EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - SL DIVISION

SL/Note 92-65 (EA)

AN ELEMENTARY APPROACH OF A TWO-DIMENSIONAL COLLIMATION SYSTEM FOR LHC

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ABSTRACT

The aim of this note is to understand the two-dimensional aspects of a transverse collimation system. A basic frame is proposed, to be improved by a more formal approach.

Geneva, Switzerland
23 November, 1992

(SL/EA/Notes. '92)

1. INTRODUCTION

The collimation in LHC must be efficient in the two transverse dimensions. Up to now, the subject has been treated in depth only as two one-dimensional systems (1). A full two-dimensional system must take into account the case of a particle which scatters, for example, in the horizontal primary collimator and is re-emitted with a substantial vertical angle. The overall problem was raised in (2), while in (3) a proposal is made to use curved collimators, but a complete treatment remains to be carried out.

In this note, I will concentrate on basic optical considerations and propose a minimal set of collimators in view of a complete system. Dispersion considerations do not change substantially the conclusions drawn below and are therefore not further discussed. A separate study of the whole collimation system including dispersion properties, based on the work of T. Trenkler (4), is going on (5).

2. APERTURE AND SCATTERING IN TWO DIMENSIONS

The starting point of this discussion is the two-step one-dimensional collimation system described in (1). It consists of :

- A primary collimator set at + $6\sigma_\beta$ in both transverse planes. They have a flat face, and are not inclined to simplify the discussion. They are named PX and PZ (P for primary, X is the horizontal plane and Z the vertical one).

- Secondary collimator jaws placed at phase advances of 30° and 150° in both planes, retracted by $1\sigma_\beta$ relatively to PX or PZ, i.e. located at $7\sigma_\beta$. They are named SX1+, SX2-, SZ1+, SZ2- (S for secondary, + sign for positive X or Z position [30°], - sign for negative X or Z position [150°]). The choice of the phase advances is made in (1).

In the primary collimator, secondary particles emitted after an inelastic collision are swept out by the D2 magnet in the Pink Book design (1). The particles causing problems are the ones which are elastically scattered out of the collimator jaw. To further simplify the discussion, the following hypothesis are used.

- The scattering in the primary collimator is isotropic in the X'-Z' plane. This is a very good approximation if the jaw is a thin scatterer, which remains barely true if a thick one is used when impact parameters are small. In fact, isotropy is not necessary here but allows, in a simple way, to express the fact that the

(1) L. Burnod, J.B. Jeanneret, CERN SL/91-39 (EA), LHC Note 167.
(2) T. Risselada et al., The CERN ISR Collimator System, IEEE Transactions on Nuclear Science, Vol. NS-26, N°.3, June 1979.
(3) P.J. Bryant and E. Klein, CERN SL/92-40 (AP).
(4) T. Trenkler, CERN/SL/92-50 (EA).
(5) J.B. Jeanneret, T. Trenkler, SL/Note, to be issued in November, 1992.

whole surface of the X'-Z' plane can be covered up to a certain angular amplitude after scattering.

- The scattering angles are in the range

$$b' \in [-b'_{max}, b'_{max}]$$

where b'_{max} is taken to be two times the divergence at $6\sigma_\beta$. This is not far from the Pink Book approach [(1)], but can be somewhat modulated by the design of the primary collimators. In practice, b'_{max} shall be maximized but this is a study which is outside the purpose of this note. The exact value of b'_{max} is affecting the efficiency of collimation but does not influence the conception of the whole system. What matters is that the b' range should be very large, say > 100 times $6\sigma_\beta'$, to dilute the density of the halo emitted by PX or PZ which falls on the aperture limitations of the machine down to 1/10 of the quench threshold to avoid the presence of the secondary collimators. In the expectable b' range of a few times $6\sigma_\beta'$, a factor 2 in that range does not change the conclusions drawn below. In normalized co-ordinates, the aperture can be defined as $L_X = L_Z = L = 6$. Then $L' = L$ and $b'_{max} = 2L' = 2L = 12$.

- Finally, I assume that the first scattering occurs in PX. Then, the "orthogonal plane" is Z. X and Z can be later exchanged to define a complete system.

3. WHAT HAPPENS AFTER SCATTERING IN PX

A particle which hits PX has a X-amplitude $A_X = L = 6\sigma_\beta$. A quite complete discussion of what happens in the X - X' phase-space already exists [(1)]. After the collision, the transverse amplitude has not changed, but an angular kick moves the particle along the X' axis in the normalized phase-space (see fig. 1b).

In the Z - Z' plane, the situation is more complicated. There is no correlation between the density of X and Z emittances. Moreover, even if coupling induces exchanges of amplitude between ε_X and ε_Z, the density of the phases $\varnothing_X$ and $\varnothing_Z$ of the particles exhibits no correlations.

The range of Z-amplitude is $Z \in [-L, +L]$, defined by PZ. The most frequent amplitude is Z = 0, even if $A_X = L$. In that case, Z = Z' = 0 before scattering in PX. This is pictured in fig. 1. The interaction occurs at the positions marked by a cross in fig. 1b and 1c. After scattering, the particles are distributed along a line parallel to the Z' axis, which is located at Z = 0 in the Z - Z' plane, because the Z co-ordinate is not changed by the scattering (fig. 1c).

When the Z-amplitude is not zero, the region of interaction is pictured by the thick line between the crosses in fig. 2a. The Z - Z' occupancy is a circle uniformly populated (the phase $\varnothing_Z$ is not correlated to the X-amplitude A_X) and passing by the two crosses of fig. 2c. The scattering in PX replaces every point on the circle

(1) L. Burnod, J.B. Jeanneret, CERN SL/91-39 (EA), LHC Note 167.

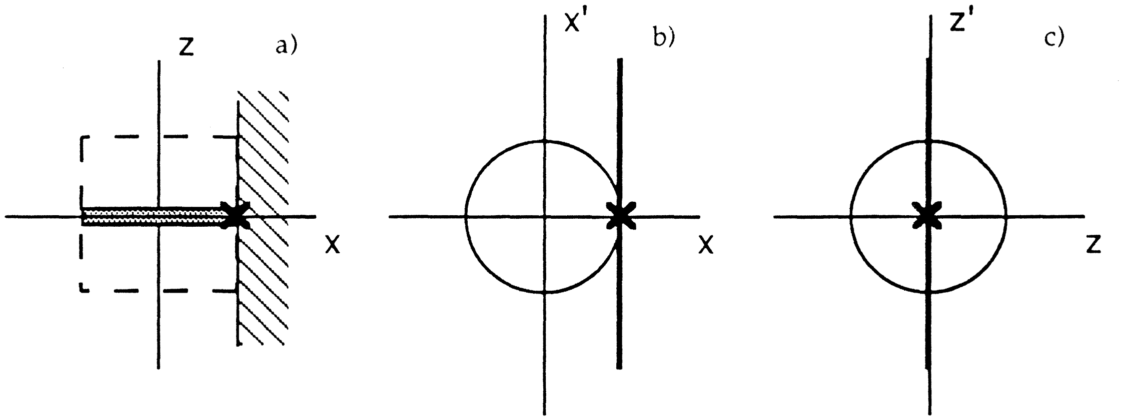

Figure 1: The transverse space x-z and the normalized phase-spaces X-X' (b) and Z-Z' (c). A particle touches the primary collimator of the x-plane while its vertical emittance is near zero. It is scattered isotropically in azimuth in the x'-z' plane.

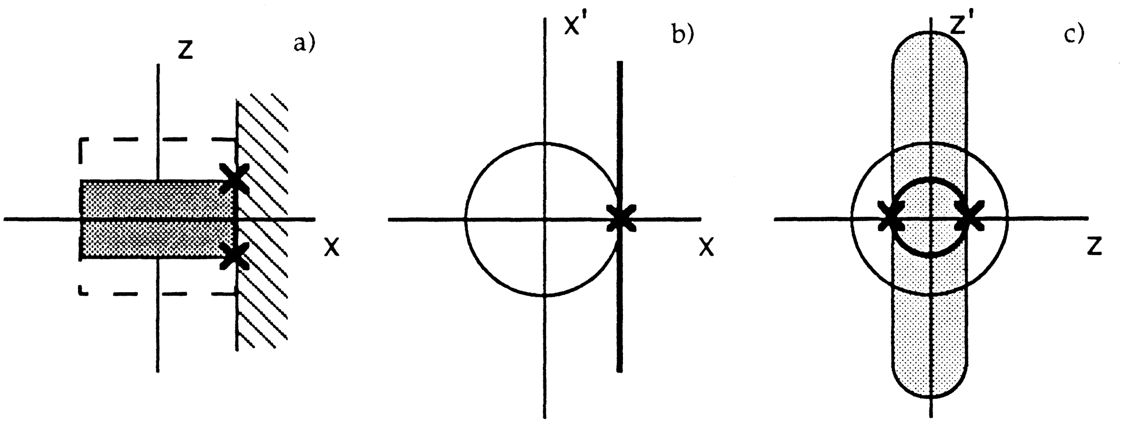

Figure 2: Same as figure 1, but the vertical emittance is different of zero.

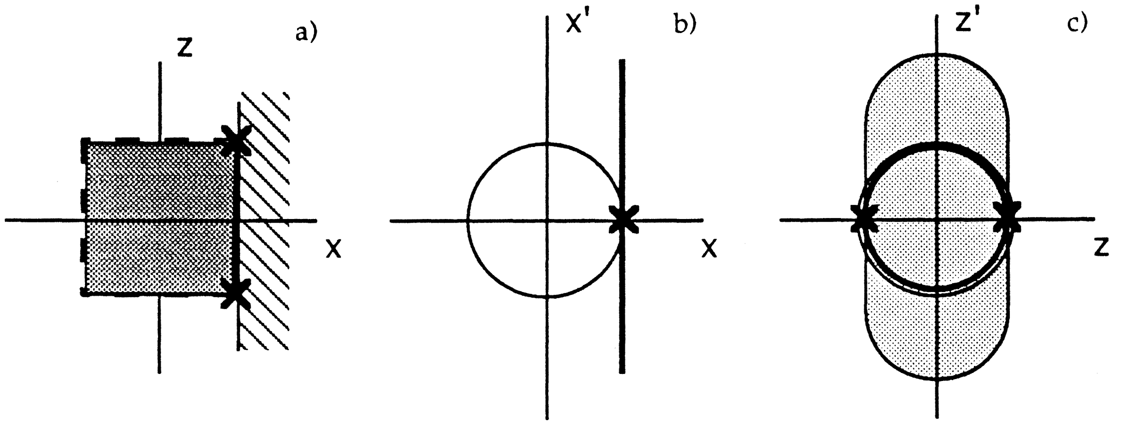

Figure 3: Same as figure 1, but the vertical emittance is near its maximum value fixed by the vertical primary collimator.

by a vertical line, like in fig. 1c. The convolution of the circle with the vertical line generates the area of scattered particles in the Z - Z' plane pictured in fig. 2c.

When the Z-amplitude is maximum, i.e. equal to $6\sigma_\beta$, the grey area of fig. 2c enlarges up to the one pictured in fig. 3c.

The super-imposition of the grey areas corresponding to all possible Z-amplitudes, weighted by their relative densities would make a distribution limited by the grey area of fig. 3c. The region of the vertical central axis has the largest density (dominance of small emittance). The density dies out on all sides (few particles with large z-emittance, and less probable large angle scattering) around the central region.

The fraction of the grey surface which is inside the L = 6 emittance circle causes no worry : the particles scattered there are back again into the aperture in the Z plane. If the X'-scattering angle is large enough, the particle is absorbed by the secondary X-collimators; if it is small it continues to turn, until it touches PX again (most probably).

All the other particles in the grey area, or at least those ones which are quite distant from the aperture circle, must be intercepted in the cleaning area just after being scattered. Part of the job will be carried out by the horizontal secondary collimators SX1+ and SX2-, when b'_x is large enough. All the other ones must be intercepted in the Z-plane.

4. HOW TO COLLIMATE IN THE ORTHOGONAL PLANE

In the orthogonal plane, the collimators SZ1+ and SZ2- will be present anyway for the one-dimensional Z-collimation. Fig. 4 indicates what is cut by these collimators.

A cut all around the 6σ circle must be effected, therefore, more collimators are needed.

By doubling SZ1+ and SZ2- with a jaw opposite to them (SZ1-, SZ2+), the cut improves as it is shown in fig. 5. This is still not enough. The particles located at the top of the remaining triangles have a transverse amplitude in the Z-plane.

$$Z_{max} = \frac{7\sigma}{\sin 30°} = 14\sigma$$

for a 7σ retraction and phase advances of 30° (see fig. 5) and 150°. A neater cut is made by installing a two-jaw collimator at $\Delta\mu_z = 90°$, as shown in fig. 6a. Then, the secondaries scattered in the orthogonal plane are cut to a

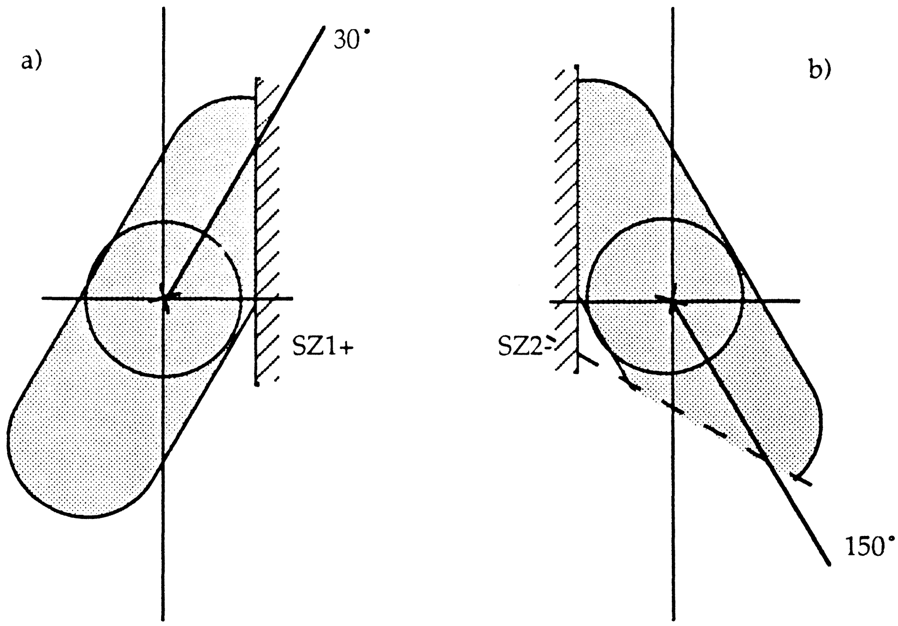

Figure 4: The normalized Z-Z' phase-space (a) at the first secondary z-collimator with the halo emitted by the primary collimator PX and (b) at the second secondary z-collimator.

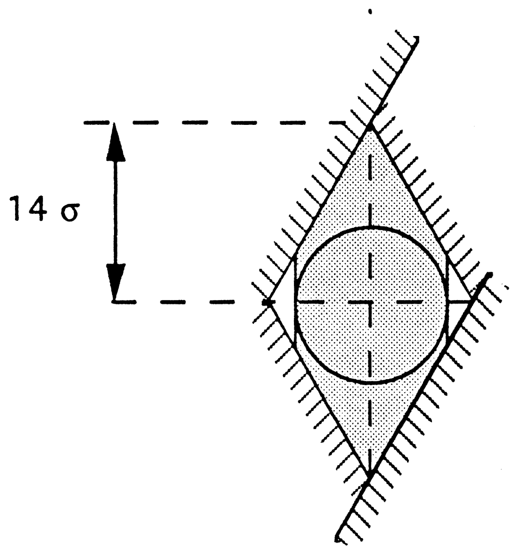

Figure 5: The normalized Z-Z' phase-space (a) at PX with the halo emitted by this collimator, cut by the four jaws located at the phase advances of 30° and 150°.

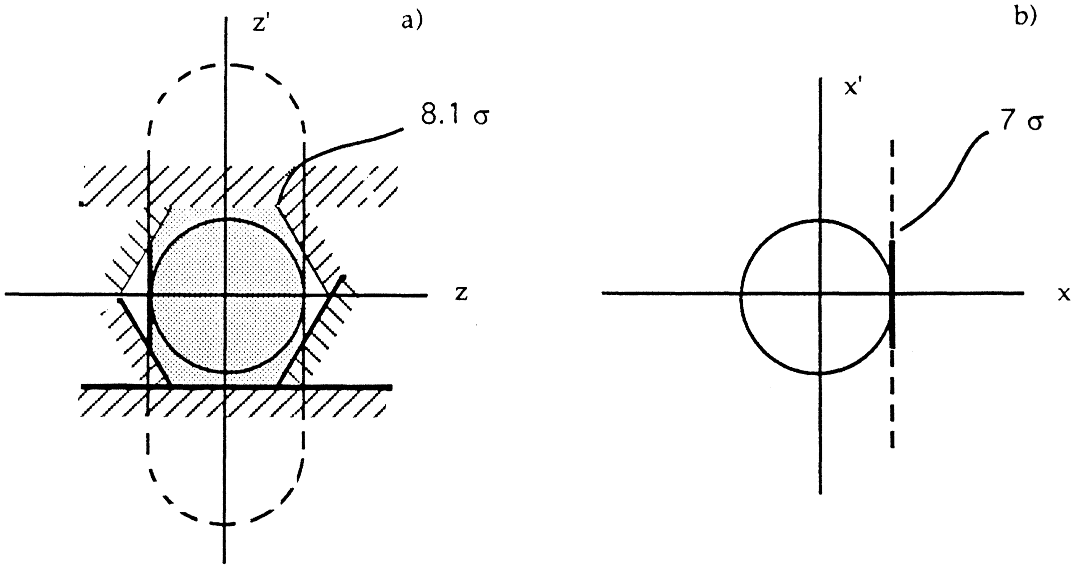

Figure 6

The normalised phase-spaces Z-Z' (a) and X-X' (b). The halo emitted by PX and cut by the secondary collimators is shown in both cases. The Z case is discussed in Section4., while the X case is discussed in (1).

regular hexagonal polygon whose inscribed circle corresponds to a retracted position of ~ 7σ. The largest remaining amplitude in the Z-plane is therefore

$$Z_{max} = \frac{7\sigma}{\cos 30^\circ} = 8.1\sigma$$

at the angles of the hexagon. This is quite a high value, if compared to the 7σ cut of the one-dimensional collimation. However, the full rate of secondaries remaining in the orthogonal plane is limited by the cut in the X-plane, and the particles are distributed quite homogeneously in phase in the Z-plane. Therefore, contrary to the well-located and dense "whiskers" (fig. 6b) of secondaries escaping the secondary collimators in the X-plane, the ones emitted in the Z-plane cannot all touch a single aperture limitation in one (or even a few) turn (a single aperture limitation has a well-defined phase-advance relative to the collimation system). Finally, after many turns, these particles will touch the primary collimator PZ, and be absorbed with high efficiency.

5. HOW MANY COLLIMATORS

A list of all the collimator jaws is given in table 1. We see that four additional secondary jaws must be added per plane to the three ones needed in the one-dimensional model. The total per plane is seven, and therefore fourteen jaws are needed for the two transverse planes, contained in four tanks.

An attempt is made in Appendix A to reduce the number of jaws. A case is discussed which requires 12 jaws instead of 14, but it has several drawbacks. The number of tanks is larger, because all phase advances are different and the largest uncovered secondary amplitudes are near 9σ. The considerations expressed in section 6 also favour the scheme of section 4.

We therefore consider our proposal to be the minimal set needed to provide a 'tight' system, i.e. a system which intercept every proton before it goes out of the dynamic aperture where the control of the trajectory of a particle is lost.

Table 1: List of collimator jaws for a two-dimensional system

Primary Jaws	Secondary Jaws Direct plane		Secondary Jaws Orthogonal plane		
0°	30°	150°	30°	90°	150°
PX	SX1+	SX2-	(SZ1+) SZ1-	90Z+ 90Z-	SZ2+ (SZ2-)
PZ	SZ1+	SZ2-	(SX1+) SX1-	90X+ 90X-	SX2+ (SX2-)

6. INJECTION CONSIDERATIONS

Even if a clean cut of the injected beams is made in the transfer lines, transient effects during the first turns after injection (and also later) imply efficient cutting of large amplitudes above a few beam units [(1)] [(6)]. Contrary to the case of stored beams, multi-turn considerations cannot be used to eliminate unwanted betatronic amplitudes when the amplitude grows very quickly. As any individual particle phases can be present, all secondary jaws will therefore serve for a few turns as primary collimators and must cover the overall phase-space. The hexagonal cut discussed above fits nicely to this purpose. The reduced set discussed in Appendix A might be acceptable if complemented with jaws installed at 180° but this addition is not making it simpler than the preferred scheme discussed in section 4.

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(1) L. Burnod, J.B. Jeanneret, CERN SL/91-39 (EA), LHC Note 167.

(6) L. Burnod, J.B. Jeanneret, CERN AC/DI//FA/Note 92-05.

7. CONCLUSIONS

While a one-dimensional collimation system requires a primary jaw and two secondary ones at phase advances of 30° and 150°, a two-dimensional system implies adding jaws at 30° and 150° on the opposite side of the one-dimensional ones in the corresponding orthogonal plane and also two at a phase advance of 90° in each plane. Fourteen jaws will be necessary for this basic scheme in the cleaning area.

It must be realized that the efficiency of interception of the collimation system must be larger than the steady rate of losses divided by the quench threshold, a value which is expected to be larger than 1000 in LHC at top luminosity (1). It seems quite probable (detailed simulations are in preparation) that a leak of many percents would occur in the orthogonal plane if nothing is done. Then, the goal of large efficiency would obviously not be met in the abscence of orthogonal plane collimation, whatever efficiency is achieved in the direct plane collimation.

The whole system defines a diaphragm of hexagonal shape in the normalized phase-space of the two transverse planes, which will be necessary to scrape transient fast losses during the injection cycle or induced by certain classes of instabilities at any time of the operation.

Acknowledgements

I wish to thank T. Trenkler who helped me to clarify some points discussed in this document.

Appendix A - A reduced set of secondary collimators

A set of four jaws 'per orthogonal plane' could be used instead of the six ones proposed in Section 4. The jaws SZ1+ and SZ2- (30° and 150°) are there anyway (section 4) and the additional ones have to complement them. The most regular figure in the normalized phase-space is obtained with jaws installed at phase advances fixed by $\Delta\mu$ = (180°-30°)/2 +30°, to equalize, and minimize, the maximum excursion in the angles of the polygon (see fig. A1). The phase advances would therefore be 30°/-75°/105°/-150° (- sign for a jaw in the negative Z side). The maximum excursion is

$$Z_{max} = \frac{7\sigma}{\cos(75°/2)} = 8.8\sigma\ ,$$

too close, or already above the dynamic aperture in collisions.

(1) L. Burnod, J.B. Jeanneret, CERN SL/91-39 (EA), LHC Note 167.

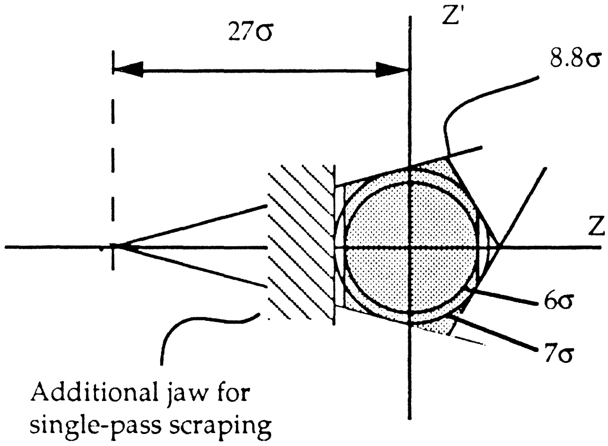

Figure A1: A four jaw for the capture of the orthogonal scattering. A fifth jaw is added for the single-pass scraping.

The region around 180° contains no excursion of the secondary halo (Section 3). However, the need of single-pass scraping outlined in Section 6 requires a jaw to be added at that phase advance to close the diaphragm, because the 4 jaws would leave an aperture of $Z = 7\sigma/\sin 15^\circ = 27\sigma$ in that region of the phase-space.

To summarize, that scheme requires 12 jaws and 6 tanks to contain them. By contrast, the scheme of section 4 needs 14 jaws and 4 tanks. The amount of hardware is therefore not much different. In addition, the jaws at 180° would be located after the triplet of quadrupoles surrouding the cleaning section. This would be a complication (larger extension of the shielding against radiation) or even a problem, depending on the proximity of the next quadrupole (quench).