Optimization of Collimator Jaw Locations for the LHC

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Abstract

- A highly effective collimation scheme is required in the LHC to limit heating of the vacuum chamber and superconducting magnets by protons either uncaptured at injection or scattered by non-linear phenomena. The proposed system would consist of one set of primary collimators followed by three sets of secondary collimators downstream to clean up protons scattered from the primaries. Each set of collimators would consist of four pairs of jaws - horizontal, vertical, and 45° and $135°$ skew. A study is reported of the optimization of the longitudinal positions of these jaws with the aim of minimizing the maximum betatron amplitudes of protons surviving the collimation system. This is performed using an analytical representation of the action of the jaws and is confirmed by tracking. Significant improvement can be obtained by omitting inactive jaws and adding skew jaws.

1 INTRODUCTION

Efficient collimation in LHC requires a *two-stage collimation system*: a primary collimator shaping the beam by limiting the maximum betatron amplitudes and secondary collimators trimming the secondary particles produced by elastic nuclear and electromagnetic interactions in the primary collimator surfaces (so-called *secondary beam halo*) [1]. The lattice of the IR3 straight section, where the betatronic cleaning will be done, and the collimator locations must be appropriately chosen to minimize the maximum betatron amplitude of uncaptured halo particles (escaping all secondary collimators).

In initial calculations [2], [3] of the maximum extent of the secondary halo the shapes of both primary and secondary collimators were assumed approximately elliptical (circular in normalized transverse coordinates). In reality each collimator will be made of several sets of flat jaws. For example, a set of four pairs of jaws – horizontal, vertical, and 45° and $135°$ skew – clustered at the same longitudinal coordinate form a regular octagon which does not deviate much from the inscribed circle.

In practice the jaws must be separated longitudinally – an additional degree of freedom which may be utilized to achieve better collimation – a deeper cut into the halo.

We describe an algorithm [4] allowing us to find the exact limits of the secondary halo in such a system of separated primary and secondary jaws, distributed along an arbitrary lattice. The code also provides automatic minimization of the maximum secondary halo amplitude.

2 COLLIMATOR DESIGN CODE DJ (DISTRIBUTION OF JAWS)

2.1 General Description

The approximations used are the same as in [2]:

- the primary jaws are assumed "pure scatterers"- scattered particles are produced along the line defining the boundary of the jaw in the transverse plane.
- the secondary jaws are assumed "black absorbers" - if a particle touches a secondary jaw it is considered lost.

The geometric representation of a *pair of opposing jaws* (POJ) in normalized transverse coordinates (X, Y) at longitudinal position s is a pair of parallel lines:

$$|X\cos\alpha_k + Y\sin\alpha_k| = n. \tag{1}$$

Here the angle α_k between the POJ and the Y axis and the aperture n (in units of r.m.s. beam size) at which the POJ is set, take discrete sets of values

$$n = \begin{cases} 6 & \text{for primary POJ} \\ 7 & \text{for secondary POJ} \end{cases}$$

$$\alpha_k = (k-1)\pi/N, \quad k = 1, 2, 3, \ldots, N. \tag{2}$$

For N = 4 (2) represents vertical (k=1), horizontal (k=3) and skew POJ (k=2,4); using large N allowed us to describe circular collimators and reproduce the results given in [2].

As *input*, DJ takes an initial distribution of POJ from a *jaw-position table*, containing for each POJ the horizontal betatron phase advance (μ_x) corresponding to its position in the lattice and its type (primary or secondary and angle α_k). The user also provides a table of IR3 lattice functions in MAD OPTICS, or DIMAD-output format.

DJ performs several kinds of calculations:

1. for a fixed jaw-position table it finds the maximum values of the amplitudes – horizontal ($A_x = \sqrt{X^2 + X'^2}$), vertical ($A_y = \sqrt{Y^2 + Y'^2}$) and combined ($A = \sqrt{A_x^2 + A_y^2}$) of halo particles escaping all secondary POJ;

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2. it minimizes the maximum combined amplitude A_{max} by distributing the secondary POJ longitudinally, thus creating new jaw-position tables;
3. it tracks particles starting from the primary POJ to find the amplitude distribution of the secondary halo.

2.2 Basic algorithm – finding the maximum halo amplitude for a given longitudinal distribution of jaws

We consider particles generated at the points P = (X, Y) on the perimeter of the octagon defined by the jaws of the primary collimator (see Figure 1) and seek to determine the range of initial angles in the $X'Y'$ plane that survives the secondary collimators. For this purpose, each secondary collimator jaw is imaged in the plane of the primary collimator. The particles escaping all secondary jaws lie inside a polygon in the $X'Y'$ plane as depicted in Fig. 1 (down). Jaws whose lines lie outside the polygon are inactive. For each point P of the octagon, the program computes A_x, A_y and A for each vertex of the polygon and chooses the maximum values $\hat{A}_x$, $\hat{A}_y$ and $\hat{A}$ associated with one of the vertices.

Finally:

1. the maximum halo amplitude is determined:

$$A_{max} = \max_P \hat{A}\ , \quad P \in \text{ all primary } POJ;$$

2. the vertex and the secondary jaws associated with A_{max} are identified.

As the point P = (X,Y) moves along each side of the octagon the point $(\hat{A}_x, \hat{A}_y)$ describes the limits of the secondary halo in the amplitude plane (Figure 2).

2.3 Minimization of A_{max}

A_{max} is minimized by changing the longitudinal location of pairs of secondary jaws, thus changing the position and orientation of the associated lines in the $X'Y'$ plane.

Although the Simplex and Newton methods minimized A_{max} successfully the algorithm finally chosen for DJ involves only the two maximum-amplitude POJ at each iteration:

1) one of the two maximum-amplitude POJ is shifted by a step ds in the appropriate direction to decrease A_{max}. Note that this may change the two maximum-amplitude POJ themselves.

2) if no decrease of A_{max} is achieved after all possible combinations are tried, the step ds is halved.

The procedure converges (asymptotically) to a POJ distribution with lower A_{max} (Fig. 2).

Minimization is done in several stages: at each stage a new primary POJ and sufficient number of secondary POJs are added so as to decrease A_{max} to some low target value (for example 8). Secondary POJ which are inactive (i.e. do not change A_{max}) are removed after each stage.

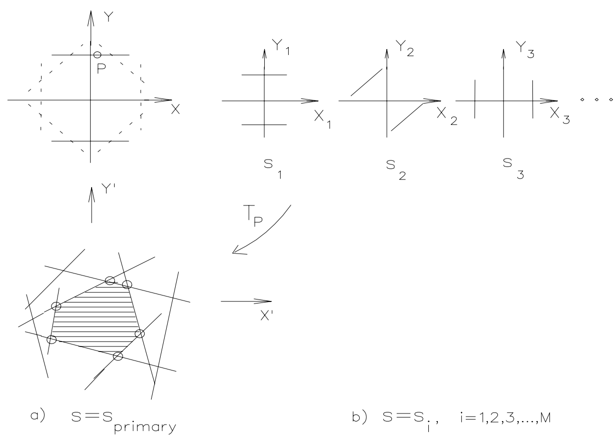

Figure 1: (a) - Normalized coordinate space (above) and angle space (below) at the longitudinal position $s_{primary}$ of the primary POJ; (b) M secondary POJ. T_P is a linear mapping (origin shift plus scaling). For each point P on the primary POJ: 1) each pair of parallel lines (stripe) in coordinate space is mapped into a stripe in angle space; 2) the overlap region of all stripes forms a polygon (shaded).

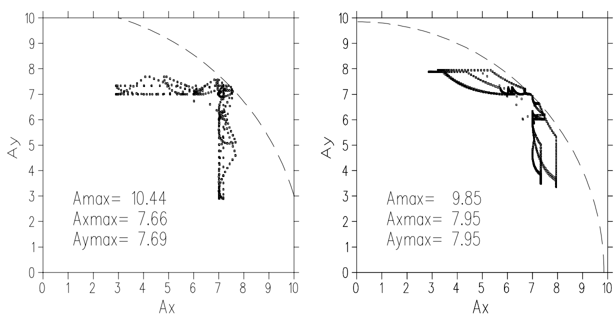

Figure 2: Secondary halo images in the amplitude plane before (left) and after (right) minimization for the lattice [1]

2.4 Tracking

A large number of particles is generated with initial coordinates taken from the same set of points P used in the mapping calculations described above. For each point P the initial angles are uniformly distributed within a cone, which should be a pessimistic assumption.

3 APPLICATIONS TO IR3 OF LHC

A preliminary study has been made of several IR3 lattices and the following features were found favourable:

– varying tune split μ_x - μ_y

– high phase advance.

The following results have been obtained for IR3 lattice [3] with tune advance 2.2 across the insertion.

If the primary jaws are all at the same location $(\mu_x =$

$\mu_y = 0$), then the secondary POJ positions after minimization are not far from the three optimum phases (μ_{opt}, $\pi/2$ and $\pi - \mu_{opt}$, where $\mu_{opt} =$ $\arccos(6/7)$) predicted by the circular-collimator model for a lattice with equal phase advances $\mu_x = \mu_y$. This is because 1) a regular octagon does not deviate much from its inscribed circle; 2) μ_x and μ_y do not differ by more than 0.2 anywhere in the collimation section (due to the high beta values). Starting from A_{max} = 9.85 for three octagonal secondary collimators located at the theoretically optimum positions, optimization using DJ reduces A_{max} to 9.5 (Fig. 3).

Given a long enough system and a sufficient number of secondaries, it should be possible to bring the maximum extent of the halo to its theoretical limit A_{max} = 7. Using 16 instead of 12 secondary POJ we were able to obtain A_{max} = 8.4 if the primary POJ were free to move, and 8.6 if they were restricted to locations of maximum beta (Figure 4). To find the optimum number of secondary POJ of each type the iterative process explained in the previous section was used.

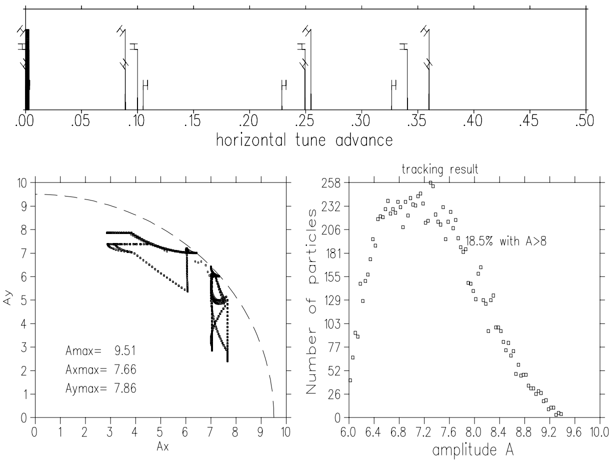

Figure 3: DJ minimization result for primary jaws (thicker lines) all at the same location: (above) distribution of the 12 secondary jaws, represented by the uprights of the H; (left) halo images and (right) amplitude distribution of the surviving secondary halo obtained by tracking.

It will be noted that the optimized distribution of the 16 POJ is very different from that in the previous case (Fig. 3), where the sets of four differently oriented POJ were clustered near the theoretical optimum positions for circular collimators and no tune split. Here 6 sets of skew POJ are required, with 45° and 135° POJ always located close together, while only 2 sets of horizontal and vertical POJ seem to be needed, and at quite separate locations. The basis for this distribution remains to be determined.

Other questions to be studied include how the collimation efficiency is affected by changes in tune or POJ location. This implies accurate simulation of scattering in the jaws coupled with tracking around the ring and will require

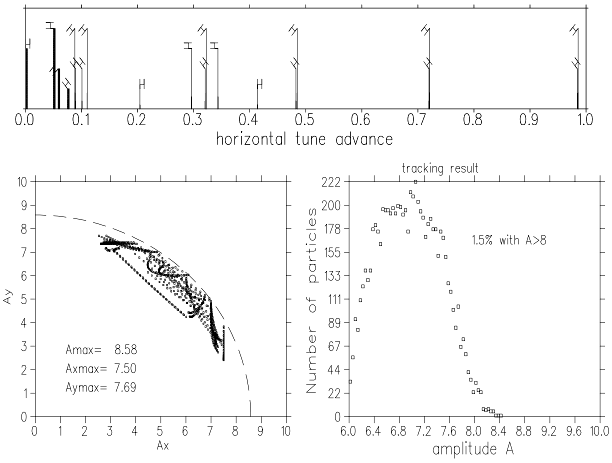

Figure 4: DJ minimization result for distributed primary jaws (thicker lines): (above) distribution of the 16 secondary jaws, (left) halo images and (right) amplitude distribution of the surviving secondary halo obtained by tracking.

other computer codes.

The optimised use of 16 separate pairs of secondary jaws instead of the three 8-jaw tanks proposed in [1] offers an improvement in the maximum amplitude of the secondary halo by ΔA=1.5 σ. This substantial gain must be compared to the effective secondary aperture of 10σ expected at injection into the LHC. Further studies, looking for optics offering the best maximum amplitudes, might offer even better results with the same number of pairs of jaws.

4 REFERENCES

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