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## 5. QUADRUPOLE FOCUSSING LENSES

Earlier in these lectures,the properties of Einzel lenses were described and we saw that these lenses require rather large longitudinal electric fields to produce the radial field components required for focussing. Consequently, the focussing effects of such lenses are called second-order effects and the lens action is rather weak in comparison with the voltages applied. For this reason, Einzel lenses are almost never used for focussing ion beams with energies above about 50 kev. For higher energies, a much higher quality and stronger lens is obtained using a field distribution known as a *quadrupole field*. Magnetic lenses of this type are used on the highest energy accelerators and electrostatic quadrupoles can be easily used to energies beyond 10 MeV.

The name quadrupole stems from the fact that the focussing field is often produced from four equi-spaced poles. Figure 33 shows the arrangement for a magnetic quadrupole where the beam is directed into the page. Ideally, the surfaces of the poles should be rectangular hyperbolas that approach the X and Y axes asymptotically. In practice, however, correctly placed cylindrical surfaces can provide a better approximation to the field when the

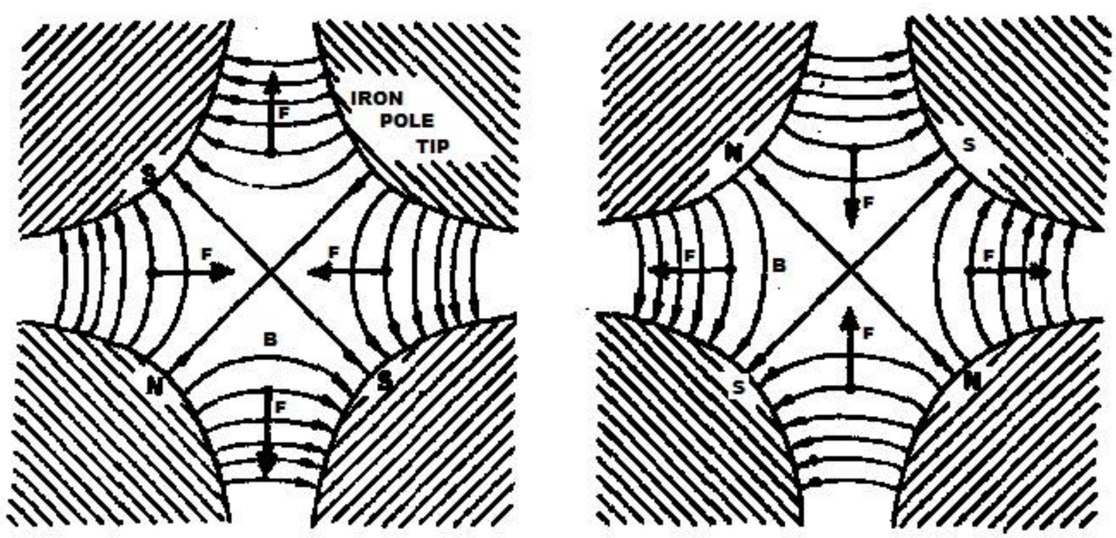


FIGURE 33.

effects of finite pole depth are included. By simple mathematics it can be shown that the magnitude of both field components is accurately proportional to the distance from the axis and so they produce "good" focussing. Quadrupoles can easily be corrected to remove any residual aberrations, even for large apertures.

The reason quadrupole fields are so highly efficient for focussing is because their fields are *transverse* to the central trajectory. Thus, they have a maximum focussing effect on the ions. A positive ion that enters the lens to the right of center in Figure 33 is subject to a *focussing force* which converges it back toward the axis. On the other hand, if the ion enters above the center of the lens, the ion is subject to a *defocussing force* that deflects it away from the axis. The lens focusses positively in the horizontal plane and negatively in the vertical plane. Clearly, if the maqrnetic polarities are reversed, so that the north poles become south and vice versa, the signs of all the forces on the ions are also reversed and this new lens would have positive focussing in the vertical plane and negative focussing in the horizontal p1ane.

The focal length of a weak quadrupole lens is easily estimated by usinq the field path integral discussed earlier. In a quadrupole 1ens, the magnetic field changes in proportion to the distance from the axis. For a quadrupole with aperture, 2a, the field a distance, d, from the axis is,

$$B = (Bo/a).d, \qquad (24)$$

where Bo is the magnetic field at the pole-tip. Ions with magnetic rigidity, $(B\rho)$, that enter the quadrupole traveling parallel and displaced a distance, d, from the central trajectory, undergo a deflection, 0, given by the field path integral:

$$\theta = (Bo/a).(ds)/(B\rho), \qquad (25)$$

where s is the path length in the quadrupole. Since $\theta = d/f$, the focal length is given by,

$$f = (B\rho).a/(Bo\ \ell), \qquad (26)$$

where $\ell = s$ is the length of the quadrupole.

At first sight, such lenses may not appear to be very useful because of the strong defocussing which always occurs in one plane. However, when two such 1enses are arranged in series, one with positive horizontal focussing and the second with negative horizontal focussing, ions entering the lens with a horizontal displacement are deflected towards the axis in the first lens. When these ions arrive at the second lens, they are closer to the axis so the outward forces are 1ess and the effect of defocussing is less. Thus, the net deflection is toward the axis and overall there will be focussing. In the same way, ions that enter the lens off-axis in the vertical direction are defocussed less than they are focussed because the particles are further away from the axis in the positive focussing e1ement. *Overall there is a net focussing in both planes.*