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Beampipes for Forward Collider Detectors

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Abstract

The configuration of a forward detector at a collider is similar to that in a fixed-target experiment except for the necessary presence of a beampipe at colliders, with the attendant possibility of secondary-particle production in the pipe wall. We review the efficacy of various beampipe geometries in minimizing this background. Less detailed discussions of this subject are given in refs. [1]-[4].

1 Straight Pipe

The simplest beampipe at a collider is a straight cylindrical pipe of radius r and thickness t. Preferably it is made of beryllium, whose radiation length is 35 cm, and whose pion interaction length is 112 cm. Straight pipes of small radius can be made as thin as 0.3 mm, corresponding to 0.001 radiation length and 0.0003 interaction lengths.

The 'beampipe problem' is that for (straight) tracks at small angles θ to the beam the effective thickness of the beampipe is

$$t_{\rm eff} \approx \frac{t}{\theta}, \qquad \text{(straight pipe)}.$$

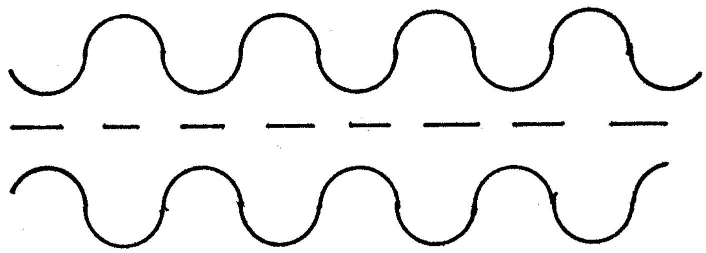
Thus, for example, for angles $\theta < 1$ mrad (or pseudorapidity $\eta \equiv -\ln\tan\theta/2 > 7.6$) the beampipe presents more than one radiation length to the track, and more than 1/3 interaction length.

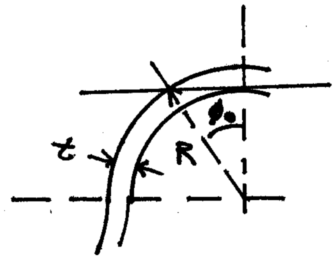
The ensuing secondary interactions render charged-particle tracking and identification very difficult, although calorimetry is less disturbed.

If one requires that less than 0.1 radiation lengths are encountered by the track, the straight pipe could not be used for $\eta > 5.3$, *etc.*

2 Corrugated Pipe

For larger radii and thin walls a straight pipe is considered unstable against implosion, and a corrugated pipe is often used. Typically the profile of the corrugations is a sequence of half circles of radius R:





For tracks at small angles to the beam the average path length T inside the pipe wall is

$$\langle T \rangle = \int_{\sin\phi_0}^{1} \frac{t}{\sin\phi} d\sin\phi = \frac{t}{2} \ln\frac{R}{t}$$

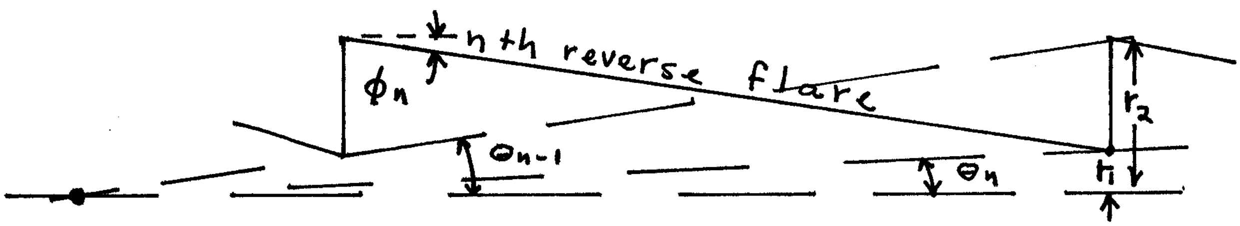
per wall crossing, noting that the longest path occurs for a track whose intercept with the arc of the pipe subtends angle ϕ_0 given by $t = R(1 - \cos\phi_0)$, as shown in the sketch. With two wall crossing per period of length $4R$, the total number of wall crossings for a track at angle θ is just $1/\theta$, and so the effective thickness of the corrugated pipe is

$$t_{\text{eff}} \approx \frac{t}{2\theta} \ln\frac{R}{t}, \qquad \text{(corrugated pipe)}.$$

Thus a corrugated pipe presents more material to a track than a straight pipe for corrugations of radius R greater than $7.4t$ – as is typical!

3 Reverse-Flared Pipe

Before considering in detail the option of a flared pipe, we examine the possibility of a reverse-flared pipe, as shown in the sketch:



While an expression for the path length inside the wall material can be derived for arbitrary configurations of flares, it is sufficient to consider a typical geometry as shown above. In this all tapered sections have the same inner and outer radii, r_1 and r_2, respectively. The spacings of the flares have been chosen so that a track that passes through the inner radius of the nth flare just passes through the outer radius of the $n+2$nd flare (meanwhile passing through an intermediate region of the $n+1$st flare). For definiteness we suppose that the track through the inner radius of the nth flare has pseudorapidity $\eta = n$, so the corresponding polar angle is

$$\theta_n \approx 2e^{-n/2},$$

for $n > 1$. The reverse flare of the nth section makes angle ϕ_n to the beam related by

$$\tan\phi_n = \frac{r_2 - r_1}{z_n - z_{n-1}} \approx \frac{r_2 - r_1}{\frac{r_1}{\theta_n} - \frac{r_1}{\theta_{n-1}}},$$

where z_n is the distance along the beams from the crossing point to the inner radius of the nth flare section. For $r_2 \gg r_1$, and $n > 1$ we approximate

$$\phi_n \approx \frac{r_2}{r_1}\theta_n.$$

A track at angle θ with $\theta_n < \theta < \theta_{n-1}$ crosses the wall of the nth flare at angle $\theta + \phi_n$. This track passes through the nth flare, the vertical section between the nth and n + 1st flare, and finally through the n + 1st flare for a total path length of

$$t_{\rm eff} = t\left(\frac{1}{\theta+\phi_n} + 1 + \frac{1}{\theta+\phi_{n+1}}\right) \approx \frac{t}{\theta}\left(\frac{r_1}{r_2}\frac{\theta}{\theta_n}(1+\sqrt{e})\right).$$

In our model θ/θ_n varies between 1 and $\sqrt{e}$ for tracks passing through the nth flare. Hence the ratio of path length in the reverse-flared pipe to that in a straight pipe obeys

$$2.6\frac{r_1}{r_2}\frac{t}{\theta} < t_{\rm eff} < 4.4\frac{r_1}{r_2}\frac{t}{\theta}, \qquad \text{or} \qquad t_{\rm eff} \approx 3.3\frac{r_1}{r_2}\frac{t}{\theta} \qquad \text{(reverse-flared pipe)}.$$

For example, if $r_1/r_2 = 1/10$ then the reverse-flared pipe presents only about 1/3 as much material as the straight pipe, IF the flared pipe could be made of the same thin material as the straight pipe.

However, as with the straight pipe, the reverse-flared pipe suffers the beampipe problem at small angles: the path length inside the wall material becomes arbitrarily large.

4 Flared Pipe

A possible solution to the beampipe problem is the use of a flared pipe with one or more conical segments in which the apex of the cone of half-angle θ_0 lies at the interaction point. The surface of the cone may be smooth, or corrugated; we have just seen how the latter presents more material to tracks that intersect the surface of the cone at small angles.

The flared pipe would be a nearly perfect solution to the beampipe problem if the interaction point were truly a point. In practice the interactions take place along a finite luminous region of the beamline with an approximately gaussian profile of r.m.s. length σ. Tracks that emanate from a point z not at the center ($z = 0$) of the luminous region will intersect the conical surface of the flared pipe if the track angle lies in some interval around θ_0. Here we calculate the corresponding pseudorapidity interval.

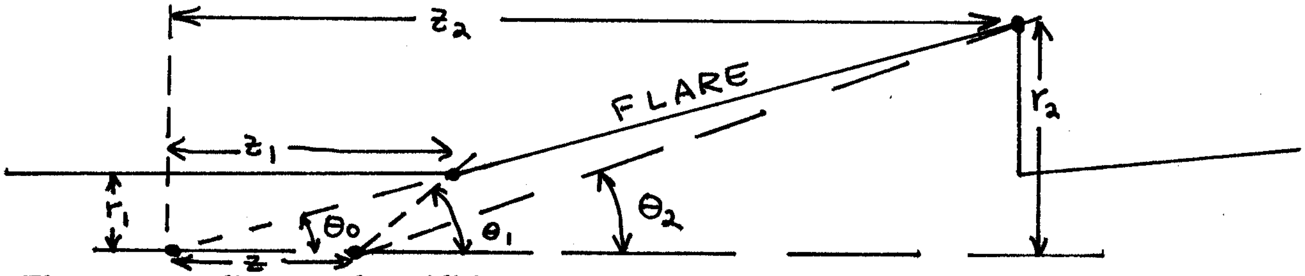
We suppose the flare begins at radius r_1 at distance z_1 from the interaction point, and ends at radius r_2 at distance z_2. These are related to the cone angle by

$$\frac{r_1}{z_1} \approx \theta_0 \approx \frac{r_2}{z_2}, \qquad \text{so that} \qquad z_2 - z_1 \approx \frac{r_2 - r_1}{\theta_0}$$

is the length of the flare along the beam. Then the angle of a track emanating from position z along the beam and intersecting the near end of the flare is

$$\theta_1 \approx \frac{r_1}{z_1 - z} \approx \theta_0\left(1 + \frac{z}{z_1}\right),$$

and similarly for θ_2, the angle of a track that intersects the far end of the flare.



The corresponding pseudorapidities are

$$\eta_i \approx \ln 2 - \ln \theta_0 - \frac{z}{z_i},$$

and so the rapidity interval for which tracks intersect the flare is

$$|\Delta\eta(z)| \approx z\left(\frac{1}{z_1} - \frac{1}{z_2}\right) = z\theta_0 \frac{r_2 - r_1}{r_1 r_2} \approx \frac{z\theta_0}{r_1}.$$

The average rapidity interval for intersection with the flare is obtained by averaging over the gaussian profile of the luminous region:

$$\langle\Delta\eta\rangle \approx 2\int_0^\infty |\Delta\eta(z)| \frac{e^{-z^2/2\sigma^2}}{\sqrt{2\pi}\sigma} dz = \sqrt{\frac{2}{\pi}} \frac{\sigma\theta_0}{r_1}.$$

At the SSC the radius of the beampipe might well be $r_1 = \sqrt{\pi/2} = 1.25$ cm, so

$$\langle\Delta\eta\rangle \approx \sigma[\text{cm}]\theta_0 \approx 7\theta_0,$$

using $\sigma = 7$ cm as anticipated at the SSC. Some numerical examples are listed below for $\langle\Delta\eta\rangle$ *vs.* the central rapidity η_0 of the flare:

$\langle\Delta\eta\rangle$	η_0
1	2.64
0.3	3.84
0.1	4.94
0.03	6.14
0.01	7.24

If a track intersects the flare the grazing angle with the conical surface is of order

$$\theta_{\text{grazing}} \approx \theta_1 - \theta_0 \approx \frac{z}{r_1}\theta_0^2.$$

As $z/r_1 \approx 1$ the grazing angle is very small, and any track that hits the flare will almost certainly interact in the flare wall.

Thus a flared pipe is of little use $\eta <$ 4-5, but a thin straight pipe suffices in this region..

5 Effect of a Magnetic Field

In the preceding we have supposed that the tracks are straight. If they encounter a magnetic field before hitting the beampipe the resulting deflections aggravate the beampipe problem.

If the kick of the magnetic field is ΔP_t then the deflection angle is

$$\Delta\theta = \frac{\Delta P_t}{P} \approx \frac{\Delta P_t}{P_t}\theta,$$

where θ is the production angle of the track. Because of the deflection, charged tracks produced within $\pm\Delta\theta$ of the cone angle θ_0 of the flare can intersect the flare, even if the luminous region had zero length.

In many detector designs the magnet kick is about 1 GeV/c which is approximately the average transverse momentum of the particles. In this case,

$$\Delta\theta \approx \theta,$$

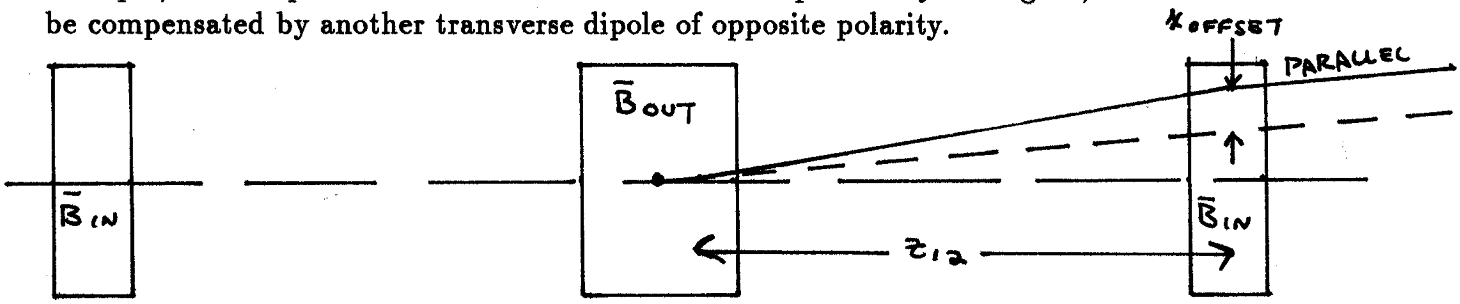
and so the rapidity interval over which tracks can be deflected into the flare is

$$\Delta\eta \approx 2\ln 2 = 1.4.$$

In this case a flared pipe is nearly useless at any rapidity.

6 Effect of an Antisymmetric Pair of Magnetic Fields

If a magnetic field exists on the beam with a transverse component, this must be compensated with an opposite field to minimize the perturbation on the orbits in the collider. For example, in an experiment that utilizes a transverse dipole analysis magnet, its field should be compensated by another transverse dipole of opposite polarity.



A charged particle that is produced at angle θ to the beam once again has angle θ after passing through both magnetic fields, but the track is offset from its original path. If each field produces kick ΔP_t, then the offset is

$$x_{\text{offset}} \approx \frac{\Delta P_t}{P_t}\frac{z_{12}}{z}x_0,$$

where x_0 would be transverse position of the track at distance z from the interaction point in the absence of the fields, and z_{12} is the distance between the two compensating field regions. For magnet kicks of order 1 GeV/c we have

$$x_{\text{offset}} \approx \frac{z_{12}}{z}x_0.$$

For tracks observed well beyond the second magnet the effect of the pair of kicks is very slight.

Also, if a flare is located beyond the second magnet, the bad influence of the first field leading to intersections of tracks with the flare is greatly reduced. The worst remaining effect is that tracks initially deflected to larger angles will strike the beampipe upstream of the flare, if their pseudorapidity is within $\ln 2$ of that of the flare.

In practice, a compensating magnet would be located no closer than about 20 m from the crossing point, so that a flare beginning there with an inner radius of 1 cm would correspond to $\eta_0 = 8.3$ Hence for compensated transverse dipoles there remains a beampipe problem in the range $5 < \eta < 8$.

7 Conclusions

A straight beampipe is the best for pseudorapidity up to 5. A corrugated pipe is mechanically superior to a straight pipe, but presents more material to small-angle tracks. A reverse-flared pipe can in principle appear thinner than a straight pipe, but still presents unacceptably large effective thicknesses for $\eta > 5$. Beyond this value a flared pipe may help reduce interactions in the pipe. A magnetic field that imparts a kick of order 1 GeV/c to charged tracks prior to the flare renders the flare largely useless. Some of this bad effect is mitigated if the necessary compensating field is applied prior to the flare. A complete solution to the beampipe problem may require spectrometer magnets that are only solenoids, quadrupoles, or higher multipoles as advocated by Bjorken [4].

8 References

[1] K.J. Foley *et al.*, *A Beauty Spectrometer for the SSC*, Proceedings of the Workshop on Experiments, Detectors and Experimental Areas for the Supercollider, R. Donaldson and M.G.D. Gilchriese eds. (Berkeley 1987) p. 759.

[2] A. Brandt *et al.*, *Study of Beauty Physics at the SPS-Collider with Real-Time Use of Silicon Microvertex Information*, Proposal to SPSC, CERN-SPSC/88-33 SPSC/P238 (16 January 1989).

[3] BCD Collaboration, *Bottom Collider Detector Expression of Interest*, EOI0008 submitted to the SSC Laboratory (May 25, 1990).

[4] J.D. Bjorken, *A Full-Acceptance Detector for SSC Physics at Low and Intermediate Mass Scales*, SLAC-PUB-5545 (May 1991), EOI0019 to the SSCL.