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# BEAM LOSSES IN THE SPS AND THE LHC DUE TO BEAM-GAS

# AND BEAM-BEAM COLLISIONS

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# Beam losses in the SPS and the LHC due to beam-gas and beam-beam collisions

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In a collider several processes contribute to systematic beam losses. The rate of beam scattering on the residual gas and of the beam-beam collisions in the intersection regions are two effects which can be calculated for the SPS and extrapolated to the LHC. The same calculations are done for both machines with the purpose to use the SPS collider as a laboratory to check our data and predictions for the LHC.

The calculated proton lifetimes are found to be higher than those measured during the last SPS p-pbar period where record luminosities and stabilities were reached. This is still to be understood quantitatively, taking into account other phenomena.

For the LHC, it is shown that the beam scattering on the residual gas can be neglected. On the other hand, the rates of secondary particles produced by nuclear reactions at the crossing points are very high, as are also the power transported onto the low-ß insertion magnets and into the arcs.

The sole purpose of this note is to provide a set of data which permit to quantify the effect of some basic phenomena and to help define a frame for further studies. No precise solutions to the problems evoked are proposed at this level of our work.

# 1 - BEAM-GAS   INTERACTIONS

The beam passing through the residual gas is scattered by Multiple Coulomb Scattering (MCS) or creates Nuclear Interactions (NI). Both depend on the gas density.

## 1-1)  Gas density

To compare the MCS and NI effects in both machines (SPS and LHC), some assumptions have to be made on the gas density. By definition the gas density is

$$\rho = N_a \cdot A \cdot m_p \quad (g/cm3)$$

where :

$N_a$ = nb of atoms / cm3 ,   A = nb of nucleons / atom,  and

$m_p$ = proton mass = $1.67 \cdot 10^{-24}$ g

At room temperature for a pressure P (Torr), the number of atoms per cm3 is :

$$N_a = m \cdot Avo \cdot P/(22400 \cdot 760) = 3.54 \cdot 10^{16} \cdot m \cdot P \quad ( cm^{-3} )$$

where Avo = $6.02 \cdot 10^{23}$  is the Avogadro's number and m the number of atoms /molecule

In a machine like the SPS working at room temperature, MCS and NI can be computed from an equivalent pressure of Nitrogen, which was about $5 \cdot 10^{-10}$ Torr during the last p-pbar period.

In a superconducting machine like the LHC, almost all the vacuum chamber is at liquid Helium temperature, 4.5 K, becoming a large cryopump. The residual pressure, measured with a room temperature connection, is expected to be at most $3 \cdot 10^{-12}$ Torr mainly due to Hydrogen if there is no leak [1]. This pressure corresponds to an atomic density at the gauge of :

$$(N_a)_{roomT} = 2 \cdot 3.54 \cdot 10^{16} \cdot 3 \cdot 10^{-12} = 2.12 \cdot 10^5 \text{ atoms/cm}^3$$

In the vacuum chamber, the density is then :

$$(N_a)_{4.5°K} = (N_a)_{roomT} \cdot (T_{room}/4.5)^{1/2} = 2.12 \cdot 10^5 \cdot (300/4.5)^{1/2} = 1.73 \cdot 10^6 \text{ atoms/cm}^3$$

The target length ,in g/cm2, equivalent to the residual gas is given by $x = \rho \cdot L$, where L is the target length in cm (one machine-turn integrated density). The number $N_c$ of atoms/cm2 corresponding to the target length is $N_c = N_a \cdot L$ . Table I gives $N_a$, $\rho$ ,x , $N_c$, for the SPS at a pressure of $5 \cdot 10^{-10}$ Torr of equivalent Nitrogen at room temperature and for the LHC (at 4.5 K) at a pressure of $3 \cdot 10^{-12}$ Torr measured with a room temperature connection (LHC1).

Another case of interest for the LHC corresponds to a local leak, mainly of Helium, over half a period, (L=100 m). The associated pressure bump is here normalized so as to have an integrated density (x in table 1) equal to that one of the case LHC1 (see column LHC2 in table 1).

| | SPS | LHC1 | LHC2 |
|---|---|---|---|
| L (cm) | $6.91 \cdot 10^5$ | $2.67 \cdot 10^6$ | $1 \cdot 10^4$ |
| Momentum (Gev/c) | 315 | 8000 | 8000 |
| Frev (KHz) | 43.4 | 11.25 | 11.25 |
| Gas | N2 | H2 | He |
| A (nucleons/atom) | 14 | 1 | 4 |
| P (Torr) | $5 \cdot 10^{-10}$ | $3 \cdot 10^{-12}$ | |
| $N_a$ (atoms/cm3) | $3.5 \cdot 10^7$ | $1.8 \cdot 10^6$ | $1.2 \cdot 10^8$ |
| $\rho$ (g/cm3) | $8.2 \cdot 10^{-16}$ | $3.0 \cdot 10^{-18}$ | $7.9 \cdot 10^{-16}$ |
| x (g/cm2) | $5.7 \cdot 10^{-10}$ | $7.9 \cdot 10^{-12}$ | $7.9 \cdot 10^{-12}$ |
| $N_c$ (atoms/cm2) | $24.2 \cdot 10^{12}$ | $4.8 \cdot 10^{12}$ | $1.2 \cdot 10^{12}$ |
| X (Rad length) (g/cm2) | 38 | 63 | 94 |
| $< \Theta >_{MCS}$ /turn (rad) | $1.84 \cdot 10^{-10}$ | $0.66 \cdot 10^{-12}$ | $0.54 \cdot 10^{-12}$ |

Table 1

## 1-2) Multiple Coulomb Scattering (MCS)

The r.m.s MCS angle per turn projected on one plane is given by :

$$< \Theta >_{MCS} = (15 \cdot 10^{-3} \cdot (x/X)^{1/2})/p$$

where

p = particle momentum in Gev/c

x = target length in g/cm$^2$

X = radiation length in g/cm$^2$

The values of $< \Theta >_{MCS}$ /turn are given in Table 1.

The case of a particle making a single Coulomb scattering with a significantly larger angle is discussed in section 1.4.2.

## 1-3) Nuclear interactions

For H2, He, and N2 , Table II gives:

- the approximate center-of-mass energy $(s)^{1/2} = (2 \cdot p \cdot A \cdot E_0)^{1/2}$ where p is the beam momentum (Gev/c), A the atomic number of the target, $E_0$ the proton rest energy (= 0.938 Gev)

- the proton-nucleon total ( $\sigma_{TOT}$ ) and elastic ( $\sigma_{ELA}$ ) cross-sections [3]

- the total ( $\lambda_{TOT}$) and elastic ( $\lambda_{ELA}$) collision lengths defined by $\lambda = (A \cdot m_p/\sigma )$ in g/cm2

- the elastic differential cross-section defined in the usual way as

$d\sigma_{ELA}/dt = a \cdot e^{(-b \cdot t)}$ , where $t = ( p \cdot \Theta )^2$, $1/b = ( p \cdot \Theta_o)^2$ and $\sigma_{ELA} = a/b$

( t : 4-momentum transfer , $\Theta$ : polar angle )

|  | SPS | | | LHC | | |
|---|---|---|---|---|---|---|
|  | p-H | p-He | p-N | p-H | p-He | p-N |
| $(s)^{1/2}$ (Gev/c) | 24.3 | 49 | 91 | 122.5 | 245 | 458 |
| $\sigma_{TOT}$ (mb) | 40 | 136 | 380 | 49 | 167 | 465 |
| $\sigma_{ELA}$ (mb) | 7.5 | 22 | 127 | 9 | 27 | 156 |
| $\lambda_{TOT}$ (g/cm2) | 41.7 | 49.1 | 61.5 | 34.0 | 40.0 | 50.3 |
| $\lambda_{ELA}$ (g/cm2) | 223 | 304 | 184 | 186 | 247 | 150 |
| a (mb/(Gev/c)$^2$) | 90 | 880 | 8300 | 126 | 1690 | $1.2 \cdot 10^5$ |
| b (Gev/c)$^{-2}$ | 12 | 40 | 66 | 14 | 47 | 77 |
| $\Theta_o$ (mrad) | 0.92 | 0.50 | 0.39 | 0.031 | 0.017 | 0.013 |

Table II

The total mean free path between 2 nuclear collisions ($mfp_{TOT}$) and between 2 nuclear elastic collisions ($mfp_{ELA}$), defined by $mfp = \lambda/\rho$ are computed below using the data of table 1.

For the SPS with a Nitrogen density of $8.2 \cdot 10^{-16}$ g/cm3 or $3.5 \cdot 10^7$ atoms / cm3 :
$mfp_{TOT} = 7.5 \cdot 10^{16}$ cm, or $1.1 \cdot 10^{11}$ SPS turns, or $2.6 \cdot 10^6$s = 29 days
$mfp_{ELA} = 22.4 \cdot 10^{16}$ cm, or $3.2 \cdot 10^{11}$ SPS turns, or $7.6 \cdot 10^6$s = 86 days

For the LHC with a Hydrogen density of $3.0 * 10^{-18}$ g/cm3 or $1.8 \cdot 10^6$
**$mfp_{TOT}$** $=1.1 \cdot 10^{19}$ cm, or $4.2 \cdot 10^{12}$ LHC turns, or $3.8 \cdot 10^8$s = **4300 days**
**$mfp_{ELA}$** $= 6.2 \cdot 10^{19}$ cm or $2.3 \cdot 10^{13}$ LHC turns or $2.0 \cdot 10^9$s = **23500 days**
They are very large for the low gas densities in the LHC case.

With the same gas and densities ($24.4 \cdot 10^{12}$ Nitrogen atoms/cm2 in the SPS , $4.8 \cdot 10^{12}$ Hydrogen atoms/cm2 in the LHC) and the cross-sections given above, the luminosity for the beam-gas nuclear interactions ( **L = $N_c \cdot N_p \cdot f_{rev}$**) and the corresponding number of events are given on Table III. For the SPS case, the beam intensities correspond to the current values obtained during the last p-pbar period. In the LHC columns, LHCN corresponds to the nominal intensity [1]and LHCM to the maximum expected intensity [2].

|  | SPS | LHCN | LHCM |
|---|---|---|---|
| $N_p$/bunch | $1.6 \cdot 10^{11}$ | $2.6 \cdot 10^{10}$ | $1.0 \cdot 10^{11}$ |
| Nr of bunches / beam | 6 | 3564 | 4875 |
| $N_p$ / beam | $1 \cdot 10^{12}$ | $0.91 \cdot 10^{14}$ | $4.87 \cdot 10^{14}$ |
| L / beam (cm-2*s-1) | $1.0 \cdot 10^{30}$ | $4.8 \cdot 10^{30}$ | $26 \cdot 10^{30}$ |
| Nuclear events / beam*s | $3.8 \cdot 10^5$ | $2.3 \cdot 10^5$ | $13 \cdot 10^5$ |
| Elastic events /beam*s | $1.3 \cdot 10^5$ | $0.42 \cdot 10^5$ | $2.3 \cdot 10^5$ |
| Tn (s) | $2.6 \cdot 10^6$ | $3.8 \cdot 10^8$ | $3.8 \cdot 10^8$ |
| Tn (Hrs) | 730 | 104000 | 104000 |

Table III

## 1-4 ) Proton lifetime

1-4-1 ) The nuclear interaction of the beam with the residual gas leads to an exponential decay of the beam intensity such as $I = I_0 \cdot e^{-t/Tn}$ or $dI = -I \cdot dt/Tn$ , Tn being the nuclear proton lifetime due to the gas.

Assuming all the protons having got a nuclear interaction are lost, the lifetime due to nuclear interactions, $Tn = I \cdot dt/dI$, is given in Table III.

These values are very large for the LHC, where the nuclear interactions on the residual gas can then be neglected as far as the lifetime is concerned.

1-4-2 ) The Multiple Coulomb Scattering progressively increases the initial emittance. After one day of storage (86400 s), the average MCS angle is

$$< \Theta >_{day} = < \Theta >_{turn} \cdot (Frev \cdot 86400)^{0.5}$$

The MCS is a continuous process, so the average angle can be compared with the standard deviation angle $\sigma'$ at beta average, due to the beam emittance $\varepsilon^*$:

$$\sigma' = ( \varepsilon^* / ( \gamma \cdot < \beta > )^{0.5}$$ at the beginning of a coast. After one day, $\sigma'$ becomes

$$\sigma'_{end} = (\sigma'^2 + < \Theta >_{day}^2 )^{0.5}$$

For the SPS, using table 1 , $< \beta > = 50m$ and $\varepsilon^* = 10 \, \pi.mm.mrad$ , we get
$\sigma' = 2.44 \cdot 10^{-5}$ rad, $< \Theta >_{day} = 1.12 \cdot 10^{-5}$ rad and $\sigma'_{end} = 2.68 \cdot 10^{-5}$ rad , or an increase of 10% after one day.

For the LHC , $< \beta > = 100m$ and $\varepsilon^* = 5 \, \pi.mm.mrad$ , we get
$\sigma' = 2.42 \cdot 10^{-6}$ rad, $< \Theta >_{day} = 1.68 \cdot 10^{-8}$ rad and $\sigma'_{end} = 2.42 \cdot 10^{-6}$ rad (!), or a relative increase of $2.4 \cdot 10^{-5}$ after one day.

So, at least for LHC, the MCS will not induce beam losses by itself. But, MCS is correct only up to a few rms values. Beyond, single Coulomb interactions shall be taken into account. The Coulomb cross section is diverging at small angles (where MCS formalism is used). But, in our case, we are interested to scattering angles beyond $\sigma'$, where the cross-sections can be computed.

At high energy, the cross-section for events with an angle larger than $\Theta = \Theta_{critic}$ is

$$\sigma_c = \frac{6.5 \cdot 10^{-32} \cdot z^2 \cdot Z^2}{E^2 \cdot \Theta_{critic}^2} \quad [cm^2]$$

where     z: charge of the incident particle in unit of e

Z: charge of the target          "

E: beam energy [GeV]

We then compute $n_1 = L \cdot \sigma_c(\Theta > \sigma')$ , $n_2 = L \cdot \sigma_c(\Theta > 2\sigma')$ , $n_3 = L \cdot \sigma_c(\Theta > 6\sigma')$ where L is taken in table III and $\sigma'$, as computed above, replaces $\Theta_{critic}$ in $\sigma_c$.

We get for the SPS :   $n_1 = 5 \cdot 10^4$ , $n_2 = 1.3 \cdot 10^4$ , $n_3 = 1.4 \cdot 10^3$ ev/s .

and for the LHC    :   $n_1 = 1.8 \cdot 10^4$ , $n_2 = 4.5 \cdot 10^3$ , $n_3 = 5 \cdot 10^2$ ev/s .

$n_3$ would be the number of particles caught by a collimator set at $6\sigma$. It is two orders of magnitude smaller than the corresponding number of nuclear elastic scattering events. This effect is negligible in terms of beam lifetime.

**1-4-3)**    Experimental values of the lifetime of one single beam are found to be smaller than those given only by nuclear and Coulomb scatterings.

The measured SPS proton lifetime when no pbar are circulating is of the order of $250 \pm 50$ hours. It is 3 times less than the value expected from the beam-gas nuclear interactions. Other effects (intrabeam scattering, Power Supply ripples, RF noise,...) can increase the emittance and reduce the lifetime. These effects cannot be yet quantified individually neither for the SPS nor for the LHC.

## 1-5 )  Influence of a collimator

### 1-5-1)  Inelastic collisions

Protons having got an inelastic collision produce secondary particles with much lower energy. Those particles are stopped in the nearby bending magnets, just downstream of the location of the interaction. The losses being distributed everywhere, a localized collimator has no effect. But the average energy deposited by meter of bending magnet is small:

~ 55 protons /m $\cdot$ s = 2.8 $\mu$w/m for the SPS

~ 49 protons /m $\cdot$ s = 63 $\mu$w/m for the LHCM

Even in the case of a Helium leak over 100 m equivalent to a target of $1.2 \cdot 10^{12}$ atoms/cm2 (LHC2 in 1-1) and with the LHCM data, the local luminosity would be $6.6 \cdot 10^{30}$. $1.1 \cdot 10^6$ nuclear events/s are produced over 100 m, i.e 11000 lost protons/m $\cdot$ s, corresponding to a power of 14 mW/m.

### 1-5-2 )  Elastic collisions

In the SPS the number of protons making an elastic collision with a Nitrogen target of $5.7 \cdot 10^{-10}$ g/cm2 is $1.3 \cdot 10^5$ p/beam $\cdot$ s with an average angle  $\Theta_0 = 0.39$ mrad

For the LHC ,with the maximum intensity (LHCM), the luminosity on the Hydrogen target (LHC1) and on the Helium target (LHC2) are respectively $26 \cdot 10^{30}$cm-2*s-1 and $6.6 \cdot 10^{30}$cm-2*s-1. The corresponding number of protons making an elastic collision are respectively $2.3 \cdot 10^5$ p/beam·s (= 0.3W), with an average angle $\Theta_0 = 34 \cdot 10^{-6}$ rad. and $1.8 \cdot 10^5$ p/beam·s (= 0.23W) with an average angle   $\Theta_0 = 18 \cdot 10^{-6}$ rad.

These average angles are quite large and produce important betatronic oscillations superposed to the closed orbit. The peak amplitude varies according to the position where the collision occurs. In the arcs, the maximum amplitude $Y_{MAX} = \beta_{MAX} \cdot \Theta_o$ is for a particle emitted with an angle $\Theta_o$ at $\beta_{MAX}$ and measured at $\beta_{MAX}$. For example, for the SPS with a Nitrogen target and $\beta_{MAX} = 107m$, $Y_{MAX}=42mm$; in the LHC with an Hydrogen target (LHC1) and $\beta_{MAX} = 169.5m$, $Y_{MAX}= 5.8mm$. Of course, $\Theta_o$ must be replaced by a distribution extending up to large values, but vanishing exponentially with t.

With such a large amplitude superposed to the beam emittance, elastic particles will be stopped by any aperture limitation (vacuum chamber or collimator). Collimators could be justified in that case to reduce the noise on the experiments, but the power involved by the beam-gas elastic scattering is not a danger for the superconducting magnets.

# 2 - BEAM-BEAM COLLISIONS

The beam-beam interactions in the intersection regions concern the hadron collisions and the global effect of one beam on the other (beam-beam effects). Only the hadron collisions are considered here.

The p-p cross-sections (elastic and inelastic) [3] are given in Table IV . The symbols are defined as in 1-3.

## 2-1 beam lifetimes

From this table the number of events can be obtained for the SPS and the LHC (Table IV). In the interaction regions (I.R) where there is no physics experiments, the hadron collisions are neglected, the two beams being separated or the I.R being set to a modest low-beta configuration. Only one LHC physics experiment is assumed to work at a given time. The SPS intensity corresponds to average p and pbar values obtained during the last p-pbar period. As in 1-3, LHCN corresponds to the nominal LHC intensity [1] and LHCM corresponds to the maximum expected intensity [2]. The beam lifetime due to collisions,  Tc = I.(dt/dI) , is calculated by assuming that all the particles having made a nuclear collision are lost.

In the SPS, the calculated beam lifetime due to beam-beam collisions is about the same as the calculated beam lifetime due to the residual gas. Adding the two effects gives a global lifetime of 340 hrs, while the measured lifetime in collision was around 50 hrs during the last p-pbar period. Other effects like beam-beam contribute to reduce the beam lifetime, but this is still to be understood quantitatively. Also, the effects may not simply add. For example, the beam-beam effect is stronger for particles of large emittance and elastic scattering (see next section) is populating the phase space mostly  in the region between 0-5 $\sigma'$. This is certainly a case where two different effects must be studied together.

## 2-2 Influence of collimators

Inelastic interactions produce a full spectrum of lower energy particles. They deposit a significant fraction of their energy in the experimental detector and in the nearby low-beta quadrupoles.

Elastic particles are characterized by small energy losses and small angles, which allows them to travel inside the vacuum chamber for long distances. Elastic particles produced at $\beta^*$ get an

average betatronic amplitude $Y = \langle \Theta_o \rangle \cdot (\beta^* \cdot \beta)^{0.5} \cdot \sin\mu$  ( $\mu$ = phase advance ), which is maximum in the low-$\beta$ quadrupoles ( $\mu$= 90° and $\beta = \beta_{MAX}$ ).

These amplitudes are computed in Table IV . They are of the same order as the beam sizes at $2\sigma$ measured at the same locations ( low-$\beta$ quads or at $\beta_{MAX}$ in the arcs).

The fraction of elastic particles outside $\pm 2\sigma'$ is small ( 8% for LHCN, <1% for LHCM ) . On the other hand, those particles emitted inside $\pm 2\sigma'$ will not hit the vacuum chamber during their first turn , but will contribute to emittance growth (see section 2.1) and finally to beam losses. After some coast duration, the total rate of losses in the ring shall be computed as a substantial fraction of the elastic cross-section , i.e. ~ $10^9$ per second and per ring. An efficient collimation system is then obviously needed.

From these considerations, one can deduce two lines for further studies.

1)   The flux of particles on all the machine elements around the main collision points is to be carefully evaluated. One-particle production at 8+8 TeV in the low-$p_t$ phase-space shall be simulated and tracking be done along the nearby machine elements.

2)   The efficiency of collimators shall be computed. First of all, the flux reemitted by a collimator shall be understood quantitatively. Then, a scheme of collimation for the LHC can be studied (locations, number of stages, ... ) and a global efficiency computed.

Only then, a relation between the luminosity and the power to be absorbed at any critical location can be established.


# CONCLUSIONS

It has been shown that in the LHC, while beam losses due to residual gas have weak effects, the secondary flux issued from 8+8 TeV interactions at the low-$\beta$ collision points is very high and offers an outstanding problem to be solved. It might be one of the most severe limitations towards high luminosities.

It is also shown that the beam life-time in the SPS collider is not fully understood quantitatively. To avoid surprises with LHC, studies should be pursued on that subject.

| | SPS | LHCN | LHCM |
|---|---|---|---|
| Momentum (Gev/c) | 315 | 8000 | 8000 |
| Total cross-section ($\sigma_{TOT}$) (mb) | 63 | 140 | 140 |
| Elastic cross-section ($\sigma_{ELA}$)(mb) | 14 | 40 | 40 |
| a (mb/(Gev/c)$^2$) | 210 | 805 | 805 |
| $1/b = (p^* \Theta_0)^2$ (Gev/c)$^2$ | 0.0667 | 0.0435 | 0.0435 |
| $\Theta_0$ (mrad) | 0.82 | 0.026 | 0.026 |
| | | | |
| Nr of interaction regions | 2 | 1 | 1 |
| Nr of bunches / beam | 6 | 3564 | 4875 |
| Nr of p / bunch ($*10^{11}$) | 1.6 | 0.26 | 1.0 |
| $N_p$ / beam | $1 \cdot 10^{12}$ | $0.91 \cdot 10^{14}$ | $4.87 \cdot 10^{14}$ |
| L / beam (cm$^{-2}$*s$^{-1}$) | $2.1 \cdot 10^{30}$ | $0.14 \cdot 10^{34}$ | $3.9 \cdot 10^{34}$ |
| **Nuclear events / s** | $2.6 \cdot 10^5$ | $2.0 \cdot 10^8$ | $5.5 \cdot 10^9$ |
| **Elastic events / s** | $5.8 \cdot 10^4$ | $5.6 \cdot 10^7$ | $1.6 \cdot 10^9$ |
| **Power in nuclear events (W)** | 0.026 | 510 | $14 \cdot 10^3$ |
| **Power in elastic events (W)** | 0.006 | 146 | $4.0 \cdot 10^3$ |
| Beam lifetime (hrs) | 1070 | 126 | 25 |
| | | | |
| $\beta^*$ in insertion (m) | 0.5 | 1 | 0.25 |
| Normalized emittance ($\pi$.mm.mrad) | 10 | 5 | 15 |
| $2\sigma$ at $\beta^*$ ($\mu$m) | 122 | 24 | 21 |
| $2\sigma'$ at $\beta^*$ ($\mu$rad) | 244 | 24 | 84 |
| | | | |
| Half aperture in low-$\beta$ quad (mm) | 83 | 20 | 20 |
| $\beta_{MAX}$ in low-$\beta$ quad (m) | 2500 | 1156 | 5019 |
| $2\sigma$ at $\beta_{MAX}$ in low-$\beta$ quad (mm) | 8.6 | 0.82 | 3.0 |
| $Y_{MAX}$ in low-$\beta$ quad (mm) | 29 | 0.88 | 0.92 |
| | | | |
| $\beta_{MAX}$ (in the arcs) (m) | 107 | 169.5 | 169.5 |
| $2\sigma$ at $\beta_{MAX}$ (in the arcs) (mm) | 1.8 | 0.32 | 0.55 |
| $Y_{MAX}$ (in the arcs) (mm) | 6.0 | 0.34 | 0.17 |
| | | | |
| % of elastics out of $\pm 2\sigma'$ | | 8 | <1 |

Table IV

## Acknowledgments

## References

1) CERN 87-05 May 87

2) CERN LHC Note 70

3) Cross-sections for the different targets and energies given here have been taken ,
   extrapolated, or deduced from the following documents :
   3.1) Review of Particle Properties from the Particle Data Group PYLBA 204,1988,
        North Holland, Amsterdam
   3.2) A.Schiz et al., PRD 21 (3010), 1980
   3.3) M.Jacob , $\alpha\alpha$ & $\alpha$p interactions at ISR energies, in 5th High Energy Heavy Ions
        Study, LBL, May 1981
   3.4) M.Bozzo et al., the UA4 collaboration, CERN-EP 84-91, July 84
   3.5) G.Matthiae, CERN-EP 84-119, Sept. 1984