11.6 * Lens Aberrations and Their Corrections

11.6.1 C_s Correction with Magnetic Hexapoles

The positive spherical aberration of an objective lens was discussed in Sect. 2.7.1. Its deleterious effects on high-resolution images were explained in the context of HRTEM imaging in Sects. 2.8 and 10.3.3, but (11.1) shows that spatial resolution in STEM mode is similarly impaired by C_s. Recall that the positive sign of C_s means that off-axis rays converge excessively compared to paraxial rays, so the off-axis rays come to focus closer to the magnetic lens. It turns out that it is impossible to eliminate the spherical aberration of a magnetic lens built as a short solenoid. One reason is that the off-axis electrons spend a bit more time in the lens, and have larger deflections during this time. Other problems come from non-ideal magnetic field distributions in short solenoids, such as a higher B_z away from the optic axis. Small, compact lenses with high magnetic fields have proved effective in minimizing C_s, although not eliminating it.

In a significant and recent development in TEM instrumentation, it is now possible to eliminate C_s. This is done with a "C_s corrector" system in series with the objective lens. This device adds extra divergence to the off-axis rays, compensating for the excessive convergence of off-axis rays caused by the spherical aberration of the objective lens.

One type of C_s corrector system, described here, uses two hexapole magnetic lenses. The fields and forces on electrons in one hexapole lens are depicted in Fig. 11.7. The electron trajectories travel down through the plane of the paper from above, and experience the Lorentz forces, $\boldsymbol{F}_{\text{mag}} = -e\,\boldsymbol{v} \times \boldsymbol{B}$, where we consider $\boldsymbol{B}$ to be in the plane of the paper. By symmetry, the fields and forces are zero for electrons that pass through the exact center of the lens, and the forces increases with radius, r. At the smallest r, the forces are dominated by terms having the lowest power of r allowed by symmetry. The linear term is disallowed since the fields and forces along the important horizontal direction in Fig. 11.7 do not change sign across the center of the lens. The quadratic term is allowed, so F increases in proportion to r^2, at least for small r. The distance over which the electrons accelerate under this force, the deflection through the lens, therefore scales with r^2.[12] The direction of this deflection is shown in Fig. 11.7b.

Figures 11.7b and 11.7c show a lateral cut of electron entry points in the hexapole field. At the center of the lens, the field, force, and deflection are all zero. Importantly, for electron trajectories to either the left or right sides of the lens center, all deflections are to the left. This reflects the symmetry of the hexapole, where North and South poles are diametrically opposed. The

[12] Recall that distance, $d = 1/2at^2$ and $a = F/m$, where a is acceleration and t is time allowed for acceleration. The time, t, is assumed the same for paths through the lens, or at least for all positions along a line like the one selected in Fig. 11.7b.

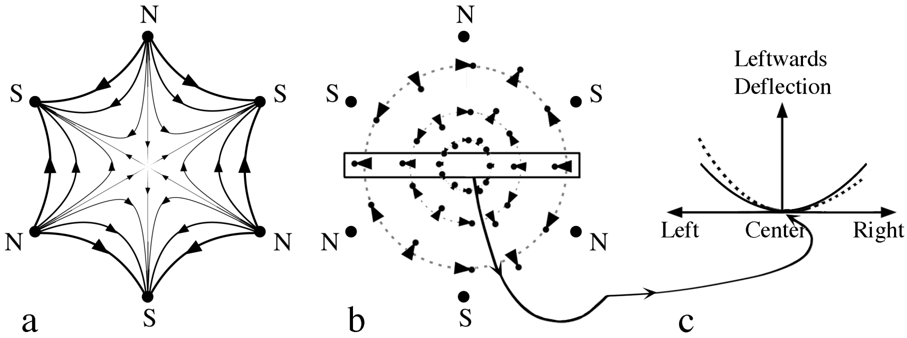

Fig. 11.7. (**a**) Magnetic poles and field directions for a magnetic hexapole lens. Thicker lines denote higher flux density. (**b**) Forces on an electron traveling down through the plane of the paper from above. The larger arrowheads denote larger forces, and the dots at the ends of the arrowheads indicate the deflections of the electrons that entered the lens on the dashed circles. (**c**) A set of deflections for electron trajectories across the center of the hexapole lens, identified with a rectangular box in part (b). Note that all deflections are to the left, but are larger further from the center of the lens.

leftwards deflections are larger away from the center of the lens, as depicted by the solid curve in Fig. 11.7c. Deflecting off-axis rays in the same direction is interesting, but this does not give the divergence needed for a C_s corrector.

In addition to the hexapole field pattern, the C_s corrector requires a "long" hexapole. With reference to Fig. 11.7b, we see that the leftmost electron moves into a region of stronger field, whereas the rightmost electron moves into a region of weaker field. Assuming the hexapole field has the same pattern some distance below the plane of the paper, the leftmost electron path will experience an increasingly larger leftwards deflection as it moves through the lens. The rightmost electron will be deflected less because it moves into a weaker field. These deflections are depicted in the dashed line of Fig. 11.7c. This gives divergence. Electron paths to the left and right of center of the lens will both be bent to the left, but the leftmost electron will be bent further, giving a divergence between left and right rays. Those electrons further from the optic axis will diverge more. This is just what is needed to compensate for the excessive convergence of the objective lens from its positive C_s.

Although this single hexapole has a negative C_s, it causes some distortions itself. Notice in Fig. 11.7b that there is a 3-fold distortion to the electron trajectories. Electron paths bunch up at 1, 5, and 9 o'clock around the center. Correction for this requires a second hexapole lens, essentially identical to the first, but operated out of phase. If the two lenses were adjacent, interchange of the North and South poles would successfully cancel this 3-fold distortion. Practical C_s corrector systems use a transfer lens system comprising two conventional lenses as shown in Fig. 11.8. The transfer lenses in the center serve to project the output from the first hexapole onto the input of the