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Modeling Injection Trajectories from the H-Minus Stripping Foil through the C7 Dipole in Booster

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H-minus particles enter the Booster through the backleg of the C5 dipole and follow trajectories through the dipole to the stripping foil in the C6 straight section. This is described and modeled in Ref. [1]. While most of the H-minus particles are completely stripped of electrons as they pass through the foil, a small fraction of them keep one or both electorns. These are of interest because they may activate accelerator components in the C6 straight or damage the C7 dipole. For the same reason, H-minus particles that miss the foil altogether are of interest. In this note we start at the foil and track these particles through the C6 straight and the C7 dipole.

1 C6 Straight Section Layout

Figure 1 shows the layout of the C6 straight section. Here the horizontal axis gives the distance in meters along the centerline of the straight starting at the H-minus stripping foil and proceeding downstream. The vertical axis gives the distance in mm from the centerline with negative numbers indicating distances toward the center of the Booster ring. The short blue and green rectangles show the location and apertures of quadrupoles QHC6 and QVC7. The black rectangle shows the location and aperture of the carbon block. The tall blue rectangle shows the location and aperture of the C7 injection kicker. The magnetic lengths (meters) of quadrupoles QHC6 and QVC6 are [2, 3, 4]

$$L_H = 0.493, \quad L_V = 0.504. \tag{1}$$

The lengths (meters) of the carbon block and kicker are [5, 6]

$$L_C = 0.346, \quad L_K = 0.152. \tag{2}$$

The half-apertures of the quadrupoles, carbon block, and kicker are 76, 60, and 54 mm respectively. The distances (meters) from the foil to the upstream ends of QHC6, the carbon block, the kicker, and QVC7 are respectively [2]

$$L_1 = 0.723, \quad L_2 = 2.580, \quad L_3 = 4.132, \quad L_4 = 4.921. \tag{3}$$

The distance (meters) from the downstream end of QVC7 to the C7 dipole entrance is [2]

$$L_5 = 0.290. \tag{4}$$

2 Transport through the Quadrupoles

The strength of the Booster quadrupoles is [2, 3, 4]

$$K = \frac{G}{B\rho} = 0.548892 \text{ m}^{-2} \tag{5}$$

where G is the gradient and $B\rho$ is the magnetic rigidity. The matricies for transport through focussing and defocussing quadrupoles are

$$\mathbf{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}, \quad \mathbf{N} = \begin{pmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{pmatrix} \tag{6}$$

where

$$M_{11} = M_{22} = \cos\phi, \quad M_{12} = \frac{1}{\sqrt{K}} \sin\phi, \quad M_{21} = -\sqrt{K} \sin\phi \tag{7}$$

$$N_{11} = N_{22} = \cosh\phi, \quad N_{12} = \frac{1}{\sqrt{K}} \sinh\phi, \quad N_{21} = \sqrt{K} \sinh\phi \tag{8}$$

and

$$\phi = \sqrt{K} s. \tag{9}$$

Here s is the distance along the axis of the quadrupole with $s = 0$ at the quadrupole entrance and $s = L_H$ or $s = L_V$ at the exit. For H-minus particles, quadrupole QHC6 is defocussing and QVC7 is focussing.

3 The C7 Dipole

Figure 2 shows a scale drawing of the Booster dipole lamination. Here the pole width is 254 mm. The distance from the pole to the backleg is 121 mm. The width of the backleg is 133 mm. The vertical gap between the poles is 82.55 mm. The shims on the poles are 19 mm wide and the vertical gap between them is 77.75 mm. The height of the lamination is 596.55 mm and the height of the H-shaped opening is 330.55 mm. The brown rectangles indicate magnet coils. G10 insulating strips are indicated by the thin green rectangles. The thin pink rectangles indicate trim windings.

Figure 3 shows a top view of the C7 Dipole. Here the beam direction is from left to right. The horizontal and vertical axes give the x and y coordinates on the magnet midplane. The units are meters. The radial and azimuthal coordinates are defined by

$$x = r\sin\theta, \quad y = r\cos\theta. \tag{10}$$

The line $\theta = 0$ marks the entrance to the magnet. The magnetic length is

$$L = 2.42 \text{ m} \tag{11}$$

and the bend angle is

$$\theta_B = 2\pi/36. \tag{12}$$

The dotted black curve is the nominal trajectory of circulating beam on the midplane; it is a circular arc with radius-of-curvature

$$\rho_0 = L/\theta_B = 13.8656 \text{ m}. \tag{13}$$

The center of curvature is the point $x = 0$, $y = 0$. The centerline of the C6 straight is perpendicular to the magnet entrance and passes through the point $x = 0$, $y = \rho_0$. As noted by Bleser [7] the centerline of the dipole is actually displaced radially outward by 0.18 mm with respect to the nominal trajectory. The practical consequences of this are negligible and we assume that the centerline and nominal trajectory coincide. The red lines and curves show the perimeter of the magnet iron. The left and right edges of the magnet iron lie on the lines

$$\theta = (\theta_B - \theta_2)/2, \quad \theta = (\theta_B + \theta_2)/2 \tag{14}$$

where $\theta_2 = 9.5763$ degrees as given by Bleser [7]. The gray curves are the projections of the walls of the vacuum chamber onto the midplane; these are 82.55 mm from the magnet centerline. The black curves are the projections of the pole and backleg boundaries. Those closest to the centerline mark the pole boundaries; they are 127 mm from the centerline. The outer black curves mark the backleg boundaries; these are 248 mm from the centerline.

4 Magnetic Field on the Dipole Midplane

Using the dimensions of the lamination, Wuzheng Meng has calculated the field on the dipole midplane. This was done using the Opera code with the assumption that the field is independent of azimuthal coordinate θ. A plot of the field as a function of radius is shown in **Figure 4**. Here the blue curve gives the field in units of the field B_c at the center of the magnet. The horizontal axis gives the radial distance from the projection of the pole edge on the midplane. The units are mm. The black lines at 0 and 121 mark the pole and backleg edges. The dotted line at -127 mm marks the center of the magnet; the red line at -44.45 mm marks the vacuum chamber wall. Numerical integration of the equations of motion using this field gives particle trajectories on the midplane. This was done in Ref. [1] to obtain the H-minus trajectories on the C5 dipole midplane. In this note we consider trajectories that are on the midplane but inside the C7 vacuum chamber. Here the field is essentially constant and the trajectory is simply a circular arc with radius-of-curvature $\rho_0 = L/\theta_B = 13.8656$ m.

5 Particle Trajectories

Particle trajectories are obtained by giving particles various positions and angles (with respect to the C6 centerline) at the foil and tracking them through the C6 straight and C7 dipole. While most of the H-minus particles are completely stripped of electrons as they pass through the foil, a small fraction of them emerge as H-minus or H-zero (neutral hydrogen) atoms. These are of interest because they may activate accelerator components in the C6 straight or damage the C7 dipole. In its nominal position the edge of the foil is -25 mm from the C6 centerline. (The minus sign indicates that the foil edge is 25 mm away from the centerline toward the center of the Booster ring.) We consider positions at the foil between -25 and -45 mm from the C6 centerline.

5.1 Trajectories Starting Near Foil Center

Figure 5 shows trajectories in the C6 straight resulting from H-minus particles with position −35 mm and angle −5 mrad at the foil. This is near the center of the foil. As noted before, the horizontal axis gives the distance in meters along the centerline of the straight starting at the foil and proceeding downstream. The vertical axis gives the distance in mm from the centerline with negative numbers indicating distances toward the center of the Booster ring. The solid blue, violet, and magenta curves are H-minus, H-zero, and H-plus (proton) trajectories respectively. Note that the H-minus and H-zero particles are stopped by the carbon block and C7 kicker respectively; only the H-plus particles make it to the C7 dipole. **Figure 6** shows the H-plus trajectory (solid magenta curve) in the C7 dipole.

5.2 Trajectories Starting at Foil Edge

Figure 7 shows trajectories in the C6 straight resulting from H-minus particles with position −25 mm and angle −1 mrad at the foil edge. Here the solid blue, violet, and magenta curves are the H-minus, H-zero, and H-plus trajectories respectively. In this case all three trajectories make it to the C7 dipole. **Figure 8** shows the trajectories in the dipole. Here we see that the H-minus and H-zero trajectories intersect the outer wall of the vacuum chamber. The dotted blue line is drawn to indicate the slope of the H-minus trajectory at the point of intersection. As the H-minus and H-zero particles pass through the chamber wall they are stripped of their electrons, becoming protons. Since the protons are still in the magnetic field of the dipole, they curve to the right veering away from the straight dotted blue and violet lines.

Note that the dotted blue line intersects the backleg 11.2 inches upstream of the downstream end of the magnet iron. This is close to the point where the conductor insulation failure occured in the C7 dipole in June 1998. (A very dark area was seen on the G10 strip that runs along the backleg; it extended from 3 to 19 inches from the downstream end of the magnet iron. The center of this area was 11 inches from the end of the magnet iron. The insulation failure occurred at the location of the jack 13 inches from the downstream end of the magnet iron.) The H-zero trajectory line does not intersect the backleg.

Figure 9 shows H-minus trajectories in the C6 straight resulting from

H-minus particles with position −25 mm and angles −2, −1, 0, 1, and 2 mrad at the foil edge. The −2 mrad trajectory intersects the C7 injection kicker; the other trajectories make it to the C7 dipole. These are shown in **Figure 10**. Here again the trajectories intersect the outer wall of the vacuum chamber. The dotted blue lines are drawn to indicate the slopes of the trajectories at the points of intersection; they intersect the backleg 11.2, 11.8, 12.4, and 13.0 inches from the downstream end of the magnet iron.

Figure 11 shows H-zero trajectories in the C6 straight resulting from H-minus particles with position −25 mm and angles −2, 0, 2, 4, 6 and 8 mrad at the foil edge. All of these make it to the C7 dipole and intersect the outer wall of the C7 vacuum chamber as shown in **Figure 12**. None of the trajectory lines intersect the backleg.

5.3 More Trajectories Starting Near Foil Center

Figure 13 shows H-minus trajectories in the C6 straight resulting from H-minus particles with position −35 mm and angles 2, 3, 5, and 7 mrad near the foil center. The 2 mrad trajectory intersects the C7 injection kicker; the others make it to the C7 dipole. These intersect the outer wall of the C7 vacuum chamber as shown in **Figure 14**. The dotted blue lines are drawn to indicate the slopes of the trajectories at the points of intersection; they intersect the backleg 12.1, 13.2 and 14.4 inches from the downstream end of the magnet iron.

5.4 Trajectories Starting Further to the Inside at Foil

Figure 15 shows H-minus trajectories in the C6 straight resulting from H-minus particles with position −45 mm and angles 2, 4, 6, 7, 9 and 11 mrad. The 2 mrad trajectory intersects the carbon block. The 4 and 6 mrad trajectories intersect the C7 injection kicker. The 7, 9, and 11 mrad trajectories make it to the C7 dipole. These intersect the outer wall of the C7 vacuum chamber as shown in **Figure 16**. The dotted blue lines are drawn to indicate the slopes of the trajectories at the points of intersection; they intersect the backleg 12.9, 14.1 and 15.2 inches from the downstream end of the magnet iron.

6 Energy Loss in the Vacuum Chamber Wall

The Booster dipole vacuum chambers are made of 2 mm thick Inconel 650. (Inconel is an alloy consisting of nickel, chromium, and iron.) Because the H-minus trajectories in **Figures 8**, **10**, **14**, and **16** intersect the C7 chamber wall at small angles, the resulting proton trajectories in the Inconel are longer than the wall thickness. They range in length from 10 to 11 mm. Using energy loss data for protons in iron we can estimate the mean energy loss for these trajectories. The stopping-power for protons with 200 MeV kinetic energy in iron is [8]

$$-\frac{dE}{dx} = 3.153 \text{ MeV cm}^2/\text{g}. \tag{15}$$

The mean energy loss in 10 mm of iron, which has a density of 7.87 g/cm^3, is then 24.8 MeV. Thus the mean kinetic energy of protons emerging from the chamber wall is 175.2 MeV.

References

[1] C. J. Gardner, "Modeling Injection Trajectories on the Midplane of the C5 Dipole in Booster", C-A/AP Note 192, February, 2005.

[2] A. Luccio and M. Blaskiewicz, "AGS Booster Parameters (MAD Output)", Booster Technical Note 196, July 23, 1991.

[3] E. Bleser, "Booster Short Quadrupole Production Measurements", Booster Technical Note 174, September 12, 1990.

[4] E. Bleser, "Booster Long Quadrupole Production Measurements", Booster Technical Note 176, September 13, 1990.

[5] Ags Department Drawings D36-M-1916-4-1 and D36-M-2006sketch.

[6] S. Y. Zhang, "Booster Injection Kicker Magnet Test", AGS department Memorandum, February 14, 1991

[7] E. Bleser, "Geometry of the Booster Injection Region", Booster Technical Note 216, January 6, 1993

[8] M.J. Berger, J.S. Coursey, and M.A. Zucker, "Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions", http://physics.nist.gov/PhysRefData

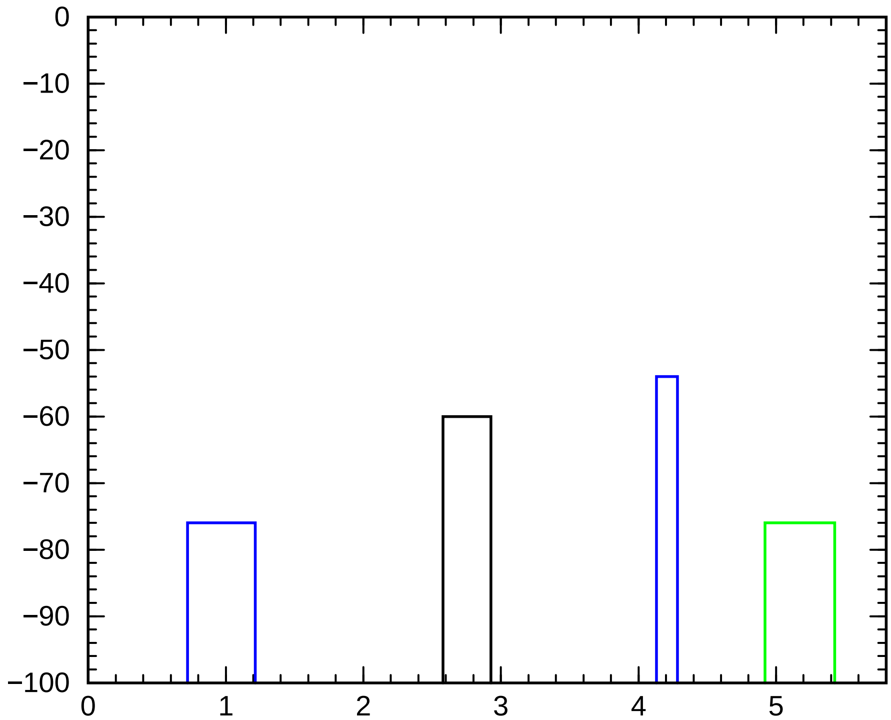

Figure 1: Layout of the C6 Straight Section. The horizontal axis gives the distance in meters along the straight starting at the H-minus stripping foil and proceeding downstream. The vertical axis gives the distance in mm from the centerline with negative numbers indicating distances toward the center of the Booster ring. The short blue and green rectangles show the location and apertures of quadrupoles QHC6 and QVC7. The black rectangle shows the location and aperture of the carbon block. The tall blue rectangle shows the location and aperture of the C7 injection kicker. The magnetic lengths of QHC6 and QVC6 are 0.493 and 0.504 m respectively. The length of the carbon block is 0.346 m. The length of the kicker is 0.152 m. The half-apertures of the quadrupoles, carbon block, and kicker are 76, 60, and 54 mm respectively. The distances from the foil to the upstream ends of QHC6, the carbon block, the kicker, and QVC7 are 0.723, 2.580, 4.132, and 4.921 m respectively. The distance from the downstream end of QVC7 to the C7 dipole entrance is 0.290 m.

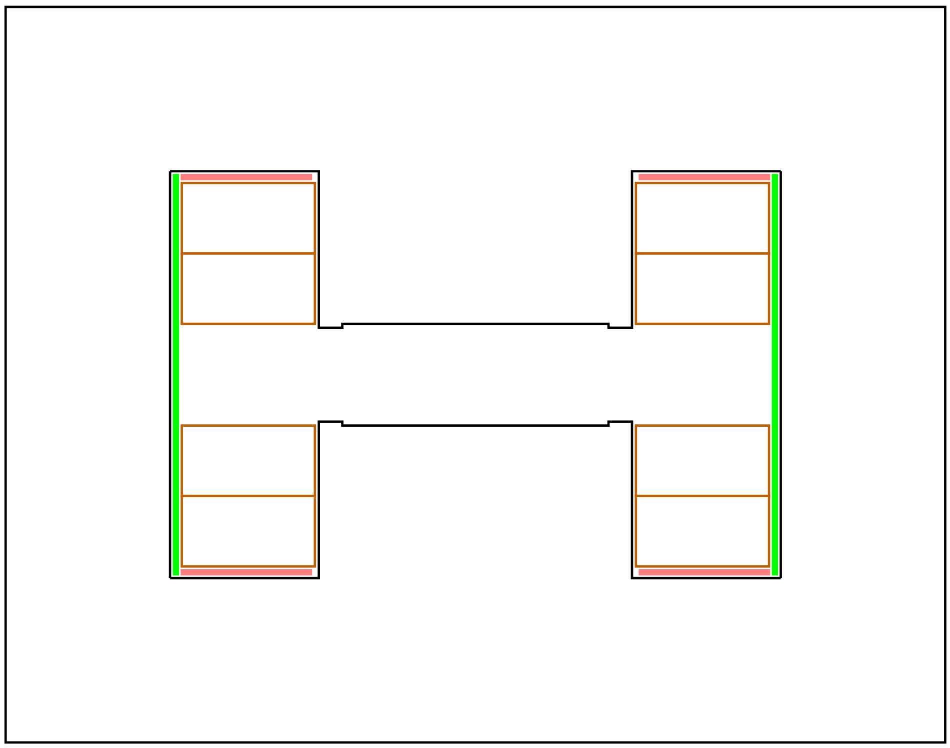

Figure 2: Scale drawing of Booster dipole lamination. The pole width is 254 mm. The distance from the pole to the backleg is 121 mm. The width of the backleg is 133 mm. The vertical gap between the poles is 82.55 mm. The shims on the poles are 19 mm wide and the vertical gap between them is 77.75 mm. The height of the lamination is 596.55 mm and the height of the H-shaped opening is 330.55 mm. The brown rectangles indicate magnet coils. G10 insulating strips are indicated by the thin green rectangles. The thin pink rectangles indicate trim windings.

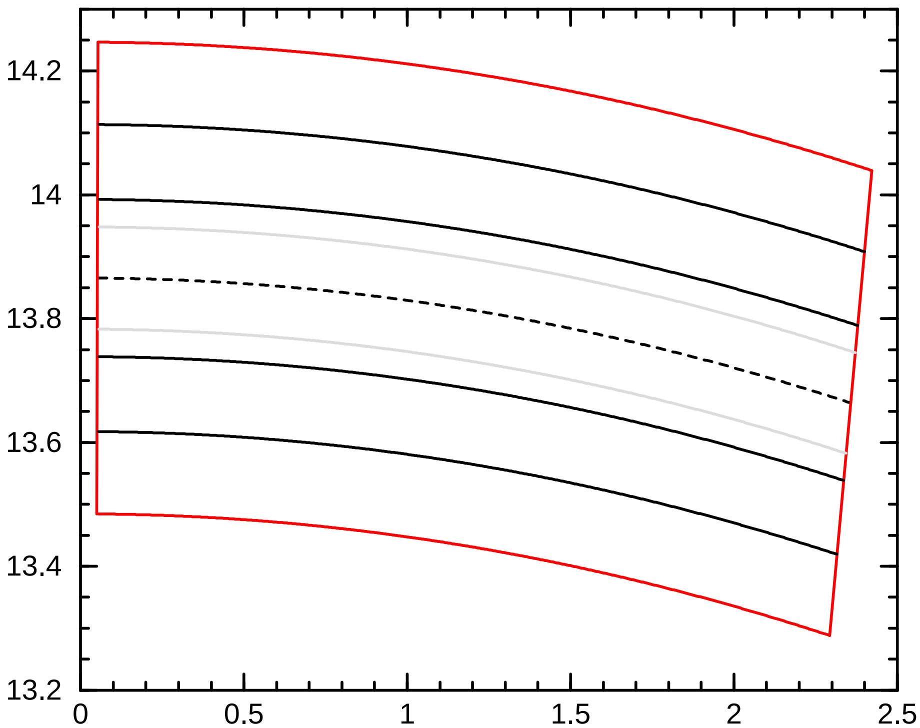

Figure 3: Top view of C7 Dipole. Beam direction is from left to right. The horizontal and vertical axes give the x and y coordinates on the magnet midplane. The units are meters. The radial and azimuthal coordinates are defined by $x = r \sin\theta$ and $y = r \cos\theta$. The line $x = 0$ marks the entrance to the magnet. The magnetic length is $L = 2.42$ m and the bend angle is $\theta_B = 2\pi/36$. The dotted black curve is the nominal trajectory of circulating beam on the midplane; it is a circular arc with radius-of-curvature $\rho_0 = L/\theta_B = 13.8656$ m. The center of curvature is the point $x = 0$, $y = 0$. The centerline of the C6 straight is perpendicular to the magnet entrance and passes through the point $x = 0$, $y = \rho_0$. The red lines and curves show the perimeter of the magnet iron. The left and right edges of the magnet iron lie on the lines $\theta = (\theta_B \mp \theta_2)/2$ where $\theta_2 = 9.5763$ degrees as given by Bleser [7]. The gray curves are the projections of the walls of the vacuum chamber onto the midplane; these are 82.55 mm from the magnet centerline. The black curves are the projections of the pole and backleg boundaries. Those closest to the centerline mark the pole boundaries; they are 127 mm from the centerline. The outer black curves mark the backleg boundaries; these are 248 mm from the centerline.

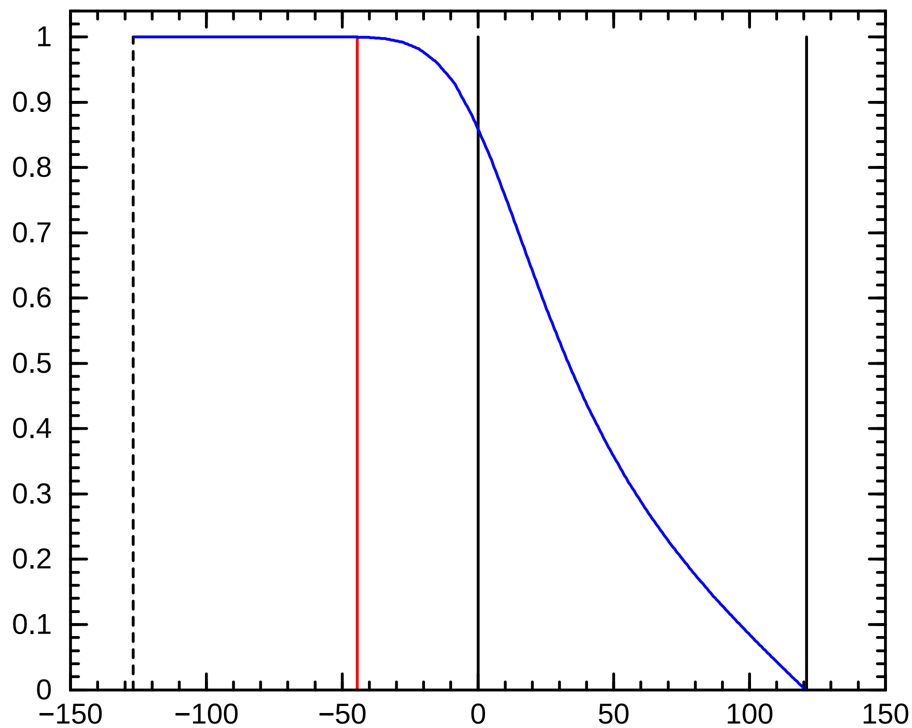

Figure 4: Magnetic field on the dipole midplane obtained by Wuzheng Meng using the Opera code. The blue curve gives the field in units of the field B_c at the center of the magnet. The horizontal axis gives the radial distance from the projection of the pole edge on the midplane. The units are mm. The black lines at 0 and 121 mm mark the pole and backleg edges. The dotted line at -127 mm marks the center of the magnet; the red line at -44.45 mm marks the vacuum chamber wall. Numerical integration of the equations of motion using this field gives particle trajectories on the midplane. This was done in Ref. [1] to obtain the H-minus trajectories on the C5 dipole midplane. In this note we consider trajectories that are on the midplane but inside the C7 vacuum chamber. Here the field is essentially constant and the trajectory is simply a circular arc with radius-of-curvature $\rho_0 = L/\theta_B = 13.8656$ m.

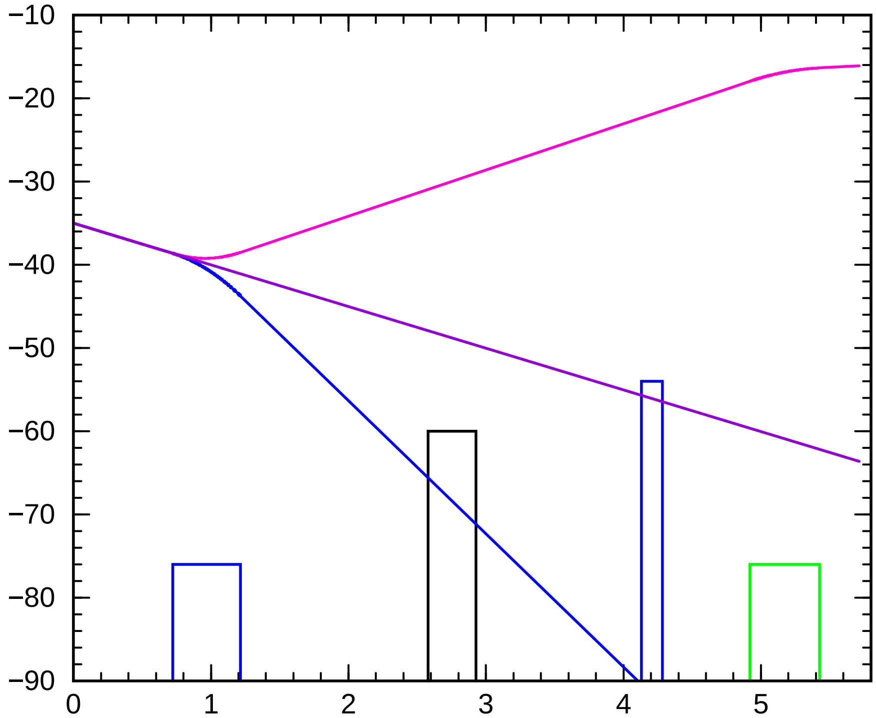

Figure 5: Trajectories in the C6 straight resulting from H-minus particles with position −35 mm and angle −5 mrad at the stripping foil. This is near the center of the foil. The horizontal axis gives the distance in meters along the centerline of the straight starting at the foil and proceeding downstream. The vertical axis gives the distance in mm from the centerline with negative numbers indicating distances toward the center of the Booster ring. The short blue and green rectangles show the location and apertures of quadrupoles QHC6 and QVC7. The black rectangle shows the location and aperture of the carbon block. The tall blue rectangle shows the location and aperture of the C7 injection kicker. The solid blue, violet, and magenta curves are H-minus, H-zero, and H-plus (proton) trajectories respectively. Note that the H-minus and H-zero particles are stopped by the carbon block and C7 kicker respectively; only the H-plus particles make it to the C7 dipole.

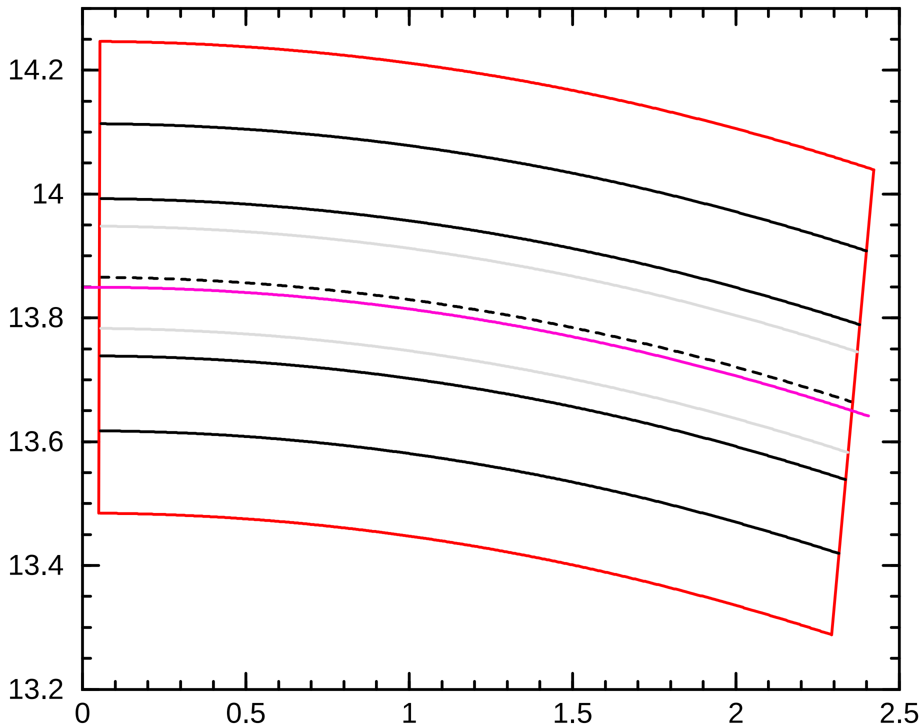

Figure 6: H-plus trajectory (solid magenta curve) in the C7 dipole resulting from H-minus particles with position −35 mm and angle −5 mrad at the foil.

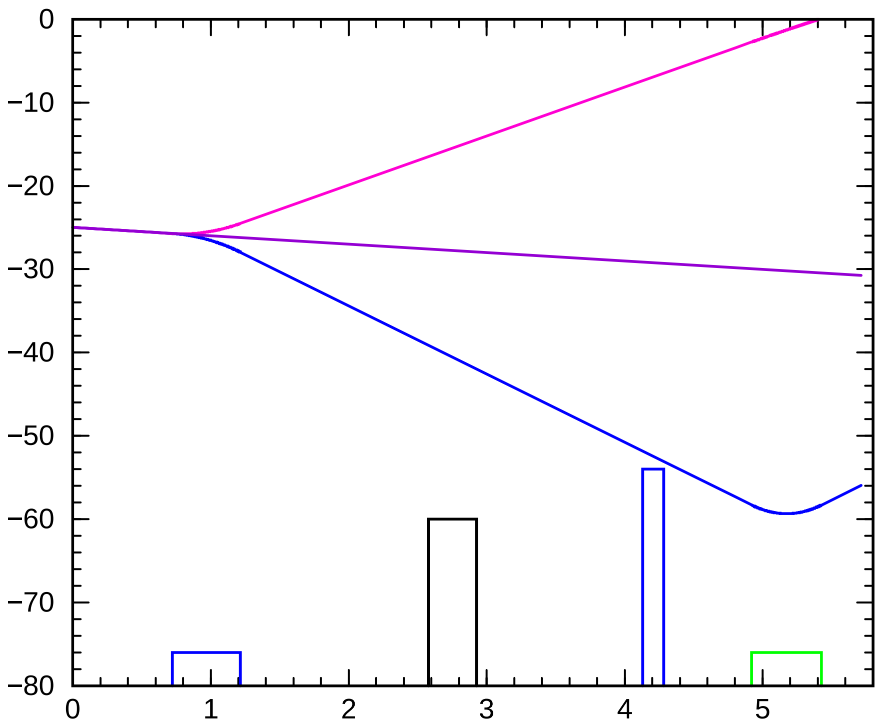

Figure 7: Trajectories in the C6 straight resulting from H-minus particles with position −25 mm and angle −1 mrad at the stripping foil edge. Solid blue, violet, and magenta lines are H-minus, H-zero, and H-plus trajectories respectively. In this case all three trajectories make it to the C7 dipole.

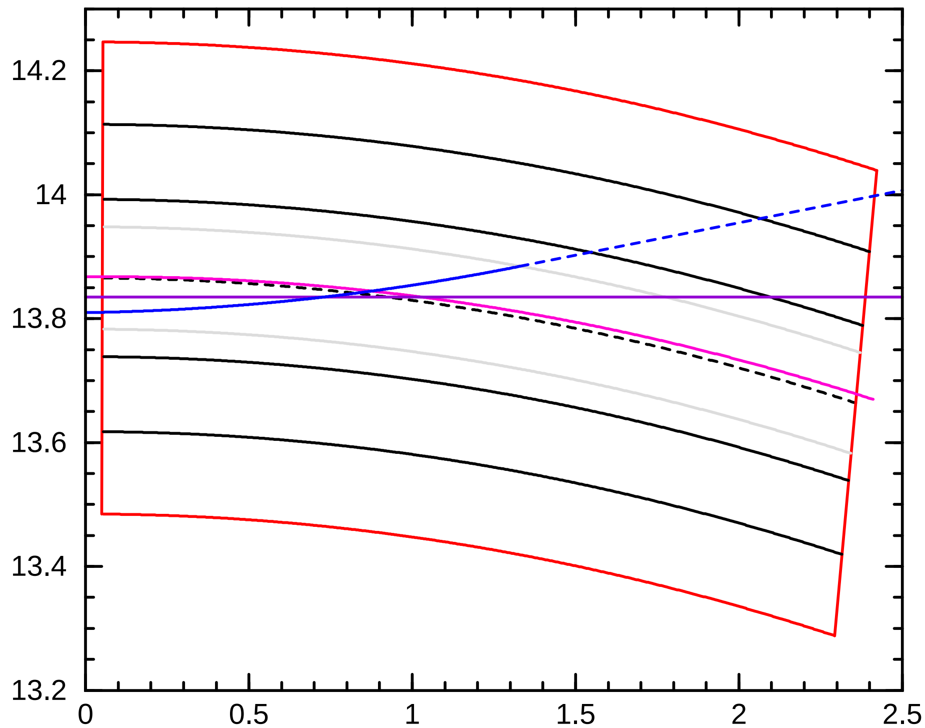

Figure 8: Trajectories in the C7 Dipole resulting from H-minus particles with position −25 mm and angle −1 mrad at foil. Solid blue, violet, and magenta lines are H-minus, H-zero, and H-plus trajectories respectively. The H-minus and H-zero trajectories intersect the outer wall of the vacuum chamber. The dotted blue line is drawn to indicate the slope of the H-minus trajectory at the point of intersection. As the H-minus and H-zero particles pass through the chamber wall they are stripped of their electrons, becoming protons. Since the protons are still in the magnetic field of the dipole, they curve to the right veering away from the straight dotted blue and violet lines. Note that the dotted blue line intersects the backleg 11.2 inches upstream of the downstream end of the magnet iron. This is close to the point where the conductor insulation failure occured in the C7 dipole in June 1998. (A very dark area was seen on the G10 strip that runs along the backleg; it extended from 3 to 19 inches from the downstream end of the magnet iron. The center of this area was 11 inches from the end of the magnet iron. The insulation failure occurred at the location of the jack 13 inches from the downstream end of the magnet iron.) The H-zero trajectory line does not intersect the backleg.

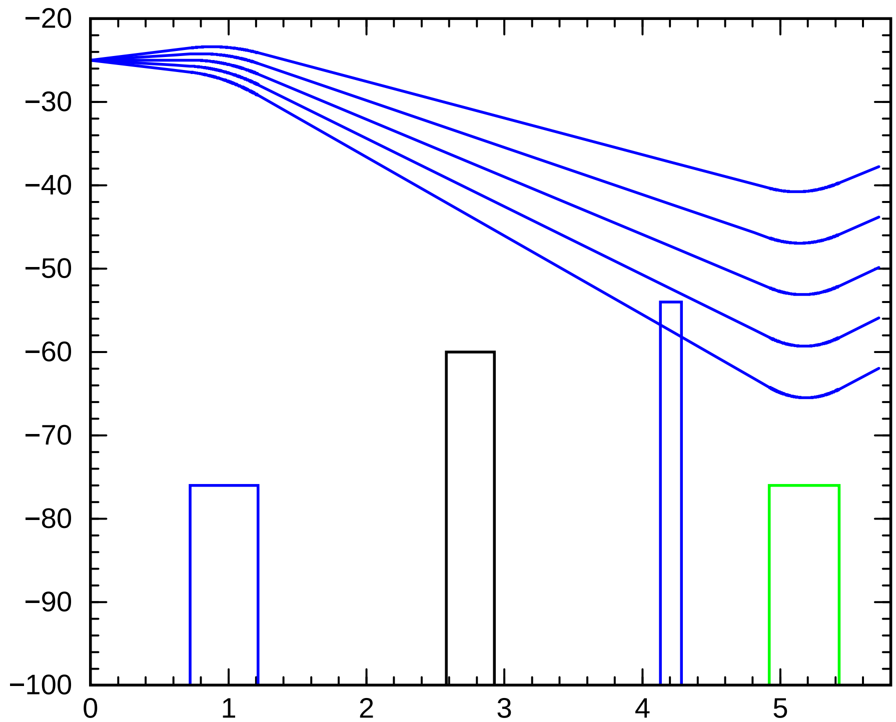

Figure 9: H-minus Trajectories in C6 Straight. Position at foil is −25 mm; angles are −2, −1, 0, 1 and 2 mrad. The −2 mrad trajectory intersects the C7 injection kicker; the other trajectories make it to the C7 dipole.

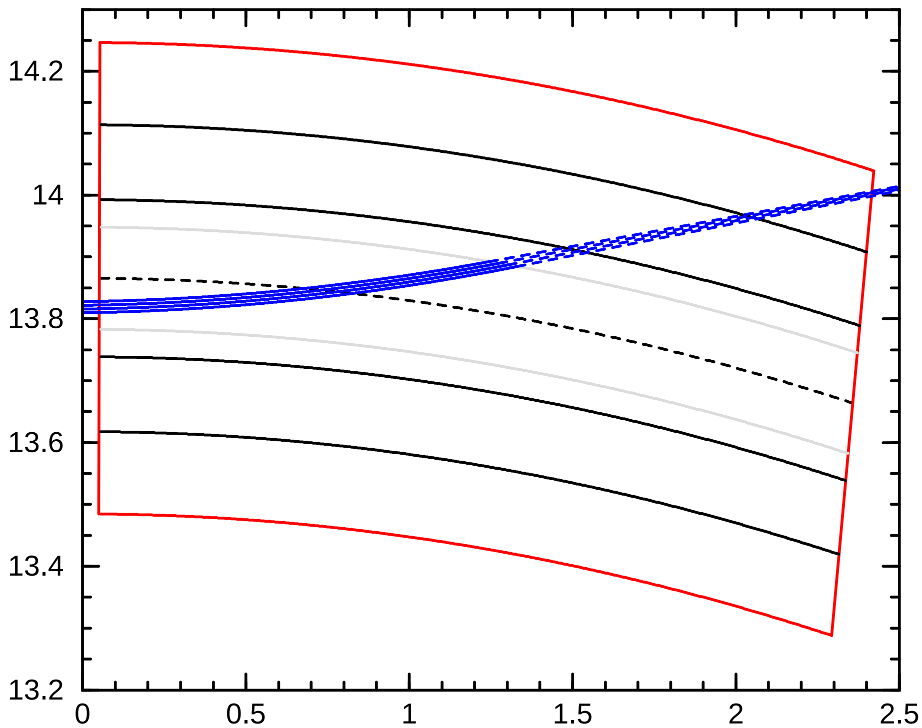

Figure 10: H-minus Trajectories in C7 Dipole resulting from H-minus particles with position −25 mm and angles −1, 0, 1, and 2 mrad at the stripping foil. The trajectories intersect the outer wall of the vacuum chamber. The dotted blue lines are drawn to indicate the slopes of the trajectories at the points of intersection; they intersect the backleg 11.2, 11.8, 12.4, and 13.0 inches from the downstream end of the magnet iron.

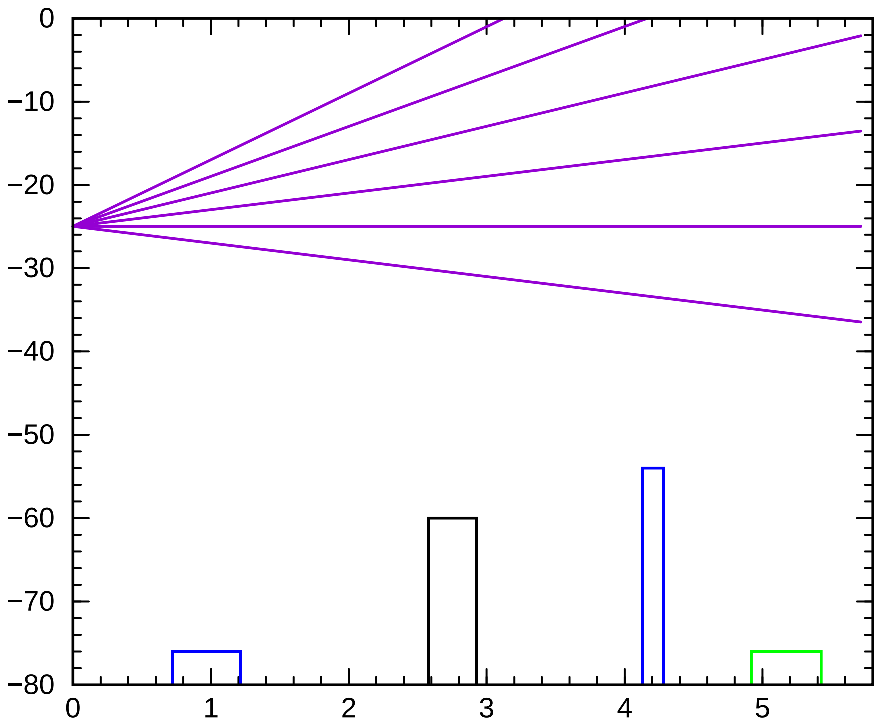

Figure 11: H-zero Trajectories in C6 Straight. The position at the foil is −25 mm; the angles are −2, 0, 2, 4, 6 and 8 mrad respectively. All six trajectories make it to the C7 dipole.

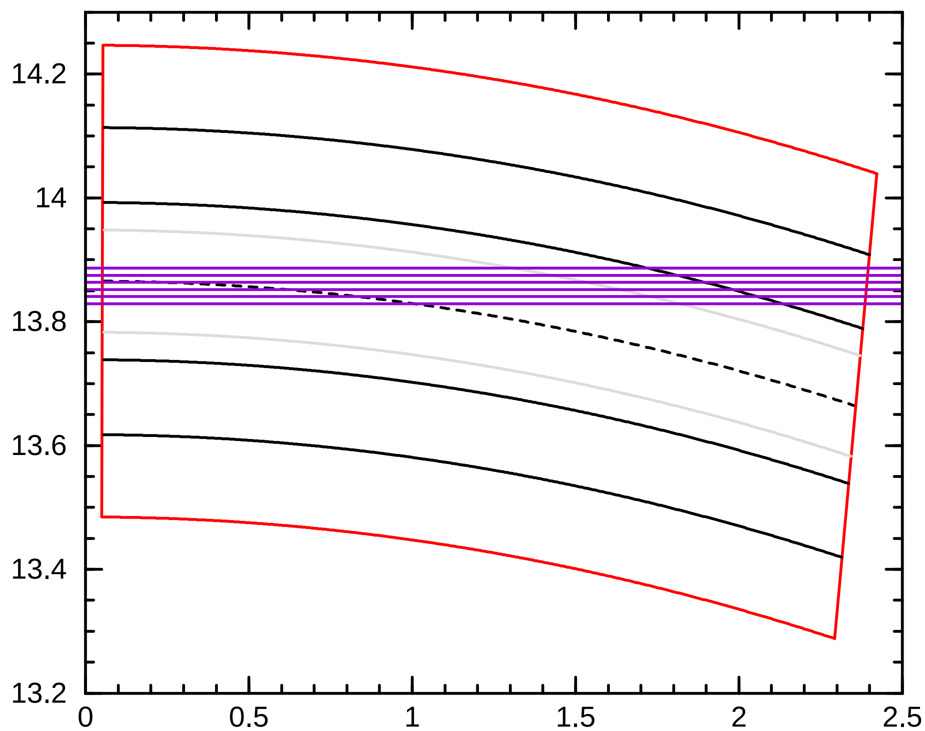

Figure 12: H-zero Trajectories in C7 Dipole resulting from H-minus particles with position −25 mm and angles −2, 0, 2, 4, 6 and 8 mrad at the stripping foil. All of the trajectories intersect the vacuum chamber wall. None of the lines intersect the backleg.

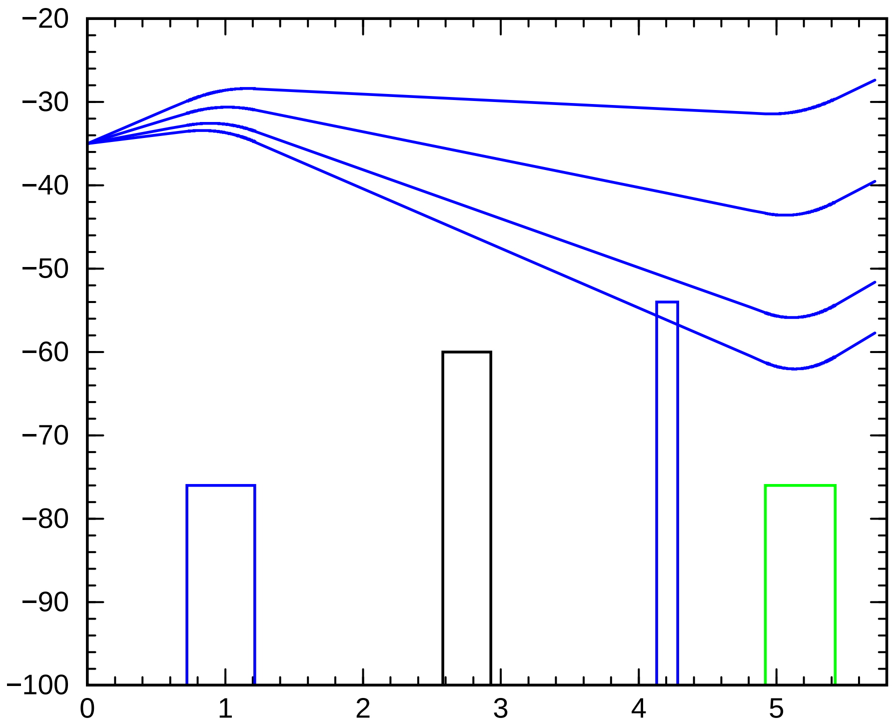

Figure 13: H-minus Trajectories in C6 Straight. Position at foil is −35 mm; angles are 2, 3, 5, and 7 mrad. The 2 mrad trajectory intersects the C7 injection kicker; the others make it to the C7 dipole.

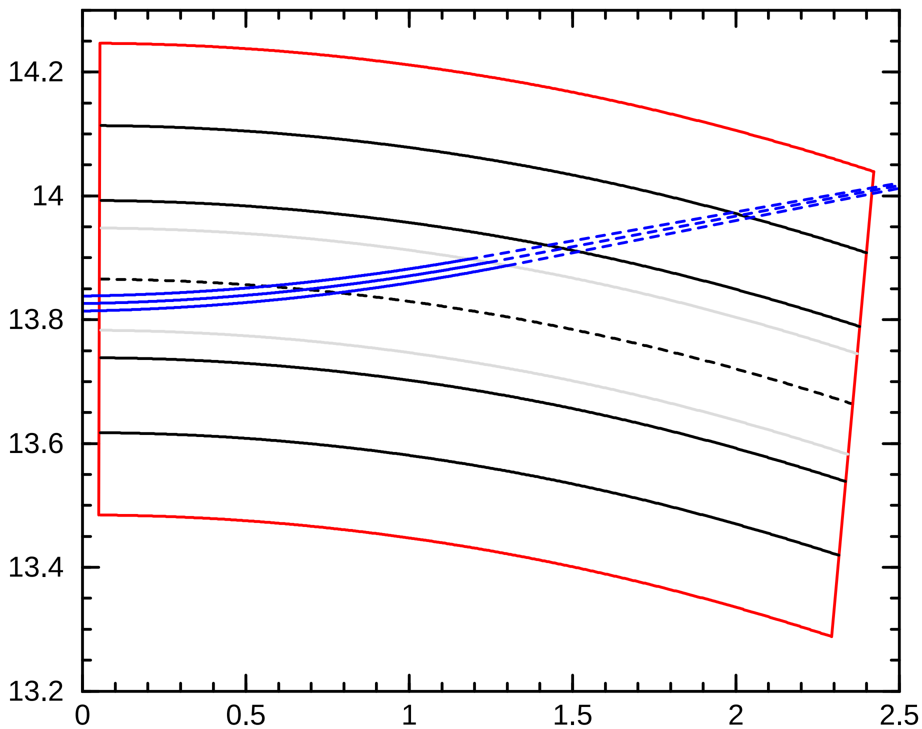

Figure 14: H-minus Trajectories in C7 Dipole resulting from H-minus particles with position −35 mm and angles 3, 5, and 7 mrad at the stripping foil. Here the dotted blue lines intersect the backleg 12.1, 13.2, and 14.4 inches from the downstream end of the magnet iron.

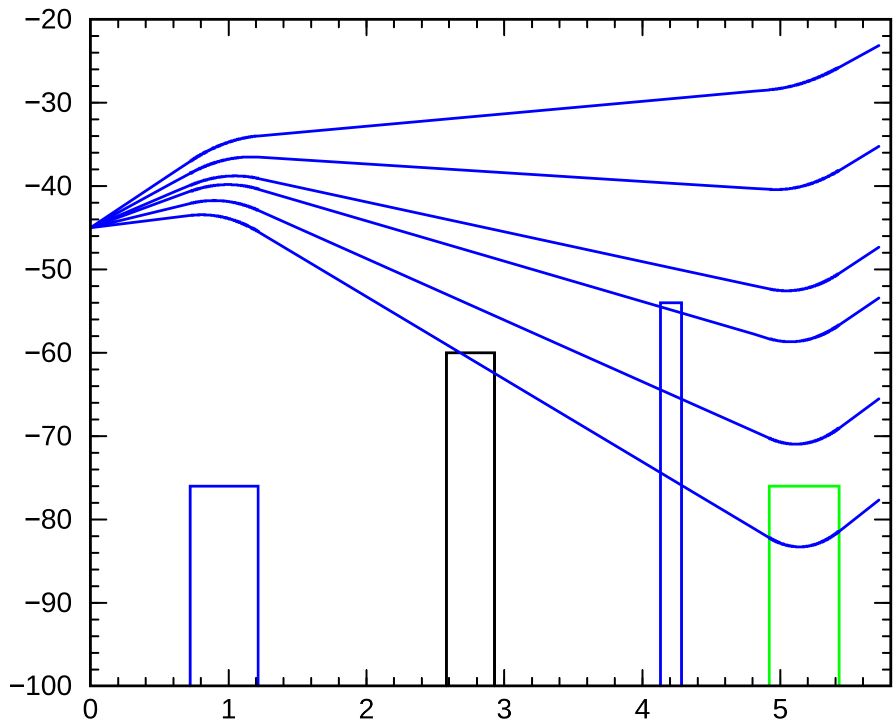

Figure 15: H-minus Trajectories in C6 Straight. Position at foil is -45 mm; angles are 2, 4, 6, 7, 9 and 11 mrad. The 2 mrad trajectory intersects the carbon block. The 4 and 6 mrad trajectories intersect the C7 injection kicker. The 7, 9, and 11 mrad trajectories make it to the C7 dipole.

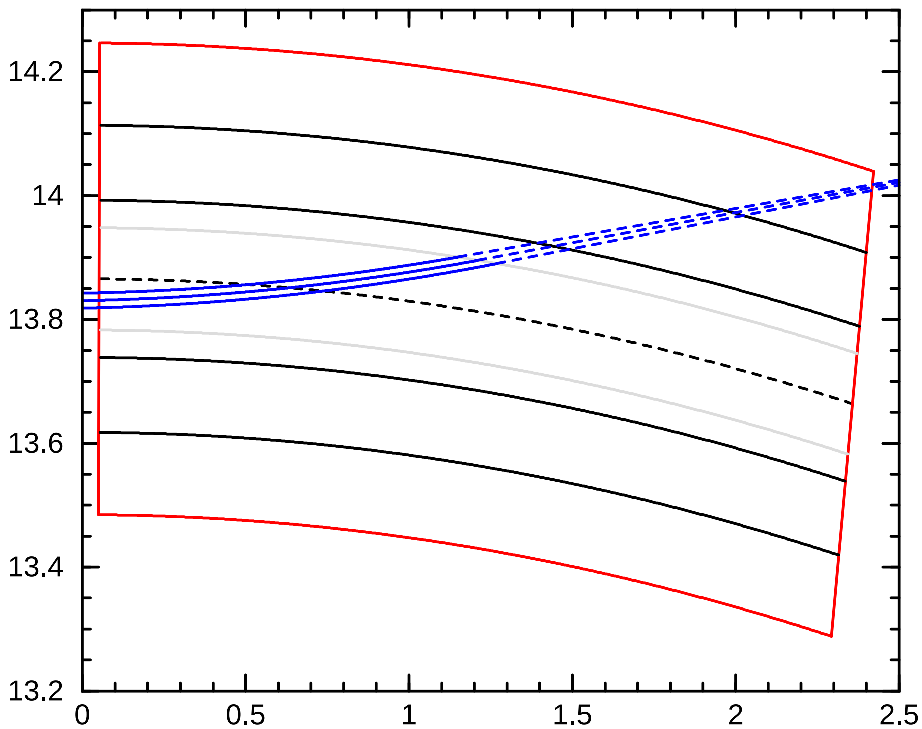

Figure 16: H-minus Trajectories in C7 Dipole resulting from H-minus particles with position −45 mm and angles 7, 9, and 11 mrad at the stripping foil. Here the dotted blue lines intersect the backleg 12.9, 14.1, and 15.2 inches from the downstream end of the magnet iron.