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# THE OPTICS AND LAYOUT OF THE CLEANING INSERTION OF LHC FOR A BETATRON-MOMENTUM COLLIMATION SYSTEM

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## ABSTRACT

We present a possible layout with corresponding optics for the central part of the cleaning insertion of LHC. We summarize constraints defined elsewhere [1,2,3] leading to a good collimation system for combined betatron-momentum collimation. These constraints link a possible layout to its optics in a unique way if one demands in addition that the twiss parameters at the entrance of the central part (downstream end of Q1) excluding dispersion are comparable to those of the pink book optics. Thus we hope that it should be possible to match this optics to the arcs.

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## 1. INTRODUCTION

We discuss the impact of a combined betatron and momentum collimation system for the LHC on the layout and optics of its cleaning insertion. This is done by stating constraints defined by an efficient collimation system. We show how these constraints link a possible layout in a unique way to an optics of the central part of the cleaning insertion of the LHC. A possible solution for a layout and corresponding optics is presented. It remains to match this optics to the arcs.

## 2. BETATRON COLLIMATION

The need of a two stage collimation system in coast at high energy with a primary collimator located at a distance of $6\sigma$ from the beam axis and secondary collimators further retracted is discussed in detail by the authors of [1].

At injection,the primary colimator shall be placed between $6\sigma$ and $7\sigma$ to accomodate for injection errors. However, after damping of the injection oscillations ( a gain of approximately $2\sigma$ in transverse amplitude) a distance of $5\sigma$ will be chosen, necessary during the process of elimination of the RF-uncaptured particles [4]. Obviously, the potential fluctuations around the optimal values of the numerous injection parameters makes it necessary to also use the secondary collimators during the whole of the injection process.

We assume that a retraction of $1\sigma$ is realistic thus positioning the secondary collimators at a distance of $7\sigma$ from the beam axis at high energy. As also shown in [1] they must longitudinally be placed at phase advances of $30^0$ and $150^0$ with respect to the primary collimator if one considers only one dimensional motion. Two dimensional betatron collimation requires two changes [2]:

- Circular collimators being approximated by a set of planar jaws mounted as an octagon.
- An additional secondary collimator at $90^0$ phase advance mainly to trap particles scattered into the plane orthogonal to their plane of motion.

## 3. MOMENTUM COLLIMATION

Particles with a too big momentum deviation from the nominal momentum might be lost somewhere in the machine where dispersion is high. The mechanism of momentum losses and a detailed quantification of them is given in [5]. To run the machine safely these particles must be intercepted by the primary collimator before touching the vacuum tube.

Thus we need a certain value of dispersion at the primary collimator. We fix its value in the following way:

A particle with zero transverse emittance touches the primary collimator when the condition

$$\left.\frac{\Delta p}{p}\right|_1 D_1 = n_1 \sigma_1 \tag{1}$$

holds, where n1 is the distance of the primary collimator from the beam axis measured in units of $\sigma$. As collimators will be placed on both sides of the beam we do not have to care about signs in equation (1) and assume that all values are positive. To insure that this particle will not be lost earlier in the arcs at locations of maximum dispersion one has to demand

$$\left.\frac{\Delta p}{p}\right|_1 D_{\max} < A \tag{2}$$

where $D_{max}$ is the maximum Dispersion and A the aperture at its location. Extracting $\Delta p/p|_1$ from (1) yields

$$\frac{n_1 \sigma_1}{A} D_{\max} < D_1 \tag{3}$$

Due to synchrotron motion particles on stable trajectories will move inside the bucket. Such particles should not be intercepted by the primary collimator. Assume a particle with $\Delta p/p = \Delta p/p|_{buck}$ being the half bucket height and betatron amplitude of $n\sigma$. The condition for not touching the primary collimator is:

$$D_1 \left.\frac{\Delta p}{p}\right|_{buck} + n\sigma_1 < n_1 \sigma_1 \tag{4}$$

If one allows the collimator to cut at approximately n = n1-1 conditions (3) and (4) yield:

$$\frac{n_1 \sigma_1}{A} D_{\max} < D_1 < \frac{\sigma_1}{\left.\Delta p/p\right|_{buck}} \tag{5}$$

The limits for D1 defined in (5) must be evaluated at the extreme energies, i.e. top- and injection energies, to cover the whole energy range. We use the values:

$D_{max} = 2m$,
$A = 15.3mm$ = (20mm aperture - 4.7mm errors of any kind),
$\varepsilon_n = 3.75mm\ mrad$;

In section 5 we show that $\beta 1 = 200m$ is a realistic value for $\beta$ at the primary collimator.

- injection (450GeV) => $\sigma 1 = 1.25mm$, $n1 = 5$, $\Delta p/p\,|_{buck} = 1.3 \cdot 10^{-3}$

(5) => $$\underline{0.82m < D1 < 0.96m} \tag{5.1}$$

- top energy (7.3TeV) => $\sigma 1 = 0.31mm$, $n1 = 6$, $\Delta p/p\,|_{buck} = 3.6 \cdot 10^{-4}$

(5) => $$\underline{0.24m < D1 < 0.86m} \tag{5.2}$$

As for beam cleaning it is very desirable to work with the same optics over the whole energy (5.1) and (5.2) determine the narrow interval

$$\underline{0.82m < D1 < 0.86m} \tag{6}$$

allowed for the value of dispersion.

One must stress that a certain degree of violation of (6) is no problem.

- The probability that zero emitance particles will reach the aperture in the arcs is very small as non-linearities of any kind will always increase the transverse emitance when $\Delta p/p$ is large as discussed in [5].
- Fixing n of (4) to n1-1 was somewhat arbitrary. We could have chosen n = n1-1.5. Then

$$\underline{0.82m < D1 < 1.3m,} \tag{6.1}$$

leaving quite a comfortable margin.

## 4. COMBINED BETATRON-MOMENTUM COLLIMATION

The average particle will have a certain excursion due to betatron motion and due to dispersion at the location of the primary collimator. If it touches the primary collimator without doing an inelastic interaction it will be scattered out again with a certain angle b' added to its divergence. The purpose of the secondary collimators is to trap such particles. As for the betatronic case [1] one can give a formula for the angle $b'_{min}$ defined such that all particles receiving a kick b' with bigger absolute value than the one of

$b'_{min}$ will be intercepted by a secondary collimator located at a phase advance $\Delta\mu$ while all other particles will pass this collimator.

$$b'_{min} = \sqrt{\frac{\varepsilon}{\beta_1}} \frac{n_2 - n_1 \cos\Delta\mu}{\sin\Delta\mu} + \frac{\Delta p}{p} \frac{D_1 \cos\Delta\mu - \sqrt{\beta_1/\beta_2} D_2}{\beta_1 \sin\Delta\mu} \tag{7}$$

Formula (7) derived in [3] contains the twiss parameters at the location of the primary (index=1) and at the location of the secondary collimators (index=2) and the distance of them to the beam axis measured in units of $\sigma$ (n1,n2), while it is completely independent of the optics which lies between the collimators. How to define the optimum collimation system by making $|b'_{min}|$ as small as possible for all $\Delta p/p$ is described in detail in [3]. The resulting conditions on the optics of the collimation system are quite complicated (formula (28) of [3]).

Relaxing a bit on the efficiency one can define much simpler conditions, by making $b'_{min}$ (instead of its derivative with respect to the phase advance) independent of $\Delta p/p$ . From (7) we get the condition

$$D_2 = \sqrt{\frac{\beta_2}{\beta_1}} \cos\Delta\mu \cdot D_1 \tag{8}$$

which has also been mentioned in [3].

One obtains small $|b'min|$ in the whole range of $\Delta p/p$ by choosing the optimum phase advances for the betatronic case ($30^0$, $90^0$ and $150^0$). Thus we obtain a collimation system which has equal efficiencies for every $\Delta p/p$ and which is optimised for the betatronic case.

How far (8) may be violated to still garantee a good collimation system will be discussed in a different note.

## 5. LAYOUT AND OPTICS

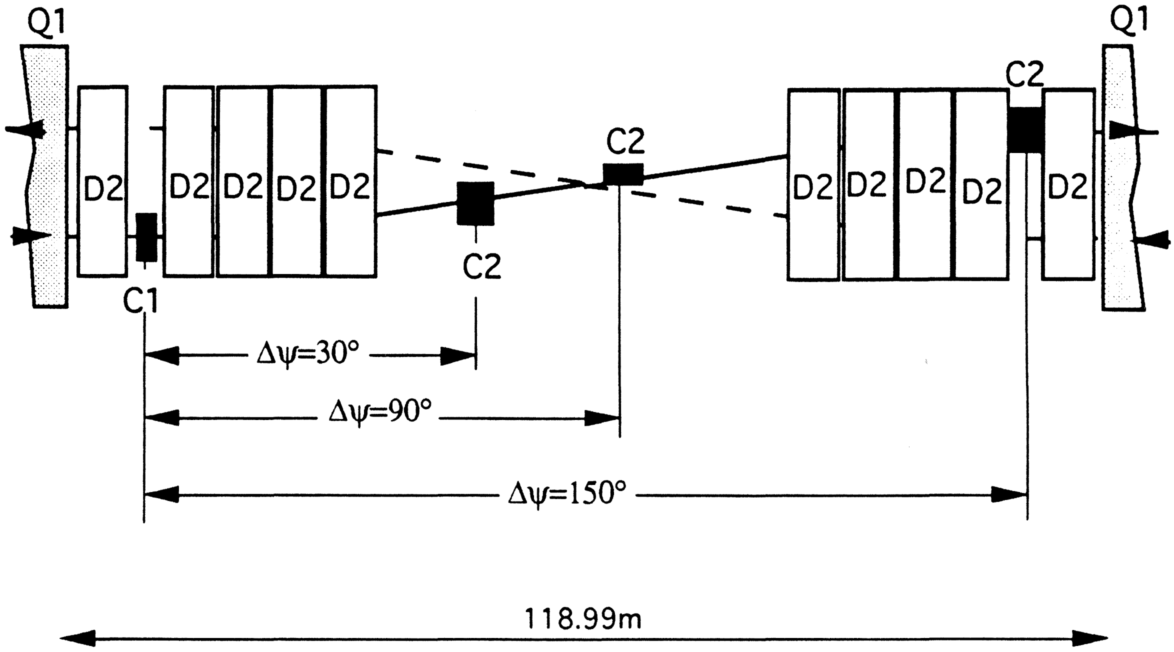


Fig. 1 Schematic layout for the central part of the collimation system of LHC

Fig. 1 shows a possible layout for the central part of the collimation system. This layout and the corresponding optics (Table 1) are defined by the following constraints:

a) The optics must be symmetric with respect to the IP as both beams need the same optical conditions.

b) No super-conducting magnets are allowed to lie in this central region where one has to deal with high levels of energy deposition and radiation.

c) A certain magnetic length of warm dipoles must lie downstream of the 150° collimators of each beam to sweep out secondary particles induced by inelastic interactions in the collimator jaws. We have chosen a magnet of approximately 1.8T and 6m length. Crude calculations indicate that this magnetic length will be of the right order of magnitude while a proof will only be given by quite detailed studies.

d) The recombination magnets D2 must separate the beams horizontally to the arc value of 180mm. This requirement defines the need of 5 elements of D2 as defined in c) on each side of the IP.

e) Due to the two dimensional concept of betatron collimation [2] the phase advances of $30^0$ ,$90^0$ and $150^0$ must lie at the same locations for both transverse planes and such that there is enough room to mount the collimators. An optics as simple as possible (no quadruples in the central collimation region) must thus have equal beta functions in both planes over the whole region.

f) Due to several reasons one could tend to put the primary collimators between the super conducting Q1 and the following element of the D2:

1) Due to the bigger distance it would be easier to establish the right phase advance between the primary and the $150^0$ collimators.

2) One could make use of the biggest value of the beta function of the whole region to create bigger impact parameters on the primary jaws.

Contradictory to these facts matching work shows that relation (8) may not be satisfied by choosing this configuration, while the symmetric approach of Fig. 1 allows to implement (8) in a very convenient way.

Choosing a value for $\beta^*$ at the IP in addition to the constraints defined above yields a unique solution and defines in addition the total length of the central part of the cleaning insertion.

g) The beta functions at the entrance of Q1 (as seen from the IP) shall not exceed a certain value, such that the maximum value of beta in the inner triplet does not exceed 630m (a value discussed in the pink book). This condition can be fulfilled by choosing a solution for which beta and alpha at the entrance of Q1 are comparable to the values of the pink book optics. This condition fixes a maximum for $\beta^*$ of about 13.5m.

Table 1 gives values of an optics with $\beta^*$=13.4m, D1=0.9m and the values of dispersion at the secondary collimators perfectly well matched to condition (8). It remains to further match this optics to the arcs.

| NAME | s [m] | $\beta x$ [m] | $\alpha x$ [1] | Dx [m] | D'x [1] | $\mu x$ [°] | $\beta z$ [m] | $\alpha z$ [1] | $\mu z$ [°] | Dx [m] equ. (8) |
|---|---|---|---|---|---|---|---|---|---|---|
| EX Q1 | 0.00 | 277.5 | 4.440 | 1.04 | -0.0151 | -2.307 | 277.5 | 4.440 | -2.307 | |
| | 1.25 | 266.6 | 4.347 | 1.02 | -0.0151 | -2.044 | 266.6 | 4.347 | -2.044 | |
| DI- | 7.4 | 215.9 | 3.888 | 0.93 | -0.0155 | -0.575 | 215.9 | 3.888 | -0.575 | |
| **C1** | **9.48** | **200.0** | **3.732** | **0.90** | **-0.0155** | **0.000** | **200.0** | **3.732** | **0.000** | **0.90** |
| | 11.57 | 184.8 | 3.577 | 0.87 | -0.0155 | 0.621 | 184.8 | 3.577 | 0.621 | |
| DI- | 17.72 | 143.6 | 3.118 | 0.77 | -0.0160 | 2.785 | 143.6 | 3.118 | 2.785 | |
| | 18.52 | 138.7 | 3.058 | 0.76 | -0.0160 | 3.110 | 138.7 | 3.058 | 3.110 | |
| DI- | 24.67 | 103.9 | 2.599 | 0.66 | -0.0164 | 6.046 | 103.9 | 2.599 | 6.046 | |
| | 25.47 | 99.8 | 2.539 | 0.64 | -0.0164 | 6.496 | 99.8 | 2.539 | 6.496 | |
| DI- | 31.62 | 71.4 | 2.080 | 0.54 | -0.0169 | 10.675 | 71.4 | 2.080 | 10.675 | |
| | 32.42 | 68.1 | 2.020 | 0.53 | -0.0169 | 11.333 | 68.1 | 2.020 | 11.333 | |
| DI- | 38.57 | 46.1 | 1.562 | 0.42 | -0.0173 | 17.636 | 46.1 | 1.562 | 17.636 | |
| **C30°** | **46.09** | **26.8** | **1.000** | **0.29** | **-0.0173** | **30.003** | **26.8** | **1.000** | **30.003** | **0.29** |
| IP | 59.49 | 13.4 | 0.000 | 0.06 | -0.0173 | 75.000 | 13.4 | 0.000 | 75.000 | |
| **C90°** | **63.09** | **14.4** | **-0.268** | **0.00** | **-0.0173** | **90.000** | **14.4** | **-0.268** | **90.000** | **0.00** |
| | 80.42 | 46.1 | -1.562 | -0.30 | -0.0173 | 132.369 | 46.1 | -1.562 | 132.369 | |
| DI+ | 86.57 | 68.1 | -2.021 | -0.41 | -0.0169 | 138.671 | 68.1 | -2.021 | 138.671 | |
| | 87.37 | 71.4 | -2.080 | -0.42 | -0.0169 | 139.328 | 71.4 | -2.080 | 139.328 | |
| DI+ | 93.52 | 99.8 | -2.539 | -0.52 | -0.0164 | 143.506 | 99.8 | -2.539 | 143.506 | |
| | 94.32 | 103.9 | -2.599 | -0.54 | -0.0164 | 143.956 | 103.9 | -2.599 | 143.956 | |
| DI+ | 100.47 | 138.7 | -3.058 | -0.64 | -0.0160 | 146.893 | 138.7 | -3.058 | 146.893 | |
| | 101.27 | 143.7 | -3.118 | -0.65 | -0.0160 | 147.217 | 143.7 | -3.118 | 147.217 | |
| DI+ | 107.42 | 184.8 | -3.577 | -0.75 | -0.0155 | 149.380 | 184.8 | -3.577 | 149.380 | |
| **C150°** | **109.50** | **200.0** | **-3.732** | **-0.78** | **-0.0155** | **150.000** | **200.0** | **-3.732** | **150.000** | **-0.78** |
| | 111.59 | 216.0 | -3.888 | -0.81 | -0.0155 | 150.576 | 216.0 | -3.888 | 150.576 | |
| DI+ | 117.74 | 266.6 | -4.347 | -0.91 | -0.0151 | 152.045 | 266.6 | -4.347 | 152.045 | |
| BEG Q1 | 118.99 | 277.6 | -4.440 | -0.93 | -0.0151 | 152.308 | 277.6 | -4.440 | 152.308 | |

Table 1: Optics corresponding to layout of Fig. 1

It is quite astonishing but satisfactory that condition (8) holds at the locations of all 3 secondary collimators while there is only one degree of freedom for matching (for example $D'_x$ at the primary collimator). The corresponding matching has also been done for the limiting values of $D_1$ being of practical interest i.e. the limits of equ. (6.1) leading as well to satisfactory results. Although the situation is slightly different for a negative sign of $D_1$ (due to the field of the recombination magnets) condition (8) can be fulfilled as well in this case. Thus we are convinced that (8) can be satisfied for a range of $D_1$ being much larger than the one of practical interest at all secondary collimators.

## 6. CONCLUSIONS

We give a possible layout with corresponding optics for the central region of the cleaning insertion of the LHC. Further we give the constraints defined by an efficient collimation system linking a possible layout to an optics in a unique way. We further discuss, that momentum collimation does not allow layouts with primary and $150^0$- collimators positioned asymmetrically with respect to the IP.

## 7. ACKNOWLEDGEMENTS

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