aberration correction projects around the world had failed and it was common understanding that the aberration correction for high resolution electron microscopy (EM) would not work and was "unthinkable", particularly for commercial instruments. The only feasible option seemed to decrease the wave length of the electrons used for the imaging of objects by increasing the accelerating voltage. Hence, instruments became larger and more expensive:



already very advanced and the proof of high resolution in materials science went up to 300kV, 400 kV and even 1.2 MV. The resolution could indeed be improved, accompanied, however, by the disadvantage of a strong increase in beam damage of the objects observed in TEM.

Although it was not in vogue to work in the field of electron optics, I could not forget my long-standing idea of compensating the largest and most important obstacle on the way to sub-angstrom resolution. There was little excitement for this idea in my biological environment, with the exception of some cell biologists who were used to working with a Scanning Electron Microscope (SEM) to examine complete cells. However, with some internal money and a cooperation with the semiconductor company ICT (Munich) we were able to start the development of an aberration corrected SEM within the EMBL. Joachim Zach, a graduate student of the Rose group, carried out a theoretical concept of an aberration corrected SEM column with which the resolution should be improved from about 5 – 6 nm down to about 1 – 2 nm. Based on this, we designed and constructed an aberration corrector in cooperation with ICT, including Stefan Lanio, an ICT scientist, working at the EMBL for two years. Within this period of constructing an aberration corrector for a SEM, Arthur Jones retired and I became group leader. Joachim Zach joined my group and continued our development. We did not have the money to buy a modern high resolution SEM; therefore, we started with a used SEM and incorporated a new electron gun with a Schottky emitter that had a higher brightness and smaller energy width. Our aberration correction system consisted of four combined electrostatic and magnetic multipoles (twelve-pole) elements. This system allowed an excitation of all needed quadrupole fields to adjust an astigmatic ray path within the corrector and to have line-foci at the center of elements 2 and 3, at which we compensated the chromatic aberration by exciting strong, almost exactly counterbalancing electrostatic and magnetic quadrupole fields. At these elements we were also able to compensate the spherical aberrations for two sections by exciting strong octopole fields. The third component of the spherical aberration was compensated by additional octopole fields at the elements 1 and 4. In 1995, we were finally able to demonstrate the full compensation of the chromatic and spherical aberration of the objective lens and an improvement of resolution from 5,8 nm down to 1,8 nm at an accelerating energy of 1 keV. This was the first time ever an improvement of resolution by means of a quadrupole-octopole corrector was achieved.

It was clear, however, that our successful correction system for a SEM was designed for very low energies. A solution for TEMs, that use higher energies in order to have mainly single scattering events when electrons are passing through a thin object, still had to be found. At the beginning of the 1990s, novel electron sources (field emission sources) for high resolution TEM and STEM were commercially available. These electron emitters had the advantages of higher brightness and a smaller primary energy width. This matched an idea that had already come up in several discussions with Harald Rose in the 1980s: By concentrating the system only on the compensation of the spherical aberration, the complexity of aberration correctors could be reduced. If the primary energy width can be kept below 1 eV and the objects are imaged with electrons having an energy of about 200 keV, the reduction of contrast due to the chromatic aberration can be minimized. As early as 1981, Harald Rose had proposed a hexapole corrector for STEM that compensated only the spherical aberration. He assumed that this corrector would be sufficient for a probe-forming electron beam, as it would not allow any field of view needed for a TEM.

The 1989 microscopy conference in Salzburg was the starting point for our development of a Cs-corrected TEM, later to be funded by the Volkswagen Foundation: The presentation of a newly ordered 1.2 MeV TEM for the MPI Stuttgart generated discussions of pros and cons of this expensive way to improve the resolving power of a TEM for materials science. Knut Urban, a materials scientist at Forschungszentrum Jülich in urgent need of a high resolution instrument, electron optics theoretician Harald Rose and I discussed possibilities to get funding for a much cheaper project with better resolution and less beam damage of the objects. At the end of 1989, Rose expanded his idea of a STEM corrector and proposed a hexapole corrector with an added transfer system, just behind the objective lens, to achieve an acceptable field of view and to employ this within a TEM. In 1990, he published his idea in the journal Optik as an "outline of a spherically corrected semi-aplanatic medium-voltage transmission electron microscope". Meanwhile, the three of us kept on discussing the realization of the proposed corrector, and in late 1990, we finalized a grant proposal for the Volkswagen Foundation. Before submission, I needed the Director General´s permission to carry out the project within the EMBL – after all a molecular biology laboratory, not a physics institute. But as all funding was external and perspectively, the instrument could later be used for structure research at the EMBL, permission was given. In summer 1991 the proposal was pre-accepted with the obligation to split the five years into two projects: Task of the first part was a proof of concept, before the state-of-the-art TEM was to be funded. Finally, in January 1992, the development of a hexapole corrector started.

So, our two aberration correction projects were running side by side: the SEM project aiming to correct the chromatic and spherical aberration between 1,5 kV and 0,5 kV, and the TEM project aiming to cancel the spherical aberration from 80 kV up to 200 kV. For the SEM project, a quadrupole/octopole corrector design had to be employed, whereas for the TEM project, a new hexapole corrector was to be developed. At the international conference in Paris in summer 1994, the proof of principle of the hexapole corrector, following the outline of Harald Rose, could be demonstrated. This made way for the funding of the new TEM. In 1995, the instrument was installed and the incorporation of the hexapole corrector began. Already at the end of 1995, Joachim Zach was able to show an improvement of resolution from 5,6 nm down to 1,8 nm by means of the SEM aberration corrector. At the same time, however, the new EMBL Director General stopped the physical instrumentation program, which meant that all contracts of my group, including my own, would terminate in July 1996. It seemed, that we were running out of time so close to the breakthrough.

So our race against time began: In summer 1996, we were able to show the compensation of the spherical aberration with the hexapole corrector in the TEM. But due to instabilities caused by the water cooling of the additional lenses in the objective lens, an improvement of resolution could not be demonstrated. I succeeded in getting money for a project extension by one year by the Volkswagen Foundation and the permission to carry out this extension using the available space without any additional funding by the EMBL. In fall 1996, we managed to get rid of some sources of the instabilities, but in spring 1997, it became clear that one source of instability in the objective lens area remained. The coming months were dramatic: I knew that we had to shut down the TEM and transfer the microscope to Jülich at the end of July. In May, I decided to design a new strong lens below the objective lens to reduce the beam diameter around the area of the instability. We were able to incorporate this new lens in June, but the first test after turning on the new lens still showed the known instabilities. However, after a few hours, at midnight, we suddenly acquired images showing an improved resolution from originally 0,24 nm down to 0,12 nm! So, at the end of June 1997, the project was finished successfully. We shot some images for conference presentations, and in July 1997, the first aberration corrected TEM was transferred to Knut Urban´s laboratory in Jülich.

This major leap would not have been possible without the following two prerequisites: Firstly, in summer 1996, when it became clear that further developments could not be realized at the EMBL, we started the company Corrected Electron Optical Systems (CEOS) in Heidelberg. The strategy to get rid of the instabilities with a specifically designed intermediate lens, within a short time frame, was only feasible with the help of one employee of CEOS who made the design and construction of the new lens his highest priority. Secondly, during the last year of the project, I was able to hire Stephan Uhlemann from the Rose group, who had already worked on the theory of the hexapole corrector during his PhD, to develop an alignment strategy. This method proved very useful to achieve a well aligned state of both the corrector and the whole instrument.

Why was CEOS founded in 1996? Just when the first SEM corrector was finished, we received a request to develop a SEM corrector for a wafer-inspection tool from the Japanese company JEOL. To carry out this task I convinced Joachim Zach (30%) to jointly found our company CEOS. Additional shareholders were Harald Rose (5%) and Peter Raynor (5%), a former electronics engineer in my group. As company, we started a co-operation with JEOL and developed the first commercially available aberration corrector for their inspection tool. While Harald Rose and Peter Raynor acted as mere shareholders, Joachim Zach and I shared the management and started the business with only three additional employees.

The presentation of the novel hexapole corrector for high resolution TEM raised much attention: Laboratories started to raise funds, several companies initiated negotiations with us to secure access to this new technology and to sell instruments including the novel corrector, the German Research Foundation launched an initiative to fund new instruments for various institutes. The growing number of activities made it necessary for CEOS to find new premises in Heidelberg, so we invested our private money for a new building to house four separate labs, one for each of our clients, the EM manufacturers Zeiss, Hitachi, JEOL and Philips/FEI. In 2003, we had secured cooperation agreements with all four companies.

In the year 2000, when the success of the new aberration correction system was apparent, well recognized and appreciated by the materials science community, the US Department of Energy started a discussion to reach further and develop an ultra-high resolution TEM at 300 kV to achieve 50 pm resolution both in TEM and in STEM. The requirement for TEMs was to compensate not only the spherical, but also the chromatic aberration. Subsequently, the TEAM project (Transmission Electron Aberration corrected Microscope) was started in 2005 and had to be finished by summer 2008. When in April 2008, a TEM prototype had been installed at the DOE lab in Argonne, as well as a Cs-corrected STEM in Oak Ridge, we finally managed to ship the whole double corrected 300 kV instrument to the NCEM/Berkeley. For the STEM we developed an advanced hexapole corrector compensating even the fifth-order limiting aberration and showing a resolution of 50 pm. However, for the Cc/Cs-corrector we detected a resolution of 55 pm at 200 kV and of just 65 pm at 300 kV, although the shorter wave length at 300 kV would be expected to show better results. Even though the aberration corrected TEM was accepted, we did not give up investigating the reasons for the loss of coherence at 300 kV and, less strong, at 200 kV. It took us until 2013 to be able to explain the reason of this reduction of resolution by calculations and experimental work (mainly by Stephan Uhlemann): Due to the large diameter of the electron beam within the corrector, free electrons in any

Maximilian and Christa Charlotte in Hawaii after a conference

metal produce small electron currents by correlation, whose small magnetic fields produce magnetic noise. As the strength of the quadrupole fields is limited, the large beam diameter is necessary to produce sufficient focusing power. Solving the riddle of the magnetic noise allowed us to upgrade the existing copy of the TEAM corrector for Jülich and, hence, improve the resolution at 200 kV and 300 kV to 50 pm.

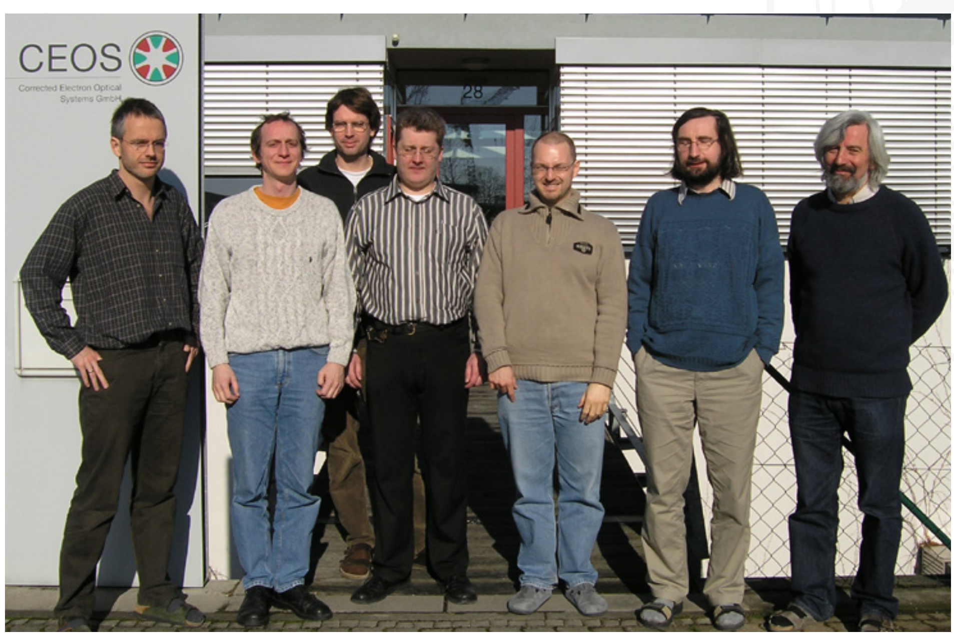
When we had just finished the TEAM project, Ute Kaiser from the University of Ulm asked for a joint project to develop a dedicated low voltage (20 kV up to 80 kV) aberration corrector. The Sub-Angstrom Low Voltage Electron microscope (SALVE) project was started as a joint project with Zeiss, co-funded by the DFG and the State of Baden-Württemberg. However, in 2013 Zeiss stopped the TEM business and a new project partner for the base instrument was found with FEI. We used the time between the negotiations of back-payment by Zeiss and the conclusion of a new agreement with FEI to modify the existing SALVE corrector and to optimize it regarding the magnetic noise. The SALVE project was finished in 2016, with a new landmark of resolution at low energies. As an example, we achieved sub-angstrom resolution even at 40 keV energy, although the wave length of electrons is much larger at this energy than at 200 kV. As figure of merit for the achieved resolution, the wave length of the electrons used for imaging was employed:

With Joachim Frank at an EM-Conference in Davos/Switzerland in 2005

The ambitious goal within the challenging TEAM project was to achieve a resolution 20 times the wavelength. We set the same goal for the SALVE project, but managed to achieve a resolution of about 15 times the wavelength between 20 – 80 kV, and topped the result of the TEAM project in this respect. This is, in comparison with an uncorrected TEM having a resolution of 100 times the wavelength an improvement by a factor of around 7 times.

In addition to these challenging R&D projects, we had to organize the production of Cs-correctors for various companies. So in 2005, when the TEAM project started, we changed the cooperation with FEI for their TEMs and STEMs and granted them permission to produce hexapole Cs-correctors based on our technology. The CEOS company grew over the years, starting as a group of five people in 1996 to an enterprise with almost 50 employees to date. Due to the strong interaction with Roses group in Darmstadt we knew his PhD students and could hire some. Finally, we gathered all together seven former PhD students of Rose all of them having very good knowledge of electron optics. We had to extend the company´s premises in Heidelberg three times, and at the end of 2019, in total around 900 hexapole correctors, based on CEOS technology, have been installed worldwide. This figure stands for about 90% of the global market of aberration corrected electron microscopes.

While my professional career moved from optician to physicist, my life changed dramatically when my wife Brigitte was



The group of former students of H. Rose working at CEOS in front of the building celebrating the 10th anniversary

With K. Urban and H. Rose after the celebration of the Honda Award in 2008

diagnosed with cancer in 1988. In 1989, we moved from Darmstadt to a village near Heidelberg to live much closer to the EMBL, where I worked at that time. She died in 1990 – in the same year when Harald Rose, Knut Urban and I set up our joint Cs-corrected TEM project and were in the middle of securing funding for this project. As Brigitte's illness progressed, she happened to meet Christa Charlotte, a Protestant pastor on maternity leave, whose younger children were about the same age as my two children. In the following months, Christa Charlotte took on the spiritual care for my wife, and after Brigitte´s death, she supported me as single parent. We fell in love, founded a common household in 1995, and are happily married since 2000. I am very happy and feel privileged to have experienced this positive change in my life thanks to my second wife and all children and grandchildren.

With H. Rose at Max's birthday-symposium at the University of Heidelberg