SSC-N-65

S. Peggs
Nov. 13, 1985

Segment Data for 'Late' Separation Optics

1 Lattice layout and optical parameters

Figures 1, 2, and 3 show the optical functions and the lattice layout for IP-to-IP segments in the lattices BW005, BW010, and BX086. In this nomenclature, 'B' refers to a particular magnet floor geometry, 'W' or 'X' refers to the branch of the low beta matching solution in four dimensional space, and '005' (etcetera) refers to the value of β^* at the collision point. Transference from the solution branch favorable for injection optics (with a peak beta of 469 metres in the triplet, and 345 metres in the rest of the segment) to the luminosity optics branch, is not difficult to perform. For example, one way is to first raise β^* slightly from 8.6 metres to about 10.0 metres, before lowering it to 1.0 or 0.5 metres.

Variable height rectangles in the figures represent the quadrupoles, with a height proportional to their field strengths. Constant height rectangles are dipoles, either horizontal or vertical. The first vertical step occurs after quadrupole 5, at a distance of 250 metres from the first IP, and the second vertical step is 180 degrees in phase downstream from the first in both planes, after quadrupole 9 at 630 metres. The total length of the segment is 1940 metres.

Horizontal dispersion in the segment is small compared to the main arc values, with a maximum of 0.911 metres in a relaxed phase trombone consisting of 70 metre half cells, containing 3 standard dipoles apiece.

2 Error sensitivities

Tables 1, 2, and 3 show compilations of optical properties and error sensitivities in the three lattices. A few words of explanation may be useful here.

The vertical separation of the ideal closed orbit from the horizontal plane, y(sep), is non-zero in the first and last five quadrupoles which are common to both beams. (After the first step the beams are separated by a total of 0.35 metres: after the second by 0.70 metres.)

The closest approach of the 'horizontal' and 'vertical' tunes, dQ(sq), is a measure of linear coupling introduced by an error rotation of one milliradian of the quadrupole in question.

A horizontal (vertical) displacement of a quadrupole by 0.2 millimetres will cause a closed orbit error in the main arcs of Xc.o. (Yc.o.) at a location with $\beta = 350$ metres, assuming that $2.\sin(\pi Q) = 1$ for the sake of definiteness.

An error of one part in 10^4 in the integrated strength KL of a quadrupole causes a tune shift error of dQx or dQy, horizontally or vertically.

A consequence of closed orbit displacement by y(sep) in a quadrupole is that the beam will sample the higher order error multipoles. The magnitude of this (vertical) effect is proportional to KL, and depends in some way on beta(y) and y(sep), though not necessarily linearly. The value KL.beta(y).y(sep) has been tabulated as a tentative measure of this effect.

A convenient overall summary of the sensitivity of a particular quadrupole in a particular set of optics is the value KL.beta, in the plane of interest.

3 Number of physically different quadrupoles and power supplies

Each of the four low beta matching quadrupoles, 1 through 4, is different in length and strength. Quadrupoles 5 through 9 (and 18 through 22), in the vertical separator / horizontal dispersion matcher, all have the same length and the same strength, independent of the value of β^* and other aspects of the optics.

Quadrupoles 10 through 17 in the phase trombone are powered antisymmetrically, for a total of four independent strengths. While the six central quadrupoles, 11 through 16, all have the same length, the end quadrupoles, 10 and 17, are made from half a vertical separator quad face to face with half a phase trombone quad. The strength of the first half is constant at the same time that the strength of the second half is variable, in an artificial arrangement which is invoked purely for the convenience of matching. It will be assumed for the purposes of numerology that in practice the two components would be combined into a single quadrupole of unique length and strength.

Thus, there are 26 quadrupoles in the segment, with 7 different lengths and 9 different strengths. (If the phase trombone is ignored, there are 18 quadrupoles, with 5 different lengths and 5 different strengths.)

4 The possibility of ±7% trims on power supplies in the phase trombone

The natural tune advance across the segment in the 0.5 (1.0) metre luminosity optics is 3.260 (3.248), very close to the value of 3.25 which is desired for good chromatic behavior. In these optics the phase trombone has not been exercised at all. However, in the injection optics the natural tune advance is 2.973, and the phase trombone has been used to add 0.299 tune units, in order to return the advance to 3.272 (with a slight overshoot). The ratios of the four phase trombone quadrupole strengths at injection to their luminosity strengths are 1.170, 1.113, 1.280, and 1.246, numbers which represent the operational dynamic range which will be required. (This ignores the potential use of the phase trombone quadrupoles as linear lattice correction elements.)

The extreme values of these four ratios, 1.113 and 1.280, can be expressed as 1.1965 x (1 ± 0.070), showing that the phase trombone could (only just) be run off a single bus, with ±7% current shunts on each magnet. However, assuming that the quadrupole strengths increase reasonably smoothly with the additional tune advance demanded, the maximum excursion of 7% could be reduced to ±3.5% by tuning the lengths of the individual phase trombone magnets.

5 The long range beam-beam effect

What follows is a summary of the effects of the additional long range beam-beam interactions in the 'late' separation scheme, as reported last week in more detail. While all the numbers presented here are for the 1.0 metre luminosity optics at 20 TeV, the results preliminarily obtained at 0.5 metres / 20 TeV, and at 8.6 metres / 1 TeV, are not significantly different. An opening half-angle of 25 microradians is assumed.

Two schemes are considered for keeping the beams apart between the end of the triplet and the first vertical step, as sketched in figure 4. The 'minimal' scheme keeps the beams separated by a roughly constant distance of about 2.6 millimetres in the drift between quads 3 and 4, by adding 9.4 and -5.0 microradian dipoles at the beginning and end, respectively. The 'maximal' scheme uses trim dipoles at the beginning, middle, and end, of the 3/4 drift, with strengths of 209.4, -400, and 195 microradians, for a peak separation of ± 1.4 centimetres.

In the 'minimal' case the beam-beam tune shift due to long range interactions is about 60% more than in the 'early' separation optics, where interactions only occur up to the end of the triplet. The increase in tune shift is reduced to only about 10% in the 'maximal' scheme.

The additional shift of the closed orbit due to the long range interactions in a single interaction region, beyond the nominal value of about one seventh of a beam sigma, is about 120% in the 'minimal' scheme, and about 30% in the 'maximal' scheme. This is at about the resolution limit of the position detectors, or of detectable luminosity loss.

6 Muon production from pion decay

The only significant source of muons downstream of an IP which distinguishes between 'early' and 'late' optics is pion decay in flight, which occurs with a decay distance which is time dilated to a maximum distance of $1.12*10^6$ metres. This distinction arises because collimators are most efficient at positions of high dispersion, such as at the end of the first vertical step, where the dispersion is (about) 0.175 metres, and where a collimator placed 5 millimetres from the beam will scrape off particles with

$$X = E/E_0 < 0.175 / (0.175 + 0.005) = 0.972 \qquad [1]$$

Since the first vertical step in the 'late' optics is about twice as far from the IP as in the 'early' optics, it might be expected that twice as many muons would be produced.

However, the situation is not nearly as bad as it appears at first sight, because

1) the pion spectrum is highly peaked at lower energy, with (approximately)

$$dN/dX = \text{constant} . (1 - X)^4 / X \qquad [2]$$

2) the triplet acts as a natural collimator of $X < 0.17$ pions, and

3) collimation of pions with $X < 0.65$ (or higher) is possible using the 1.5 centimetre dispersion produced in the bump in the 'maximal' scheme.

An admittedly crude calculation of the number of muons made in the 'early' and 'late' collimation geometries sketched in figure 5 shows that about $2.0*10^{-3}$ of the pions which leave the triplet decay into muons in region A, in both optics. An additional fraction of about $1.4*10^{-6}$ pions decay in region B of the 'late' optics, a negligible increase in the muon flux, even ignoring the muons made before the end of the triplet and muons made by other mechanisms.

7 Independent orbit steering at the collision point

While the dipole trim magnets which are used in the 'minimal' or 'maximal' schemes can also be used to adjust the collision angle and transverse position, steering both beams at the same time in a common-mode manner, it seems wise to also have complete control over each beam independently. One satisfactory way to do this has been devised by Mike Harrison (unpublished), using standard horizontal and vertical dipole correctors, each with an integrated strength of 3 Tesla metres producing a peak angular kick of 45 microradians at 20 TeV.

Two dipole correctors per plane are placed on either side of the IP, at locations in the vertical separators close to appropriately focussing quadrupoles with betas of about 300 metres, spaced orthogonally by 90 degrees in phase. Such dipoles in 1.0 metre luminosity optics can move the beam at the IP by at least ±0.78 millimetres, and by at least ±780 microradians. This corresponds to about 100 times the natural size of the beam in both cases.

Table 1: BW005, luminosity lattice with beta star = 0.5 metres

Quad #	s (m)	L (m)	K *1000 (m**-2)	KL *100 (m**-1)	beta(x) (m)	beta(y) (m)	KL.beta(x)	KL.beta(y)	y(sep) (mm.)	dQ(sq)	Xc.o. (mm)	Yc.o. (mm)	dQx	dQy	KL.beta(y) *ysep (mm)
	0.0				0.5	0.5									
LOW-BETA MATCHING SECTION															
1	27.3	13.6	3.619	4.92	1709.4	1292.8	84.13	63.63	0.89	0.0233	7.61	6.62	0.00067	0.00051	56.6
2	47.0	21.8	3.627	7.91	7952.4	1673.0	628.79	132.28	1.03	0.0917	26.37	12.10	0.00501	0.00105	136.3
3	65.5	12.1	3.800	4.60	3021.5	6799.1	138.93	312.62	2.07	0.0663	9.45	14.18	0.00111	0.00249	647.1
4	204.6	9.0	3.033	2.73	155.8	209.6	4.25	5.72	1.67	0.0016	1.27	1.48	0.00003	0.00005	9.6
VERTICAL SEPARATOR / HORIZONTAL DISPERSION MATCHER															
5	250.0	7.5	2.039	1.53	335.7	58.9	5.13	0.90	2.92	0.0007	1.05	0.44	0.00004	0.00001	2.6
6	345.0	"	"	"	41.7	234.9	0.64	3.59		0.0005	0.37	0.88	0.00001	0.00003	
7	440.0	"	"	"	335.7	58.9	5.13	0.90		0.0007	1.05	0.44	0.00004	0.00001	
8	535.0	"	"	"	75.7	439.5	1.16	6.72		0.0009	0.50	1.20	0.00001	0.00005	
9	630.0	"	"	"	335.7	58.9	5.13	0.90		0.0007	1.05	0.44	0.00004	0.00001	
PHASE TROMBONE			(left unsqueezed - natural segment tune advance is 3.260, very close to 3.25)												
10	725.0			1.83	41.7	234.9	0.76	4.30		0.0006	0.44	1.05	0.00001	0.00003	
11	795.0	10.0	2.124	2.12	234.9	41.7	4.99	0.89		0.0007	1.22	0.51	0.00004	0.00001	
12	865.0	"	2.124	2.12	41.7	234.9	0.89	4.99		0.0007	0.51	1.22	0.00001	0.00004	
13	935.0	"	2.124	2.12	234.9	41.7	4.99	0.89		0.0007	1.22	0.51	0.00004	0.00001	
14	1005.0	"	same as 13		41.7	234.9	0.89	4.99		0.0007	0.51	1.22	0.00001	0.00004	
15	1075.0	"	same as 12		234.9	41.7	4.99	0.89		0.0007	1.22	0.51	0.00004	0.00001	
16	1145.0	"	same as 11		41.7	234.9	0.89	4.99		0.0007	0.51	1.22	0.00001	0.00004	
17	1215.0		same as 10		234.9	41.7	4.30	0.76		0.0006	1.05	0.44	0.00003	0.00001	
VERTICAL SEPARATOR / HORIZONTAL DISPERSION MATCHER															
18	1310.0														
19	1405.0		SAME AS FIRST VERTICAL SEPARATOR												
20	1500.0														
21	1595.0														
22	1690.0								-0.71						-3.6
LOW BETA MATCHING SECTION															
23	1735.5								0.81						3.5
24	1874.6		SAME AS FIRST LOW BETA MATCHING SECTION						1.40						194.5
25	1893.0								2.23						1402.2
26	1912.7								1.05						88.3
	1940.0				0.5	0.5									
TYPICAL MAIN ARC QUAD (for comparison)															
		5.00	2.034	1.017	350.0	115.0	3.56	1.17		0.0010	0.71	0.41	0.00003	0.00001	

Table 2: BW010, luminosity lattice with beta star = 1.0 metres

Quad #	s (m)	L (m)	K *1000 (m**-2)	KL *100 (m**-1)	beta(x) (m)	beta(y) (m)	KL.beta(x)	KL.beta(y)	y(sep) (mm.)	dQ(sq)	Xc.o. (mm)	Yc.o. (mm)	dQx	dQy	KL.beta(y) *ysep (mm)
	0.0				1.0	1.0									
LOW-BETA MATCHING SECTION															
1	27.3	13.6	3.308	4.50	845.8	655.2	38.05	29.48	0.61	0.0107	4.89	4.31	0.00030	0.00023	18.0
2	47.0	21.8	3.589	7.82	3714.6	960.6	290.63	75.16	0.79	0.0470	17.83	9.07	0.00231	0.00060	59.4
3	65.5	12.1	3.809	4.61	1382.5	4076.9	63.72	187.90	1.70	0.0348	6.41	11.01	0.00051	0.00150	319.4
4	204.6	9.0	1.920	1.73	162.5	199.9	2.81	3.45	1.70	0.0010	0.82	0.91	0.00002	0.00003	5.9
VERTICAL SEPARATOR / HORIZONTAL DISPERSION MATCHER															
5	250.0	7.5	2.039	1.53	335.7	58.9	5.13	0.90	2.21	0.0007	1.05	0.44	0.00004	0.00001	2.0
6	345.0	"	"	"	41.7	234.9	0.64	3.59		0.0005	0.37	0.88	0.00001	0.00003	
7	440.0	"	"	"	335.7	58.9	5.13	0.90		0.0007	1.05	0.44	0.00004	0.00001	
8	535.0	"	"	"	75.7	439.5	1.16	6.72		0.0009	0.50	1.20	0.00001	0.00005	
9	630.0	"	"	"	335.7	58.9	5.13	0.90		0.0007	1.05	0.44	0.00004	0.00001	
PHASE TROMBONE (left unsqueezed - natural segment tune advance is 3.248, very close to 3.25)															
10	725.0			1.83	41.70	234.90	0.76	4.30		0.0006	0.44	1.05	0.00001	0.00003	
11	795.0	10.0	2.124	2.12	234.90	41.70	4.99	0.89		0.0007	1.22	0.51	0.00004	0.00001	
12	865.0	"	2.124	2.12	41.70	234.90	0.89	4.99		0.0007	0.51	1.22	0.00001	0.00004	
13	935.0	"	2.124	2.12	234.90	41.70	4.99	0.89		0.0007	1.22	0.51	0.00004	0.00001	
14	1005.0	"	same as 13		41.70	234.90	0.89	4.99		0.0007	0.51	1.22	0.00001	0.00004	
15	1075.0	"	same as 12		234.90	41.70	4.99	0.89		0.0007	1.22	0.51	0.00004	0.00001	
16	1145.0	"	same as 11		41.70	234.90	0.89	4.99		0.0007	0.51	1.22	0.00001	0.00004	
17	1215.0		same as 10		234.90	41.70	4.30	0.76		0.0006	1.05	0.44	0.00003	0.00001	
VERTICAL SEPARATOR / HORIZONTAL DISPERSION MATCHER															
18	1310.0														
19	1405.0		SAME AS FIRST VERTICAL SEPARATOR												
20	1500.0														
21	1595.0														
22	1690.0								0.26						1.3
LOW BETA MATCHING SECTION															
23	1735.5								0.86						2.4
24	1874.6		SAME AS FIRST LOW BETA MATCHING SECTION						0.92						58.6
25	1893.0								1.44						418.5
26	1912.7								0.70						26.6
	1940.0				1.0	1.0									
TYPICAL MAIN ARC QUAD (for comparison)															
		5.00	2.034	1.017	350.0	115.0	3.56	1.17		0.0010	0.71	0.41	0.00003	0.00001	

Table 3: BX086, injection lattice with beta star = 8.6 metres

Quad #	s (m)	L (m)	K *1000 (m**-2)	KL *100 (m**-1)	beta(x) (m)	beta(y) (m)	KL.beta(x)	KL.beta(y)	y(sep) (mm.)	dQ(sq)	Xc.o. (mm)	Yc.o. (mm)	dQx	dQy	KL.beta(y) *ysep (mm)
	0.0				8.6	8.6									
LOW-BETA MATCHING SECTION															
1	27.3	13.6	3.346	4.55	108.4	83.3	4.93	3.79	0.97	0.0014	1.77	1.55	0.00004	0.00003	3.7
2	47.0	21.8	3.365	7.34	469.2	107.9	34.42	7.92	1.13	0.0052	5.94	2.85	0.00027	0.00006	8.9
3	65.5	12.1	3.504	4.24	208.0	423.0	8.82	17.93	2.27	0.0040	2.29	3.26	0.00007	0.00014	40.7
4	204.6	9.0	-0.678	-0.61	171.8	133.5	-1.05	-0.81	1.97	-0.0003	-0.30	-0.26	-0.00001	-0.00001	-1.6
VERTICAL SEPARATOR / HORIZONTAL DISPERSION MATCHER															
5	250.0	7.5	2.039	1.53	329.2	56.2	5.03	0.86	1.33	0.0007	1.04	0.43	0.00004	0.00001	1.1
6	345.0	"	"	"	45.0	324.1	0.69	4.96		0.0006	0.38	1.03	0.00001	0.00004	
7	440.0	"	"	"	329.2	56.2	5.03	0.86		0.0007	1.04	0.43	0.00004	0.00001	
8	535.0	"	"	"	70.1	318.6	1.07	4.87		0.0007	0.48	1.02	0.00001	0.00004	
9	630.0	"	"	"	329.2	56.2	5.03	0.86		0.0007	1.04	0.43	0.00004	0.00001	
PHASE TROMBONE			(squeezed by 0.299 units of tune, raising segment advance from 2.973 to 3.272)												
10	725.0			2.14	45.0	324.1	0.96	6.94		0.0008	0.54	1.44	0.00001	0.00006	
11	795.0	10.0	2.364	2.36	269.7	17.2	6.38	0.41		0.0005	1.45	0.37	0.00005	0.00000	
12	865.0	"	2.719	2.72	22.3	344.8	0.61	9.38		0.0008	0.48	1.89	0.00000	0.00007	
13	935.0	"	2.647	2.65	333.6	17.5	8.83	0.46		0.0006	1.81	0.41	0.00007	0.00000	
14	1005.0	"	same as 13		17.5	333.6	0.46	8.83		0.0006	0.41	1.81	0.00000	0.00007	
15	1075.0	"	same as 12		344.8	22.3	9.38	0.61		0.0008	1.89	0.48	0.00007	0.00000	
16	1145.0	"	same as 11		17.2	269.7	0.41	6.38		0.0005	0.37	1.45	0.00000	0.00005	
17	1215.0		same as 10		324.1	45.0	6.94	0.96		0.0008	1.44	0.54	0.00006	0.00001	
VERTICAL SEPARATOR / HORIZONTAL DISPERSION MATCHER															
18	1310.0														
19	1405.0		SAME AS FIRST VERTICAL SEPARATOR												
20	1500.0														
21	1595.0														
22	1690.0								2.66						13.4
LOW BETA MATCHING SECTION															
23	1735.5								1.99						-2.1
24	1874.6		SAME AS FIRST LOW BETA MATCHING SECTION						1.59						14.0
25	1893.0								2.34						80.5
26	1912.7								1.09						5.4
	1940.0				8.6	8.6									
TYPICAL MAIN ARC QUAD (for comparison)															
		5.00	2.034	1.017	350.0	115.0	3.56	1.17		0.0010	0.71	0.41	0.00003	0.00001	

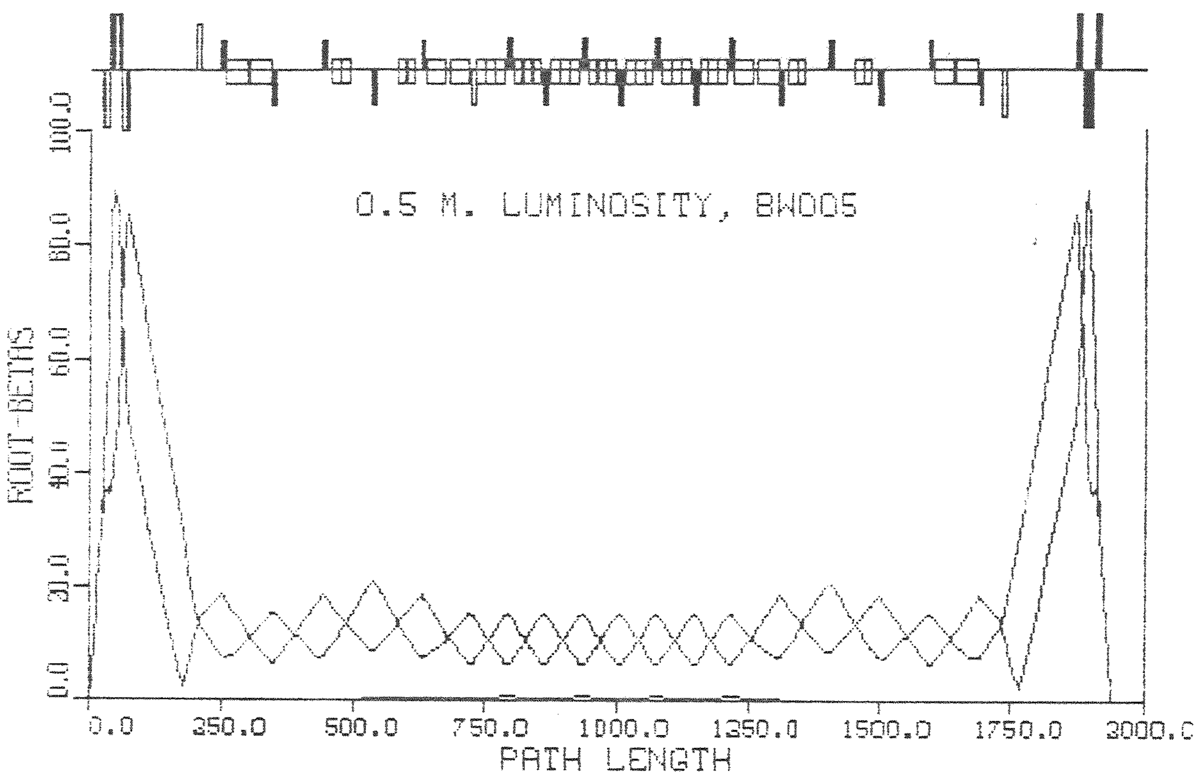

Figure 1: Optics in the $\beta^* = 0.5$ lattice BWØØ5

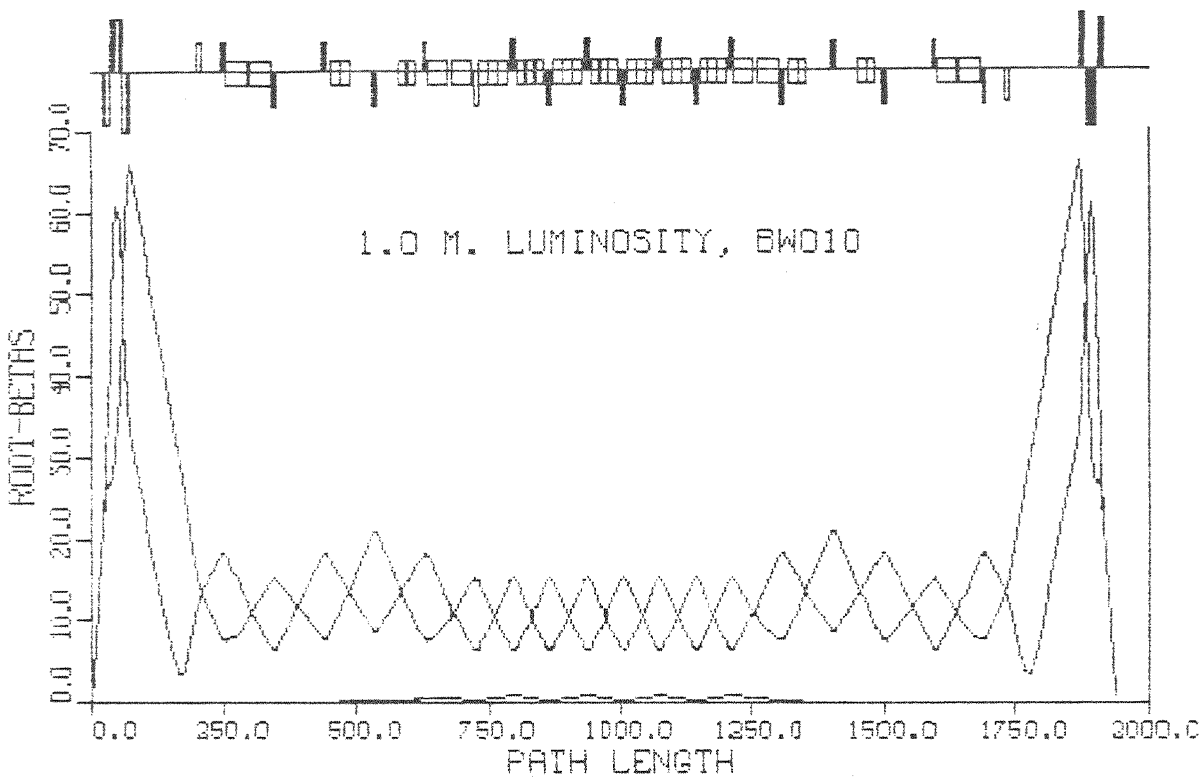

Figure 2: Optics in the $\beta^* = 1.0$ lattice BW010

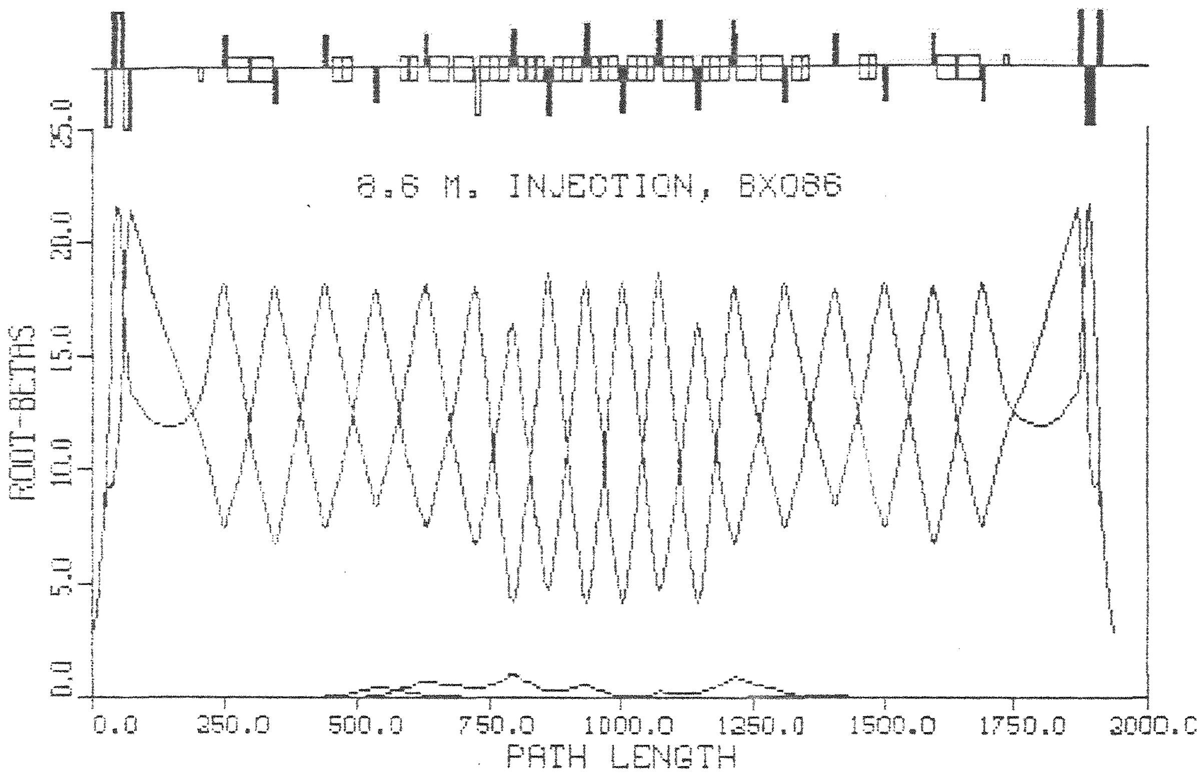

Figure 3: Optics in the $\beta^* = 8.6$ lattice BX086

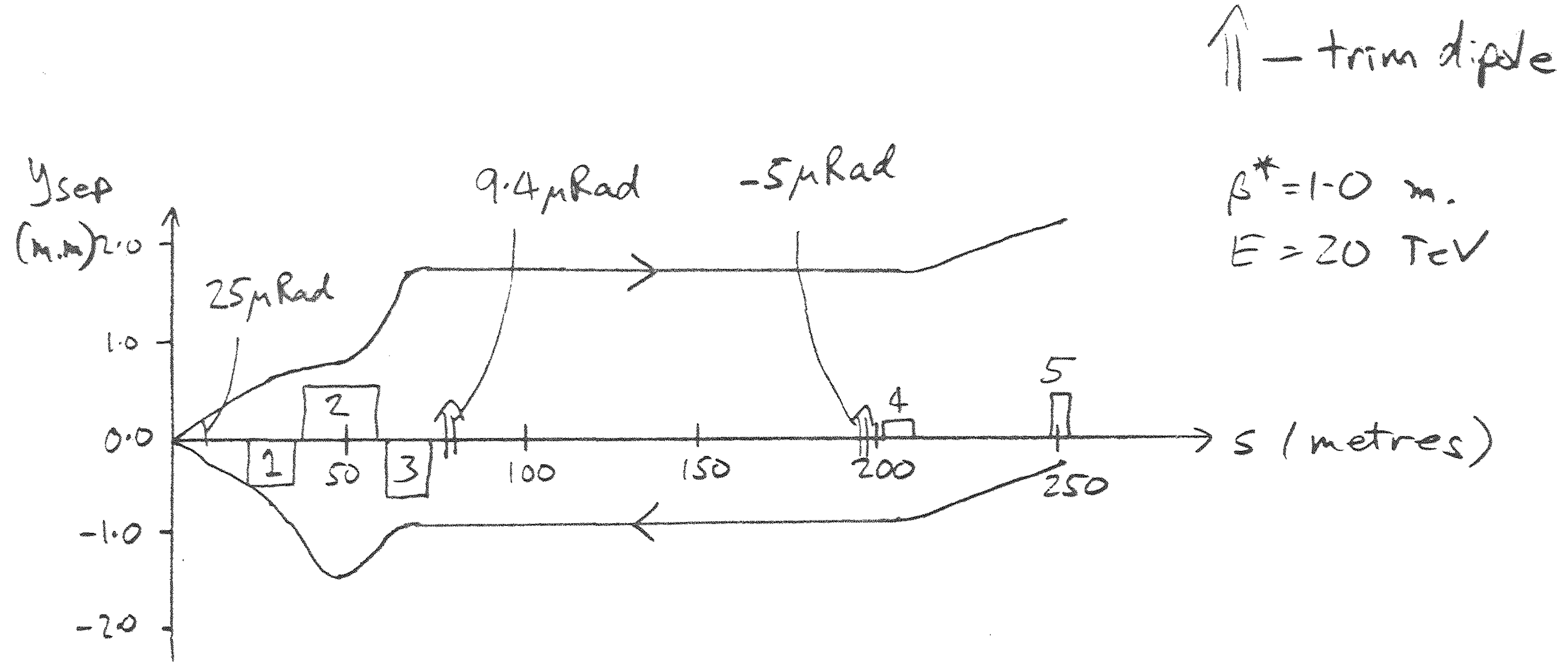

Figure 4a: 'Minimal' scheme, with two trim dipoles

NOTE SCALE CHANGE

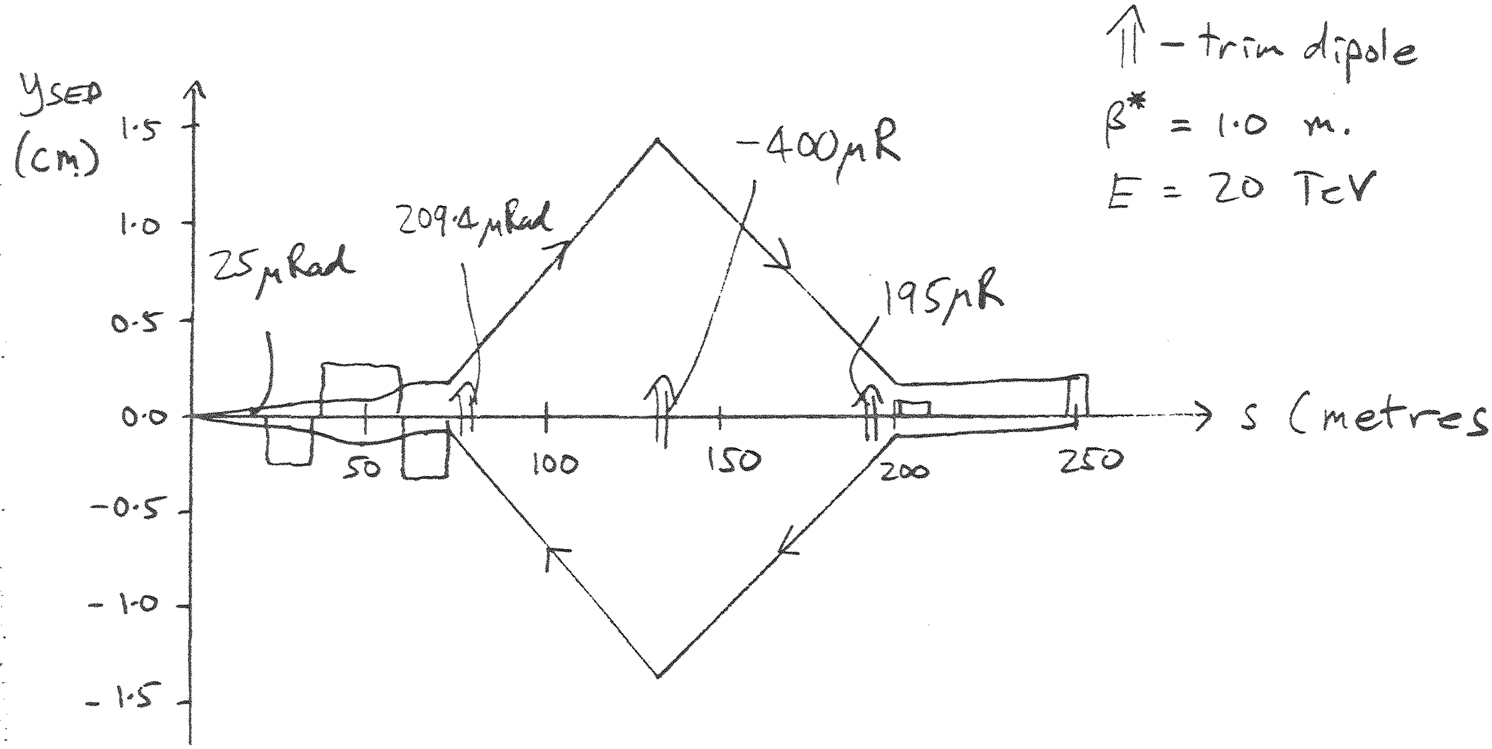

Figure 4b: 'Maximal' scheme, with three trim dipoles

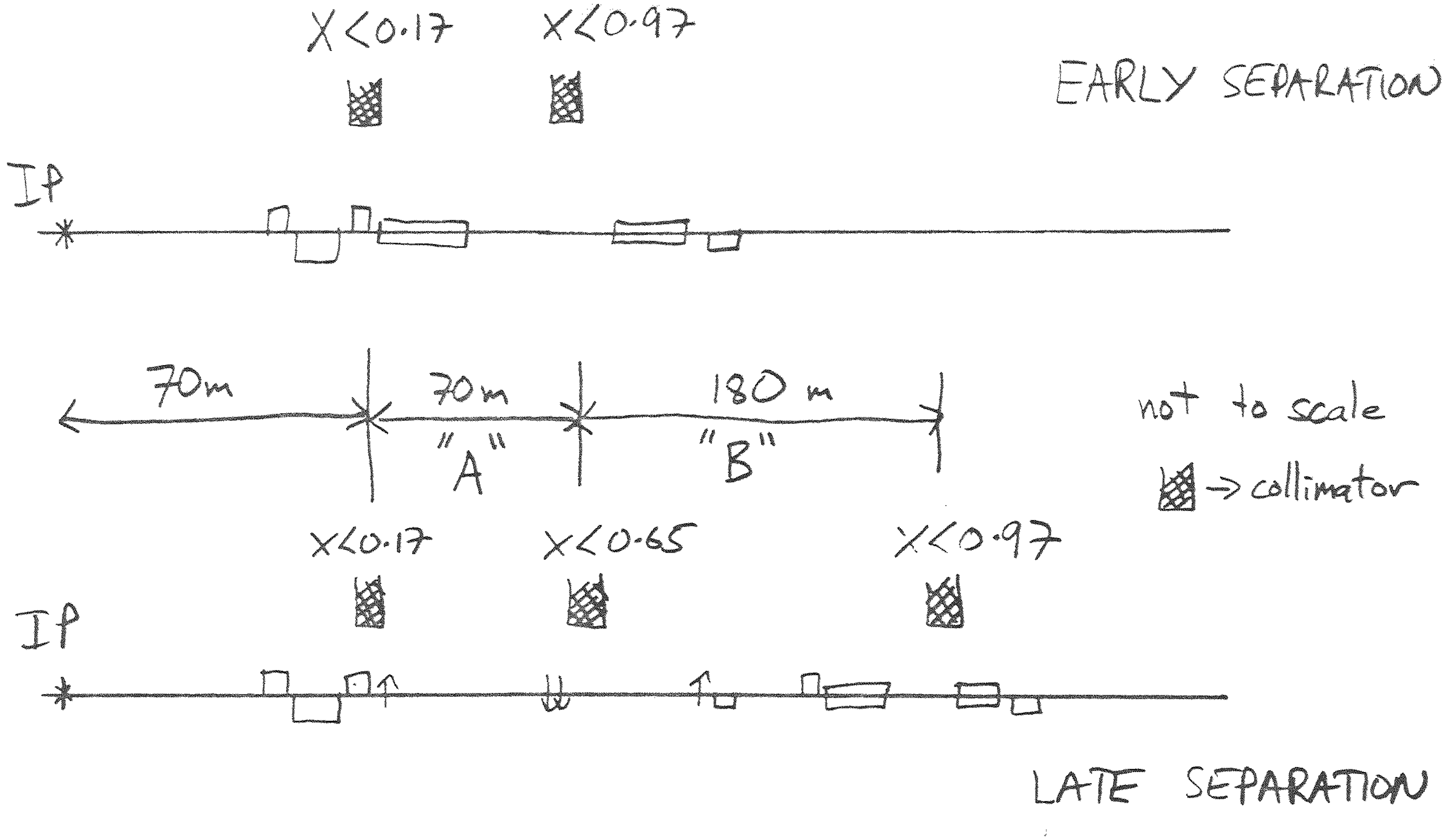

Figure 5: Sketch of 'early' and 'late' collimation schemes