APSU-2.03-TN-001

APS-U Definitions of Signs and Conventions Related to Magnets

Revision 0

Advanced Photon Source

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August 21, 2014

Revision History

Revision 0	Aug 21, 2014	First published version

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1. Introduction

The APS-U is planned to be a 4th generation hard X-ray light source utilizing a multi-bend achromat (MBA) magnet lattice. The MBA lattice will be installed in the existing APS storage ring enclosure. The stored electron beam will circulate clockwise when viewed from above. The X-ray beamlines will for the most part exit at the same source points as the present APS.

This document defines the signs and conventions related to the APS-U MBA magnets. Included in this document are: the local magnet coordinate system, definitions of mechanical and magnetic centers, definitions of multipole field errors, magnetic roll angle, and magnet polarities.

2. Coordinate system local to a magnet

The local coordinate system for a magnet is defined with the positive z-axis (longitudinal) pointing in the e^- beam direction and the positive y-axis (vertical transverse) pointing up. The positive x-axis (horizontal transverse) is defined using a right-handed coordinate system. In the case of APS-U, with the e^- beam circulating clockwise in the storage ring when viewed from above, the positive x-axis thus points radially outward, as shown in Fig. 1. The radial and angular coordinates of a point P are denoted by r and θ in a cylindrical coordinate system, where θ is the angle measured going from the positive x-axis towards the y-axis. The origin, O, of the coordinate system is located at the magnetic center of the magnet, as defined in the next section.

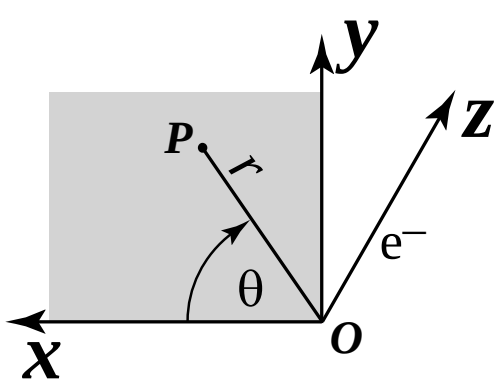


Fig. 1 Local magnet coordinate system looking from the upstream side of the magnet. The z-axis is along the direction of travel of the electron beam and points into the paper.

3. Mechanical and magnetic centers

3.1 The longitudinal center of the magnet is defined as the midpoint of the planes formed by the two end faces of the magnet poles. The magnet ends near the pole tips may be chamfered to tune the field quality. The surfaces away from the chamfers are to be used in this case. Some magnets may have pole extensions to gain some extra integrated field (mushroom ends). These extensions are expected to be symmetric on

the two ends of the magnet and thus are not expected to affect the longitudinal center. Therefore, surfaces away from the poles can be used in these cases also.

3.2 In the transverse direction, a **mechanical center** can be defined by fitting the as-built pole profiles to the ideal pole profiles. This can be done by a detailed survey of the as-built poles. A procedure to do this was developed for the NSLS-II magnets, for example, but is outside the scope of this document. This procedure for APS-U will be developed by the APS-U survey group and may be addressed in a separate document.

3.3 For multipole magnets (quadrupoles, sextupoles, etc.), a **magnetic center** in the transverse plane can be defined based on magnetic measurements. The magnetic center of a quadrupole is defined as the point where the magnetic field is zero. The magnetic center of a sextupole is defined as the point where the field gradients dB_y/dx ($=dB_x/dy$) and dB_x/dx ($=dB_y/dy$) are simultaneously zero.

3.4 Since the field is expected to be more or less uniform in a pure dipole magnet, the mechanical and magnetic centers are assumed to be the same for a dipole.

3.5 In the case of the Q-bend magnets (M3 and M4) in the APS-U MBA lattice, both the quadrupole and the dipole components are strong. The magnetic center of a Q-bend magnet in the y direction is defined as the point where the field component B_x is zero. The magnetic center in the x direction is defined as the point where the ratio of the field gradient, G, and the vertical component of the field, B_y, has a prespecified value. These values for the M3 and M4 magnets will be specified by the APS-U accelerator physics group based on the final lattice design.

4. The vertex point

The vertex point for a bending magnet is defined as the intersection point of the entrance and the exit beam vectors, as shown in Fig. 2. The actual beam path does not pass through the vertex point. If the total bending is assumed to occur abruptly at a single point, then the vertex point is where this would seem to occur to an external observer. If the magnetic field profile is symmetric in the entrance and exit halves of the magnet, then the vertex point will be in the longitudinal center of the bending magnet. For the longitudinal gradient L-bend magnets, the field profile is not symmetric, and the vertex point is shifted from the longitudinal center towards the higher field region.

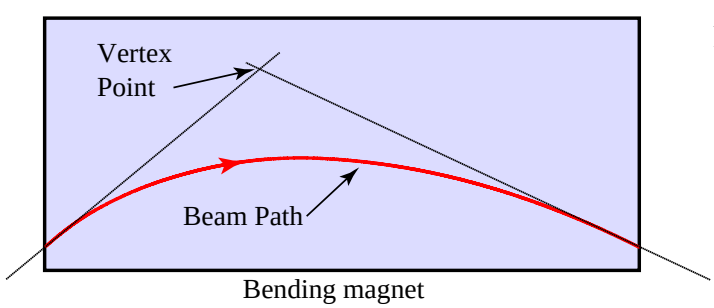


Fig. 2 The vertex point of a bending magnet. The beam path shown is as computed for a 6 GeV e^- beam in a 5-segment M1 type L-bend dipole. The vertical scale is magnified to show curvature clearly.

5. Field description in terms of harmonics

5.1 The field components B_y and B_x in the aperture of the magnet, when integrated along the length of the magnet, can be expressed in terms of an expansion of the type:

$$\int_{-\infty}^{\infty}\left[B_y(x,y,z)+iB_x(x,y,z)\right]dz=\sum_{n=0}^{\infty}\left[N_n+iS_n\right]\left(\frac{x+iy}{R_{ref}}\right)^n \tag{1}$$

where the constants N_n and S_n are the strengths of the normal and skew 2(n+1)-pole harmonic components of the field and R_{ref} is an arbitrarily chosen *reference radius*. Thus N_0 and S_0 represent the normal and skew dipole components, N_1 and S_1 represent the normal and skew quadrupole components, and so on.

5.2 The quantities N_n and S_n in Eq. (1) have units of Tesla.m and scale with reference radius as R_{ref}^n. These are also dependent on the choice of the location of the origin, and orientation of the x-y axes of the coordinate system.

5.3 A positive normal term produces positive values of B_y on the magnet midplane (y = 0) for $x > 0$. Similarly, a positive skew term produces positive values of B_x on the magnet midplane (y = 0) for $x > 0$. The effect on the electron beam arising from fields corresponding to various terms is discussed in Sec. 7

5.4 The coordinate system to be used for reporting the field expansion coefficients in Eq. (1) is oriented as described in Sec. 2, with the origin located at the *magnetic center* of the magnet, as defined in Sec. 3. The y-axis is chosen to be normal to a reference plane defined by fiducials on the top surface of a standalone magnet, or a magnet assembly, as the case may be. The reported field expansion coefficients must be rotated by the user of the data to account for any roll of the reference surface introduced (intentionally or unintentionally) during installation (see also Sec. 6.4).

5.5 The reference radius, R_{ref}, is chosen to be 10 mm for all the magnets in the APS-U MBA lattice. (A change of reference radius to 8 mm is under consideration at present.)

5.6 The n-th derivatives of the integrated field components, evaluated on the magnetic axis, are given in terms of the harmonic coefficients, N_n and S_n, by the following equations:

$$B_n=\left[\frac{\partial^n}{\partial x^n}\left\{\int B_y(x,y,z)dz\right\}\right]_{x=0;y=0}=\frac{n!N_n}{R_{ref}^n} \tag{2}$$

$$A_n=\left[\frac{\partial^n}{\partial x^n}\left\{\int B_x(x,y,z)dz\right\}\right]_{x=0;y=0}=\frac{n!S_n}{R_{ref}^n} \tag{3}$$

Since the coefficients N_n and S_n scale as R_{ref}^n, the derivatives B_n and A_n do not depend on the choice of the reference radius and have units of Tesla.m$^{(1-n)}$. It is worth

pointing out here that in most of the magnet-related literature, the symbols B_n and A_n are used to denote the normal and skew components of the field, which are denoted by the symbols N_n and S_n here. This is done to be consistent with the definition of the symbols B_n and A_n used by accelerator codes such as MAD and Elegant.

5.7 In a uniform region away from the ends of a long magnet, where the field components may be considered to be independent of the longitudinal position, an expansion similar to Eq. (1) may also be used for the local fields $B_y(x,y)$ and $B_x(x,y)$ instead of the integral field. The coefficients corresponding to N_n and S_n, of Eq. (1) are in units of Tesla in this case. *No separate symbols are being defined for the local field coefficients for the APS-U magnets.* The same symbols as in Eqs. (1-3) may be used with an accompanying clarification (e.g. by stating the units explicitly – Tesla for N_n or S_n and Tesla.m^{-n} for B_n or A_n) to indicate that these refer to a local field.

5.8 The normalized normal and skew harmonic coefficients (or "*multipoles*") are defined as:

$$\begin{aligned} b_n &= 10^4 \times N_n / B_{ref} = 10^4 \times B_n R_{ref}^n / (n! B_{ref}) \ \text{(in "units")} \\ a_n &= 10^4 \times S_n / B_{ref} = 10^4 \times A_n R_{ref}^n / (n! B_{ref}) \ \text{(in "units")} \end{aligned} \tag{4}$$

where b_n and a_n are the "normal" and "skew" normalized multipole coefficients and B_{ref} is a "reference field" used for normalization. B_{ref} is typically the magnitude of the most dominant integrated field harmonic evaluated at R_{ref} and is in Tesla.m (in Tesla for a local field). Since the harmonic terms other than the main field are generally very small compared to the main term, a multiplying factor of 10^4 is included in the definition of the normalized harmonic coefficients in Eq. (4) for convenience. The quantities b_n and a_n are dimensionless and are said to be in "units" when defined with the factor of 10^4 as in Eq. (4). Thus 1 "unit" of a harmonic represents field strength of 0.01% of the reference field when evaluated at the reference radius. It should be noted that although the normalized harmonics defined above are dimensionless, their values do depend on the choice of reference radius (see Eq. (6) below).

5.9 If the $n=m$ term is the most dominant term ($m = 0$ for a dipole magnet, $m = 1$ for a quadrupole, etc.) in Eq. (1), and the magnitude of field produced by this term at the reference radius is chosen as the reference field, then

$$B_{ref} = \left|N_m + iS_m\right| = \left|B_m + iA_m\right| \frac{R_{ref}^m}{m!} \tag{5}$$

$$\begin{aligned} b_n &= 10^4 \times N_n / \left|N_m + iS_m\right| = 10^4 \times \frac{m!\, B_n R_{ref}^{n-m}}{n! \left|B_m + iA_m\right|} \ \text{(in "units")} \\ a_n &= 10^4 \times S_n / \left|N_m + iS_m\right| = 10^4 \times \frac{m!\, A_n R_{ref}^{n-m}}{n! \left|B_m + iA_m\right|} \ \text{(in "units")} \end{aligned} \tag{6}$$

5.10 The definitions in Eqs. (5) and (6) will be used to express the integrated field quality in all the APS-U magnets. In the case of the Q-bend magnets M3 and M4, where both the dipole and the quadrupole terms are strong, the dipole term ($m = 0$) will be used for normalization as it happens to be stronger than the quadrupole term at the chosen reference radius of 10 mm (applies also if the reference radius is changed to 8 mm).

6. Magnetic roll angle

6.1 It is desired that the magnets be installed with a roll such that the skew component of the main field term (or the normal component in the case of skew quadrupole correctors) is zero when the y-axis of the coordinate system is aligned to the global machine coordinate system (nominally gravity).

6.2 The roll angle of a magnet is defined as the amount by which the magnetic midplane is rotated CW (when viewed from the *upstream* end) relative to a reference horizontal plane defined by the fiducials on the top surface of the magnet, as shown in Fig. 3. The same definition applies to the case of a multi-magnet assembly (or a standalone multi-axis corrector), except that each magnet element (or a specific corrector) in the assembly can have a different magnetic roll angle relative to the reference plane.

6.3 In the case of an integrated magnet assembly consisting of several magnets, or a standalone multi-axis corrector, the assembly can be installed to minimize the roll of all magnet elements in an average sense only. *For the purpose of installation*, an overall *magnetic roll of an assembly* can be defined as an average of the roll angles of all the magnet elements in the assembly. If significant misalignment between different elements is found, one may use a weighted average based on strengths or the impact on beam dynamics, as to be determined by the APS-U accelerator physics group.

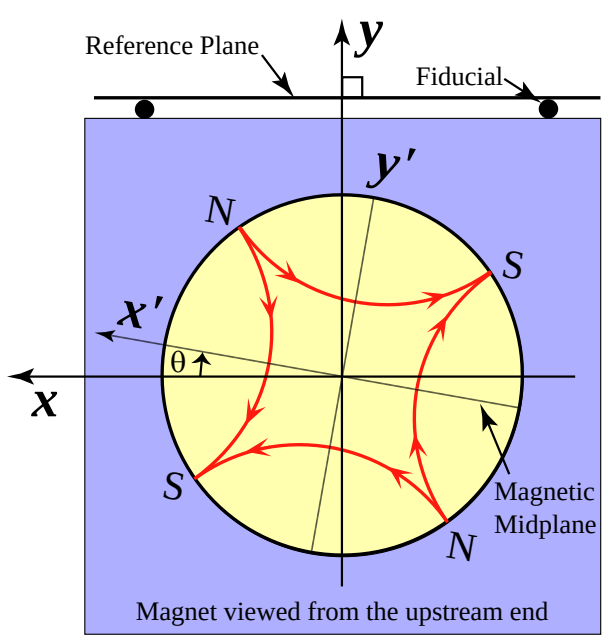


Fig. 3 A magnet with a positive magnetic roll with respect to a reference plane defined by the fiducials on the top surface, as viewed from the upstream end. The magnetic measurement frame is x-y, with the y-axis normal to the reference plane. x'-y' is a frame aligned to the magnetic midplane. A magnet with a positive magnetic roll should be installed with the reference plane rotated CCW. The harmonics data reported from measurements should be rotated *by the data user* to account for any roll of the reference plane in installation.

6.4 The field harmonics of all magnets will be reported in a frame oriented such that the y-axis is normal to the reference plane defined by the fiducials on the top surface of the magnet, or a magnet assembly (See Sec. 5.4 and Fig. 3). These harmonics must be transformed by the user of the data to a frame rotated based on the actual roll of the reference plane introduced during installation (either intentionally based on magnetic measurements or unintentionally). *The survey group should provide this installation data as part of the magnet database.* The effect of this transformation is expected to be small in most cases, except for those harmonics that are very large (mainly the most dominant term, and higher harmonics in sextupoles and some correctors).

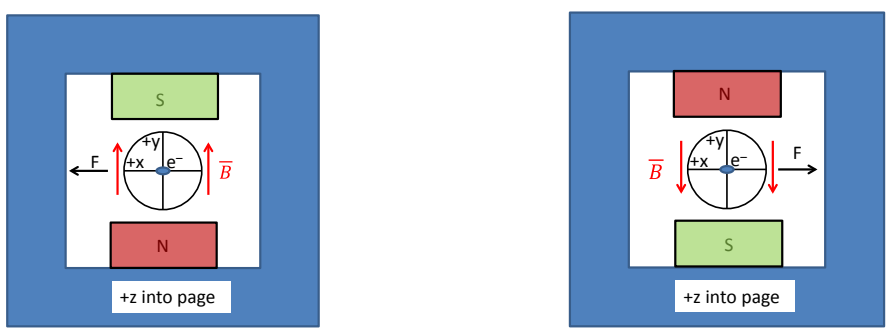
6.5 A magnet (or a magnet assembly) with a positive value of magnetic roll angle should be installed with its fiducial reference plane rolled CCW (when viewed from the upstream end), as shown in Fig. 3. Similarly, a magnet with a negative value of magnetic roll angle should be installed with its fiducial reference plane rolled CW.

7. Magnet field polarities and terminal markings

7.1 Horizontal Bending, Vertical Field, Normal Dipole

(a) For an outboard-bending (towards positive x) of an e^- beam traveling along the positive z-axis, the dipole field vector $(\vec{\mathbf{B}})$ points up as shown in Fig. 4(a). This corresponds to a positive normal dipole, or $B_0 > 0$.

(b) The main bending magnets in the APS-U (M1, M2, M3, and M4) bend the e^- beam inboard (towards negative x) to keep it on a closed circular path. The dipole field vector $(\vec{\mathbf{B}})$ must point down in these magnets, as shown in Fig. 4(b). Accordingly, these are negative normal dipoles with $B_0 < 0$.



(a) Positive horizontal bending (b) Negative horizontal bending

Fig. 4 Horizontal bending, normal dipole fields for an electron beam traveling into the page (view from the upstream end). The Lorentz force is in the direction of the vector **F**. The magnet terminals are to be marked with (+) and (–) such that when current enters the (+) terminal, the field direction produced is as shown in (a) for horizontal bending correctors, and as shown in (b) for main dipoles M1, M2, M3, and M4.

(c) In the case of horizontal bending dipole correctors (also referred to simply as horizontal correctors), the field may point either up or down depending on the sign of correction needed.

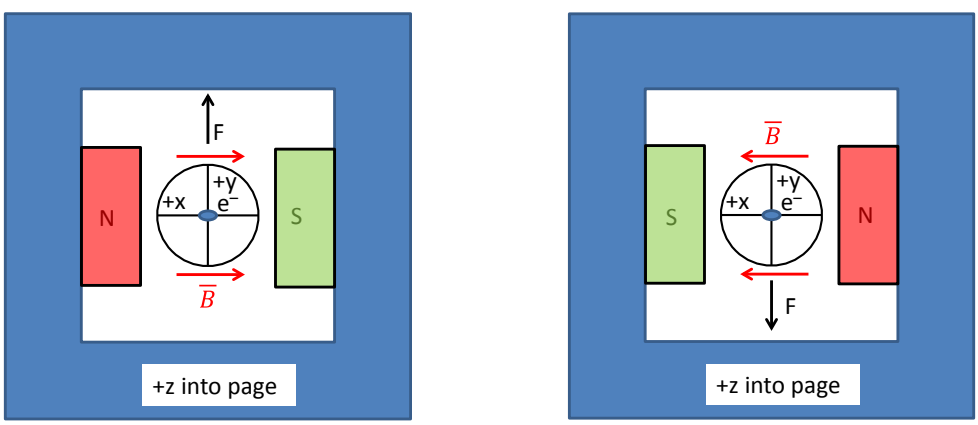
(d) The magnet terminals in the horizontal bending dipole correctors should be marked with (+) and (–) such that when the current enters the (+) terminal, it produces an e^- beam deflection towards positive x, or dipole field pointing up ($B_0 > 0$), as shown in Fig. 4(*a*).

(e) The magnet terminals of M1, M2, M3, and M4 magnets should be marked with (+) and (–) such that when the positive lead of the power supply is connected to the (+) terminal, it produces a dipole field pointing downward ($B_0 < 0$), as in Fig. 4(*b*). This is opposite of the polarity convention for the horizontal correctors, as described above in 7.1(d).

7.2 Vertical Bending, Horizontal Field, Skew Dipole

(a) For an upward bending (towards positive y) of the e^- beam traveling along the positive z-axis, the dipole field vector ($\vec{\mathbf{B}}$) points to the right when viewed from the upstream end, as shown in Fig. 5(*a*). This corresponds to a negative skew dipole, or $A_0 < 0$. A negative bending vertical corrector is shown in Fig. 5(*b*).

(b) The magnet terminals of vertical bending correctors (also referred to simply as vertical correctors) should be marked with (+) and (–) such that when the current enters the (+) terminal, it produces an upward deflection (towards positive y) of the e^- beam, or a dipole field pointing to the right when viewed from the upstream end ($A_0 < 0$).



(*a*) Positive vertical bending (*b*) Negative vertical bending

Fig. 5 Vertical bending, skew dipole field for an electron beam traveling into the page (view from upstream end). The Lorentz force is in the direction of the vector **F**. The magnet terminals are marked such that a positive bending field, as shown in (*a*), is produced when current enters the (+) terminal.

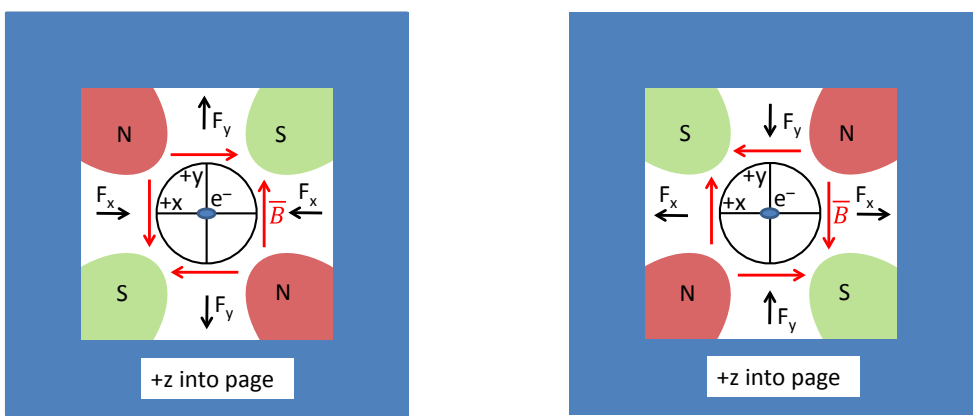
7.3 *Quadrupoles: Focusing and Defocusing*

(a) A focusing quadrupole is defined as one that focuses the e^- beam along the horizontal axis (x) and defocuses it along the vertical axis (y).

(b) For an e^- beam traveling along the positive z-axis, the field vector ($\vec{\mathbf{B}}$) points down ($B_y < 0$) in the left half of the aperture ($x > 0$) for a focusing quadrupole when viewed from the upstream end, as shown in Fig. 6(a). This corresponds to a negative normal quadrupole, or $B_1 = dB_y/dx < 0$ (see Sec. 5.3).

(c) A defocusing quadrupole is defined as one that defocuses the e^- beam along the horizontal axis (x) and focuses it along the vertical axis (y). The field in a defocusing quadrupole has a polarity opposite to that of a focusing quadrupole, as shown in Fig 6(b). Thus a defocusing quadrupole corresponds to a positive normal quadrupole, or $B_1 > 0$ (see Sec. 5.3) for an e^- beam traveling along the positive z-axis.

(d) All quadrupoles to be built for the APS-U project will have a predetermined location in a cell of the MBA lattice, and their intended polarity will be known. All quadrupole magnet leads should be marked with (+) and (–) such that when the positive lead of the power supply is connected to the (+) lead, the resulting focusing/defocusing property of the magnet is in agreement with the APS-U MBA lattice. In addition, the (+) lead should be marked with either "**F**" (horizontally focusing) or "**D**" (horizontally defocusing) to indicate the focusing property when the positive lead of the power supply is connected to this lead.



(a) Horizontally focusing quadrupole (b) Horizontally defocusing quadrupole

Fig. 6 Field ($\vec{\mathbf{B}}$) at off-center locations and Lorentz forces (F_x and F_y) in a quadrupole for an e^- beam traveling into the page (view from the upstream end) – (a) for a focusing quadrupole, and (b) for a defocusing quadrupole. The magnet terminals should be marked such that the appropriate pole configuration is produced, based on location of the quadrupole in the lattice, when current enters the (+) terminal.

7.4 *Skew Quadrupole Correctors*

(a) A skew quadrupole is obtained by rotating a normal quadrupole by ±45 degrees and either focuses or defocuses the e^- beam along the line $x = y$ depending on the magnet polarity and the direction of rotation.

(b) A configuration as shown in Fig. 7 is obtained by rotating a focusing quadrupole [see Fig. 6(*a*)] CW by 45 degrees, when looking from the upstream end. This configuration focuses an e^- beam (traveling in the positive Z direction) along the line $y = x$, and defocuses along the line $y = -x$.

(c) The configuration shown in Fig. 7 produces $B_x > 0$ for $x > 0$ and corresponds to a positive skew quadrupole term or $A_1 = dB_x/dx > 0$ (see Sec. 5.3). (B_x is positive for $x < 0$ also from skew quadrupole symmetry.)

(d) The magnet terminals of skew quadrupole correctors should be marked with (+) and (–) such that when the current enters the (+) terminal, it produces a field configuration as shown in Fig. 7 ($A_1 > 0$), and focuses an electron beam traveling in the positive *z*-direction along the line $y = x$.

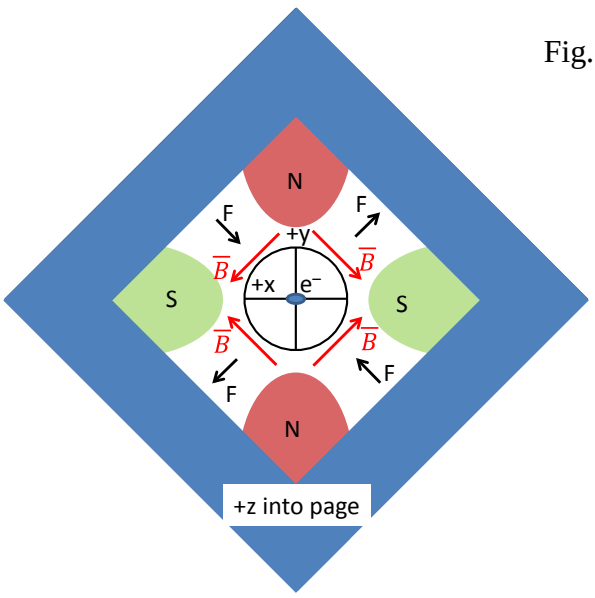


Fig. 7 A skew quadrupole obtained by rotating a focusing quadrupole of Fig. 6(*a*) CW by 45 degrees, when viewed from the upstream end. Field ($\vec{\mathbf{B}}$) at off-center locations and Lorentz forces (**F**) on an e^- beam traveling into the page are shown. The magnet terminals should be marked with (+) and (–) such that this pole configuration is produced when the current enters the (+) terminal, resulting in a magnet that focuses the electron beam along the line $y = x$.

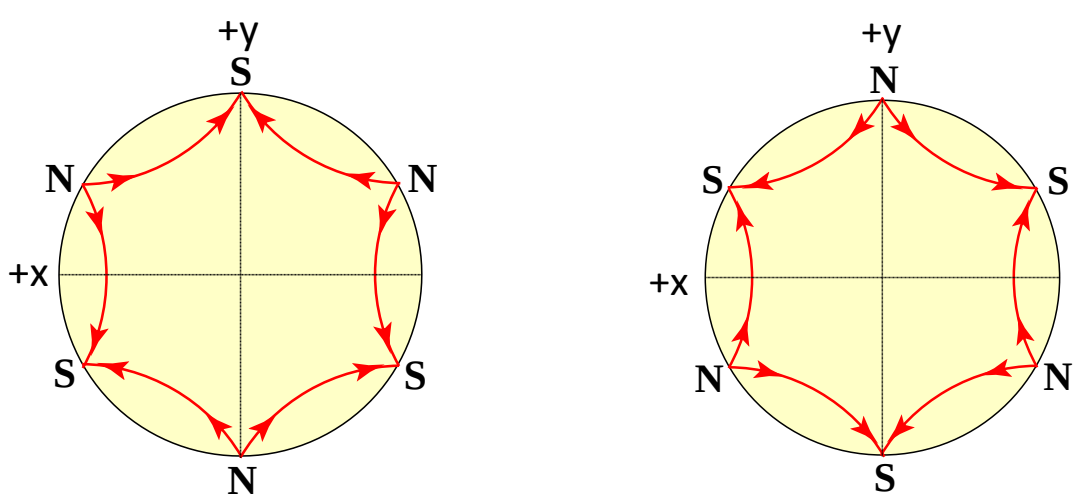
7.5 *Sextupoles: Focusing and Defocusing*

(a) A focusing sextupole is defined as one that provides a horizontally focusing field gradient for a beam displaced from the magnet center along the positive *x*-axis. This also provides a horizontally defocusing field for a beam displaced along the negative *x*-axis.

(b) For an e^- beam traveling in the positive z-direction, a focusing sextupole produces a gradient $G = dB_y/dx < 0$ for $x > 0$ [see Sec. 7.3(b)], and $G > 0$ for $x < 0$. This corresponds to a negative normal sextupole or $B_2 < 0$ (see Sec. 5.3). The field configuration for a focusing sextupole for APS-U is shown in Fig. 8(*a*).

(c) A defocusing sextupole is defined as one that provides a horizontally defocusing field gradient for a beam displaced from the magnet center along the positive x-axis. This also provides a horizontally focusing field for a beam displaced along the negative x-axis. The field in a defocusing sextupole is shown in Fig 8(*b*). Thus a defocusing sextupole corresponds to a positive normal sextupole, or $B_2 > 0$ (see Sec. 5.3), for an e^- beam traveling along the positive z-axis. The field gradient, $G = dB_y/dx$ is positive for $x > 0$ in this case.

(d) All sextupoles to be built for the APS-U project will have a predetermined location in a cell of the MBA lattice, and their intended polarity will be known. All sextupole magnet leads should be marked with (+) and (–) such that when the positive lead of the power supply is connected to the (+) lead, the resulting focusing/defocusing property of the magnet is in agreement with the APS-U MBA lattice. In addition, the (+) lead should be marked with either "**F**" (for focusing) or "**D**" (for defocusing) to indicate the focusing property when the positive lead of the power supply is connected to this lead.



(*a*) Focusing Sextupole (*b*) Defocusing Sextupole

Fig. 8 Pole configurations and magnetic field lines in (*a*) a focusing sextupole, and (*b*) a defocusing sextupole for an e^- beam traveling in the positive z direction (into the page). The harmonic coefficient B_2 is negative for focusing and positive for defocusing sextupole. The magnet terminals should be marked as described in Sec. 7.5(d) such that when the positive lead of the power supply is connected to the (+) lead, the resulting focusing/defocusing property of the magnet is in agreement with the APS-U MBA lattice.

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