FLUKA implementation and preliminary studies of the AD-target area

Marco Calviani / EN-STI, Elzbieta Nowak / EN-STI

Keywords: AD target, iridium, FLUKA, horn, antiproton yield, PSAIF, dump, collimator

Summary

In the context of the AD-target long term consolidation activities, a simulation framework was needed in order to address specific requirements of upgrade projects as well as to investigate possible new operational procedures in order to improve the anti-proton production yield. The present work illustrates the details of the implementation of the AD-target area in the FLUKA Monte Carlo code as well as comprehensive studies on the sensitivity of the anti-proton yield as a function of mechanical parameters and beam line settings.

1. Introduction

The present note describes an implementation of the anti-proton decelerator (AD) target area into the FLUKA Monte Carlo code (1, 2), which includes the complete antiproton production assembly, the focussing horn, collimators and proton dump as well as the magnetic dog-leg, which performs the antiproton momentum selection. Based on that, the radiation field expected in the target area during operation has been calculated and then compared with available measurement cross-checks. Additionally, the note describes the investigations of the antiproton yield sensitivity on the transversal and longitudinal alignment of both the production target and the focussing horn.

2. The Antiproton Decelerator (AD) target area

The AD target area is a secondary beam production zone, where antiprotons are produced, collimated and momentum-selected to prepare for their injection into the antiproton decelerator (AD) ring. The area is located roughly 10 meters underground in building 853 (on the CERN Meyrin site) and the production is performed by using the 26 GeV/c proton beam extracted from the CERN’s Proton Synchrotron (PS). After being dispatched into the TT2 transfer tunnel the beam is deflected into the FTA transfer line and then injected in the target area.

The current configuration of the target area includes several elements, which have the objective of providing the highest transmission efficiency in the AD acceptance and to
collimate as much as possible – in the target area – all secondary particles produced in the target but which are outside of the AD momentum and space acceptance, with the main aim of minimizing activation of the dog-leg magnetic elements as well as downstream beam intercepting devices. The current geometry of the beam line dates back to 1987, when the anti-proton accumulator (AA) target area installations have been dismantled (following the termination of the SppS program) to make space for the ACOL project, which required a complete revision of the production zone. The main elements present in the actual target area, together with their functions, thoroughly described in the next sections, are the following:

- The production target, responsible for the production of secondary particles (among which the anti-protons) due to the nuclear interactions between the proton beam and the spallation material (iridium in this case).

- The magnetic horn, which consist of two coaxial conductors which encompass a closed volume; a toroidal magnetic field is applied inside this volume, with an intensity inversely proportional to the distance from the horn axis. Charged particles entering the magnetic volume are bent by the field and focused (or defocused) in the forward direction (depending on the respective charge).

- The collimator located behind the target/horn, which allows reducing the showering toward the AD hall and reduce the absorbed dose received by the downstream machine equipment and therefore lower their activation rate.

- The proton dump, which collects the uncollided or elastically scattered primary proton beam from the PS.

- The magnetic “dog-leg”, a dispersion region designed as a spectrometer and composed by a set of bending dipoles and quadrupoles. It allows the application of a momentum cut of ±3% around the momentum mean value of 3.57 GeV/c, for which the AD ring is designed.

In addition to these devices which act as beam intercepting and transmitting device elements, the target area encloses also shielding components, cooling devices, monitoring systems and other support elements which are integral part of the AD target area. The present FLUKA implementation includes also those to the best of our current knowledge.

2.1 Antiproton production

The basic production reaction for antiprotons is the following:

\[ p + N \rightarrow p + N' + \bar{p} + p + X \]

Where N is the target nucleus, \( \bar{p} \) the resulting anti-protons and X other particles emitted in this process. The anti-proton distribution has a forward yield that rises proportionally to the incident proton energy. For a given proton energy the forward yield rises with antiproton energy until reaching a peak (see later sections); the rise with incident proton energy favours high incident energies, but the production rate depends on the cycling rate of the proton source, which might increase with the primary proton energy. For energy conservation reasons the minimum kinetic energy of the protons required to produce two “extra” particles (with total rest energy of \( 2m_0c^2 \)) is 5.6 GeV.
3. FLUKA implementation of the AD target area

This section describes the FLUKA implementation of the AD-target area, with complete references to the used technical drawings and to the assumptions made in those cases where reliable information was not available.

Concerning the source term part, the simulation considers realistic AD user PS cycle, with a 26 GeV/c momentum proton beam and a transversal Gaussian beam size of 1 mm in the horizontal and 0.5 mm in vertical plane (at $1\sigma$) (16). The beam on the target consists of 4 bunches spaced by 105 ns with each a bunch length of 30ns at $4\sigma$ with a momentum spread $\Delta p/p$ of $1.31\times10^{-3}$ at $2\sigma$ (3).

The present FLUKA AD target zone implementation includes the following elements: the antiproton production target, a horn, one main collimator plus two acceptance collimators in the dog-leg, a proton dump, ten magnets situated downstream the target and two focussing magnets placed upstream the target. For what concerns the concrete shielding blocks, due to the absence of an overall technical drawing specifying the civil engineering configuration of the zone, their position and thickness were implemented based on the AD target area drawings coming from the RAMSES supervision. The mutual position of the target, collimator, dump and the accurate matching of the position of the dog-leg magnets were performed based on a single technical drawing, available on EDMS (https://edms.cern.ch/document/223854). All the drawings and technical documents used in the present work and which form the base for the AD target area implementation in FLUKA can be found in the CERN Engineering & Equipment Data Management Service (EDMS), in the AD (Antiproton Decelerator) section (https://edms.cern.ch/nav/P:CERN-0000092501:V0/P:CERN-0000092501:V0).

All FLUKA results presented in chapters 4 to 7 are corresponding to an AD target area implementation without the presence of the COH6042 and SLH6038 collimators (i.e. considered to have fully opened jaws not reducing the anti-proton yield towards the target area).

A general view of the AD-target area as implemented in FLUKA is shown in Figure 1.

Figure 1. The figure shows the FLUKA implementation of the whole AD target area including the beam intercepting devices and magnetic elements. We can observe the position of the production target, of the horn, main collimator (COL6005) and proton dump. All the magnets in AD target zone have been implemented as well: two upstream magnets (QDE9050 and QFO9052), four magnets downstream the collimator, the QDE6010, QFO6020 main
quadrupoles, BHZ6024 and BHZ6025 (C-shaped main dipoles) and the other six magnets of the dog-leg (QDE6030, BHZ6034, BHZ6035, QFO6040, BHZ6044 and BHZ6045).

3.1 Implementation of the antiproton production target and horn

Due to the R&D nature of the installation before the refurbishment towards an anti-proton decelerator, several different types of production targets were built, in order to search for the combination which would have resulted in the highest yield and radiation/mechanical resistance; at least 11 different designs have been realized as subsequent improvement as well as geometrically adapted to accommodate different types of focusing devices (i.e. magnetic horns or lithium lens).

Among eleven different kinds of targets designs, with different core geometric configuration, spallation material (copper, rhenium, tungsten and iridium), dimensions and housing shape, the target assembly numbered “7” was chosen for FLUKA implementation, as it represents the production module presently installed in AD target area since the last exchange performed in 2009.

This antiprotons production target is constituted by axially symmetric and concentric elements. On the beam axis, the core of the target is an iridium rod, which has 3 mm in diameter and 55 mm in length. The iridium rod is divided into six parts, five of them 10 mm long and one 5 mm long. Together with a 1 mm thin alumina end plug (introduced to improve the fatigue lifetime of the downstream exit window), the target is embedded in a graphite cylinder with a diameter of 15 mm. The front part (the rounded part of the graphite cladding) was designed based on the drawing PS-C-6169-60-4 (https://edms.cern.ch/document/1180241/1) (Figure 2).

The external part of the target is constituted by a robust, double-walled and water-cooled titanium alloy container. The assumed material mass % composition is as follows: 89.55% Ti, 6% Al, 4% V and 0.25% Fe, with a compound density of 4.42 g/cm³. This high-precision alloy is designed to withstand the impact of high intensity proton beams. The titanium alloy housing together with its cooling system was implemented into FLUKA geometry according to drawings numbered PS-C-2198-60 and PS-C-2199-60 (https://edms.cern.ch/document/1180249/1)

The target assembly is cooled by a dedicated water loop embedded in the titanium alloy casing, not in contact with the graphite or with the iridium raw material. The water cooling system is composed by 8 separated pipes, with a front plenum created to improve the cooling of the thinner downstream window as well as the respective water inlet and outlet (see Figure 3 for further details).
Figure 2. FLUKA geometry implementation of the antiproton production target design (target #7). The iridium rod (in green) is embedded in a graphite hollow container (in blue), and surrounded by a water-cooled (dark brown parts) titanium alloy (in purple). The proton beam is coming from the left toward the right side.

Figure 3. The figure shows a FLUKA 3D model of the water cooling system inside the titanium alloy, housing the pipes, the upstream water collector as well as the front water layer cooling the downstream window. The water is coming from the upstream collector, flows towards the downstream zone by means of pipes, is collected in the front common plenum and then flows back toward the other collector. The titanium alloy casing was removed to reveal the water circulation.

In order to improve the realistic representation of the target configuration, the external support such as the holder, table (simplified version) and the hanger (used for remote control of the target) were also implemented (see Figure 4).
A pulsing magnetic horn ("antiproton collector") is used to focus the diverging anti-proton beam in both transverse planes. The shape and the mechanical design of the magnetic horn are described in Ref. (4) and the FLUKA implementation of the inner conductor is shown in Figure 5. The horn is operated with a current of 400 kA with the pulsing synchronized with the PS beam on target. The thickness of the internal conductor ranges from 3 mm close to the horn neck to 1.6 mm or 1 mm depending on the horn side, going further towards the external parts. The thickness of the inner conductor has been engineered to be as small as possible to decrease the anti-proton reabsorption and multiple Coulomb scattering inside horn material but thick enough to guarantee the mechanical integrity during the pulsing process. The magnetic horn implementation in FLUKA geometry has been performed based on the drawings listed in EDMS 1180248 (https://edms.cern.ch/document/1180248).

The external layer of the internal conductor has been modelled as elliptical for upstream part (towards the target) and parabolic for downstream part (towards the main collimator). The internal layer is a more sophisticated combination of elliptical/parabolic shape and several truncated cones, to obtain the best fitting to the original design (Figure 5).

The horn material is composed of a special resistant aluminium alloy EN AW-7075 (AlZn5, 5MgCu) – also known as Perunal-215 - with an assumed density of 2.8 g/cm³. The assumed Perunal-215 mass % composition is as follows: Al - 88.42 %, Zn - 5.6 %, Mg - 2.5 %, Cu - 1.6 %, Fe - 0.5%, Si - 0.4 %, Mn - 0.3 %, Ti - 0.2 %, Zr - 0.25 %, Cr - 0.23 % (18). This material has been chosen in Ref. (4) for its high tensile strength in a dynamic stress.
environment due to the fact that the horn should withstand high mechanical stresses and work in an intense radiation field.

The horn external aluminium conductor – in electrical contact with the power-carrying strip lines – carries the current to and from the internal conductor. As mentioned in Section 2, a toroidal magnetic field is created in the region between the two conductors, with an intensity inversely proportional to the distance from the horn axis. The horn is cooled by a high pressure compressed air flow. Due to the absence of technical drawings describing the external conductor shape, this was implemented thanks to the drawings in Ref. (18).

Figure 6. The figure shows the horn vertical/horizontal cross section (axially symmetric geometry), showing the shape of the internal conductor (in blue), and the external aluminum conductor (in yellow). The two vertical elements downstream the target are the strip lines, which carry the high current by means of air-cooled conductor plates from the power converters to the horn.

3.2 Main ADT collimator

A collimator (COL6005) is situated 110 cm downstream from the target; it consists of an inner part made mostly of an “anticorodal” alloy (also known as “antico”) and steel, with an external zone made of concrete. The latter part acts as a support as well as shielding for the target area. The core part – i.e. collimator tube - is divided into four hollow regions - each of them made of different material – contained inside the antico block, which has an external dimensions of 80x15x160 cm. The empty internal regions are made by open cylinders with an internal diameter, length and the respective material as presented in Table 1.

The main collimator provides an aperture limitation for anti-protons with high transverse momentum (i.e. with angular divergence outside the aperture of the downstream main dipoles) but also absorbs all other species of secondary particles with large divergence. This collimator allows as well reducing the showering towards the AD hall and decreases the dose received by the downstream machine elements as well as the activation level of the equipment in the AD-target area.
Table 1. The table shows the collimator core geometry and the corresponding material composition.

<table>
<thead>
<tr>
<th>Region</th>
<th>Internal diameter [cm]</th>
<th>Internal and external region material</th>
<th>Length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region 1</td>
<td>6.0</td>
<td>antico</td>
<td>30.0</td>
</tr>
<tr>
<td>Region 2</td>
<td>7.0</td>
<td>steel</td>
<td>50.0</td>
</tr>
<tr>
<td>Region 3</td>
<td>8.0</td>
<td>steel</td>
<td>50.0</td>
</tr>
<tr>
<td>Region 4</td>
<td>9.0</td>
<td>antico</td>
<td>30.0</td>
</tr>
</tbody>
</table>

The assumed composition of the anticorodal alloy – antico 100 (EN AW-6082, AlMgSi1) mentioned above is as follows (in mass %): Al - 97.25%, Ti - 0.2%, Fe - 0.5%, Zn 0.2%, Mg - 0.4%, Mn - 0.4%, Si - 0.6%, Cu - 0.1% with a density of 2.71 g/cm³ (18).

The FLUKA implementation of COL6005 is based on the various drawings available in EDMS 1175525 (https://edms.cern.ch/document/1175525) and 1175598 (https://edms.cern.ch/document/1175598/1).

The remaining part of collimator is constituted by the concrete blocks below and above the core, up to the ceiling, as well as by the water cooling circuit (corresponding drawings available at https://edms.cern.ch/document/1175599/1); the latter provides the removal of the heat, produced by the secondary particles losing the energy in collimator, by conduction via a water-cooled aluminium block in contact with the antico and with the steel.
3.3 Proton dump

The proton dump is used to provide absorption of the uncollided or elastically scattered proton beam as well as for those secondary particles which are not bent by the BHZ6024 and BHZ6025 dipole magnets downstream the collimator. It is also sufficiently thick to provide radiation protection for the downstream AD-hall and protects the hall itself from eventual incorrect pulsing of the BHZ6024 and BHZ6025 dipoles (see Ref. 5).

The dump is a steel and concrete assembly situated 12.76 m downstream from the antiproton target. The steel core dimensions are as follows: 120(W)x100(H)x240(L) cm³. The stainless steel block is divided into ten parts, 24 cm long each. A final concrete block with a length of 300 cm and a height of 265 cm is located right behind the steel core. In front of the dump, also a marble shielding block is present (160(W)x175(H)x50(L) cm³) with an open gap of 82(W)x54(H)x50(L) cm³ in order to accommodate the proton beam impinging on the steel core of the dump.

![Diagram of the proton dump](https://edms.cern.ch/document/1175552/1)

Figure 8. The figure shows the FLUKA implementation of the dump: a. vertical transversal cross section showing the central steel part, the concrete shielding located around it and the aluminium box housing the cooling system, placed laterally on a specially designed position on the steel core; b. longitudinal cross section of the dump, showing the core (10 steel parts), the hollow front marble block, and the concrete shielding/remaining part of the dump (https://edms.cern.ch/document/1175552/1)

The dump cooling system is constituted by a water cooled aluminium block in contact with the steel core and it is placed in a tilted configuration in a top/side opening of the dump (yellow element in Figure 8). Next to the cooling boxes an additional concrete block is present.
to shield the personnel entering target area from the residual dose rate of the dump. The cooling of the assembly takes place by means of conduction between the steel blocks and the aluminium cartridge, with the latter directly cooled by the main AD water circuit (6).

3.4 Magnets in the dog-leg of the AD target area (BHZ/QDE/QFO)

In order to correctly simulate the yield of antiprotons being extracted from the AD target area towards the injection into AD, it has been necessary to model all the magnets present in AD target dog-leg line. Up to ten magnets have been implemented, among which four quadrupoles (two focusing and two defocusing antiprotons in the horizontal plane) and six bending dipoles. The two main dipoles in AD target dog-leg (BHZ6024 and BHZ6025) (the blue elements in Figure 9) are used to separate negatively charged particles from the primary proton beam, with the remaining acting as a double spectrometer to select particles with $3.57 \text{ GeV}/c \ (\pm 3\%)$ momentum, corresponding to the AD-ring acceptance.

![Figure 9](https://edms.cern.ch/document/223854/0)

Figure 9. Picture of the target area, taken downstream the collimator towards the dump: the blue magnets are the BHZ6024 and BHZ6025 dipoles with the respective strip lines (the magnets are “single-turn” elements) while the red magnet is the QDE6030 quadrupole. In the central part the dump block is visible.

The implementation of the dog-leg magnets into FLUKA, as well as the accurate position matching were performed based on the drawing available in EDMS 223854 (https://edms.cern.ch/document/223854/0). This is the only available drawing which describes the dimensions of the target area elements and their mutual configuration, and has been the only source for the magnets position implementation. All necessary dimensions were measured, and additional fitting with the FLUKA geometry was performed (see Figure 10).
Figure 10. The figure shows a superposition between the dog-leg technical drawing (available at https://edms.cern.ch/document/223854/0) (in blue) and the FLUKA geometry implementation (in black) used for preparing and matching magnets positions.

The FLUKA design of quadrupoles was made based on the drawings available in EDMS 1175530 and 1175532, available at the following links (https://edms.cern.ch/document/1175530/1 and https://edms.cern.ch/document/1175532/1). The material composition of the aperture and the outer part of magnet is electrical steel with following mass % composition: Fe - 97.136%, Si - 2.7%, Mn - 0.15%, P - 0.01%, S - 0.001%, C - 0.001% and a density of 7.65 g/cm³.

The first two dipoles BHZ6024 (https://edms.cern.ch/document/1175533/1) and BHZ6025 (https://edms.cern.ch/document/1175534/1) are a special type of magnets: their aperture is designed as open on one side (“C” shape) to avoid the possibility that protons would hit the external part of the magnet when directed towards the dump (see Figure 11 a.). They are also designed to withstand a high cumulated dose of around 10⁸-10⁹ Gy, assumed to be cumulated over 10 years of continuous AD target operation (7) (Chapter 7). The two quadrupoles downstream the collimator - QDE6010 and QFO6020 - have an aperture shape as shown in Figure 11 b. with a gap width of 19 cm and 20 cm for QDE6010 and QFO6020, respectively.

Figure 11. The FLUKA geometry implementation of the a. BHZ6024 and BHZ6025 dipoles b. QDE6010 and QFO6020 quadrupole magnets (for the latter one the aperture shape is exactly the same but there is a difference of 1cm in its dimension).

The remaining dipoles BHZ6034 (https://edms.cern.ch/document/1175536/1), BHZ6035 (https://edms.cern.ch/document/1175538/1), BHZ6044 (https://edms.cern.ch/document/1175540/1) and BHZ6045 (https://edms.cern.ch/document/1175541/1) have the same closed geometry (see Figure 12).
In the FLUKA implementation the material composition of the whole magnet is simplistically assumed to be electrical steel. The aperture, width and the height as well are precisely set according to specifications of each magnet.

Figure 12. The FLUKA geometry implementation of the a. BHZ6034, BHZ6035, BHZ6044, BHZ6045 dipoles, b. of the QDE6030 and QFO6040 quadrupoles.

A critical aspect of the simulation was to identify the proper magnetic fields and gradients (corresponding to the real applied magnetic fields and gradients), as these operational data are not well documented. Two approaches were hence taken to infer these values. The first one is based on the calculation of the magnetic field needed to track antiprotons of a given momentum along dog-leg and the second one is based on the magnets specifications and the operational currents.

1. In order to obtain the dipoles magnetic field necessary to provide antiprotons of 3.57 GeV/c with the right track inside the central aperture of the double spectrometer, the following formula, which describe the angular kick given to a particle of momentum \( p \), has been considered:

\[
\theta \text{[rad]} = 0.299 \cdot B[T] \cdot L[m]/p\left[\frac{GeV}{c}\right] \quad (I)
\]

Where \( \theta \) is the deflection angle, \( B \) is the dipole magnetic field and \( L \) is the magnet effective length. The magnetic field which should be implemented for the first two dipoles (of the same length) in order to obtain a kick to direct the particles aligned to the axis of the following QDE6030 quadrupole was calculated assuming a deflection angle of 14° (0.244 rad), a length of the dipoles BHZ6024 and BHZ6025 of 2x1.54 m and expected momentum of the anti-protons after dog-leg line as 3.57 GeV/c. The corresponding magnetic field to be applied is equal to 0.944 T.

For the chain of four dipoles downstream, the same approach was used to calculate the magnetic field yielding the result of 1.05352 T.

2. Following the second approach mentioned above, the dipole magnetic fields and the quadrupole gradients were calculated according to the specifications data, taking into account the specified effective length of the magnetic field, which is in reality longer than the nominal one due to the presence of the fringe fields. This approach required several approximations to get the effective length and the integrated magnetic field corresponding to the operational current of the magnets. All calculations and approximations were performed based on the Technical Specifications.
of the Magnets for ACOL Injection Line and additional measurement notes dated back to 1987 (see Refs. (8), (9), (10), (11) and (12)).

All the extracted dipole field values based on the two methods are listed in Table 2. The quadrupole gradients are all taken from the specification documents.

Table 2. The table shows the list of parameters for the AD-target dog-leg magnets. The column “calculation” specifies the dipoles fields corresponding to a central orbit for 3.57 GeV/c anti-protons.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Current [kA]</th>
<th>Aperture length [m]</th>
<th>Effective length [m]</th>
<th>Magnetic field (dipoles) (calculation)</th>
<th>Magnetic field (dipoles) or gradient (quadrupoles) (specification)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QDE6010</td>
<td>2.998</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>8.6 [T/m]</td>
</tr>
<tr>
<td>QFO6020</td>
<td>3.172</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>7.7 [T/m]</td>
</tr>
<tr>
<td>BHZ6024</td>
<td>3.79</td>
<td>1.54</td>
<td>1.63</td>
<td>0.9441 [T]</td>
<td>1.0754 [T]</td>
</tr>
<tr>
<td>BHZ6025</td>
<td>3.79</td>
<td>1.54</td>
<td>1.63</td>
<td>0.9441 [T]</td>
<td>1.0754 [T]</td>
</tr>
<tr>
<td>QDE6030</td>
<td>1.9</td>
<td>0.69</td>
<td>0.7548</td>
<td>-</td>
<td>4.2249 [T/m]</td>
</tr>
<tr>
<td>BHZ6034</td>
<td>1.78</td>
<td>1.38</td>
<td>1.4634</td>
<td>1.0535 [T]</td>
<td>0.9917 [T]</td>
</tr>
<tr>
<td>BHZ6035</td>
<td>1.78</td>
<td>1.38</td>
<td>1.4634</td>
<td>1.0535 [T]</td>
<td>0.9917 [T]</td>
</tr>
<tr>
<td>QFO6040</td>
<td>0.874</td>
<td>0.69</td>
<td>0.7766</td>
<td>-</td>
<td>2.2801 [T/m]</td>
</tr>
<tr>
<td>BHZ6044</td>
<td>1.817</td>
<td>1.38</td>
<td>1.4631</td>
<td>1.0535 [T]</td>
<td>1.0120 [T]</td>
</tr>
<tr>
<td>BHZ6045</td>
<td>1.817</td>
<td>1.38</td>
<td>1.4631</td>
<td>1.0535 [T]</td>
<td>1.0120 [T]</td>
</tr>
</tbody>
</table>

4. Overview of the energy deposition in the various elements

The knowledge of the energy density and the corresponding total deposited energy in each element of the AD target area – in particular those located along the beam axis – is very important for the evaluation of the water cooling needs in the context of an eventual upgrade of the AD-target cooling station.

Table 3. Total energy deposition in the most loaded elements of the AD target area, together with the power deposited for two beam production modes.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1Target</td>
<td>2.53</td>
<td>23.4</td>
<td>253</td>
</tr>
<tr>
<td>2Horn</td>
<td>1.31</td>
<td>12.1</td>
<td>131</td>
</tr>
<tr>
<td>3Collimator</td>
<td>16.9</td>
<td>156.0</td>
<td>1690</td>
</tr>
<tr>
<td>4Dump</td>
<td>25.8</td>
<td>239.0</td>
<td>2580</td>
</tr>
<tr>
<td>5Magnets</td>
<td>2.1</td>
<td>19.4</td>
<td>210</td>
</tr>
<tr>
<td>6Concrete shielding</td>
<td>2.82</td>
<td>26.1</td>
<td>282</td>
</tr>
</tbody>
</table>

1 – iridium rod, including the graphite cladding, titanium housing, water
2 – internal and external conductor, supplementary aluminium plate
3 – core part (steel and antico), concrete, aluminium part of cooling system, antico base
4 – core part (steel), concrete, antico base and legs, aluminium part of cooling system
5 – all the magnets in the AD target area (coil and external part of magnet)
6 – all the concrete blocks in the AD target area (excluding concrete part of the collimator and dump)
The total energy deposited in various elements of the AD target area expressed in kJ/pulse is shown in Table 3, assuming a pulse intensity of \(1.5 \times 10^{13}\) p/spill. The same table also reports the average deposited power in various elements of the AD target area for a repetition rate of 108 s (corresponding to the present operation) and of 10 s, which might correspond to an enhanced version of the present operating mode, where 8-10 pulses being sent to the anti-proton target every 10 seconds.

Most of the energy deposition inside the anti-proton production module is cumulated in the iridium core – i.e. 52% of the total energy deposited (2.53 kJ/pulse). The remaining energy is divided between graphite (17%), titanium alloy (29%) and the circulating cooling water inside the titanium housing (1.6%) and the other additional elements like the table, hanger and the vertical holder. The energy deposition in the horn structure is cumulated mostly in the inner and external conductor, which accounts for about 49% of the total 1.31 kJ/pulse. The remaining energy is deposited in the external service elements (Figure 13).

![Energy deposition in the target and horn](image13)

Figure 13. Energy deposition map (in J/cm\(^3\)/pulse of 1.5\(\times\)10\(^{13}\) protons) in the target and in the horn. The vertical projection averaged over the horizontal range of [-1, 1] cm.

![Energy deposition in the collimator](image14)

Figure 14. Energy deposition map for the main collimator (COL6005) (in J/cm\(^3\)/pulse of 1.5\(\times\)10\(^{13}\) protons). The vertical projection averaged over the horizontal range of [-8, 8] cm bigger than the hole diameter. The maximum energy deposition is located in the steel part of the core.
The total energy deposited in the main collimator is equal to 16.9 kJ/pulse, with its core part cumulating 66% of this value. The remaining energy is divided between the concrete shielding placed around the collimator, the core and the cooling system elements (Figure 14). The proton dump receives about 25.8 kJ/pulse, with the steel core part collecting almost 98% of the total energy (Figure 15). The concrete shielding around the steel core takes the remaining 2% of the total energy deposition (Figure 16). The magnets in total receive roughly 2.1 kJ/pulse, while concrete shielding in the AD target area cumulates energy of 2.82 kJ/pulse.

Figure 15. Energy deposition map in the proton dump (in J/cm³/pulse of 1.5x10¹³ protons) averaged horizontally over the range of [-12, 12] cm. The maximum energy density is concentrated in the steel core of the dump.

Figure 16. Global map of energy deposition in the AD-target area (in J/cm³/pulse of 1.5x10¹³ p/spill). The plot is averaged in the vertical plane over the range of [-20, 20] cm around the beam axis.
The maximum energy density (expressed in J/cm$^3$/pulse) deposited in the AD-target area as a function of longitudinal Z position, averaged over the vertical range ±100 cm is presented in Figure 17. For each local maximum of the deposited energy, the corresponding element of the AD target area has been recognized and reported in this figure. The highest deposited energy value, as indicated in Table 3, is observed for the proton dump (for a longitudinal coordinate 12.5 m downstream the target). The energy deposited in the target and in the main collimator can be recognized as the maximum situated at z coordinates around 0 cm and about 100 cm, respectively. The remaining local maxima of the energy density correspond to the downstream magnets located between the main collimator and the dump, and those located close to the proton dump in the dog-leg close to the concrete wall. The latter is an artefact of the simulation, as in reality the beam proceeds towards the AD-hall via a beam pipe in the concrete wall.

Figure 17 was generated by FLUKA with an assumed size of each bin equal to 20 cm in the longitudinal direction (z), which is larger than the iridium target itself. This partly washes out the peak of the energy distribution for the target. To extrapolate more precisely the peak energy density in the target and horn, a more fine binning representation is shown in Figure 18. This FLUKA–generated plot has been performed with bin spacing equal to 1 cm, showing a maximum energy deposition density of about 100 J/cm$^3$ for the iridium part of the target.

![Figure 17](image.png)

Figure 17. Maxima of the energy density (J/cm$^3$/pulse of 1.5x10$^{13}$ p/spill) deposited along the Z axis in the AD target area. The size of the bin in the longitudinal direction is equal to 20 cm, i.e. larger than the target element. The bin size for the X and Y direction is equal to 10 cm. For a more refined energy density see Figure 18.
5. FLUKA – predicted anti-proton yield

In the current section we describe some anti-proton yield studies based on the described FLUKA geometry, with the objective of understanding the sensitivity of the yield to several possible mechanical inaccuracies in the relative positioning of the target/horn assembly. We also investigate the effect of the collimator, the efficiency of the double spectrometer to perform the momentum selection of the anti-protons as well as the magnitude of the effect of the focussing horn.

As can observed in Figure 19, a broad anti-proton energy distribution ranging from 100 MeV up to about 20 GeV is expected after the main collimator, downstream from the horn. This is the reason why the dog-leg magnets has been designed and adapted to the requirements to provide a narrow antiproton momentum selection (3.57 GeV/c ± 3%) at the end of the dog-leg, to help reducing activation of the main AD ring elements\(^1\).

---
\(^1\) During the AA (Antiproton Accumulator) running period, there was only a dipole doublet momentum-selecting the particles with the momentum cooling being performed in the accumulator ring. This was leading to higher activation levels in the main ring, which are strongly reduced in the present configuration, where the activation is concentrated mainly in the target area.
Figure 19. The figure shows a comparison between the anti-proton energy distribution obtained after the main collimator COL6005 and after the magnet dog-leg for the nominal target-to-horn distance of 18 cm. It is evident the effect of the double spectrometer in efficiently cutting the anti-protons outside of the AD-ring acceptance (around 2.75 GeV, corresponding to 3.57 GeV/c). Also note that the selected pbar energy corresponds to the anti-protons forward yield peak region.

One of the important objectives of the present work has been to evaluate how much an eventual misalignment of the target/horn assembly could affect the anti-proton yield at the end of the magnet dog-leg as well as to find the optimal theoretical distance between target and horn in order to maximize the anti-proton production yield (by assuming a fixed current in the magnetic horn).

Several FLUKA simulation runs were performed for different target-horn longitudinal distances corresponding to 0.5, 6, 12, 14, 16, 18, 24, 40, 70, 100 cm. The target to horn distance has been assumed for the current investigations as the longitudinal distance between the downstream part of the target (the “nose”) and the upstream part of the horn external conductor (see Figure 20).
Figure 20. The target-to-horn longitudinal distance is assumed for the present FLUKA simulation as the distance between “nose” of the target and the upstream part of the horn external conductor, measured along the proton beam line axis.

By comparing the total anti-proton fluence cumulated anti-protons around the mean momentum value, its maximum value total anti-proton fluence evaluated after the dog-leg (close to the injection point to AD-ring) has been obtained for a distance of 18 cm between target and horn (see Table 4). This distance has been taken as the nominal one to carry out further investigations, as the evaluation of the effect of a target/horn position misalignment and of the anti-proton yield in case of absence of the pulsing horn.

Table 4. The table shows the simulated anti-proton production yield (integrated over the energy spectrum emerging after the dog-leg) as a function of the target-to-horn distance, including the ratio of the yield with respect to the 18 cm case. It is worth noticing that the horn current has been maintained fixed at 400 kA for all the cases.

<table>
<thead>
<tr>
<th>Target to horn distance [cm]</th>
<th>Anti-proton yield after dog-leg [pbar/p]</th>
<th>Error [%]</th>
<th>Normalized yield (Y/Y_{18\text{cm}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>(2.10 \times 10^{-6})</td>
<td>~30</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>(6.39 \times 10^{-6})</td>
<td>14</td>
<td>0.28</td>
</tr>
<tr>
<td>12</td>
<td>(1.35 \times 10^{-5})</td>
<td>~10</td>
<td>0.59</td>
</tr>
<tr>
<td>14</td>
<td>(1.84 \times 10^{-5})</td>
<td>11</td>
<td>0.81</td>
</tr>
<tr>
<td>16</td>
<td>(2.01 \times 10^{-5})</td>
<td>9</td>
<td>0.89</td>
</tr>
<tr>
<td>18</td>
<td>(2.27 \times 10^{-5})</td>
<td>6</td>
<td>1.00</td>
</tr>
<tr>
<td>24</td>
<td>(1.56 \times 10^{-5})</td>
<td>6</td>
<td>0.69</td>
</tr>
<tr>
<td>40</td>
<td>(2.86 \times 10^{-6})</td>
<td>16</td>
<td>0.13</td>
</tr>
<tr>
<td>70</td>
<td>(1.07 \times 10^{-6})</td>
<td>43</td>
<td>0.05</td>
</tr>
<tr>
<td>100</td>
<td>(2.16 \times 10^{-7})</td>
<td>17</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The production yield corresponds to \(2.27 \times 10^{-5}\) anti-protons per primary proton on the target at the end of the dog-leg, close to the injection to AD ring for the nominal distance. By comparing the optimal value with the other cases, it is clear that there is a strong gradient in both directions (going upstream and downstream there is a variation of 30/40% for a 6 cm longitudinal shift). It is obvious that the target to horn distance value is a crucial parameter and should be selected and set with the highest precision to guarantee an optimum pbar production for the AD ring collector. Much longer target-horn distances (40, 70 and 100 cm) have been taken also into account in order to check for the effect of large longitudinal shifts. For these configurations FLUKA simulations reveal a significant decrease in anti-proton production yield even by two orders of magnitude (for the 100 cm of distance) with respect to
the optimal case. It is however worth noticing that from the technical point of view distances between target and horn larger than 20 cm are not feasible due to mechanical constraints.

Figure 21 shows the anti-proton energy distribution between 2 GeV and 3.5 GeV for different target-horn relative distances between 0.5 cm and 70 cm.

Figure 21. The figure shows the pbar fluence after the last magnet of the dog-leg for different target-horn distances: 0.5, 6, 12, 18, 24 and 70 cm. One can observe that for the specific anti-proton energy which is required by the main AD ring i.e. 2.75 GeV (corresponding to 3.57 GeV/c momentum), the maximum anti-proton fluence value is expected for the target to horn distance of 18 cm.

It is worth mentioning that the AD target area implementation into FLUKA geometry is limited only to the pbar production area up to the BHZ6045, without the latter part of the extraction line going toward the AD ring. Hence the ending concrete wall has been modelled as a unit without any beam pipe passing through it. This is the reason for the observed anti-proton interaction with the thick concrete wall at the end of the target zone.
Figure 22. The figure shows the anti-proton fluence map in the whole AD target area for a horizontal cut, averaged over the vertical range of [-10, 10] cm, for a proton beam intensity of $1.5 \times 10^{13}$ p/pulse.

5.1 Misalignment of target and horn position with respect to the beam axis

The target and horn are installed in two independent tables (called “chariots”), which can move transversally with respect to the beam axis. The structure has been originally constructed this way in order to perform maintenance operations during machine stops and to allow for equipment exchange in case of need.

No realignment has been ever performed on this equipment since its installation in 1987, due to the complexity of operating with geometer devices in extremely radioactive and small areas. In the current section it is investigated the sensitivity of the anti-proton yield in the case of a possible transversal misalignment, which might lead to a reduction of anti-proton yield or, more seriously, to a damage to the target and its housing and/or to the magnetic horn.

Figure 23. The figure shows the adopted coordinate system to simulate a vertical, horizontal and diagonal misalignment of the target and magnetic horn.
The simulations were performed assuming the nominal target-to-horn distance of 18 cm, and considering a target-only shift of 2 mm and 5 mm in the horizontal and vertical axis, as well as both at the same time (diagonal shift by 2.8 mm and 7.1 mm respectively) while maintaining the horn position fixed.

Table 5. The table shows the effect on the anti-proton yield at the end of the dog-leg due to the introduction of a target transversal position misalignment.

<table>
<thead>
<tr>
<th>Anti-proton yield after dog-leg [pbar/p]</th>
<th>Error [%]</th>
<th>Normalized yield Y/Y_{on axis}</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 mm vertically</td>
<td>1.65x10^{-5}</td>
<td>11</td>
</tr>
<tr>
<td>2 mm horizontally</td>
<td>1.93x10^{-5}</td>
<td>10</td>
</tr>
<tr>
<td>2.8 mm diagonally</td>
<td>1.44x10^{-5}</td>
<td>12</td>
</tr>
<tr>
<td>5 mm vertically</td>
<td>2.28x10^{-5}</td>
<td>9</td>
</tr>
<tr>
<td>5 mm horizontally</td>
<td>2.19x10^{-5}</td>
<td>10</td>
</tr>
<tr>
<td>7.1 mm diagonally</td>
<td>2.00x10^{-5}</td>
<td>10</td>
</tr>
<tr>
<td>target on axis</td>
<td>2.27x10^{-5}</td>
<td>6</td>
</tr>
</tbody>
</table>

The results of these simulations are shown in Figure 24 and 25 and reported in Table 5. As one can observe there are no dramatic changes in the antiproton yield calculated after the dog-leg in the case of a target transversal misalignment. This is determined by the fact that in case of target transversal position misalignment by 2 mm, the primary proton beam hits mostly the graphite cladding, instead of the iridium rod. Since the anti-proton production cross-section is almost independent (to a certain degree) of the material used, there is no indication of a very large reduction in the antiproton production. On the contrary, from a mechanical point of view, we might induce damage in the material and on the target casings, due to the asymmetric propagation of shock waves and due to the temperature increase per pulse.

For the 5 mm target position misalignment, the beam would hit the titanium casing and partly the graphite target enclosure. In this case the anti-proton yield is even closer to antiproton production with the target in on-axis configuration. However, similarly to the case of 2 mm target shift, this configuration would cause quick target assembly damage in the titanium alloy housing, including possibly its melting.
Figure 24. The figure shows the antiproton fluence at the end of the dog-leg, corresponding to a vertical, horizontal and combined transversal misalignment of the target position by 2 mm with respect to the beam axis.

Figure 25. The figure shows the antiproton fluence at the end of the dog-leg corresponding to a vertical, horizontal and combined transversal misalignment of the target position by 5 mm to the beam axis.
As the next considerations will show the antiproton yield is indeed much more sensitive to eventual errors in the horn transversal position. The FLUKA simulations for the horn position misalignment investigation were performed according to the same procedure as for the target case, keeping this time the target fixed in the nominal position. The results of these studies are presented in Table 6, Figures 26 and 27.

Table 6. The table shows the effect on the antiproton yield due to the introduction of the horn transversal position misalignments (keeping the target in the nominal axis configuration).

<table>
<thead>
<tr>
<th>Antiproton yield after dog-leg [pbar/cm²/p]</th>
<th>Error [%]</th>
<th>Normalized yield Y/Y₀ on axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 mm vertically</td>
<td>1.35x10⁻⁵</td>
<td>15</td>
</tr>
<tr>
<td>2 mm horizontally</td>
<td>1.51x10⁻⁵</td>
<td>13</td>
</tr>
<tr>
<td>2.8 mm diagonally</td>
<td>1.29x10⁻⁵</td>
<td>15</td>
</tr>
<tr>
<td>5 mm vertically</td>
<td>8.38x10⁻⁶</td>
<td>19</td>
</tr>
<tr>
<td>5 mm horizontally</td>
<td>6.47x10⁻⁶</td>
<td>22</td>
</tr>
<tr>
<td>7.1 mm diagonally</td>
<td>3.69x10⁻⁶</td>
<td>14</td>
</tr>
<tr>
<td>Horn on axis</td>
<td>2.27x10⁻⁵</td>
<td>6</td>
</tr>
</tbody>
</table>

The results show a stronger dependence of the anti-proton yield at the end of the dog-leg on the horn transversal position with respect to the beam axis. A very sizable difference is observed for the 5 mm horn shift, where the antiproton yield is reduced by a factor of between 2.7 and 6.2 (the latter corresponding to the diagonal shift).

The main conclusion of these studies is that the transversal misalignment of the horn is much more critical for the antiproton yield than the target one. The FLUKA simulation results reveal the need for a precise and accurate sub-millimeter horn positioning in AD target area with respect to the beam axis, in order to maximize the collection of anti-protons. This is especially important due the fact that no installation realignment is performed before each machine restart after the winter stop. Some of these potential errors could be cured by fine tuning the way how the protons hit the target, but the degree of freedom for their settings make the optimal configuration quite hard to find (Ref. 16).
Figure 26. The figure shows the anti-proton fluence after the dog-leg for a horn misalignment of 2 mm in the horizontal and vertical axis respectively and along both of them at the same time (diagonally).

Figure 27. The figure shows the anti-proton fluence for horn a misalignment of 5 mm, in the horizontal and vertical axis respectively and along both of them at the same time (diagonally).
5.2 The horn magnetic field effect

FLUKA simulations were also performed in order to quantitatively state the effectiveness of the horn magnetic field in focusing the wanted secondary particles and to compare the anti-proton yield with and without the presence of the focussing horn.

Technically the horn (as the element of geometry) has been left at the same position but the magnetic field has been set to zero, in order to simulate a failure of the horn during a nominal AD operational run. In order to compare to the optimum of pbar yield, the 18 cm target-to-horn distance has been chosen again as reference. The results, shown in Table 7, indicate significant yield degradation for a non-pulsing horn, with the pbar yield after the dog-leg reduced by almost two orders of magnitude (factor of 50).

Table 7. The table shows the comparison of the anti-proton yield after the dog-leg and the collimator with and without the horn magnetic field.

| Horn mag. field on | Antiproton yield after the dog-leg [$\bar{p}/p$] | 2.3x10⁻⁵ ±6% |
| Horn mag. field off | Antiproton yield after the collimator [$\bar{p}/p$] | 4.8x10⁻⁷ ±18% |

Figure 28. The figure shows the antiproton fluence after the main COL6005 collimator with (in blue) and without (in red) the horn magnetic field.

Figure 28 shows a comparison of the pbar yield after the main collimator with (blue points) and without (red points) the horn pulsing, showing - in addition to a global decrease of yield – also a slight shift of mean energy; similarly, Figure 29 shows the corresponding comparison of the anti-proton fluence after the end of the dog-leg (in this case the shift
of energy is not evident, as the momentum selection has already taken place in the dog-leg spectrometer).

The current results therefore show that the correct operational status of the horn (implying maintenance, procurement of working spares and the availability of a horn test bench) is a mandatory precondition for a successful antiproton decelerator physics program. It is not operationally possible to guarantee an acceptable level of anti-protons unless the horn is correctly providing the pulsed magnetic field.

Figure 29. The figure shows the anti-proton fluence after the magnet dog-leg with (in blue) and without (in red) the horn pulsing. A reduction of yield by almost two orders of magnitude is expected without the horn.

6. Available simulation cross-check

In order to get confidence in the quality of the AD-target FLUKA simulation framework, in this section we will discuss the available cross-checks between some simulation results and the measurement of radiation-related variables in the AD-target area. Some of the data have been acquired with the aim of performing this cross-check, while others refer to the data from 90s.

6.1 RadMon studies

A RadMon detector, extensively used in the LHC for the R2E Project activities (13), was installed in the AD target area on 31.08.2011 and removed three months later on 07.12.2011 at the end of the 2011 AD operation. The detector is able to measure the fluence of high energy hadrons via SRAM memories as well as to measure the cumulated dose via RadFETs chips.

The approximate RadMon position in the AD target area was 1.2 m on the right side of the main ventilation door and 1.2 m from the first shielding blocks at 1.2 m from
the ground (see Figure 30 for reference); the detailed positioning of the detector (present accuracy ±20 cm) was not possible due to the high radiation levels during the access.

In order to normalize the simulation data and compare with measurements the reference parameter is the total number of protons received by the AD target. This variable has been evaluated using TIMBER and the FTA.TFA9012:INTENSITY variable, corresponding to a beam current transformer located in the FTA transfer line from TT2 to the target area. The ADE::SEG_1 fundamental variable has to be applied to the data. The evaluated number of protons cumulated during the reference period is $7.43 \times 10^{17}$ POT.

FLUKA simulations indicate that the dose cumulated at RadMon position is corresponding to about 60 Gy. As expected, strong radiation gradients are observed in the vicinity of this RadMon location: changing the position of the scoring box by 20 cm along the vertical direction modifies the calculated dose by as much as 50%; even more significant gradients are obtained by considering a longitudinal shift, which could account to as much as a factor of 2 increase for a 50 cm displacement towards the ventilation door (due to higher exposure, see Figure 30). Moreover, FLUKA simulations indicate that at the considered RadMon position the high energy hadron fluence (Figure 31) and thermal neutron fluence over the detector working period are equal to $3 \times 10^{11}$ HEH/cm$^2$ and $1.5 \times 10^{12}$ nth/cm$^2$ respectively, with similar gradients as the dose one.

![Figure 30. FLUKA-simulated dose cumulated in the target zone in the period 31.08-7.12.2011 averaged over the vertical range [0, 10] cm corresponding to the vertical RadMon position.](image)

For what concerns the RadMon measured value, the two RadFETs installed on the box (having two slightly different sensitivities), give a dose of $\sim 50 \pm 15$ Gy in quite good agreement with the prediction from simulations, considering that the dose is measured by RadMon in SiO$_2$ equivalent.

As the RadMon memories are sensitive to both thermal neutrons and high energy hadrons, two voltages have been used to extrapolate the so-called $R_{\text{factor}}$, i.e. the ratio between the thermal neutron and the high energy hadron fluence (see Ref.(13)). The measured $R_{\text{factor}}$
value has been evaluated to be around 5±40%, in very good agreement with the same quantity evaluated via FLUKA simulations (5±10%) (for the assumed location of the RadMon monitor) (see Figure 32). Based on this value, and using the SRAM memories one could infer a high energy hadron fluence of ~6x10^{11} HEH/cm^2 (±40%); the disagreement in this case is larger (almost a factor of 2), but reasonably good considering the large intrinsic uncertainties of the RadMon calibrations and position.

Figure 31. The figure shows HEH fluence distribution cumulated over the period 31.08-07.12.2011, averaged over the vertical range [0, 10] cm corresponding to the vertical position of the RadMon detector.

Figure 32. The R factor map (thermal neutron fluence to high energy hadron fluence ratio) in the AD target area for a vertical range [0, 10] cm.
6.2 PSAIF irradiation slot – PS-ACOL Irradiation Facility

The PS-ACOL Irradiation Facility (Ref. 14) was installed more than 20 years ago for materials irradiation testing. The irradiation facility in AD target area consists of a vertical basket which is able to move from the surface directly 22 cm above the proton beam line, about 235 cm upstream of the beam dump (see Figure 1). In order to have another cross-check for the present simulation, a comparison of the simulated results with experimental data obtained in the framework of the PSAIF measurements has been performed. To this purpose, specific additional scoring regions at the position corresponding to the real PSAIF facility position were added to the model.

The FLUKA simulation results have indicated that the dose deposited in a box 20x20x20 cm$^3$ of air at the nominal PSAIF position, is equivalent to 75 mGy/pulse (for 1.5x10$^{13}$ p/pulse), and 73 mGy/pulse (for the same beam intensity) (±5%) for the same box made of Plexiglas. Dose measurements performed in 1990 at the PSAIF irradiation facility showed values from 73 mGy/pulse to 80 mGy/pulse (for a nominal intensity of 1.4x10$^{13}$ protons per pulse) for different dosimeters (14). The analogous measurements, one year later, showed doses about 10% lower from 66 mGy to 78 mGy per pulse. One can observe a fairly good agreement between the experimental data from the PSAIF irradiation facility and the FLUKA simulation results.

7. Radiation environment of the AD-target area

In order to understand the radiation field present in the AD target area during operation, the dose, the high energy (>20MeV) hadron fluence and the Si 1MeV equivalent neutron fluence have been investigated with FLUKA considering a standard operational year, corresponding to 2.1x10$^{18}$ POT. As matter of comparison, Table 8 reports the cumulated proton intensities for time periods in: half year 2009, 2010 and part of 2011.

Table 8. Cumulated proton beam intensity on the target obtained using TIMBER, TFA9012 transformer data filtered by the ADE::SEG_1 fundamental.

<table>
<thead>
<tr>
<th>Time period</th>
<th>2009 (11.06.-07.12.)</th>
<th>2010 (12.04.-22.11.)</th>
<th>2011 (11.04.-16.11.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulated proton beam intensity</td>
<td>1.41x10$^{18}$</td>
<td>2.1x10$^{18}$</td>
<td>1.93x10$^{18}$</td>
</tr>
</tbody>
</table>

The map of the dose cumulated per year in the whole AD target area close to the beam axis is presented in Figure 33. The hottest areas are clearly those behind the shielding walls in the beam zone, with doses up to several hundreds of kGy/y in the vicinity of the target and several kGy/y along the last four magnets of the dog-leg.

In order to compare the cumulated dose evaluated from the FLUKA simulations one can refer to the measurement data obtained by DGS/RP group over the period from February 2009 to March 2011 (Ref. 15). The integrated dose measured by RPL detectors amounts to 77 kGy for the detector placed upstream the target (around 20 cm upstream the target entrance window, at around -40 cm in vertical direction) and 67.7 Gy after the BHZ6045 magnet (at 10-20 cm in vertical plane).

The integrated dose evaluated by FLUKA simulation (for the cumulated proton beam intensity of 3.51x10$^{18}$ POT) for the upstream detector location amounts to 50-100 kGy for the assumed vertical range of [-40, -30] cm, and varies between 90 and 130 Gy for the second
considered position for the vertical range \([10, 20]\) cm. Even though the knowledge of the precise RPL detector location is limited and that the dose shows very strong gradient in the vertical plane, the results obtained are consistent with the measured data within a factor of 2.

Figure 33. FLUKA-generated map of the cumulated dose in the AD target area (expressed in Gy) for a nominal year \((2.1 \times 10^{18} \text{ POT})\), the horizontal cut averaged over the vertical range of \([-10, 10]\).

The dose cumulated by the magnet coils in the AD target area also has been a subject of our studies. The results of our investigation for several magnets of the dog-leg are presented in Table 9. Two different operational scenarios have been considered; the 108 s cycle corresponds to the present operational parameters, while the 2.4 s one corresponds to the maximum achievable by the installation. The highest dose is reached for the C-shaped main dipole coils BHZ6024 and BHZ6025, for which the averaged dose is equal 1.7 Gy/pulse and 0.28 Gy/pulse, respectively, for an annual dose of up to 0.54 MGy/year in the present scenario and up to 22 MGy/year for a 2.4 s cycle.

According to the Ref. (7) the first two dipoles mentioned above are designed to withstand a cumulated dose up to \(10^8\)-\(10^9\) Gy, over a period of ten years, assuming the 2.4 s pulse repetition rate scenario. The FLUKA simulation results show agreement with those anticipations.
Table 9. The table shows a summary of the average dose cumulated by the coils of several magnets situated in the AD target area as simulated by the FLUKA Monte Carlo code for different operational scenarios.

<table>
<thead>
<tr>
<th>Magnet coil</th>
<th>Dose [mGy/pulse]</th>
<th>Dose cumulated [Gy/year] 108s cycle</th>
<th>Dose cumulated [Gy/year] 2.4 s cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>QDE6010</td>
<td>170</td>
<td>5.4x10^4</td>
<td>2.3x10^6</td>
</tr>
<tr>
<td>QFO6020</td>
<td>100</td>
<td>3.1x10^4</td>
<td>1.3x10^4</td>
</tr>
<tr>
<td>BHZ6024</td>
<td>1700</td>
<td>5.4x10^6</td>
<td>2.2x10^7</td>
</tr>
<tr>
<td>BHZ6025</td>
<td>280</td>
<td>8.8x10^4</td>
<td>3.8x10^5</td>
</tr>
<tr>
<td>BHZ6034</td>
<td>14</td>
<td>4.4x10^4</td>
<td>1.9x10^4</td>
</tr>
<tr>
<td>BHZ6035</td>
<td>5</td>
<td>1.5x10^4</td>
<td>6.7x10^3</td>
</tr>
<tr>
<td>BHZ6044</td>
<td>3</td>
<td>9.5x10^3</td>
<td>1.3x10^5</td>
</tr>
<tr>
<td>BHZ6045</td>
<td>0.48</td>
<td>1.5x10^2</td>
<td>6.3x10^3</td>
</tr>
</tbody>
</table>

The high energy hadron fluence cumulated per year in the AD target area is presented in Figures 34 and 35 while the Si 1 MeV equivalent neutron fluence is shown in Figure 36, assuming an annual cumulated POT value of 2.1x10^{18} p/year. The level of the high energy hadron fluence reaches up to 10^{15} HEH/cm^{2}/year close to the target around the beam axis, and nowhere in the target area is below 10^{11} HEH/cm^{2}/year (Figure 35) except the zone downstream the dump.

The analysis of the results shows that the radiation level in the AD target zone is too high for putting any type of active electronics, even with the present reduced cycle. Equipment will suffer from single even upsets due to HEH as well as long-term total ionising dose effects.

Figure 34. The figure shows the high energy (E>20MeV) hadron fluence in the AD-target area cumulated per nominal year (2.1x10^{18} POT), averaged over the vertical range of [-10, 10] cm (around the beam axis).
Figure 35. The figure shows the high energy (E>20MeV) hadron fluence in the AD-target area cumulated per nominal year (2.1x10^{18} POT), averaged over the vertical range of [150, 200] cm, close to the ceiling of the target zone.

Figure 36. The figure shows the 1MeV equivalent neutron fluence cumulated per year in the AD-target area (2.1x10^{18} POT). The horizontal cut averaged over the vertical range [-10, 10] cm is presented.
8. Conclusion

This ATS note provides a description of the antiproton production target area (AD-target) and its implementation in the FLUKA Monte Carlo code; this includes the complete antiproton production assembly, the focussing horn, the main collimator, the proton dump as well as the magnets of the dog-leg.

Based on this geometry implementation, comprehensive FLUKA studies have been carried out with the objective of investigating the anti-proton yield and in particular its sensitivity to the mutual longitudinal target/horn distance as well as the effects of possible transversal misalignments of the target and horn position.

As expected, the results show that the longitudinal distance significantly affects the anti-proton yield; it must therefore be chosen and set with the highest precision to the focal point of the horn. The investigation of the effect of transversal misalignment indicates that the horn positioning is much more critical for the anti-proton yield that the target one and accounts for a roughly 40% reduction for a 2.8 mm diagonal shift.

Furthermore, a detailed evaluation of the energy deposited in each component of the target assembly and the remaining functional elements has been performed in view of a potential update of the target area cooling station.

The expected radiation field in terms of dose, energy hadron fluence (HEH), thermal neutron fluence and Si 1MeV equivalent neutron fluence inside the AD target area during operation has been the additional subject of our studies; the simulation results have been compared with available measurements; the good agreement gives confidence in the reliability of the simulation framework.

9. References


[4]. D. Boimond, M.Frauchiger, T. Kurtyka, M. Lubrano di Scampamorte, R.Maccaferri, S.Maury, L. Nikitina, J-C. Schnuringer, Consolidation of the 400kA magnetic horn for AAC antiproton production, s.l.: CERN/PS 94-02 (AR), 06.05.1994.


[17]. T. Eriksson, private communication.

[18]. S. Sgobba, private communication.