Most critical collimator-mask-magnet sequence in the SPS-to-LHC transfer lines: energy deposition study.

M. Marzo EN-STI-FDA, F. Cerutti EN-STI-FDA, A. Lechner EN-STI-FDA, V. Vlachoudis EN-STI-FDA

Keywords: Collimator, energy deposition, mask, FLUKA

Summary

This technical note refers to a study on the relation between the impact conditions of the SPS 450GeV proton beam and the energy deposited downstream the Target Collimator Dump Injection Long (TCDIL) collimators [1], in the SPS-to-LHC transfer lines TI2 and TI8. Such an analysis is relevant in order to simulate the worst scenario of failure, in case the beam impacts on the TCDIL collimator’s jaw, in the frame of the LHC Injectors Upgrade (LIU), in view of the High Luminosity LHC (HL-LHC) phase.

Previous studies already showed the dependency of the energy deposited in the downstream masks on the collimators-masks distance [2]. In absence of a (realistic) impact parameter, we perform now a study to select the most pessimistic one, trying to understand the origin of the various components responsible for the energy deposition on the downstream mask and magnet.

The set up of the Monte Carlo FLUKA [3] [4] simulations and the most relevant results will be presented in this document. A sensitivity analysis was also conducted, choosing the worst case collimator-mask-magnet sequence in the two transfer lines (the TCDIH.87822 will be our target collimator), with the smallest collimator-mask distance.

1 Introduction

In case of a failure, the SPS beam impacts the TCDIL collimator’s jaw (Figure 2). As a consequence of the impact, primary protons interact with the graphite of the jaws, developing a particle shower. A certain amount of energy will be deposited in the jaws, while another fraction of particles won’t be stopped, will generate other secondary particles or deposit energy in the downstream elements.

As specified in the Summary, we choose the worst case collimator-mask-sequence in the SPS-to-LHC transfer lines, that is to say the TCDIH.87822 collimator, the TCDIM.87831 mask and the MBIAH.87833 magnet (Figure 1). The reason why this configuration is the most critical is dependent- as anticipated- on the distance collimator-mask: the lower the distance between

This is an internal CERN publication and does not necessarily reflect the views of the CERN management.
the two elements, the higher the impact of the developing particles shower on the downstream mask [2] (3.25 m is the distance between the two, the lowest in TI2 and TI8). This assumption has been taken as starting point to carry out a sensitivity analysis, aiming at the selection of the worst impact condition.

![Figure 1: Most critical collimators-masks-magnets sequences in TI2 and TI8.](image)

<table>
<thead>
<tr>
<th>New Collimator Name</th>
<th>Position ( s_{\text{on}} ) [m]</th>
<th>Length [m]</th>
<th>Downstream Mask</th>
<th>Position ( s_{\text{on}} ) [m]</th>
<th>Centre-to-centre Distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCDIH.29049</td>
<td>2972.250</td>
<td>2.5</td>
<td>TCDIM.29059</td>
<td>2975.733</td>
<td>4.433</td>
</tr>
<tr>
<td>TCDIH.29206</td>
<td>3016.500</td>
<td>2.5</td>
<td>TCDIM.29241</td>
<td>3032.171</td>
<td>16.621</td>
</tr>
<tr>
<td>TCDIV.29233</td>
<td>3028.170</td>
<td>2.5</td>
<td>TCDIM.29241</td>
<td>3032.171</td>
<td>4.951</td>
</tr>
<tr>
<td>TCDIH.29464</td>
<td>3099.170</td>
<td>2.5</td>
<td>TCDIM.29472</td>
<td>3101.809</td>
<td>3.589</td>
</tr>
<tr>
<td>TCDIV.29508</td>
<td>3108.250</td>
<td>2.5</td>
<td>TCDIM.29527</td>
<td>3116.402</td>
<td>9.102</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Collimator Name</th>
<th>Position ( s_{\text{on}} ) [m]</th>
<th>Length [m]</th>
<th>Downstream Mask</th>
<th>Position ( s_{\text{on}} ) [m]</th>
<th>Centre-to-centre Separation [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCDIH.87606</td>
<td>2432.032</td>
<td>2.5</td>
<td>TCDIM.87658</td>
<td>2456.232</td>
<td>25.150</td>
</tr>
<tr>
<td>TCDIV.87644</td>
<td>2450.745</td>
<td>2.5</td>
<td>TCDIM.87658</td>
<td>2456.232</td>
<td>6.437</td>
</tr>
<tr>
<td>TCDIV.87804</td>
<td>2501.125</td>
<td>2.5</td>
<td>TCDIM.87831</td>
<td>2512.730</td>
<td>12.555</td>
</tr>
<tr>
<td>TCDIH.87822</td>
<td>2510.430</td>
<td>2.5</td>
<td>TCDIM.87831</td>
<td>2512.730</td>
<td>3.250</td>
</tr>
<tr>
<td>TCDIH.87939</td>
<td>2566.345</td>
<td>2.5</td>
<td>TCDIM.87966</td>
<td>2576.219</td>
<td>10.824</td>
</tr>
<tr>
<td>TCDIV.88121</td>
<td>2620.897</td>
<td>2.5</td>
<td>TCDIM.88132</td>
<td>2625.125</td>
<td>5.178</td>
</tr>
</tbody>
</table>

1.1 The TCDIH.87822 collimator

The TCDIL collimator TCDIH.87822 (length 2.26m) mainly consists of an external tank, start and end plates, jaws supports and flanges in stainless steel (304L, \( \rho = 8.02 \frac{g}{cm^3} \)), while jaws are in graphite (\( \rho = 1.83 \frac{g}{cm^3} \)). It is a horizontal collimator, its jaws are in vertical position and can move horizontally (Figure 2).

In order to calculate the half gap of the collimator\(^1\)- useful to define the impact conditions-some beam parameters have to be known. Starting from:

- The nominal emittance for LHC \( \epsilon_n = 3.5 \mu m \);
- The relativistic gamma \( \gamma = 479.60 \);
- The \( \beta \) function (at the upstream end of the TCDIH.87822) \( \beta = 79.47 \)

One can compute then the nominal value of \( \sigma \):

\[
\sigma_n = \sqrt{\frac{\epsilon_n \beta}{\gamma}} = 0.76 mm
\]  

From \( \sigma_n \), the half gap of the collimator can be calculated as:

\(^1\)The half gap of a collimator is defined as half the distance between the 2 jaws (Figure 2a)
Given Equation (2), the aperture of the collimator (distance between the two jaws) is twice the half gap (6.84 mm).

The impact parameter $b$ is finally defined as:

$$ b = x_{\text{impact}} - 4.5\sigma_n $$

Where $x_{\text{impact}}$ is the actual coordinate of the beam center impacting the jaw (Paragraph 2.1).

1.2 The TCDIM.87831 mask

The MBIA mask TCDIM.87831 (Figure 3) is a 50 cm long cylinder, having an external diameter of 15 cm and 5.2 cm thick wall (internal profile is circular, Figure 3a), in stainless steel (304L). It is located downstream the TCDIL, after 3.2 m. Its main function is to shield the downstream magnet from the energetic particles emerging after the interaction between the protons beam...
of the SPS and the graphite jaws of the collimator (Figure 5).

(a) xy plane section: circular profile  
(b) 3D view

Figure 3: TCDIM.87831 mask.

1.3 The MBIAH.87833 magnet

The MBIAH.87833 magnet is 3.88m long and it has a low carbon steel ($\rho = 7.87 \frac{g}{cm^3}$) yoke, surrounding the inner coils. Of primary interest are the copper coils ($\rho = 8.96 \frac{g}{cm^3}$). After the interaction of the shower with the mask, a fraction of secondary energetic particles will reach the magnet. The most critical portion of the coils is represented by the upstream return coils (magenta in Figure 4): they are closer to the beam, so highly exposed to the particles shower.

Figure 4: MBIAH.87833 magnet, 3D view.
2 FLUKA simulations

2.1 Geometry and the LineBuilder

The origin of the FLUKA reference system is placed at the entrance of the collimator, between the 2 jaws, in the xy plane (Figure 2a). The y coordinate is upward, the z is in the beam direction (Figure 5).

The beam is displaced with respect to the origin, as we want to simulate different impact conditions. We can define the displaced coordinates of the beam center as $x_{impact}$ and $y_{impact}$: being the TCDIH.87822 an horizontal collimator, $y_{impact}$ will be zero, while $x_{impact}$ will change according to the impact parameter (Equation 3).

Depending on the choice of $b$, different scenarios will then arise downstream the collimator:

- For low $b$ values (impact closer to the beam axis), the most energetic secondary particles emerging from the interaction between the proton beam and the graphite jaw will leave the collimator exiting from the gap of the collimator itself;

- On the other hand, for higher $b$ values (further from the beam axis), a bigger amount of secondary energetic particles will leave the collimator from the jaw.

This is mainly due to the different amount of material the developing shower is interacting with in the two different scenario and it has, of course, a repercussion on the energy deposition profile in the downstream mask: the energy distribution is asymmetric and change as a function of $b$ in the xy plane (Paragraph 3.1.2).

It’s clear, from these preliminary considerations, that different impact parameters originate different scenarios in terms of increases of temperature in the downstream elements.

![Figure 5: Collimator-mask-magnet worst case sequence: coordinate system.](image-url)
The geometry we want to simulate has been built using the LineBuilder [5] and visualized through Flair [6]. It consists of (Figure 5):

- The already described collimator-mask-magnet sequence;
- The tunnel: walls are made of concrete and the tunnel is filled up with air;
- The beam pipe: a cylinder of 6.3 cm external diameter, 0.15 cm thick, in stainless steel (304L), with vacuum inside.

2.2 Beam characteristics

The beam used for the simulations is a Gaussian beam of $450\frac{GeV}{c}$ protons, whose center is located at $(x_{impact}, 0)$. Different $b$ impact parameters have been chosen, namely 1mm, 2mm, 3mm, 4mm, 5mm, 7mm, 10mm, to carry out a sensitivity analysis, by changing the impact conditions.

Considering the emittance of the beam $\epsilon_b = 2.1\mu m$, the shape of the beam can be easily determined, introducing the $\sigma^x_b$: and $\sigma^y_b$

$$\sigma^x_b = \sqrt{\frac{\epsilon_b\beta_x}{\gamma}} = 0.59mm \quad \sigma^y_b = \sqrt{\frac{\epsilon_b\beta_y}{\gamma}} = 0.50mm$$

(4)

Where $\beta_x = 79.47$ m and $\beta_y = 57.95$ m have been used.
2.3 Transport of particles

The energy thresholds of the Monte Carlo simulations for production and transport of secondary particles are set to 100keV, while for neutrons down to thermal energies. This means that in general particles having energies higher than 100keV will interact with matter and produce other particles which will be in turn transported in the region by the Monte Carlo code. Those further particles will generate other secondaries that will be tracked by FLUKA only if they have energies higher that 100keV. If, on the other hand, one particle has energy lower than 100keV, it will deposit all its energy on spot, without generating other secondaries. Neutrons are treated in the same way, but the energy cutoffs for transport and production of secondaries is $10^{-5}$eV.

2.4 Scoring

The relevant quantity for our study is energy, that is to say the energy density deposited by each primary (the FLUKA code computes energy density and normalizes it per primary). Energy density is calculated by FLUKA in $\frac{GeV}{pp\cdot cm^3}$ ($pp$ stands for primary proton).

Considering that we have 288 bunches of protons each one containing $2.3 \cdot 10^{11}$ protons, the increase of adiabatic temperature $\Delta T$ due to the radiation exposure can be obtained by dividing by the density $\rho$ and the specific heat $c_p$ of the material of the considered sensitive volume. In the case of interest, $c_p^{SS304L} = 0.45 \frac{J}{gK}$ has been used to calculate the energy deposition in the stainless steel body of the mask, $c_p^{Copper} = 0.38 \frac{J}{gK}$ for the magnet coils. Given the high increase of temperature expected in the graphite of the jaws, directly impacted by the proton beam, $c_p^{Graphite}$ has not been considered constant with temperature, but tabulated values as a function of temperature have been used.

The region of the jaws where we simulate the energy deposition has been discretized in bins of 0.02x0.02x2 cm$^3$. For the mask we chose 180 bins in azimuthal direction, 0.05 cm long in radial direction and 1.25 cm along z. In the return coils of the magnet the bin size is instead 0.25x0.25x2 cm$^3$. 
3 Outcome of the FLUKA simulations

3.1 Energy deposition

In this section the results of the sensitivity analysis varying $b$ will be presented. As already specified, particular attention will be given to the energy (density) deposition in the TCDIL collimator’s jaws (graphite), in the downstream mask (stainless steel 304L), whose role is to shield the magnet and in the magnet’s coils (Copper).

3.1.1 Energy deposited in the collimator

The $\Delta T$ profile in the xy plane for a 4mm impact parameter is reported in Figure 6, where 3 different relevant section of the impacted jaw are presented: the $\Delta T$ peak profile takes place after $\sim$15cm far from the upstream end of the jaw. Figure 6b shows how the shower develops along the two jaws, at beam height. The $\Delta T$ in the non-impacted jaw is actually zero at the beginning of the collimator and in general lower than the impacted jaw.

![Figure 6: $\Delta T$ distribution, 4mm impact parameter ($x_{\text{impact}} = 7.42\text{mm}$).](image)
From Figure 7, it’s evident how for small values of impact parameters a portion of the shower exits the collimator from the gap, without interacting with the impacted jaw (i.e. \(b = 1\) mm).

On the other hand, for higher values of \(b\), the shower mostly develops within the jaw (i.e. \(b = 4\) mm, Figure 7). It will be more densely populated and in this case the most energetic particles responsible for energy deposition in the downstream elements will reach the mask, after leaving the collimator by escaping from the jaw.

**Figure 7:** \(\Delta T\) peak profile in the impacted jaw of the collimator, for 3 different values of impact parameters.
Figure 8: $\Delta T$ peak profile along $z$, in the TCDIL jaws.

Taking a look at the $\Delta T$ peak profile along $z$ (Figure 8) for different values of $b$, the highest peak location is $\sim 15$ cm far from the upstream end of the collimator. It is also worth noticing how for small values of the impact parameter the $\Delta T$ peaks in the downstream sections of the collimator are lower than in the case of higher impact parameters (magenta curve with respect to the yellow one and the others, Figure 8). The maximum peak of adiabatic temperature simulated in the jaw is $\sim 1100$K.
3.1.2 Energy deposition in the downstream mask

The TCDIM mask is the first element downstream the collimator affected by the change of the impact conditions. As pointed out in the previous paragraph, by varying the value of $b$ from 1mm to 15mm, the fraction of particles populating the shower that exits from the half gap or from the jaw changes and this is reflected on the energy distribution profile in the mask. Considering the 1mm and 3mm impact parameters, the $\Delta T$ peaks (red regions) are located in the left half of the xy section of mask. This suggest that the particles actually depositing the biggest amount of energy are the ones exiting- in this case- the gap of the collimator (first two plots in Figure 9).

For opposite reasons, from to 5mm to 15mm (impact parameters), the peaks of $\Delta T$ shift to the right half of the xy section of the mask and gradually increase. In this case the maximum of energy deposition is due to particles coming from the jaw of the collimator, the impacted one, as previously pointed out.

![Figure 9: $\Delta T$ in $xy$ plane at $z_{T_{peak}}$ for the TCDIM: 1mm, 3mm, 5mm, 7mm, 10mm, 15mm impact parameters.](image)

The change of the impact conditions has consequences not only in terms of $\Delta T$ profile in the $xy$ plane of the mask, but also from a quantitative point of view. By rising the value of $b$ from 1mm to 3mm, for instance, a shift along the z coordinate of the $\Delta T$ peaks can be found, as reported in Figure 10. The peak of the yellow curve ($b=3$mm) is found at a lower value of
Figure 10: $\Delta T$ peak profile along $z$, varying impact parameters: from a 1mm to 15mm impact parameter the peak moves towards the upstream end of the mask.

$z$ than the magenta curve ($b = 1\text{mm}$): the two peaks have anyway the same value, $\sim 140K$ and this maximum takes place between 4 and 6 cm from the upstream end of the mask. For impact parameter between 7mm and 15mm, the peaks of $\Delta T$ do not considerably shift along the $z$ coordinate, but increase: 150K in the case of 7mm, 190K in the case of 10mm and 270K in the case of a 15mm impact parameter.

The 10mm impact parameter has been taken as reference in the specific case of the TCDIH.87822 collimator, as worst case scenario: higher $b$ values are unrealistic.
3.1.3 Energy deposited in the magnet’s coils

The return coils at the entrance of the magnet are closer to the beam pipe than the inner coils, so more exposed to radiation. They represent the most critical region of the magnets downstream the mask.

As clearly visible from Figure 12, where the ∆T peak profile along z for the upper return coil in the upstream end of the collimator is presented (the lower return coil shows the same ∆T peaks behavior), the worst impact condition for the magnet is the 1mm impact parameter 11. In the other impact configurations the return coils seem to be better shielded by the mask: from 1mm to 7mm (magenta, yellow and light blue curves in Figure 12) the effect of the mask is dominant, while for $b = 10mm$ and $b = 15mm$ (blue and brown plots) there is a slight increase of the ∆T peaks, due to a fraction of the most energetic particles reaching the coils.

The ∆T peaks for $b = 1mm$ is $\sim 10K$, while in the 10mm impact parameter configuration (the most critical one for the collimator and the mask) the increase of temperature is $\sim 8K$.

![Figure 11: ∆T profile in the return coils at $z_{peak}$, $b = 1$ mm.](image-url)
Figure 12: $\Delta T$ peak profile along $z$, upper return coil.
3.2 Total energy

In Figure 13 the fraction of total energy per region, varying the impact parameter, is presented. Considering that we have a beam of 288 bunches, each of $2.3 \times 10^{11}$ protons of 450GeV (Paragraph 2.4), the total energy involved in our simulations is 4.77MJ.

![Figure 13: Fraction of total energy deposited in all the most relevant regions of the beam line.](image)

In the following, a summary of the (total) energy distribution on the main regions of the geometry we simulated in FLUKA is reported:

- A large fraction (25–35%) is deposited on the collimator and another significant part in the tunnel (20–28%);
- The energy simulated in the mask and the magnet are respectively ~ 8% and 15–18% of the total;
- The *escaping energy*, that is the energy of particles escaping the system, is 10–28%: a certain amount of particles, in fact, will end up downstream the magnet$^2$;
- The *discarded energy*, energy of particles that are discarded (typically neutrinos that FLUKA always discards by default), represents ~ 2% of total energy;
- The *missing energy* is the difference between the total energy and all the other energies calculated by FLUKA. It is ~ 5% of the total energy;
- With *other* we mean the fraction of energy deposited in regions other than the ones presented. This energy is almost negligible.

$^2$When the impact parameter is 1 mm, the escaping energy is higher. A larger fraction of shower, in this case, leaves the collimator from the gap, does not interact or partially interacts with the mask and the magnet and finally reaches regions located downstream the magnet.
3.2.1 Total energy in the collimator’s main regions

The total energy in the collimator is 1.2 ÷ 1.7 MJ. It’s typically higher for higher values of impact parameters (Figure 13 and Figure 14) and distributed as follows:

- 6 ÷ 12% of the total in the impacted jaw;
- ~ 5% in the non-impacted jaw;
- 8 ÷ 9% in the collimator’s tank;
- 8 ÷ 10% in the other collimator’s regions.

The most critical impact condition for the collimator (~1.7 MJ) and the impacted jaw (~0.5 MJ) is then \( b = 10 \text{mm} \).

![Figure 14: Fraction of total energy deposited in the regions of the collimator.](image-url)
3.2.2 Total energy in the magnet’s main regions

The total energy in the magnet is $0.7 \div 0.9$ MJ: it typically decreases as the impact parameter rises (see Figure 13).

This is the overall picture of the energy distribution in the different magnets’s regions:

- $\sim 10\%$ of the total in the magnet’s yoke;
- $\sim 3\%$ of the total in the return coils;
- $\sim 1.5\%$ of the total in the inner coils;
- $\sim 1\%$ of the total in the other magnet’s regions.

The most critical impact condition for the magnet and the return coils is then $b = 1\ mm$, respectively corresponding to $\sim 0.86$ MJ and $\sim 0.07$ MJ (Figure 15).

![Figure 15: Fraction of total energy deposited in the most impacted regions of the magnet.](image-url)
4 Conclusions

From the conducted study, it’s evident that the beam impact conditions are actually crucial for the energy distribution profile in the downstream mask and the magnet: changing $b$, the fraction of the developing particles shower that exits the collimator from the gap or the impacted jaw changes.

Our Monte Carlo simulations, aiming at selecting one possible worst case impact configuration, showed us that the 10mm impact parameter is the most critical impact condition concerning the collimator’s impacted jaw and the mask. In these cases we have:

- $\Delta T_{\text{peak}}=1100\text{K}$ and $E_{\text{tot}}=0.5\text{MJ}$ for the graphite jaw;
- $\Delta T_{\text{peak}}=190\text{K}$ and $E_{\text{tot}}=0.35\text{MJ}$, concerning the stainless steel mask.

On the other hand, due to the actual shielding effect of the mask that is apparently more effective for higher values of $b$, the 1mm impact condition is the most critical one for the magnet’s copper return coils, where we simulated a $\Delta T_{\text{peak}}=11\text{K}$ and $E_{\text{tot}}=0.07\text{MJ}$.)
References


