THE LATTICE DESIGN AND TOLERANCE ANALYSIS OF THE CBA TRANSPORT LINE*

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Summary

The beam transport line from the AGS to CBA is 600 m long and consists of 70 bending magnets and 20 quadrupoles, as well as several special injection components. The beam has to bend 117 horizontally and drop 1.8 m in elevation. To insure that it has momentum acceptance of $\Delta P/P = \pm 1\%$ and the transverse emittance dilution is within 30%, a detailed tolerance analysis has been carried out on the requirements of the AGS beam properties, magnetic field quality of the transport magnets, and misalignment errors. Field quality tolerances of $\Delta B_0/B \leq 1 \times 10^{-3}$ for bending field, $\Delta G/G < 5 \times 10^{-3}$ for gradient field and $\Delta B_2/B < 2.5 \times 10^{-4}$ cm^{-2} of the sextupole components in the bending magnets are indicated.

The CBA Beam Transport Line

CBA is located to the north of the AGS in such a way that the present AGS fast extraction system and part of the existing experimental beam transport tunnel can be used.[1] For the discussion of the transport line, we find it is very convenient to introduce the coordinate system shown in Figure 1. With the 6th intersection point (IP6) as origin, the Y-axis is defined to be the line joining CBA and IP6 pointing away from CBA and the X-axis is the line perpendicular to the Y-axis at IP6 pointing to the east. Defined this way, the X-axis is also the bisection line of the crossing angle at IP6 and the Y-axis in the reverse direction is 2° east of the BNL grid north.

The beginning of the transport line is the center of the 8° bend (point A) which is about 100 m from the extraction point H13 of the AGS. In the X-Y coordinate introduced above, it is about 405 m in y and 47 m in x. The beam has to bend 20° total near point B and C to join the Y-axis and continues on until it reaches the switch magnet which will steer the beam either to the right arc (Y-line) or the left arc (X-line) to enter the big-bend (81.5°) section of the transport line. Finally, the beam passes through a matching section to join the CBA lattice at point G which is equivalent to CBA ring magnet Q60. In summary, a complete transport line from the AGS to CBA is about 600 m long, has to bend 117° horizontally and drops 1.8 m vertically from point B to point D.

The 20° bend consists of eight equally-spaced combined function gradient magnets in a FODO lattice structure. The gradient of the magnets is chosen to suppress the dispersion at the end of the last magnet. A phase advance of 180° from B to C gives the desired result. The vertical drop of 1.8 m is accomplished by two pitching magnets at B and D, a phase advance of 360° between them serves to suppress the vertical dispersion at point D. An additional six quadrupoles are employed to carry the beam up to switching magnet, WSD, at point E and are used also for betatron matching into the big bend arc.

The upstream portion of the big bend arc consists of 24 gradient magnets in 6 cells of FOFDOD lattice structure which is necessary if we want to have maximum betatron function occur at the limited free space between magnets. The 24 gradient magnets cover a 64 bend which is followed by a matching section formed by three separate function FODO cells. The six quadrupoles are used not only to match the standard CBA lattice function, but also to provide the tuning flexibility for any CBA lattice change.

The CERN AGS[2] program is used to design the optical functions of the transport line. In every section the phase advance per cell is about 90° for the convenience of correction elements, the dispersion function has been properly reduced to zero before a long straight part of the line and finally at the entrance to the CBA lattice (Q60) both the transverse betatron functions and the dispersion function are

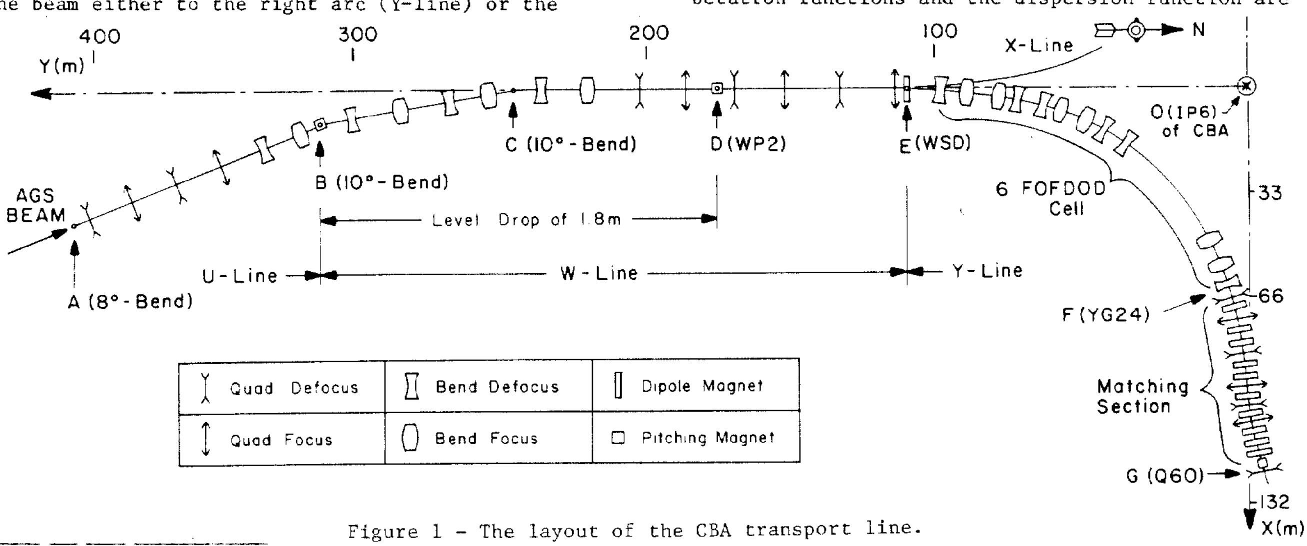

Figure 1 - The layout of the CBA transport line.

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properly matched. The whole line is designed to be able to take a beam of transverse emittances $\varepsilon_x = \varepsilon_y = 2$ mm-mrad and with momentum acceptance of $\Delta P/P = \pm 0.3\%$ from the AGS to switch magnet and ± 1% from the switch magnet on all the way into the CBA. In other words, the big bend has identical acceptance as CBA.

REGION / FUNCTION	W-LINE	BIG-BEND	MATCHING
LATTICE TYPE / CELL LENGTH (m)	FODO/35.5	FOFDOD/18.5	FODO/20
L (m) / θ (deg)	3.7/2.5	3.7/2.7	3.7/3.4
B_o (KG) / G (KG/cm)	11.7/0.25	12.6/0.37	15.8/1.5 (Q)
β_{max} (m)	55.0	27.0	53(V)/30(H)
$X_{p,max}$ (m)	4.0	2.2	2.0
$\Delta P/P$	± 0.3 %	± 1%	± 1%
SAGITTA (mm)	20	22	28
APERTURE (mm, V/H)	35/70	28/100	25/100

Table I - Summary of the lattice and magnet parameters.

The results of the design are briefly summarized in Table I where the number given applies to the bending magnet in each region. It can be seen that at all the bending magnets, the horizontal aperture is much larger than the vertical one. The combined function magnet is chosen to accommodate such a beam shape and to eliminate the additional quadrupole for focusing in those regions. Overall, there are 70 bending magnets and 20 quadrupoles needed, as well as several special injection components.

Requirements of the AGS Beam Quality

In the CBA design, the two rings will collide with each other with crossing angle $\alpha = 11$ mrad. The luminosity expected at each crossing point is

$$L = \frac{1}{ce^2\ \alpha\ \sqrt{\pi}}\ \frac{I^2}{\sigma_v^*} \qquad (1)$$

where I is the total current in the beam and σ_v^* is the RMS vertical beam size. In Equation (1) the I^2 and σ_v^* terms are strongly influenced by the quality of the AGS beam and the beam transport. For given CBA magnet aperture, the rf stacking process implies that the total amount of current stacked is inversely proportional to the momentum spread of the injected AGS beam and which in turn is proportional to the square root of the longitudinal phase space area ε_ℓ. On the other hand, the σ_v^* is proportional to the vertical emittance of the AGS beam ε_v; therefore,

$$L\ \alpha\ \frac{1}{\varepsilon_\ell\ \varepsilon_v^{1/2}} \qquad (2)$$

If the longitudinal and transverse errors contribute equally and independently to the luminosity change, the resultant error in luminosity can be found to be:

$$\delta\ L/L = -\ 1/2\ \left((\delta\varepsilon_v/\varepsilon_v)^2 + (2\ \delta\varepsilon_\ell/\varepsilon_\ell)^2\right)^{1/2} \qquad (3)$$

Assuming that the beam from the AGS has vertical emittance of $\varepsilon_v = 0.5$ mm-mrad and longitudinal phase space area $\varepsilon_\ell = 1.06$ ev-sec, for a 20% change in luminosity, the corresponding errors in energy and position can be found to be:

$$\delta\varepsilon_\ell/\varepsilon_\ell = 7\% \begin{cases} \delta E/\Delta E = 5\%, & \delta E/E = 2.5 \times 10^{-5} \\ \delta\theta/\Delta\theta = 5\%, & \delta\theta = 1.8^\circ \end{cases}$$
$$\delta\varepsilon_v/\varepsilon_v = 28\% \begin{cases} \delta y/\Delta y = 20\%, & \delta y = 0.5\ \text{mm} \\ \delta y'/\Delta y' = 20\%, & \delta y' = 40\ \mu\text{rad} \end{cases} \qquad (4)$$

where Δ represents the size of each parameter and δ represents the error allowed. For example, the vertical beam size at Q60 is $\Delta y = 2.5$ mm and the allowed error is $\delta y = 0.5$ mm. The energy stability requirement is tighter than we currently can produce. A study program has demonstrated that the short term (within 30 minutes) energy reproducibility of the AGS beam is within 5×10^{-5}. To limit the luminosity change to be less than 20%, a bunch-to-bunch longitudinal damping system will be needed to correct the energy errors of the injected beam within CBA.

The question of how to realize the requirements in Eq. (4) at point Q60 will be addressed in a detailed report. From now on we will concentrate on the tolerances of the beam transport line in terms of its own criteria stated therein.

Bending Field Errors

Since the big bend region has to accept a momentum spread of ± 1%, the field quality requirements on the magnets are most stringent in this region; therefore, we will use this part of the line as an example to discuss the effects of field errors on the beam qualities. The same principles and considerations have also been applied to other parts of the transport line to arrive at the required tolerances.

First we will consider the effects of the random bending field errors on the particle trajectory. Im principle, the trajectory error in a transport line can be corrected by moving the magnets whenever it is necessary. But in practice the trajectory error will be limited by the decision on how many magets to move and how often to move them. For our design, we impose the condition that the maximum allowed horizontal trajectory error is $\Delta x = \pm 10$ mm and that for the vertical trajectory is $\Delta y = \pm 5$ mm. Then the requirement on the bending field error and its correction system is designed to be compatible with the allowed errors.

Assuming that a set of position monitors and steering dipoles will be provided every betatron wavelength apart and that all the field errors are random in origin, then the accumulated position error in one wavelength (16 magnets for big bend lattice) will be

$$\Delta x = 2.5 \times \left[\sum_{i=1}^{16} \beta_{17}\ \beta_i (\sin\ \psi_{i,17}\ \ \delta\theta)^2\right]^{1/2} \leq 10\ \text{mm} \qquad (5)$$

where $\delta\theta$ is the RMS bending error introduced by the field error and the factor of 2.5 is used to insure that the peak position error is less than 10 mm. For a simplified estimate, one may assume that a group of 4 magnets has phase difference of 90°, 180°, 270° and 360° from magnet No. 17; therefore, only 8 magnets contribute to the position error. We further assume that the average betatron function of 18 m be used for every magnet, then the allowed RMS bending error at each magnet is

$$\delta\theta \leq \frac{10}{2.5 \times 18 \times \sqrt{8}} = 0.08\ \text{mrad} \qquad (6)$$

From Table I, each magnet bends 2.7°(= 47.12 mrad) implying that the random field error allowed is $\Delta B_o/B = 1.7 \times 10^{-3}$. For the design criterion we demand

$$\Delta B_o/B \leq 10^{-3} \qquad (7)$$

for the bending field error. Similar accuracy is required for the trajectories of off-momentum particles; therefore, the above field uniformity should be satisfied everywhere inside the ± 4 cm region of the horizontal aperture. The same argument can be applied to the vertical plane to obtain $\Delta\theta \leq 0.04$ mrad.

Gradient Field Errors

The relationship of betatron function and dispersion function to a systematic gradient change in the lattice can be found by running the lattice design program at different gradients. The results show that a systematic change of the gradient up to $\Delta G/G \lesssim 10^{-2}$ only introduces a few percent change in betatron function and dispersion function. For design criterion, we demand that $\Delta G/G\,)_{sys} \leq 5 \times 10^{-3}$.

On the other hand, a random gradient error from magnet to magnet can cause orbit error for the off-momentum particles. From Table I, the gradient of the big bend magnet is G = 0.37 kG/cm. Assuming that the random gadient error is $\Delta G/G = 5 \times 10^{-3}$, then it gives rise to a bending field error at ± 4 cm of $\Delta B_o/B = 0.6 \times 10^{-3}$ which is well within our requirements for orbit error. Therefore, for the requirements on the gradient errors, be it systematic or random, we demand that

$$\Delta G/G \leq 5 \times 10^{-3} \qquad (8)$$

Sextupole Component in Bending Magnets

We employ the ray tracking program TURTLE[3] to check the phase space dilution and distortion introduced by the sextupole component in the gradient magnet. Three modifications are made on the TURTLE ray generation routine to serve our needs: 1) the initial coordinates of the particle produced by the random number generator at the center of quarupole satisfying the following condition,

$$\left(\frac{x}{x_o}\right)^2 + \left(\frac{x'}{x'_o}\right)^2 = 1 \qquad (9)$$

where $x_o = (\varepsilon\beta)^{1/2}$ and $x'_o = (\varepsilon/\beta)^{1/2}$ with $\varepsilon = 1$ mm-mrad and $\beta = 110$ m at the entrance of the big bend. Instead of the conventional equal or "≤" sign in Equation (8), the "=" sign is chosen to populate only the boundary of the phase ellipse to highlight the non-linear effect on large amplitude, 2) the correlation is between x and x' instead of x and y and 3) in addition to central momentum, particles with ± 1% momentum deviation are also generated to show the chromatic effect in one graph. To see the chromatic effects, the phase spase distribution at the end of the transfer line, Q60, is displayed for comparison.

The program introduces non-linear effects by accepting the field change introduced by the sextupole component $\Delta B_2/B$. We have done the tracking run with input parameters $\Delta B_2/B = 1,2,3,4,5 \times 10^{-4}$ cm^{-2}. Shown in Figure 2 is the result for a run with hypothetical sextupole strength of $\Delta B_2/B = 5 \times 10^{-4}$ cm^{-2}. It can be seen that the phase space ellipse is distorted by the sextupole components in the bending magnet and the asymmetry of the effect on positive and negative momentum deviation. Comparing the results from Figure 2 and that from linear lattice calculations by AGS program for $\Delta P/P = 1\%$ beam, we have

	$\Delta B_2 = 0$	$\Delta B_2/B = 5 \times 10^{-4}$	% Change
x_p	- 0.88 m	- 0.80 m	10%
$x_{p'}$	83 mrad	105 mrad	27%

Comparing the results from the tracking runs at various sextupole levels, we find that if we limit $\Delta B_2/B < 2.5 \times 10^{-4}$cm^{-2}, there will be negligible chromatic distortion at Q60.

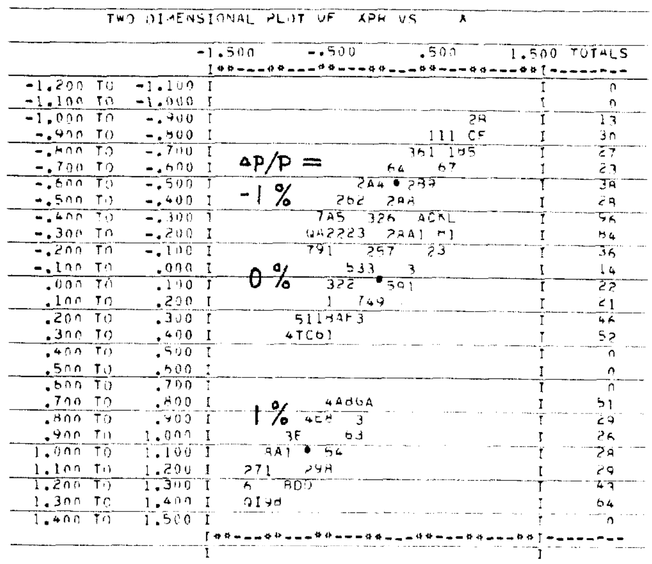

Figure 2 - Effect of the sextupole on the phase space ellipse at Q60 (result shown for $\Delta B_2/B = 5 \times 10^{-4}$ cm^{-2}).

The magnetic field measurement[4] on a prototype gradient magnet shows that the bending and gradient field errors are a factor of two lower than the tolerance set here and that of the sextupole field is a factor of ten lower.

Effect of Magnet Misalignment

The misalignment of either a gradient magnet or quadrupole magnet can cause position error. We already established that the allowed field error is $\Delta B/B = 10^{-3}$ which sets the limit of misalignment error of gradient and quadrupole magnets. The final results and criteria are

	Gradient Magnet G = 0.37 kG/cm	Quadrupole G = 1.5 kG/cm
$\delta x)_{rms}$	0.34 mm	0.45 mm
$\delta y)_{rms}$	0.17 mm	0.23 mm

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