Fermilab

TM-1124
0400

COLLINS' BYPASS FOR THE MAIN RING*

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I. Apologia

There exists a hand-written (but eminently readable) note by Tom Collins on this subject:

> "A By-pass for the Main Ring around BØ (or DØ) after Doubler Operation", June 1981
>
> A technically sound by-pass can be built, which is simple to operate. It disturbes 1/12 of the ring.

In May or June, 1981, a number of people attended a meeting to listen to his presentation of the design. I am sure I was not the only one at the meeting who failed to appreciate the difficulties involved and the ingenious nature of his solution. Even with the written note, I found it hard to see how he arrived at the final design in which some parameters are specified with the accuracy of five digits. My difficulty to understand his work is almost entirely in the area of three-dimensional geometry, a subject about which I know very little. Even Tom admitts that it is not easy to draw a picture of a screw thread, the essential feature of the design. As far as I know, he has not issued any other report on this subject after the original hand-written one. According to Dave Johnson, Lee Teng checked Tom's numbers and found them to be correct. Dave himself tried independently and came to the same conclusion so that at least three people (maybe more although I am not aware of anyone else) have gone through the

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* After seeing the name "The Great Doubler Shift", I am tempted to call this "The Great Main Ring Screw".

arithmetics of the bypass. For reasons which, I believe, are not quite logical or sound, it is again[1] my fate to act as the recorder of other people's work. In all fairness to myself, I should mention that I too have gone through the numbers independently. The specific values of geometrical parameters given in this report are all mine (errors, if any, and everything). However, the lattice parameters such as β's and momentum dispersions have been obtained by Dave Johnson who used his geometrical parameters. Since two geometries, mine and Dave's, are indistinguishable for any conceivable purpose, this "mixing" should be excusable.

In order to avoid any misunderstanding, let me summarize the history of the bypass design, that is, who did what:

1. The main ring bypass presented in this report was designed by Tom Collins in June 1981. As far as I know, nobody else was involved.
2. Both Lee Teng and Dave Johnson have checked Tom's design and found it to be correct.
3. Geometrical parameters given in this report have been ground out by me in May-June, 1982. They are not identical to Tom's original numbers but the difference is insignificant.
4. Lattice parameters of the main ring with the bypass have been given to me by Dave Johnson who used his geometrical parameters.

It is regrettable that a rather lengthy story must be included here because of the abnormal and unhealthy practice of someone doing the work and another reporting on it, especially when the reporter's contribution cannot be called substantial. The only justification for this seems to be the desirability of having reports made with some sort of identifiable numbers, e.g., TM-1124.

II. Requirements and Design Considerations

Tom Collins lists five constraints to be satisfied in an acceptable bypass design. Inasmuch as the design is his, I will record here his constraints verbatim:

a) space must be generated for additional bending elements in a practical manner,
b) the new path must "close" to the old orbit to a high precision in both horizontal and vertical, and at all energies, with a minimum of external programmed control,
c) the path length must be the same as before - or differ by an integral number of rf wavelengths -,
d) the betatron functions must be matched,
e) residual new dispersion (change of η) <u>outside</u> the by-pass must be small.

Specific design features to cope with these constraints are as follows:

a) <u>space</u> Tom's solution involves no real added space for the necessary bends. Instead, a number of dipoles are converted to vertical bends and they are ramped, together with neighboring horizontal dipoles, at twice the normal field of all other dipoles. Since the saturation becomes nontrivial beyond ∿18 kG, this mode will limit the main ring operation to ∿200 GeV or lower. One system, called (a) by Tom, uses eight vertical dipoles and the equal number of horizontal dipoles excited by a special power circuit. This produces a vertical orbit displacement of 19' or so. Another system, called (a)+(b), creates 25' with twelve vertical dipoles and fifteen horizontal dipoles. The total number of dipoles in the main ring for this system will be 771 instead of 774.

b) <u>geometric closure</u> There are really no "tricks" here. One must follow the orbit and see to it that it closes without any kinks at both ends of the bypass. The three-dimensional geometry for this calculation is very difficult to draw and equally difficult to visualize.

c) <u>path length</u> The path length is made exactly the same as the original orbit length (and the length of the superconducting ring) by bending up-and-down combined with a small (∿2') amount of inward bypass. The inward bend decreases the orbit length by "cutting across" and compensates for the extra $\sim$8" length coming from the vertical bending. Inward bends are created by rolling the vertical dipoles and the amount of rolls is adjusted for the horizon closure of the orbit.

d) matching of betatron functions The lattice structure is essentially unchanged since quadrupole locations along the path remain the same. This is possible when the path length is unchanged. Effects coming from the special dipoles are negligible. In order to avoid some strange and uncomfortable coupling between horizontal and vertical directions, Tom adopted the geometry of a screw thread, to me the most ingenious of design features. In the screw-thread geometry, all elements (dipoles and quadrupoles) between two vertical bends have the common pitch ("vertical" angle or "fore and aft" angle) and zero roll. The roll here means a rotation of magnets around the incoming beam direction. As the orbit goes up or down, the bend center of dipoles is also moved up or down in order to maintain the same pitch. A conceptually much simpler geometry is what Tom calls a "great circle". There is only one bend center common to all dipoles and it is on the horizontal plane of the ring. The undesirable features of this arrangement are summarized by Tom and I quote:

" — every magnet has a different pitch and roll,
— the vertical kick to flatten the by-pass at the top is substantially less than the initial kick preventing simple series operation,
— quads are also rolled; at the top, they can be levelled creating horizontal-vertical coupling, or continue rolled confusing horizontal and vertical dispersion!

All difficulties are resolved by constructing a Screw Beam."

e) external dispersion This is minimized by the optimum choice of locations for the vertical bends. Ideally speaking, there should be no vertical dispersion η_y outside the bypass. It is possible to achieve this by locating a pair of bend-up and bend-down of equal angle at two places in the ring with the same β_v and the phase distance of $2n\pi$. Since a realistic bypass should be limited to a reasonable length which covers but a small fraction of the ring, the phase distance between bends is unlikely to be exactly $2n\pi$. Tom's criterion here is to limit the maximum $|\eta_y|$ to $\sim$0.5m outside so that there will be very little loss of $\bar{p}p$ luminosity caused by the dispersion mismatch. Assuming that the total radial beam size is determined by the quadratic sum of betatron amplitude and momentum dispersion, one sees that this is reasonabl for

— 8 GeV protons from booster to main ring,
— 150 GeV protons from main ring to superconducting ring,
— 8 GeV $\bar{p}$ beam from the accumulator to main ring, and
— 150 GeV $\bar{p}$'s from main ring to superconducting ring.

For the solution (a) in Tom's note, the vertical bends are chosen to be at

A39-3,4 (up); B12-3,4 (down) - phase advance 348°
A47-3,4 (down); B18-3,4 (up) - phase advance 348°.

For the solution (a)+(b), there are two extra pairs in addition to these. At each bend location, there is only one dipole and it is at the center of four original dipole slots:

A42 (up); B13 (down) - phase advance 348°
A47 (down); B17 (up) - phase advance 349°.

III. Formulas for Geometry and for SYNCH (or TRANSPORT)

There are many formulas given in Tom's note which are presumably necessary and sufficient for the screw thread geometry. Instead of struggling to reproduce them, I have used my own recipe in following the orbit in space. The coordinate system (X,Y,Z) is the so-called main ring coordinates (X,Y) with the vertical coordinate Z added. The original main ring plane is Z = 0 and Z is positive going up in space. Two angles are needed, θ_h and θ_v. When the orbit is projected on Z=0 plane, θ_h is the angle between the positive Y-axis and the projected orbit. Note that the positive Y-axis is the "Project North" and the main ring beam direction in the transfer hall is θ_h = +22mrad by definition. AØ is the origin of the main ring coordinate system.

The vertical angle θ_v is the angle between the orbit and its projection on Z=0 plane. A very useful, general formula was shown to me by Leo Michelotti. A vector $\bar{v}$, when rotated around a unit vector $\bar{e}$ by an angle θ, becomes $\bar{v}'$:

$$\bar{v}' = \cos(\theta)\cdot\bar{v} + \sin(\theta)\cdot(\bar{e}\times\bar{v}) + (1 - \cos\theta)(\bar{e}\cdot\bar{v})\cdot\bar{e}$$

In formulas given below, the subscript "1" is used for the incoming beam and "2" for the outgoing beam.

1. <u>drift or quadrupole</u>, length D.

θ_h and θ_v unchanged,

$Z_2 = Z_1 + D\cdot\sin(\theta_v)$,

$X_2 = X_1 + D\cdot\cos(\theta_v)\sin(\theta_h)$, $Y_2 = Y_1 + D\cdot\cos(\theta_v)\cos(\theta_h)$.

2. <u>horizontal dipole</u>, <u>no roll</u>, arc length $\ell>0$, bend angle $\phi>0$.

Define $R \equiv \ell/\phi$ and $d \equiv R\cdot\tan(\phi/2)$.

θ_v unchanged but $\theta_{h,2} = \theta_{h,1} + 2\cdot\sin^{-1}\{\sin(\phi/2)/\cos(\theta_v)\}$,

$Z_2 = Z_1 + 2\cdot d\cdot\sin(\theta_v)$,

$X_2 = X_1 + (\Delta x)\cos(\theta_{h,1}) + (\Delta y)\sin(\theta_{h,1})$,

$Y_2 = Y_1 - (\Delta x)\sin(\theta_{h,1}) + (\Delta y)\cos(\theta_{h,1})$

where $\Delta x \equiv d\cdot\cos(\theta_v)\cdot\sin(\theta_{h,2} - \theta_{h,1})$,

$\Delta y \equiv d\cdot\cos(\theta_v) + d\cdot\cos(\theta_v)\cos(\theta_{h,2} - \theta_{h,1})$.

Note that the magnet pitch δ is almost but not exactly the same as the beam pitch θ_v,

$$\delta = \sin^{-1}\{\sin(\theta_v)/\cos(\phi/2)\}.$$

3. <u>vertical dipole with roll</u>, arc length $\ell>0$, roll angle $\tau>0$,

for 'bend up and in', bend angle $\phi>0$,

for 'bend down and out', bend angle $\phi<0$.

Regardless of their polarities, vertical dipoles are always rolled such that the top surface is tilted inward. In the parlance of main ring tunnel, the roll is always "wall-side up, aisle-side down".

Define: $R \equiv \ell/\phi$, positive or negative,

$d \equiv R \cdot \tan(\phi/2)$, always positive.

Then, $\sin(\theta_{v,2}) = \sin(\theta_{v,1})\cos(\phi) + \cos(\theta_{v,1})\sin(\phi)\cos(\tau)$,

$$\Delta x \equiv d\cdot\sin(\phi)\sin(\tau), \qquad (\Delta y)_a \equiv d\cdot\cos(\theta_{v,1}),$$

$$(\Delta y)_b \equiv d\cdot\{\cos(\theta_{v,1})\cos(\phi) - \sin(\theta_{v,1})\sin(\phi)\cos(\tau)\},$$

$$\Delta y \equiv (\Delta y)_a + (\Delta y)_b,$$

$$\theta_{h,2} = \theta_{h,1} + \tan^{-1}\{(\Delta x)/(\Delta y)_b\},$$

$$Z_2 = Z_1 + d\cdot\sin(\theta_{v,1}) + d\cdot\sin(\theta_{v,2}),$$

$$X_2 = X_1 + (\Delta x)\cos(\theta_{h,1}) + (\Delta y)\sin(\theta_{h,1}),$$

$$Y_2 = Y_1 - (\Delta x)\sin(\theta_{h,1}) + (\Delta y)\cos(\theta_{h,1}).$$

Once the geometry is fixed, one can calculate the lattice parameters using a standard program such as SYNCH. However, Dave Johnson has found out that SYNCH in the presently available version cannot handle a bending element with a roll properly. He had to replace such an element with a suitable matrix. He then checked the bypass part with TRANSPORT which can handle any rolls. The angle to be used for the X-Y rotation (Type Code 20.) should be as follows:

1. pure vertical kick (for kick down)

   $+90^\circ$ at the entrance, -90° at the exit.

2. horizontal bend <u>with no roll</u>

   At the entrance and at the exit, rotate by the same amount <u>in the same direction</u> (not the reverse);

   $$\text{angle} = \sin^{-1}\{-\tan(\phi/2)\cdot\tan(\theta_v)\}$$

where the bend angle ϕ is always positive but the beam pitch θ_v can be positive, negative or zero.

3. vertical bend with roll $\tau>0$.

At the entrance, rotate by $-90^\circ + \tau$ for 'bend up & in',
$+90^\circ + \tau$ for 'bend down & out'.

At the exit, rotate by α,

$$\tan(\alpha)\sin(\tau) = \cos(\phi)\cos(\tau) - \tan(\theta_{v,1})\sin(\phi),$$

τ is always positive,
ϕ is positive for 'bend up & in', negative for 'bend down',
$\theta_{v,1}$ is the vertical angle of the incoming beam,
α is positive and less than 90° for 'bend up & in',
negative and $|\alpha|$ larger than 90° for 'bend down & out'.

IV. Geometry of the Screw Orbit; Lattice Parameters

For the exact orbit closure five quantities X, Y, Z, θ_h and θ_v at the downstream end of bypass must take the original values of the main ring. In addition, it is desirable to have the bypass long-straight "flat", i.e., $\theta_v=0$ on top of the bypass. There are four free parameters at one's disposal, roll angles at four vertical bend locations.* For two more parameters needed to meet six conditions, Tom chooses to displace quadrupoles (A39-1,A42-1) and (B18-1,B19-1) vertically such that they always kick the beam downward. The amount of kick angle would then be independent of the beam energy if one ignored the remanent quadrupole gradient at 8 GeV. However, he cannot be really serious in this proposal; the necessary displacement is only five to six mils giving $\sim$-10μrad at each of two locations. It should be mentioned here that the standard steering dipoles used in the main

* Tom's solution (a) will be presented here although the geometry for his solution (a)+(b) has also been worked out and available.

ring for the closed-orbit correction at 8 GeV can produce $\int B \cdot d\ell \simeq$ ± 200 G-m each which corresponds to $\sim 30\mu$rad at 200 GeV. It is hard to imagine that the bypass would work without some sort of vertical and horizontal steering system that could track the beam from 8 GeV to 200 GeV. The necessary vertical bend of 20μrad total would easily be absorbed in the system.

coordinates

upstream, station A39 ($Z = \theta_v = 0$)

X	Y	θ_h
962.531'	2,285.083'	0.8175454 rad.

downstream, station B19 ($Z = \theta_v = 0$)

X	Y	h
2,507.920'	3,128.673'	1.3127319 rad.

note: $\theta_h(\mathrm{B19}) - \theta_h(\mathrm{A39}) = (2\pi/774)\times 61$

design parameters

1. pure vertical kicks (steering dipoles)

   -10.70μrad at station A39,
   -11.03μrad at station B18.

2. vertical bends with roll τ

   A39-3,4 'bend up & in', $\tau = 0.10961$ rad each,
   A47-3,4 'bend down & out', $\tau = 0.11260$ rad each,
   B12-3,4 'bend down & out', $\tau = 0.11301$ rad each,
   B18-3,4 'bend up & in', $\tau = 0.10998$ rad each.

Coordinates at each station between A39 and B19 are given in Table 1 where numbers in parentheses are for the original main ring.

Table 1. Bypass coordinates. Numbers in parentheses are for the original main ring ($Z=\theta_v=0$).

station	X(feet)	Y(feet)	θ_h(rad)	Z(inches)	θ_v(rad)
A39	962.531	2,285.083	.8175454	0.000	0.00000
	(962.531)	(2,285.083)	(.8175454)		
A42	1,034.911	2,350.493	.8535781	19.286	.0322656
	(1,034.808)	(2,350.639)	(.850017)		
A43	1,109.464	2,413.368	.8860663	57.063	.0322656
	(1,109.175)	(2,413.813)	(.882488)		
A44	1,186.021	2,473.789	.9185544	94.840	.0322656
	(1,185.554)	(2,474.539)	(.914959)		
A45	1,264.500	2,531.691	.9510426	132.617	.0322656
	(1,263.864)	(2,532.754)	(.947430)		
A46	1,344.818	2,587.013	.9835307	170.393	.0322656
	(1,344.023)	(2,588.396)	(.979902)		
A47	1,426.890	2,639.697	1.0160189	208.170	.0322656
	(1,425.946)	(2,641.406)	(1.012373)		
A48	1,533.772	2,703.332	1.0448499	226.656	.0000000
	(1,509.547)	(2,691.728)	(1.044844)		
BØ	1,686.376	2,787.887	1.0692033	226.656	.0000000
	(1,685.357)	(2,789.756)	(1.069198)		
B11	1,772.743	2,835.248	1.0692033	226.656	.0000000
	(1,771.723)	(2,837.117)	(1.069198)		
B12	1,870.616	2,887.172	1.1016746	226.656	.0000000
	(1,869.596)	(2,889.042)	(1.101669)		
B13	1,958.274	2,929.994	1.1304914	207.364	-.0322641
	(1,957.352)	(2,931.709)	(1.134140)		
B14	2,047.177	2,970.092	1.1629795	169.589	-.0322641
	(2,046.446)	(2,971.504)	(1.166611)		
B15	2,137.335	3,007.281	1.1954677	131.815	-.0322641
	(2,136.786)	(3,008.386)	(1.199083)		
B16	2,228.654	3,041.523	1.2279558	94.040	-.0322641
	(2,228.275)	(3,042.315)	(1.231554)		
B17	2,321.037	3,072.779	1.2604440	56.265	-.0322641
	(2,320.818)	(3,073.256)	(1.264025)		
B18	2,414.047	3,102.116	1.2766880	18.491	-.0322641
	(2,413.981)	(3,102.275)	(1.280261)		
B19	2,507.920	3,128.673	1.3127319	.000	.0000000
	(2,507.920)	(3,128.673)	(1.312732)		

Dave Johnson used SYNCH with some modifications to calculate lattice parameters when the bypass was introduced at BØ in the main ring. He then used TRANSPORT to check the parameters inside the bypass, from A39 to B19. Lee Teng has the output from this SYNCH run while Dave is keeping the TRANSPORT results. Outside the bypass, there are no big surprises. As Tom has predicted, the maximum $|\eta_y|$ is ∿0.5m and the perturbation to η_x is totally negligible. Inside the bypass, the change in η_x (which is really the momentum dispersion in the bend plane) from the original main ring value is not significant as one can see from Table 2.

Table 2. The momentum dispersion in the bend plane with and without bypass.

	with bypass	without bypass		with bypass	without bypass
A39 =	2.86m	2.84m	A42 =	5.77m	5.67m
A43 =	3.45	3.32	A44 =	5.63	5.36
A45 =	2.63	2.50	A46 =	3.36	3.26
A47 =	1.36	1.40	A48 =	1.74	2.00
B12 =	1.07	1.26	B13 =	2.02	2.13
B14 =	1.71	1.68	B15 =	4.04	3.84
B16 =	3.00	2.84	B17 =	5.91	5.65
B18 =	3.02	2.94	B19 =	4.17	4.13

The substantial change is of course the appearance of the dispersion η_y in the plane perpendicular to the bend plane of each dipole. If this is too large, the gap of some dipoles may not be enough for the total "vertical" beam size. Potentially troublesome spots are:

1) A39-3,4 vertical bend
   Presumably, main ring B2 dipoles (rotated) will be used here.
   gap = 1.9", η_y= 3.6 - 4.9m, β_y= 43 - 77m

2) A48-4,5 horizontal bend, B1 dipoles.
   gap = 1.4", η_y = 2.8 - 3.8m, β_y = 43 - 67m.

3) upstream end of the long straight, vertically focussing 7' quadrupole, the vertical gap is $2\sim3.4$".
   η_y = 5.1 - 5.2m, β_y = 118 - 123m.

4) B18-3,4 vertical bend (main ring B2 dipoles)
   gap = 1.9", η_y = 3.2 - 3.8m, β_y = 42 - 73m.

V. Foreboding* (or Pessimist Speaking)

It is reassuring to see the statement by Tom Collins, which is cited on the first page, that this bypass design is "technically sound". Going over the calculation, one does not see any errors or even some difficulties that may occur in the operation of the bypass. Yet, I do not believe this is a project we can contemplate lightheartedly. There have been no analyses of the necessary steering system and other correction systems, this mostly because of our ignorance on the alignment accuracy we should be able to achieve. Installation of dipoles and quadrupoles with their pitches and rolls is certainly a challenging task but a large dose of frustration seems unavoidable.
As Tom has pointed out, it is not easy to construct special magnets for vertical bends. We would probably use the existing main ring B2 dipoles for this purpose. The physical dimension of the gap is no more than 1.9" and the available magnetic aperture must certainly be less than that. The aperture may be enough, even at A39-3,4 where the dispersion η_y is almost 5m and β_y is close to 80m, for the 8 GeV proton beam provided the steering is done properly. However, it is not so obvious that the same gap is large enough to accomodate the precious $\bar{p}$ bunches with their uncertain transverse emittance and momentum spread.

* "a vague fear of the future, inferred irrationally from clues in the present." - The American Heritage Dictionary of the English Language, New College Edition.

The situation would be more serious if the clearance of 19' were not enough and we had to consider the solution (a)+(b). The maximum dispersion inside the bypass is close to 8m for this solution. By giving θ_h with an eight-digit accuracy, I may have succeeded in showing that the orbit closure is mathematically perfect. However, nobody should be fooled by this to mean that the system should work like a Swiss watch.

Reference

1. EXP-83, August 15, 1977; EXP-84, August 25, 1977; TM-1032, March 17, 1981.