

## Chicago Aberration Correction Work

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Albert Crewe brought many improvements to electron microscopy through the techniques of accelerator physics. Soon after earning his PhD, he saved the 450 MeV synchrocyclotron project at the University of Chicago. At the time this was the highest energy particle accelerator in the world. It was working nicely except for the fact that the beam could not be extracted from the machine. Crewe introduced corrections to the field that allowed the beam to be extracted. A decade later he was the Director of the Particle Accelerator Division at Argonne National Laboratory and finishing construction of the Zero Gradient Synchrotron, operated by the University of Chicago. I became aware of Crewe in about 1962 when I visited ZGS during an open house as a junior high school student. His next position was director of Argonne National Laboratory when he chose to start a small project on scanning electron microscopy. While in high school, I had a very brief visit to Crewe's electron microscopy lab at Argonne. Crewe chose the smallest, brightest source of electrons, namely field emission, so the probe size would be limited by lens aberrations. To minimize aperture aberrations in the electron gun, he worked with Jim Butler to develop an appropriate accelerating field. Crewe chose to set the axial electric field to zero at the entrance and exit of the accelerator; the simplest field that does this varies quadratically along the z axis. Since the accelerating field should depend on only r and z and not on  $\phi$ , field is fully specified in three dimensions and the electrode shapes are defined. He soon found that quadrupole lenses commonly used in accelerators were inferior to round lenses. Crewe learned about Scherzer's theorem and had Cohen and Meads design a spherical aberration corrector based on Scherzer's quadrupole octopole design and Deltrap's improvements. Work started on the corrector I was to be involved with while I was in high school. Crewe returned to the University of Chicago and his electron microscopy lab came as well. His teaching duties that year were first year physics and I was in that class. Crewe offered me a summer job making field emission sources in his lab. Michael Thomson was finishing up his postdoc in Crewe's lab at this time. One of his projects was analyzing the off axis aberrations of the quadrupole octopole corrector designed by Cohen and Meads. We had very little interaction. Joe Wall, Michael Isaacson and Dale Johnson were graduate students at the time and did a great job of teaching me the science and technology of FE STEM. Crewe liked using transfer matrices for first order optics; they had served him well during his days doing particle accelerators. One particular system he liked was a negative optical space which he described as a solution looking for a problem. I rapidly moved through the physics curriculum and when it was time to choose a thesis project, Crewe asked me to do the corrector. Unfortunately getting the corrector working was deemed to be mere technology by the physics department, so the actual thesis would be written on an unusual scattering problem that would arise in the corrected microscope: The beam would be sufficiently small that it would not uniformly illuminate an atom - an assumption normally made in scattering theory. It didn't take long to work this out quantum mechanically but observing it was problematical. Crewe had some biting comments along these lines in one of his last papers: "Some Chicago Aberrations" [1]. I began studying the tolerances of the corrector and realized that it would have to be aligned to a much tighter tolerance than the extraordinary accuracy to which it was being built. Since the tolerances could not be met mechanically, a method of moving the center of the octopoles electrically was developed. It was possible to do this just as it was possible to move the

center of a quadrupole by adding two orthogonal dipole fields. In the case of the octopole, six orthogonal lower order fields were needed, namely two orthogonal hexapole fields, two orthogonal quadrupole fields, and two orthogonal dipole fields. The corrector was redesigned to include coils to excite these modes. Since 8 (octopoles) and 6 (hexapoles) are incommensurate, the turns per pole piece varied. The drive electronics was arranged so that an adjustable fraction of the primary octopole current could be used to excite the lower order moments as well as an independently adjustable current. Later I discovered there was some residual hysteresis in the permanent magnet corrector was made from which greatly complicated the task of alignment. Further analysis showed that the spherical aberration of the combined corrector – objective lens was not constant. On almost the day I realized this, Harold Rose showed up to begin a one year sabbatical with Crewe. I put this to him and he explained combination aberrations to me in about 5 minutes. Because the corrector was located about 15 centimeters ahead of the objective lens, the third order deflection it introduced would cause a ray to enter the objective at a different point. This would cause a small change in the objective's third order deflection which is a fifth order deflection or secondary spherical aberration. Born and Wolf's chapter on Diffraction Theory of Aberrations [2] explained how to use this information to determine the optimum operating conditions for the microscope. Meanwhile, in another part of Crewe's lab, Bill Parker discovered the transformation of the off axis aberration coefficients of a round lens which allowed the cancellation of anisotropic coma. This work was replicated elsewhere and proved crucial to reducing the off axis aberrations in scanned lithography systems. I reflected on the possibility of making a third order corrector using combination aberrations directly. A pair of oppositely excited hexapoles, with second order aberration, would generate a third order combination aberration. Although this aberration was cylindrically symmetrical, it was of the wrong sign, just as a quadrupole doublet always forms a converging lens. The way to flip the sign of the combination aberration was to use the solution waiting for a problem, the negative optical space. Several years later when I joined IBM Research I was able to use their newly developed SCRATCHPAD symbolic computation system to work out the higher order combination aberrations to make sure they did not overwhelm the benefits of correction[3]. Albert Crewe and David Kopf then developed a similar corrector which used the self combination aberrations developed in a pair of long hexapoles or sextupoles which were optically placed atop one another to allow cancellation of the underlying second order aberration. Peter Hawkes discovered the self combination aberration in long hexapoles in 1965. In 1988 IBM Research granted me a one year sabbatical at the University of Chicago to work on this corrector. Zhifeng Shao extended combination correctors to higher orders and discovered that nonsymmetrical spherical aberration can arise in the case of octopoles generating a fifth order correction aberration. Jiye Ximen had a sabbatical at Crewe's Lab. He worked on the aberration problem for a long time, and developed the so called Hamiltonian method and transfer matrices for higher order optics. Crewe's last graduate student, Frank Tsai, successfully demonstrated a system which utilized a magnetically focused electrostatic mirror which was free of both first order chromatic aberration and primary spherical aberration. This system utilized a constant axial magnetic field and a constant axial electric field as the mirror. Crewe's final project, done with Bud (Oscar) Kapp, utilized a permanently magnetized sphere as a lens. This dipole field had low (but non zero) aberration coefficients.

## References

- [1] A.V. Crewe, *Microsc. Microanal.* **10** (2004) 414. (includes many additional references)
- [2] M. Born & E. Wolf, *Principles of Optics*, 3<sup>rd</sup> Ed., Pergamon Press, 1965.
- [3] V. Beck, *Optik.* **53** (1979) 241.