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Optics Upgrade for Switchyard

Thomas R. Kobilarcik

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Abstract

An upgrade of the Switchyard optics is proposed. This upgrade extends the P3 (old Main Ring) lattice through enclosure C. The septa for the 3-way Meson Area split is moved from enclosure F1 to enclosure M01. The functionality of the Meson Target Train is preserved. Finally, for the purpose of demonstrating that the resulting split can be transported, a straw-man lattice is proposed for enclosure M02 and beyond.

1 Introduction.

The present optics for Switchyard were designed to preserve the possibility of 800 GeV beam to the Proton area and 120 GeV beam to the Meson, Neutrino, and Muon areas. The result was a set of point-to-point optics which, as per the design constraints, was able to transport low intensity beam to the Meson area.[1]

The constraints have changed. There is no longer need for 800 GeV beam in the fixed target area; there are no users in the Neutrino or Muon areas; high intensity beam is needed in the Meson area.

2 Proposed Lattice

The proposed lattice, along with geographic boundaries, is shown in Figure 1. The P3 lattice is extended to the end of Enclosure B. Doublets exist at the downstream and upstream ends of Enclosures B and C, forming a low-beta insert to transport the beam through the berm-pipe. The lattice is continued through Enclosure C, which ends in a triplet.

A 60 m drift separates Enclosures C and F1. Enclosures F1, F2, F2, and M01 are then separated by approximately 150 m (500 ft.). Doublets are placed in F2 and F3; F1 requires two doublets.

In this design, the P1 and P2 lines are ignored, and one assumes that the beam is exactly matched into the P3 line. It will be shown later that this assumption is probably not valid, but that the design is robust enough to compensate for the mismatch.

[1] "Switchyard in the Main Injector Era Conceptual Design Report" FERMILAB-TM-2014.

One notes that beta function becomes very large through Enclosure M01. This is addressed in the next section.

A straw-man lattice is shown from Enclosure M02 onward. Two doublets are located at the upstream end of M02 in order to capture the beam from the three-way split and match it into the lattice.

3 The Three-Way Split

Presently, the three-way split is initiated in Enclosure F1, where the beam is split vertically by a set of electrostatic septa (Switchyard style septa). The beam then drifts to Enclosure M01, where the beam is separated horizontally by a set of magnetic septa (three-way Lambertson magnets). The beam then drifts through the Meson Target Train, and into Enclosure M02. No optics exist between the F1 electrostatic septa and M02 – a distance of approximately 580 m.

The new split moves the electrostatic septa into the upstream end of Enclosure M01, and relocates the magnetic septa to the downstream end of M01. There is a 61 m drift between the electrostatic and magnet septa, which provides adequate vertical separation. Horizontal separation is provided by the 23 m drift through the Meson Target Train. The optics in F3 shape the beam for the three-way split.

The present separation between the MW/ME and MC beamlines at the downstream end of the Meson Target Train is 12.513 in., and the separation at the upstream face of the collimator is 11.624 in.[2] Moving the horizontal bend point to the end of M01, and matching the separation at the downstream end of the collimator, would require the upstream separation to be 10.134 in. – a difference of 1.5 in. This mismatch is too large – the Meson Target Train must be pulled, and the collimator re-worked.

The drift between the F3 and M02 optics is sizable, which accounts for the growth in beta. This could be reduced by adding optics at the upstream end of M01, but this would require the splitting station to move further downstream, and preclude the preservation of the Meson Target Train.

4 Beam Size and Apertures

Figure 2 shows horizontal and vertical apertures and 95% beam envelope. The horizontal envelope and apertures are shown in the positive direction, while the vertical envelope and apertures are shown in the negative direction.

The top graph has a maximum scale of 40 mm – slightly larger than the 38.5 mm half-aperture of a 3Q120 quadrupole. By inspection, one sees that all apertures are easily cleared. The middle graph has a finer scale (20 mm) and also indicates geographic boundaries.

[2]Refer to "Meson TeV II Target Rain Assembly" Drawing 1214-ME-174072.

Finally, the bottom graph shows the M01/M02 regions – the areas where the beam is closest to any apertures. The 10 mm vertical apertures at 2050 m represent the electrostatic septa. The 15 mm vertical apertures at 2125 m represent the magnetic septa. We see that even in these regions, the beam easily clears the apertures. We also note that in these calculations, the entire beam is sent through the smallest apertures.

Figure 3 is a more analytical approach to the same material. The graphs show horizontal and vertical aperture clearance. The aperture size is divided by the beam size (calculated using the 95% emittance).

$$FOM = \frac{aperture - beam(95\%)}{2 \times beam(1\sigma)}$$

The smallest value in the lattice region is about 2.5 (horizontal, at approximately 1100 m). This is the location of lambertson magnet which switches beam from the Switchyard Dump to the Meson beamline. This restriction can be eliminated by replacing the two-way lambertson with an EPB dipole.

In the region of the splitting stations, the minimum figure-of-merit is 2, indicating that the clearance to the aperture is equal to the beam size.

For completeness, the existing P1 through P3 lattice was modeled[3], along with existing beam conditions[4]. The results are shown in Figure 4. This model indicates that there may be a slight mismatch into the P3 line, which has not been corrected (i.e., in this calculation the mismatch was propagated though the beamline); however, the final triplet in Enclosure C, and the F1 through F3 doublets have bean adjusted on the order of ten percent. The result is similar to that obtained using an idealized beam and optics.

5 Magnet Specs

The proposed beamline has four major sections: - the extension of the P3 line into Enclose B. - the continuation of the lattice into Enclosure C. - transport from Enclosure C, through the F1/F2/F3 enclosures, to the M01 splitting station. - the M01 splitting station (which has already been described).

The P3 extension consists of B2 dipoles and long Main Ring quadrupoles (IQ84 quads). Each focusing quadrupole is preceded by a Switchyard style horizontal BPM, and followed by a Main Injector style horizontal trim (IDH trim). Each defocussing quadrupole is preceded by a Switchyard style vertical BPM, and followed by a Main Injector style vertical trim (IDV trim).

The main elements of the Enclosure C continuation are EPB dipoles and 3Q120 quadrupoles. The trim/corrector scheme is as per the P3 line continuation.

3Q120 quadrupoles are used in the F1 Enclosure, and existing correctors are re-used. Due to space constraints, 3Q60 quadrupoles are used in the F2 and

[3] Private communication, Dave Johnson

[4] Private communication, Ming-Jen Yang

F3 Enclosures, and existing correctors are re-used. When new correctors are needed, IDH or IDV are chosen (although this is not essential).

Matching sections have a pair of BPMs before the optics, and are followed by a pair of correctors.

Table 1 lists specifications for the quadrupole magnets. Table 2 lists specifications for the dipoles. Table 4 lists the center of each dipole and quadrupole along the beamline (the septa and lamberstons are shown for completeness).

6 Conclusion

It is possible to extend the optics of the P3 lattice through the end of Enclosure C. Due to the long drift spaces between Enclosure C, the F Enclosures, and M01, the lattice cannot be extended in that region – one must rely on point-to-point optics. This is the major weakness in any redesign of the Meson Area, and can only be addressed through extensive civil construction. However, the existing geometry may be adequate to allow clean transport of beam to M01.

The splitting station may be relocated to M01. However, this would involve reworking (or at least removing) the Meson Target Train. The decision to remove or rework the train will not affect this proposed optics, but will impact operations.

New optics downstream of the Meson Target Train should be developed based on the needs of the fixed target program.

Magnet	Function	Type	Station [m]
QF48	QUAD	IQ84	743.587
HF481	RBEND	MRB	749.797
QF49	QUAD	IQ84	773.330
QA11	QUAD	IQ84	803.073
HA111	RBEND	MRB	809.284
HA112	RBEND	MRB	815.659
QA12	QUAD	IQ84	832.817
QA13	QUAD	IQ84	862.560
HA133	RBEND	MRB	881.521
HA134	RBEND	MRB	887.897
QB11	QUAD	IQ84	892.304
QB12	QUAD	IQ84	922.047
QB13	QUAD	IQ84	951.791
VB131	RBEND	MRB	958.001
VB134	RBEND	MRB	977.127
QB14	QUAD	IQ84	981.534
QB15	QUAD	IQ84	1011.277

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Magnet	Function	Type	Station
QB21	QUAD	3Q120	1040.386
QB22	QUAD	3Q120	1045.054
QC11	QUAD	3Q120	1091.554
QC12	QUAD	3Q120	1096.221
HC131	RBEND	2WLAM	1111.520
HC132	RBEND	2WLAM	1114.873
VC131	RBEND	EPBB	1120.862
QC21	QUAD	3Q120	1125.482
QC22	QUAD	3Q120	1155.226
HC221	RBEND	EPB	1161.323
HC222	RBEND	EPB	1164.676
HC223	RBEND	EPB	1168.029
HC224	RBEND	EPB	1171.381
HC225	RBEND	EPB	1174.734
HC226	RBEND	EPB	1178.087
HC227	RBEND	EPB	1181.440
QC23	QUAD	3Q120	1184.969
HC231	RBEND	EPB	1191.498
HC232	RBEND	EPB	1194.851
HC233	RBEND	EPB	1198.204
HC234	RBEND	EPB	1201.557
HC235	RBEND	EPB	1204.909
QC24	QUAD	3Q120	1214.712
QC25	QUAD	3Q120	1244.456
QC26	QUAD	3Q120	1274.199
QC27	QUAD	3Q120	1303.943
QC28	QUAD	3Q120	1333.686
HC281	RBEND	EPB	1342.553
HC282	RBEND	EPB	1345.906
HC283	RBEND	EPB	1349.258
HC284	RBEND	EPB	1352.611
HC285	RBEND	EPB	1355.964
QC29	QUAD	3Q120	1363.429
HC291	RBEND	EPB	1369.375
HC292	RBEND	EPB	1372.728
HC293	RBEND	EPB	1376.081
HC294	RBEND	EPB	1379.434
HC295	RBEND	EPB	1382.787
HC296	RBEND	EPB	1386.139
HC297	RBEND	EPB	1389.492

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Magnet	Function	Type	Station
QC2A	QUAD	3Q120	1393.173
VC2A1	RBEND	EPB	1416.211
VC2A2	RBEND	EPB	1419.563
QC2B	QUAD	3Q120	1422.916
QC31	QUAD	3Q120	1442.450
QC32	QUAD	3Q120	1446.803
QC33	QUAD	3Q120	1451.155
V211	RBEND	EPB	1516.889
Q211	QUAD	3Q120	1520.394
H211	RBEND	EPB	1525.728
Q212	QUAD	3Q120	1529.081
Q213	QUAD	3Q120	1549.663
Q214	QUAD	3Q120	1559.016
Q221	QUAD	3Q60	1717.861
Q222	QUAD	3Q60	1719.690
M00U-1	RBEND	CRD	1872.489
M00U-2	RBEND	CRD	1874.104
M00U-3	RBEND	CRD	1875.720
Q231	QUAD	3Q60	1880.910
Q232	QUAD	3Q60	1882.739
M01D-1	RBEND	B1M	2031.981
M01D-2	RBEND	B1M	2035.333
FSEP-1	SEPTUM	FTSEP	2045.715
FSEP-2	SEPTUM	FTSEP	2049.715
FLAM-1	HKICK	3WLAM	2113.842
FLAM-2	HKICK	3WLAM	2117.195
FLAM-3	HKICK	3WLAM	2120.548
M02Q1	QUAD	3Q120	2150.059
M02Q2	QUAD	3Q120	2160.489
M02Q3	QUAD	3Q120	2181.611
M02Q4	QUAD	3Q120	2191.888
M03Q1	QUAD	3Q120	2231.083
M03Q2	QUAD	3Q120	2270.279
M03Q3	QUAD	3Q120	2309.474
M03Q4	QUAD	3Q120	2348.669
M03Q5	QUAD	3Q120	2387.864
M03Q6	QUAD	3Q120	2427.059
M03Q7	QUAD	3Q120	2466.255
M03Q8	QUAD	3Q120	2505.450

Table 4: Center points of magnetic elements.

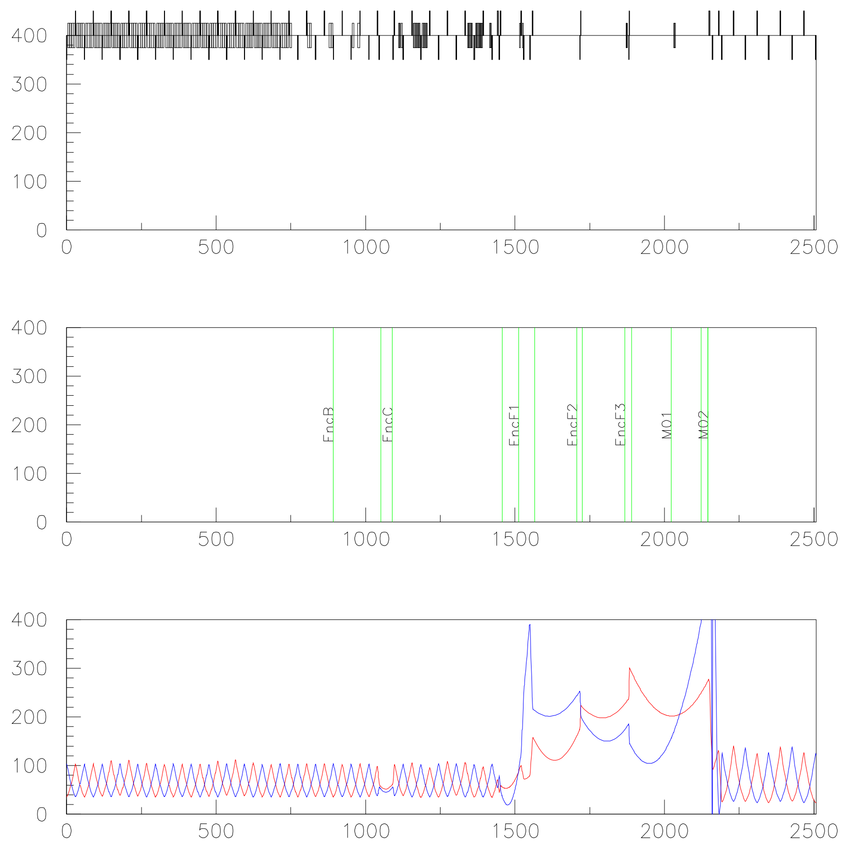

Figure 1: Optical elements, lattice functions, and geographic boundaries of the proposed optics upgrade.

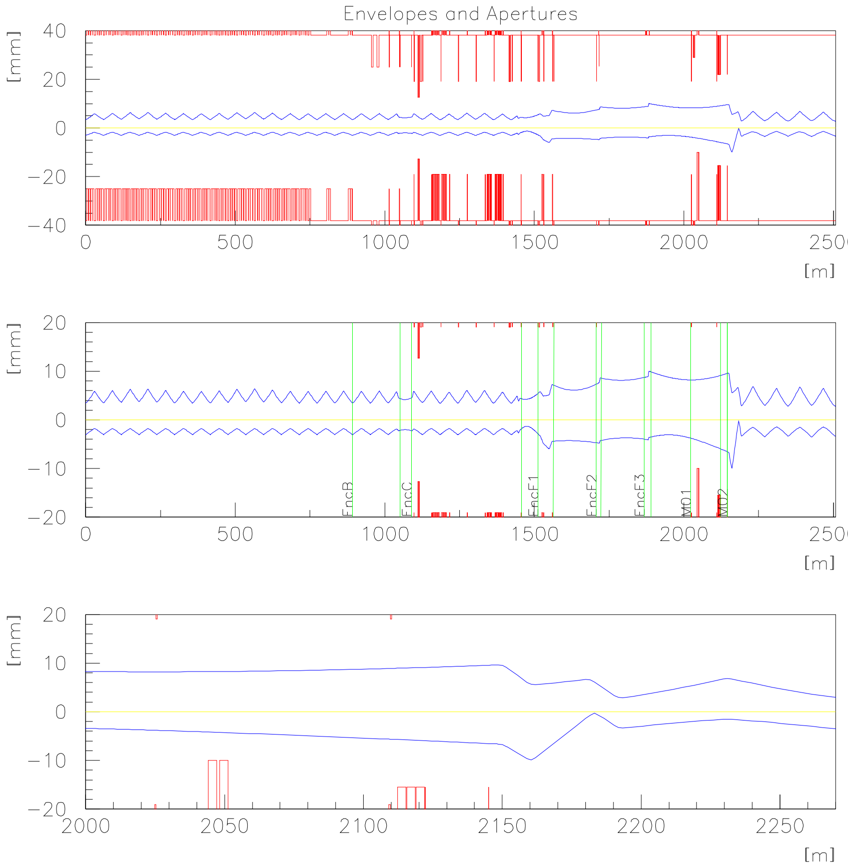

Figure 2: Apertures and beam envelopes. Envelope is for 95% emittance. Horizontal envelope and apertures are shown in the positive direction. The top plot shows the beam from MI extraction into Enclosure M03. The middle plot shows the beam in Switchyard (Tranfer Hall to M01). The bottom plot shows the beam in the new M01 splitting station.

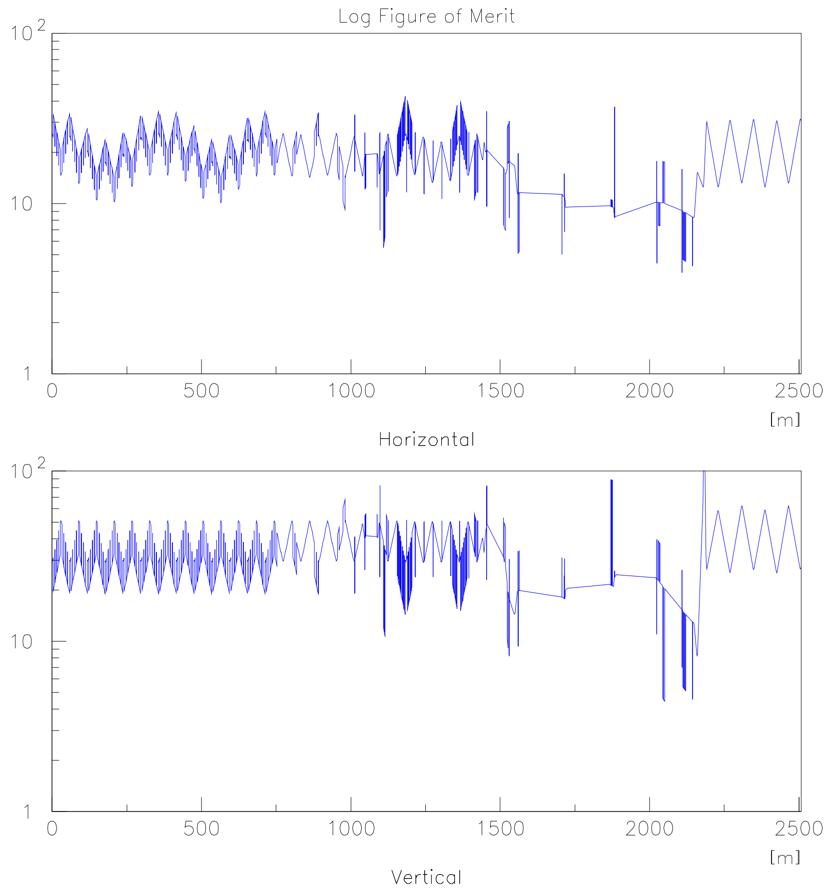

Figure 3: Horizontal (top) and vertical figure-of-merit. The figure-of-merit is the separation between the aperture and beam envelope (95% emittance) divided by the beam width (1σ emittance). Note the log scale.

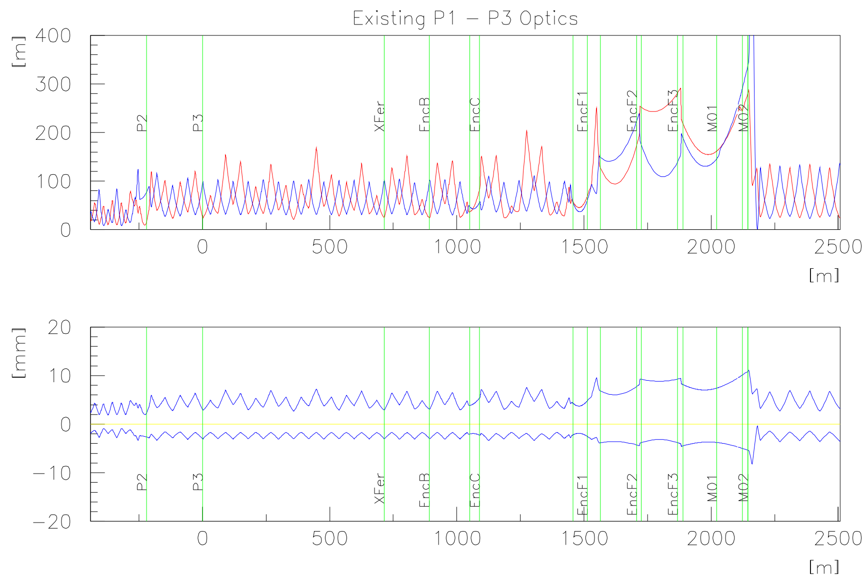

Figure 4: Beta functions (top) and 95% beam envelope (bottom) using existing beam and P1 though P3 lattice.

Magnet	Type	K1 $[m^{-2}]$	gradient [T/m]	current [amp]	comment
QF4[7-9]	IQ84	0.01581	6.32818	-.-	P3 lattice quads
QA1[1-3]	IQ84	0.01581	6.32818	-.-	P3 lattice quads
QB1[1-5]	IQ84	0.01581	6.32818	-.-	P3 lattice quads
QB21	3Q120	+0.02270	9.08601	48.9	matching doublet
QB22	3Q120	-0.01830	7.32484	39.4	matching doublet
QC11	3Q120	-0.01830	7.32484	39.4	matching doublet
QC12	3Q120	+0.02270	9.08601	48.9	matching doublet
QC2[1-B]	3Q120	0.01119	4.47896	24.1	Enc C lattice quads
QC31	3Q120	+0.02654	10.62302	57.2	transport triplet
QC32	3Q120	-0.03703	14.82180	79.8	transport triplet
QC33	3Q120	+0.01469	5.87989	31.7	transport triplet
Q210	3Q120	+0.00948	3.79451	20.4	first F1 doublet
Q211	3Q120	-0.00712	2.84988	15.3	first F1 doublet
Q212	3Q120	-0.01295	5.18343	27.9	second F1 doublet
Q213	3Q120	+0.01204	4.81919	26.0	second F1 doublet
Q221	3Q60	-0.04146	16.59497	89.4	F2 doublet
Q222	3Q60	+0.04174	16.70705	90.0	F2 doublet
Q231	3Q60	-0.04315	17.27142	93.0	F3 doublet
Q232	3Q60	+0.04231	16.93520	91.2	F3 doublet
M02Q1	3Q120	+0.01482	5.93192	31.9	M02 matching optics
M02Q2	3Q120	-0.02633	10.53897	56.8	M02 matching optics
M02Q3	3Q120	+0.02284	9.14205	49.2	M02 matching optics
M02Q4	3Q120	-0.04687	18.76041	101.0	M02 matching optics
M03Q	3Q120	0.01175	4.70311	25.3	lattice

Table 1: Quadrupoles used in the proposed upgrade. Polarities are indicated by the K1 value. The P3 extension should be run off the existing P3 bus. Quadrupoles in M02 and beyond are shown only as proof-of-principle – the exact design will depend on users. Quadrupoles running over 80 amps should be ramped.

Magnet	Type	θ [$mradian$]	field [T]	current [amp]	comment
HF481	B2	2.35	0.15495	401.5	parallel to A0
HA11[1-2]	B2	7.84	0.51694	1337.6	horizontal dogleg
HA13[3-4]	B2	-7.84	0.51694	1337.6	horizontal dogleg
VB131	B2	8.89	0.58618	1439.7	vertical dogleg
VB134	B2	-8.89	0.58618	1439.7	vertical dogleg
HC13[1-2]	EPB	-4.01	0.52661	593.0	Meson/Neutrino split
VC131	EPB	-5.64	0.74067	833.5	vertical height
HC22[1-7]	EPB	-6.86	0.90088	1013.4	arc1, angle 1
HC23[1-5]	EPB	-5.76	0.75643	852.0	arc1, angle 2
HC28[1-5]	EPB	-5.76	0.75643	852.0	arc2, angle 2
HC29[1-7]	EPB	-6.86	0.90088	1013.4	arc2, angle 1
VC2A[1-2]	EPB	5.99	0.78663	885.3	up-hill to Meson
V210	EPB	-4.62	0.60672	682.5	vertical adjustment
H210	EPB	0.97	0.12738	144.0	horizontal adjustment
M00U[1-3]	CRD	-0.02	0.00657	10.2	vertical adjustment
M01D[1-2]	B1M	-3.73	0.48984	-.-	flatten trajectory

Table 2: Dipoles used in the proposed upgrade. Polarities are indicated by the bend angle.