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Collimation efficiency in the presence of collimator misalignment and sample closed orbit errors

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Summary

We present robustness studies of the LHC collimation system and report tracking results at injection obtained with a combined code DIMAD + STRUCT. Besides a description of the simulation tool, featuring inelastic nuclear scattering and chromatic tracking including sextupoles, we discuss first results on combined betatron and momentum collimation inefficiency when the off-momentum halo is included. We assume (as a simplified example) a constant aperture limit R = 2 cm around the ring at all drift entrances, a sample closed orbit error generated by transverse offsets of two arc quadrupoles and corrected within the insertions, and random transverse collimator misalignments.

1 Introduction

We have used Dimad ([2]), to track for several hundreds of turns the halo created at injection by the IR7 primary vertical collimator. The LHC lattice is version V6.3 for Beam 1, with thick elements. Tracking includes particle propagation through the collimator material, a feature made possible by the new collimator element in Dimad, based on the main block of the code `STRUCT`, [1]. This tool should be considered complementary to other available tools for collimation studies (`K2, SIXTRACK`). The new capabilities of Dimad are described in the Appendix.

At present, a matter of great concern is the behaviour of an imperfect collimation system, and in particular how to set tolerances on jaw misalignment and orbit excursions within the collimation insertions. A model of a collimation system with errors has therefore been developed and first results from tracking are presented here, and also compared (section 4.2) with previous results from other approaches [4]. Some of the model features and simplified assumptions are: it uses the full lattice at injection (both IR7 and IR3 insertions); it assumes a constant around the ring radial aperture; it applies sample closed orbits outside the collimator sections and random transverse collimator misalignments within; it takes into account the energy losses occurring as halo particles traverse the jaws. To explain our choice of model and the approximations made, the following considerations apply.

At injection, one is mostly interested in halo loss rates in the arcs. The inefficiency is therefore computed with respect to arc losses by setting an aperture limitation (R=2 cm) at all drift entrances. By shifting two arc sextupoles, an artificial error closed orbit is created. We correct the orbit to zero within the collimation insertions, but impose large collimator misalignment with respect to the chamber axis (this should give a rough idea of what happens if the orbit is not corrected).

No field errors have been included, the chromaticity being set to 2 units in both planes by the lattice sextupoles alone. The code Dimad is based on second order TRANSPORT maps with kicks describing the action of higher order multipoles and also accepts symplectic ray tracing [3]. It is believed that it describes with sufficient accuracy the short-term motion (< 1000 turns), including off-momentum and far from the axis.

The jaw material and thickness used are: for primary – Al (20 cm); for secondary – Cu (50 cm).

The off-momentum halo created by energy losses in the jaws

At injection, the initially nearly on-momentum particles emerging from the IR7 primary collimator lose their energy via inelastic nuclear interactions within the jaws with resultant negative momentum offsets of the circulating halo down to about -1%.

The motion within the collimator material is governed by the `STRUCT` block, an important parameter being the maximum loss of momentum that a particle may suffer during nuclear interaction. By setting the corresponding `STRUCT` parameter `dpplim` to (practically) infinity, we assume that all off-momentum particles are kept.

We will show that under such assumption: 1) the losses on the 2-cm radial aperture are largely caused by off-momentum tertiary halo particles; 2) in the case of a realistic and hence misaligned system IR7 and IR3 work together even with respect to halo born at the IR7 primary collimator only.

Secondary halo consists of particles emerging from the primary collimator during the first passage. These do not reach the arc or the IR3 collimators in one turn, but are either absorbed during the first passage through IR7, or receive additional deflecting kicks on subsequent passages and are gradually absorbed or scattered in the IR7 secondary collimators,

Due to the nature of nuclear interactions, the particles emerging at some turn from the IR7 secondary collimators (tertiary halo) may acquire both large negative momentum offsets and large betatronic amplitude. Such particles are lost at the high dispersion locations in the arc, or reach the high-dispersion place in IR3 and hence the IR3 collimators (mostly during the same turn).

At the same time, the capacity of IR3 for stopping off-momentum particles effectively is restricted by the value of the ring momentum acceptance $|\delta_{cut}| = 3.5\ 10^{-3}$. This is because IR3 is designed [*] to effectively absorb the **circulating beam** particles, i.e. the ones with $|\delta| < |\delta_{cut}|$. The above criterion however can only serve as a rough estimate.

When designing the ideal system (for $\Delta p/p = 0$), it has been assumed that the total halo created at the IR7 primary collimators is almost entirely absorbed in the IR7 secondaries. This indeed turns out to be the case, with the exception of the highly off-momentum tertiary halo described above.

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[*] By increasing the normalized dispersion at the IR3 primary collimator.

2 Initial conditions and tracking procedure

Optics, LHC lattice, collimator settings. This study is based on injection optics Version 6.3 (tunes Q_x=64.28, Q_y=59.31) with the emittance and beam energy being set to either their injection or collision values. The IR7 and IR3 collimators are adjusted to their ideal apertures, according to the corresponding beam envelopes (see below the definition of ideal system).

The choice of the **equilibrium impact distribution** (see [7], [8]) is crucial for defining efficiency.

The initial point for tracking is set just before the first primary (vertical) collimator of IR7* and two beams, each composed of particles with zero normalised angle and zero momentum offset, are generated entering the upper and lower jaw (Fig. 1). Each beam has zero size in direction parallel to the jaw surface and a rectangular distribution over impact parameters. We use an elimination procedure – only particles impacting within 1 micrometer from the jaw edge are tracked. The corresponding BEAM and GENERATE commands are shown in the Appendix. The two beams are tracked until all particles are lost in collimators, or on the aperture limitations. At injection, even for the ideal system, less than 200 turns are needed. Tracking is stopped, if less than 10 particles are still circulating. Whether this small but long-living halo fraction will reach the aperture, or will be captured, does not change the results.

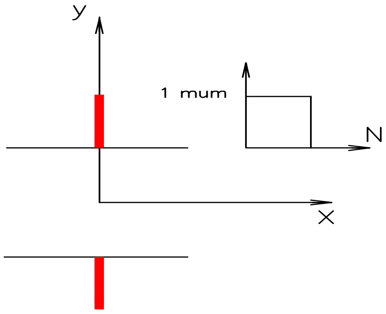

Figure 1: (colour) The first (vertical) primary collimator and the impact distribution (red) – 1 μm size in y direction and zero size in direction parallel to the jaw border.

3 Collimation systems with misalignment

We consider collimators fixed at some, possibly imperfect, positions with respect to the vacuum chamber axis. In a machine with misalignments, the on-momentum closed orbit within the IR7 and IR3 insertions deviates from this axis (kind 1, Fig 2). Among many possible corrected systems, such as: fully corrected within the insertions (kind 3), orbit corrected to some extent at the primary collimator only (kind 2) – both may be with or without collimator misalignment – we only consider the following case:

orbit corrected within the collimator-occupied sections (same as if the collimators were aligned w.r.t. uncorrected orbit) plus random transverse displacement of the midpoint (center) of each pair jaws w.r.t. to the vacuum chamber axis. All collimator centres are randomly displaced, except for the first primary collimator in IR7.

Table 1 defines the four different cases considered:

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* A similar procedure and lattice has been set to model the halo created by IR3 (not reported here)

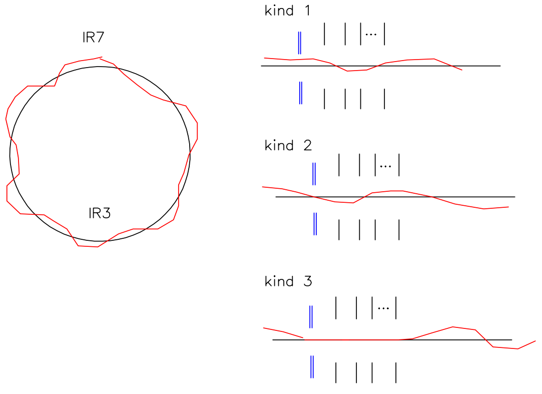

Figure 2: Possible uncorrected and corrected orbits

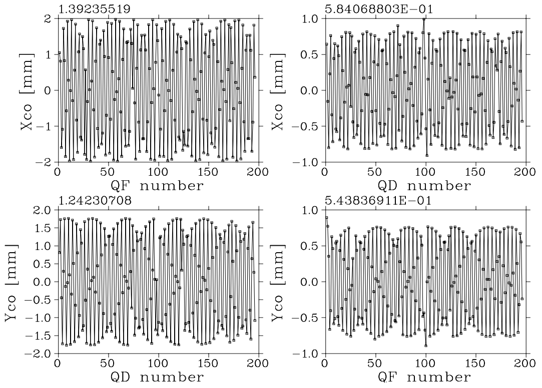

Figure 3: The orbit CO2 – 4mm peak to peak in the arc

Table 1: Collimation systems with misalignment

ideal	all collimators at ideal apertures no misalignment
corrected CO2	orbit corrected to zero within the COS sections
corrected CO2 + jaw mis.	corrected plus transverse collimator misalignment

- **ideal system** is the error-free machine plus sextupoles (at chromaticity 2), with all collimators set at their ideal normalized aperture w.r.t. the vacuum chamber axis: $n_1 = 6, n_2 = 7$ in IR7, $n_1 = 8.5, n_2 = 9.5$ in IR3 (σ units; n_1 for primary, n_2 for secondary) and with rotation angles as defined in the LHC database *. The collimator parameters of the ideal system, namely lattice functions at collimators and jaw orientation angles, are the same as in `www.cern.ch/LHC-collimation.`

- By shifting a pair (QF and QD) of arc quadrupoles in transverse directions, a nonzero closed orbit is created, with nearly equal r.m.s. and maximum displacements in both planes (Table 2 and Figure 3). For the **corrected** system the orbit is corrected to zero within the collimator-occupied sections, i.e. from the entrance of the first to the exit of the last collimator in each IR7 and IR3. In practice, such correction is achieved by applying four combined (coordinate and angle) kicks (see Fig 4). The kicks preserve the uncorrected orbit outside the two COS. We notice that 1) the orbit within the IR7 Right Dispersion Suppressor (RDS7) is thereby left uncorrected; 2) an ideal every-turn correction has been assumed.

- For the **corrected + jaw mis.** the midpoints of the collimators are assigned random transverse displacements dx, dy with respect to the vacuum chamber axis. A flat distribution is used within the interval $(-|dx|_{max}, |dx|_{max})$ and the same for y.

3.1 The "2-cm inefficiency"

By setting a radial aperture R=2 cm at all drift entrances, the "2-cm inefficiency" w.r.t. particles lost in some section of the ring is defined to be the ratio:

$$N_{part\ lost\ at\ 2cm-apert.\ section}/N_{total\ lost\ part.}$$

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* The real-space distance between the jaw and the chamber axis is expressed through the emittance, horizontal and vertical beta function at the collimator, its rotation angle and the normalized aperture.

	CO2
MAX at arc quadrupoles	2
RMS at arc quadrupoles	1.4
MAX at IR7 collimators	1.5

Table 2: Uncorrected CO2 – approximate excursions in mm (nearly equal in x and y)

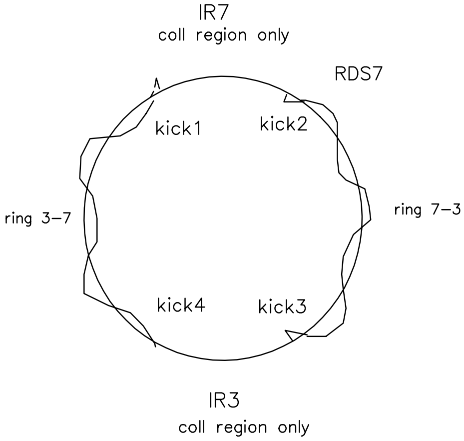

Figure 4: The two lattice sections occupied by collimators in IR7 and IR3 called below **collimator-occupied sections COS7 and COS3**. Four orbit-correcting kicks are applied at the entrances and exits of the two COS. The region outside both COS is left uncorrected – it consists of RDS7, ring 7-3 and ring 3-7 (RDS7 is excluded from ring 7-3).

The four different aperture sections of interest are COS7, COS3, outside both COS and ring 7-3 + ring 3-7. The last (fourth) inefficiency part corresponds to particles lost outside both COS and also escaping the RDS7 (we denote it by “ ring 7337”).

4 Results

4.1 The effect of the variable `dpplim`

If during a nuclear interaction the momentum offset of a particle $|\Delta p/p|$ exceeds `dpplim`, the particle is counted to be lost in the collimator. Particles reaching high betatron amplitudes also have large momentum offset $|\Delta p/p|$, hence the choice `dpplim` strongly affects the fraction reaching the 2-cm aperture.

For all calculations `dpplim` is set to the maximum value 0.3, as allowed by `STRUCT`. In effect, all off-momentum particles are allowed to circulate freely (without acceleration). With `dpplim` set to 0.5%, all losses are strongly reduced, as shown in Table 3 for one seed.

	Inj		Col	
`DPPLIM=`	0.3	.005	0.3	.005
absorbed in coll-s	0.9447	0.9676	0.9988	0.9994
COS7 aperture	0.0538	0.0314	0.	0
COS3 aperture	0	0.0004	0.	0
outside COS aperture	0.0013	0.0009	0.0008	0

Table 3: Effect of changing `dpplim`. Fraction absorbed in collimators and losses on the 2-cm pipe. Numbers smaller that 5.10^{-5} are shown as zero. The IR3 collimators are retracted.

4.2 Integrated inefficiency and comparison with the results in [4]

By removing the 2 cm aperture limitation, the integrated inefficiency found by `DIMAD + STRUCT` has been compared with the one in [4] (collision energy and optics; IR7 collimators only; micrometer impact depth on the first primary, uniform distribution of impact parameters). The corresponding inefficiency curves are shown on Figure 5 – the lower curves, corresponding to 1μm initial beam size are to be compared with the results in [4]. The seed to seed variation is seen in Fig. 4.2.

Sample one-seed runs, with and without aperture limitation, were made at injection and collision. Table 4 shows the integrated inefficiency value at 20 sigma (collision and injection) and the 2-cm inefficiency computed over different ring sections.

	integr. ineff. for $A_r = 20$ no apert. besides coll-rs		2-cm inefficiency (apert. limit 2 cm))				
	at $D_x \approx 0$	at $D_{x,arc}$	in coll-s	COS7	COS3	outside COS	ring 7337
Collision							
Ideal	510^{-4}	0.001	0.9989	0	0	0.0007	$\sim 10^{-5}$
Injection							
Ideal	510^{-4}	810^{-4}	0.9461	0.0523	0.	.0015	0.0001

Table 4: Ideal system (no IR3 collimators) for one seed (10^5 particles). Left: integrated inefficiency as defined in [4]; Right: "2-cm inefficiency" w.r.t. different ring sections.

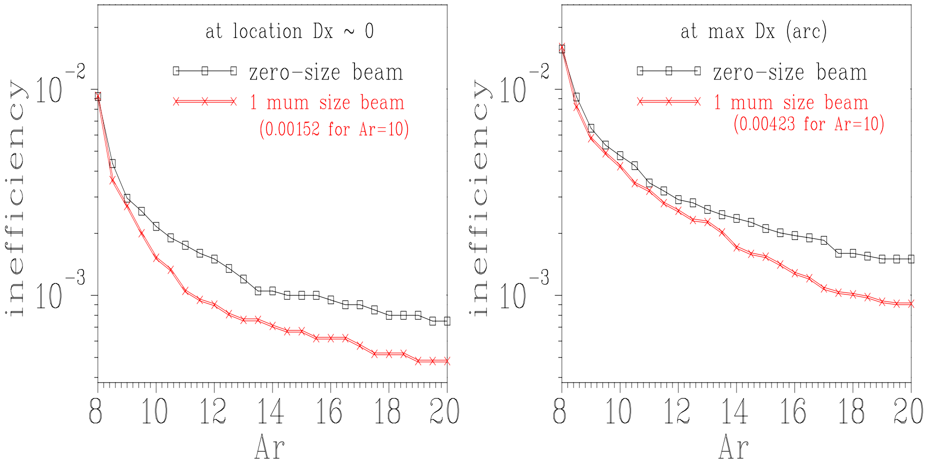

Figure 5: Ideal system (no IR3 collimators) for one seed (8 10^4 particles). Integrated inefficiency at collision (as in [4]). Left: computed at location just before the first primary; Right: at maximum dispersion near one of the arc focusing quadrupoles.

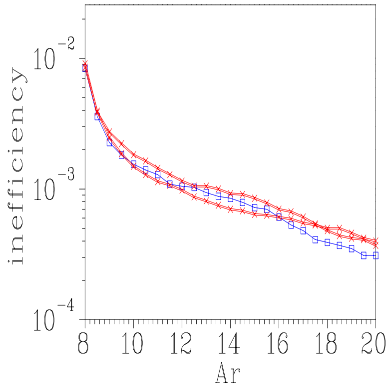

Figure 6: Seed-to-seed variation of the integrated inefficiency shown in Figure 5, left.

4.3 Effects of orbit error and jaw misalignment at injection

The fraction of halo reaching the ring 7337 aperture is of the order of 10^{-4}, hence for meaningful statistics one needs to track around 10^6 particles. We choose instead to track several smaller patches, each corresponding to a new initial seed for the impact distribution and simultaneously new initial seed in the `STRUCT` module, and record average and maximum values over the patches. With 8 10^4 particles per patch, the patch to patch fluctuation is due solely to the `STRUCT` random generator, since the impact distribution is sampled with sufficient accuracy. For the present study, ten such patches (seeds) have been generated and applied to each Ideal and Corrected CO2 system.

The 2-cm aperture limitation was applied for all calculations in the section. Initially, the IR3 collimators were retracted. The first two rows of Table 5 show average and maximum values of the quantity in each column with an accuracy down to 10 particles ($\sim 10^{-5}$). For the average (first row), the sum of the numbers in columns 2 to 5 is unity. The fraction lost in RDS7 is given by the difference of the numbers in the last two columns.

As seen in Table 5, the presence of the corrected CO2 causes an increase of the average losses over ring 7337 by 35 %, w.r.t Ideal, while the maximum value changes half as much.

<table>
<tr><th colspan="6">Halo losses, injection, no IR3 coll-s
10 seeds $\times 810^4$ part</th></tr>
<tr><th rowspan="2"></th><th rowspan="2">absorbed in collimators</th><th colspan="4">on the 2 cm radial apert</th></tr>
<tr><th>COS7</th><th>COS3</th><th>outside COS</th><th>ring 7337</th></tr>
<tr><td></td><td colspan="5">Ideal</td></tr>
<tr><td>ave</td><td>0.94514</td><td>0.05344</td><td>0.00002</td><td>0.00140</td><td>1.710^{-4}</td></tr>
<tr><td>max</td><td>0.94606</td><td>0.05424</td><td>0.00005</td><td>0.00156</td><td>2.510^{-4}</td></tr>
<tr><td></td><td colspan="5">Ideal + corrected CO2</td></tr>
<tr><td>ave</td><td>0.94493</td><td>0.05355</td><td>0.00002</td><td>0.00149</td><td>2.310^{-4}</td></tr>
<tr><td>max</td><td>0.94604</td><td>0.05407</td><td>0.00003</td><td>0.00160</td><td>2.810^{-4}</td></tr>
</table>

Table 5: Average and maximum values of 10 seeds (`STRUCT` random generator). The IR3 collimators are retracted

<table>
<tr><th colspan="6">Halo losses, injection, no IR3 coll-s
worst seed w.r.t. CO2 effect</th></tr>
<tr><th rowspan="2"></th><th rowspan="2">absorbed in collimators</th><th colspan="4">on the 2 cm radial apert</th></tr>
<tr><th>COS7</th><th>COS3</th><th>outside COS</th><th>ring 7337</th></tr>
<tr><td>Ideal</td><td>0.94474</td><td>0.05383</td><td>0.</td><td>0.00135</td><td>1.610^{-4}</td></tr>
<tr><td>corr. CO2</td><td>0.94494</td><td>0.05355</td><td>0.</td><td>0.00155</td><td>2.810^{-4}</td></tr>
<tr><td>corr. CO2 + worst seed 0.5 mm jaw mis.</td><td>0.94389</td><td>0.05412</td><td>0.00005</td><td>0.00205</td><td>7.610^{-4}</td></tr>
<tr><td>corr. CO2 + worst seed 1 mm jaw mis.</td><td>0.94385</td><td>0.05158</td><td>0.0001</td><td>0.00455</td><td>1.910^{-3}</td></tr>
</table>

Table 6: The worst seed w.r.t. CO2 effect on ring 7337 losses.The IR3 collimators are retracted.

Some explanations apply. For all ten random systems, when the corrected orbit was added, the fraction lost outside the collimator occupied section increased, while the fraction lost in ring 7337 was sometimes smaller or remained the same – the increase being absorbed inside RDS7 (where the orbit is not corrected). Another factor is the action of the orbit correcting kicks, which tend to improve quality. They redirect the particles at the entrance to the primary collimator, thus sending them into the secondary jaws a little more efficiently.

Introducing the IR3 collimators was found to have an improving statistical effect, with respect to the maximum inefficiency values, i.e. on the worst seeds. Table 6 shows the worst seed with respect to effect of the corrected CO2, i.e. the seed that produced the largest increase of ring 7337 occupancy after corrected CO2 was added (this seed turned out to be also the worst w.r.t. increase of losses outside COS). For this seed, the jaw misalignment was added on top of corrected CO2 (Table 6) and the IR3 collimators were switched on – Table 7. Their improving effect w.r.t ring 7337 loses is seen to be around 60%.

With jaw misalignments, the total fraction escaping COS and reaching the rest of the ring is determined by the partially destroyed collimation quality (larger escaping window through the collimators), as shown in Table 8. For jaw misalignment amplitudes 0.5 mm and 1 mm, the ring 7337 losses increase 4.7 and 12 times respectively. In this case the IR3 collimators have been unable to improve efficiency, as is seen in Table 7.

Table 7: Same seed as on Table 6, but IR3 collimators included.

Halo losses, injection, with IR3 coll-s **worst seed w.r.t. CO2 effect**		
	on the 2 cm radial apert	
	outside COS	ring 7337
Ideal	0.00137	1.410^{-4}
corr. CO2	0.00150	1.710^{-4}
corr. CO2 + worst seed 0.5 mm jaw mis.	0.00205	7.410^{-4}
corr. CO2 + worst seed 1 mm jaw mis.	0.00443	1.810^{-3}

Individual particles are lost on the COS3 aperture even if the IR3 collimators are missing – this is because of the high-dispersion peak still being present there. If IR3 was missing together with its optics, these would have been lost in the arcs.

The fraction lost over ring 7337 is not only composed of particles reaching the arcs, but also includes the losses at the high beta location in IR6, element BPMYC (where radius 2 cm corresponds to aperture $\sim 10\ \sigma$). The fraction lost on BPMYC was between 30 and 70 % of the total ring 7337 occupancy and for most seeds increased when errors were included.

	outside COS
Ideal	0.00135
seed 1	0.00391
2	0.00336
3	0.00431
4	0.00532
5	0.00525
6	0.00548
7	0.00455
8	0.00522
9	0.00543
10	0.00450

Table 8: Halo losses for the 10 seeds of **CO2 + jaw misalignment** ($|dx|_{max} = |dy|_{max} = 1\ mm$).

The code provides a listing of the names of all elements receiving non-zero losses and the number of particles lost. The following listing corresponds to the ring 7337 case of Table 6 with 0.5 mm jaw misalignment.

```
  #     elm.name  drift name    s[m]      N lost      #     elm.name  drift name    s[m]      N lost

  325   RBA78B1   D000039       837.017       4     10099   BPMYC     D000024     23306.371       7
  329   BPM       D000056       838.538       1     10101   RQ5L6B1   D000023     23310.043       1
  831   ROFA78B1  D000057      1908.191       1     10131   MKD       D000180     23341.918       1
 1099   RCSA78B1  D000040      2494.945       1     10133   BPMYC     D000024     23342.771      15
 1497   D000014   MCBX3L8      3456.911       1     10135   RQ4L6B1   D000023     23346.443      17
 1578   RQ5R8B1   D000071      3680.509       1     10179   BPMYC     D000024     23722.771       4
 5932   BPMW      RCBWH5R3    13647.172       1     10181   RQ5R6B1   D000023     23726.443       2
```

5 Summary and conclusions

Comparisons of the integrated inefficiency, as computed with the DIMAD + STRUCT model, with previous results [4] (collision energy, no aperture limitations) show satisfactory agreement [6].

We have studied the inefficiency of an imperfect collimation system at injection. Only the halo produced at the IR7 primary collimator has been simulated. We have approximately replaced the LHC vacuum chamber with a 2-cm radial aperture limitation at all drift entrances.

For the ideal system, studied with $\sim 10^6$ particles, the 2-cm inefficiency with respect to ring 7337 was found to average $1.7\ 10^{-4}$ with maximum $2.5\ 10^{-4}$ (this includes the losses on a ~ 10 sigma absorber) and w.r.t. to the RDS7 – $\sim 1.310^{-3}$ [*] .

A sample closed orbit, corrected at every turn to zero within the jaw sections of both IR7 and IR3, has been found to increase the average occupancy of ring 7337 by around 40 %, nearly preserving the maximum occupancy. Introducing IR3 has in this case an improving effect on the worst error seeds (around 60 %).

The worst seed of random uniform transverse misalignment of all collimators in both planes and both directions with amplitude 0.5 mm, added on top of the corrected orbit, increased the losses nearly 5 times with respect to Ideal.

In future one should consider a more realistic chamber geometry. Correct treatment of the off-momentum particles requires acceleration to be included in the model.

Acknowledgements:

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[6] (to be published)

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[*]. The losses occurring in the dispersion suppressor have been studied in more detail in [9].

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6 Appendix: collimation capabilities of Dimad

To study propagation of the halo, the basic block of code STRUCT has been implemented in Dimad. Next we describe the new `collimator` element and `set-collimator` operation, discuss some universal and special (LHC) features, and present sample input and output lists.

Tracking of GeV protons with their penetration and scattering inside the collimator material was first introduced in Dimad during the KAON factory studies [10]. The collimator is treated during tracking as an arbitrary element [2]. In a similar way, for the purposes of LHC collimation, a new beamline element (rectangular collimator) has been created that coincides with the basic module of STRUCT. The element has three parameters: aperture [m], rotation angle [rad] and kind of material (3 possible kinds). The parameters are passed to the tracking module via a new operation `SETCOL`, which can be used along with the standard Dimad operations such as tracking, field errors and misalignment, closed orbit correction, analysis of geometric and chromatic aberrations etc.

The input lattice for Dimad is, with minor differences (such as as TITLE), identical to the one of MAD8 (line format). Just as in MAD, the `USE` command is applied to identify the beamline. Next follow `DIMAT`, to pass the expanded line to the Dimad routines, the `BEAM`, to define the initial beam centroids (an arbitrary number of them) and corresponding beam sizes, and `GENERATE` – to generate the desired particle number and distribution. At this stage commands related to errors and misalignment can be introduced.

Before one proceeds with tracking, the `SETCOL` command must be called at least once for every collimator present in the beamline of use, in order to indicate how *individual collimators* are to be treated. The parameters of `SETCOL` allow:

– when applied to a primary collimator, to trigger the "discard by impact" procedure, i.e. to discard at the first turn coordinates getting outside some desired impact distance. By adjusting the parameters of `BEAM` and `GENERATE`, an arbitrary impact distribution may be defined.

– to treat the collimator as a drift, or as a black absorber;

– to store in disk file coordinates or/and amplitudes of particles reaching the collimator entrance;

In accordance with the standard database names of primary and secondary collimators of IR3 and IR7, the kind of collimator is recognised by the combination of characters ("P" or "S") and (3 or 7) in the collimator name.

By installing an arbitrary number of *test collimators* with arbitrary names and applying to them appropriate `SETCOL` operations, the halo can be analysed at chosen locations around the ring.

To this end, the beam line must contain a special collimator element named `DUMMY`, preceding any other collimator and invisible to the beam (with large aperture and zero length). This element serves to pass, via corresponding `SETCOL DUMMY` operation, *global parameters* of the collimation system and *global commands*, i.e. such that will affect all collimators during one or more tracking runs. Global parameters are:

– the beam energy and emittance;

– the ideal normalised apertures for primary and secondary collimators in IR3 and IR7 (given these, all collimators are intrinsically adjusted to their real-space offsets and angles according to the emittance);

– the momentum cut-off `DPPLIM`;

The global commands switch on or off:

– the radial aperture at the entrance of all drifts;

– the random transverse misalignment;

– a procedure that distributes particles in amplitude or coordinate bins, as they pass an arc quadrupole (not applied in this paper).

Sample Dimad input:

```
! Snapshot date: 03/12/01 Time: 131444
...                                         <--  LHC B1 lattice here in line format
                                                 STARTS AT IR7 PRIMARY called TCPA
k2d=-0.106404818276                         <--  must have correct chromaticity 2
k2f=0.065210125333

TCPA: COLLIMATOR,L=.05,p1=1,p2=0.006,p3=1.57
...                                               p1 = material
...                                               p2 = half dist between jaws
                                                  p3 = angle in rad
USE, LHCB1
MATRIX                                       <-- show the 2 ord matr. and chrom.
...
MACHINE                                      <-- the Twiss
...
SET COL
DUMMY
SET COL
TCPA   5  0  10   10  0,     <-- name, iprint, iblack, Apx, Apy, m/turn
...
SET SYMPLECTIC OPTION ON
BEAM                             <-- beam sigmas in TRANSPORT not.
1.e-40  0 0 0 0 0
1.e-40 0 0 0 0
1.e-6 0 0 0                      <-- mum impact distr (uniform)
1.e-40 0 0
1.e-40 0
1.e-40
-1,

MISALIGNMENT DEFINITION                        <--  shift in transv. dir. 2 arc quads
RQFA78Bx   .75e-3 0.  0       0. 0. 0. 0. 1
RQDA78Bx   0      0.  .75e-3  0. 0. 0. 0. 1                CO2  = 4 mm peak to peak
99,
SET MISALIGNMENT
REFERENCE ORBIT                                 <-- find closed orbit
...
GENERATE PARTICLES
45000                                                <-- per jaw
0.0  0.0  0.66224207E-02  0.69429323E-04  0.0  0.0 <--   beam centroids
0.0  0.0 -0.66224207E-02 -0.69429323E-04  0.0  0.0,

TRACKING
```

The Dimad printout contains:

- total number of particles before and after discard by impact;
- collimator names and number of particles lost in each collimator – total (third column) and within turn intervals: $0-10$, $10-20$, … (next five columns);
- numbers of particles and fractions lost in collimators and on the aperture inside and outside the collimator occupied sections.

Sample Dimad output

```
 OPERATION LIST ,
 TRACKING
 tot part   90000
 total latt elts 11517
 tot arc quads    392
     turn   ncpart
       1   90000
 discarded (impact) =  15279
       2    9437
...
      65       6
 LAST  6  ARE NOT TRACKED

Loss statistics after passage   65

        coll. name  lost    10    20    30    40    50
     1    DUM          0     0     0     0     0     0
     2    TCPA     29044 28640   214   171    14     5       <-- first primary
     3    TCPB         8     8     0     0     0     0           of IR7
     4    TCPC       718   679    31     6     1     1
     5    TCPD       831   789    22    17     2     1
     6    CS71      4974  4909    37    26     1     1
     7    CS72      3086  3033    30    18     4     1
     8    CS73      3569  3519    24    23     3     0
     9    CS74      6083  5994    47    34     6     2
    10    CS75      6336  6253    48    31     2     2
    11    CS76      4822  4750    36    29     5     2
    12    CS77      1382  1363    12     7     0     0
    13    CS78      1710  1680    17    11     2     0       <--  all IR7 secondary
    14    CS79        52    52     0     0     0     0            coll-s are loaded
    15    CS710     3251  3204    27    17     3     0
    16    CS711      319   315     1     3     0     0
    17    CS712       43    43     0     0     0     0
    18    CS713      295   273    18     4     0     0
    19    CS714      180   170     7     3     0     0
    20    CS715     3585  3522    38    22     2     1
    21    CS716      329   324     2     2     0     1
    22    TCP3         0     0     0     0     0     0
    23    CS31         0     0     0     0     0     0       <-- the IR3 coll-s. are retracted
    24    CS32         0     0     0     0     0     0
    25    CS33         0     0     0     0     0     0
    26    CS34         0     0     0     0     0     0
    27    CS35         0     0     0     0     0     0
    28    CS36         0     0     0     0     0     0
    29    TJ           0     0     0     0     0     0

Discarded at impact     15283
Total entered           74717

Collimator losses
IABS=1                  25593
Win                     44778
DppLim                    246
total lost in coll-s    70617              0.94513
```

```
total lost coll apert    1756

Aperture losses
 apert  COS7              3995     0.05347
 apert  COS3                 4     0.00005
 apert  outside COS         99     0.00132
 total lost on apert.    4098              0.05485

total lost              74715              0.99997
total survived              6              0.00008
turn-in turn-out      1    65
```