REVIEW OF THE MAIN-RING APERTURES

L. C. Teng

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Several meetings were held during April to re-examine the aperture requirement for the main ring. This is a summary of the discussions during the meetings and the decision resulting from the review.

The aperture requirement at injection is the following:

Table 1

	B1		B2	
	Width	Height	Width	Height
Emittance	1.58"	0.74"	1.20"	1.00"
Momentum spread	0.40"	0	0.31"	0
Poor field region	0.50"	0	0.50"	0
Subtotal	2.48"	0.74"	2.01"	1.00"
Closed-orbit errors	1.16"	0.68"	0.88"	0.88"
Grand total	3.64"	1.42"	2.89"	1.88"
(design	5"	1.5"	4"	2")

This table shows that the design aperture heights agree well with the grand totals. The design aperture heights are also needed to give an incoherent transverse space charge limit of 10^{14} p/pulse. Therefore, even if the closed-orbit errors are eliminated the design aperture heights are still required.

The aperture width required for extraction given in the Design Report is the following:

Table 2

(Placement of septum from beam center line = 3 cm,
Beam amplitude growth for jumping across septum = 1 cm)

	B1 Width	B2 Width
Emittance requirement	3.15"	2.38"
Momentum spread	0.04"	0.03"
Poor field region	0.50"	0.50"
Subtotal	3.69"	2.91"
Closed-orbit errors	1.16"	0.88"
Grand total	4.85"	3.79"

These grand totals again agree well with the design aperture widths of 5.0" and 4.0". Several recent developments and considerations suggest the possibility of reducing the aperture width.

(1) If the closed-orbit errors at extraction can be eliminated by proper position adjustment of the ring magnets the aperture widths can be reduced to the subtotals in Table 2; namely 3.7" for B1 and 3.0" for B2, which also agree with the grand totals at injection.

(2) The recent development by A. Maschke in using wire septum for holding very high electric field implies that the design extraction efficiency can be obtained with a smaller

amplitude growth at extraction. The aperture width requirement with this optimistic extraction system can be as follows:

Table 3

(Placement of septum from beam center line = 2 cm,
Beam amplitude growth for jumping across septum = 0.5 cm)

	B1 Width	B2 Width
Emittance requirement	1.97"	1.49"
Momentum spread	0.04"	0.03"
Poor field region	0.50"	0.50"
Subtotal	2.51"	2.02"
Closed-orbit errors	1.16"	0.88"
Grand total	3.67"	2.90"

Thus, with the optimistic extraction system even including the closed-orbit errors aperture widths of 3.7" for B1 and 3.0" for B2 seem to be adequate. Furthermore, if the closed-orbit errors can be eliminated altogether (at both injection and extraction) with the optimistic extraction system the aperture widths can be reduced to 2.5" for B1 and 2.0" for B2 (subtotals in Table 1 and 3).

(3) A recent study indicated that with a slight modification of the lattice β_x can be made much larger (5 to 10 times) in the long straight section insertion than that in the normal cells. This implies that even with the Design Report extraction

system (performance specified in Table 2) the apertures in the normal cells do not have to be larger than those required for injection. This, again gives an aperture width of 3.7" for B1 and 3.0" for B2 with closed-orbit errors, and 2.5" for B1 and 2.0" for B2 without closed-orbit errors.

The various positive and negative aspects of a reduction in aperture width are the following:

(A) Positive

(1) With smaller aperture widths the magnets could be smaller in cross-section. Computer studies indicate that to reduce the aperture width of a bending magnet by δ all one has to do is to take a vertical slice of width δ out of the middle of the magnet, reduce the return yoke thickness by $\frac{\delta}{2}$ all around, and leave the coil configuration unchanged. Redesign of the quadrupole magnets would require a little more effort. Also, since the stored energy in the magnetic field is reduced the power supply would be smaller. But as it is well known that the width of the aperture (as compared to the height) does not have a strong influence on the cost of a bending magnet.

(2) With a smaller aperture width the RF cavities could be reduced in diameter. This leads to some saving in the cost of material (copper) for the cavities.

(3) With a smaller aperture beam position sensors can be made to give better accuracy. The precision in position measurement is roughly proportional to the aperture.

(4) A rough estimate gives a cost reduction of \$1.5 - 2.0 million from items (1) and (2) above when the aperture widths are reduced to 2.5" for B1 and 2" for B2.

(5) As an exercise and to exhibit the strong dependence of cost on the aperture height if both the heights and the widths of the apertures are reduced by a factor $\sqrt{2}$ the savings in cost of the magnet and power supply can amount roughly to \$10 million. This height reduction decreases the space charge limit to the design intensity of 5×10^{13} p/pulse. Such a height reduction would imply putting unwarranted confidence on the calculation of the space charge limit. Changing the aperture height would also necessitate a total redesign and model test of the magnets. The time and cost incurred in this effort would significantly offset the \$10 million cost reduction. In any case, it is certainly worth \$10 million to double the ultimate intensity capability of the accelerator.

(B) Negative

(1) The magnet model test program indicated that because of the rather jagged mating surfaces of the upper and lower lamination stacks of the bending magnets the aperture height variation from magnet to magnet and within each magnet during a pulsing cycle can be as large as a mil which corresponds to a $\frac{\Delta B}{B}$ of 10^{-3}. To eliminate closed-orbit errors throughout the entire pulsing cycle would require much larger and separately programmed power supplies for all trimming

dipoles. The cost for such trimming dipoles and power supplies is prohibitively high. Therefore it would be inadvisable to ignore all closed-orbit errors and consider aperture widths of 2.5" for B1 and 2.0" for B2 adequate even for the most optimistic case.

(2) The longitudinal phase space mismatches caused by space charge forces during transition crossings in both the booster and the main ring result in increases of the momentum spread of the beam. Moreover, errors in synchronization during transfer of the 12 or 13 beam pulses from the booster to the main ring will also add to the momentum spread. Pessimistic estimate gives a factor 4 increase in $\frac{\Delta p}{p}$ from the combination of all these effects. The main ring aperture width requirement immediately after transition is, therefore, as shown in the following table.

Table 4

	B1 Width		B2 Width	
Emittance	1.22"		0.92"	
Momentum spread	0.67" (no blowup)	2.68" (4 x blowup)	0.51" (no blowup)	2.03" (4 x blowup)
Poor field region	0.50"		0.50"	
Subtotal	2.39"	4.40"	1.93"	3.45"
Closed-orbit errors	1.16"		0.88"	
Grand total	3.55"	5.56"	2.81"	4.33"

This table shows that without any blowup in momentum spread there is indeed no additional demand on aperture widths at transition, but if the blowup is really as large as the pessimistic estimate of a factor of 4 careful trimming to reduce the closed-orbit errors is needed to insure no beam loss at transition with the present design aperture widths of 5" for B1 and 4" for B2.

Various schemes for reducing or eliminating the blowup in crossing transition have been proposed and are being studied. But it is extremely improbable that the increase in $\frac{\Delta p}{p}$ can be eliminated altogether.

(3) Several undesirable features of the high β insertion were pointed out.

(a) The beam width due to momentum spread is increased by about a factor of 2 with the high β insertion. This is especially troublesome at transition when the beam width due to momentum spread is already large. On the other hand, it is possible to pulse on the high β matching quadrupoles only at extraction, thereby keeping the momentum width normal at transition.

(b) Since the closed-orbit error is proportional to $\sqrt{\beta}$, the horizontal error will be bigger in the insertion where β_x is large.

(c) Using the third integral resonance for extraction the beam amplitude growth per turn at the septum for given sextupole strength is proportional to $\frac{d^2}{\sqrt{\beta_x}}$ where d is the separation of the septum from the center line. To obtain the same amplitude growth per turn for higher β_x the septum has to be placed farther away from the beam center line. This means that with the high β insertion although the aperture widths in the normal cells of the lattice could be smaller the aperture widths of the magnets in the insertion must be larger in order to retain the same extraction efficiency. This would partially offset the cost saving in reducing the aperture widths in the normal cells.

Balancing the positive and negative aspects of reductions in aperture widths and re-examining the data given in the tables, it was decided that the present design apertures of 5.0" x 1.5" for B1 and 4.0" x 2.0" for B2 do indeed represent a proper balance between conservatism and brashness.