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Some Chicago Aberrations

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The account that follows is based on my own memory although some of it can even be documented.

The story begins in 1966. At that time I was a beginner in electron microscopy and we (Isaacson, Wall and Johnson) were attempting to get a field emission tip to function as the source of electrons in the first STEM. There was not much encouragement to think that it would work, nothing except the skill of those students. Nevertheless one could hope. I recall reading Zworykin's book with its account of the ideas of Scherzer on correction of aberrations. There was also a review on the subject by Septier. It looked like a good idea and the STEM was clearly the instrument of choice for a corrector. I asked David Cohen to investigate the concept and he produced a set of guidelines for a device with four quadrupoles and three octupoles. When I applied this to a 30 kV STEM, the whole thing looked feasible - except for the mechanical tolerances. A few months later I left Argonne and found Walter Mankawich at the UofC, a man who could machine to micron tolerances. We began a long journey together and he used every spare moment to build jigs and fixtures.

Vernon Beck took over the project when he joined our group. He changed the design somewhat and added new features [1] and we built a new STEM to test the device. I recall that both Michael Thomson and Harold Rose spent a year or so in our laboratory in those years, but although both of them had experience in the correction business they had other interests and did not get involved in the work.

We attempted to operate it in 1976, but we were not able to make it work [2, 3]. In spite of the 40 trim coils we could not find a suitable setting. The effective centers of the quadrupoles and octupoles could not be brought together. My own conclusion at the time - right or wrong - was that the iron of the pole pieces was not sufficiently uniform. In any case, no other student would take a chance on it and so the work on aberration correction stopped.

The next event came when I gave a series of lectures to my group on electron optics. After discussing guns and round lenses I also talked about quadrupoles and octupoles. After finishing the course one of the students (I think it was Isaacson) pointed out that I had not mentioned sextupoles. This prompted me to calculate their properties and to my astonishment the third order aberrations were cylindrically symmetric about the axis and of the opposite sign to those of round lenses! (This result had also been noted by Hawkes but I was unaware of it).

My calculations are notoriously full of errors so I asked David Kopf to check them. He found that I was correct.

The difficulty in using sextupoles as a corrector is that of finding an electron optical system that eliminates the second order focusing effect while retaining the third order aberrations. I am embarrassed by the length of time it took me to devise such a system. It was only when I recalled the use of field lenses in light optics that the solution appeared. It was to place a non-rotating round lens (actually two) between two sextupoles, imaging one on to the other. With a suitable physical rotation between the two, the desired result is obtained. I submitted a paper on this idea in July 1981 [4]. Shao later added to the concept by considering the fifth order aberrations as well and devising a way to control them [5].

One of the advantages of using sextupoles is that the required excitation is small enough that one can use air coils - no iron is needed. With funding from the NSF we began construction of a 200 kV STEM with a sextupole corrector. Unfortunately, when the system was more than half finished, their enthusiasm ran out and we had to abandon the project. I believe that it would have worked.

The third - and maybe final - attempt at correction occurred as a result of an academic exercise in which I am trying to develop electron optics "ab initio", starting with uniform fields. Surprisingly this is not readily available in the literature.

It was of academic interest to consider a uniform magnetic field superimposed on a uniform electrostatic field with an arbitrary angle between them. The focusing properties are remarkably simple and the most interesting case was the magnetically focused electrostatic mirror [6]. It turned out to have third order aberrations with opposite sign to those of a round lens. It was then possible to design a system with zero aberrations. Frank Tsai was the one who operated the device and showed that he could eliminate both chromatic and spherical aberration [7, 8]. This concept remains a curiosity because it is difficult to design a useful optical system. The only one appears to be a STEM configuration.

We obtained DOE support for such a system and once again the funding was terminated when the project was incomplete.

The sum total of our efforts is not very encouraging, one technical failure, two funding failures and one success. But perhaps we did stimulate ideas and encouraged competition.

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