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P42 T4/XTAX transmission efficiency - FLUKA

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Summary

The studies reported here are part of the ECN3 Beam Delivery Task Force's mandate. Designated by the PBC Study Group, the primary objective of the Task Force is to assess the technical feasibility of increasing the proton beam intensity transported along the P42 line to the ECN3 cavern of the North Area in order to satisfy the demands of a set of PBC experimental physics proposals.

The purpose of this note is to present the findings on the transmission efficiency from the T4 target to the associated Target Attenuator eXperimental areas (XTAX), along the P42 line. Different Beam Intercepting Devices (BIDs) configurations have been investigated using realistic beam distributions, considering both the requirements of the proposed experiments and the North Area's characteristic proton sharing scenario.

Contents

1 Introduction

The Experimental Cavern 3 (ECN3) is an underground hall at the CERN's SPS North Area (NA). It offers unique opportunities for potential high-impact particle physics programmes, there is therefore a strong interest to fully exploit the SPS for Fixed Target (FT) physics, which has resulted in the possibility of siting a future High Intensity (HI) experimental facility in ECN3.

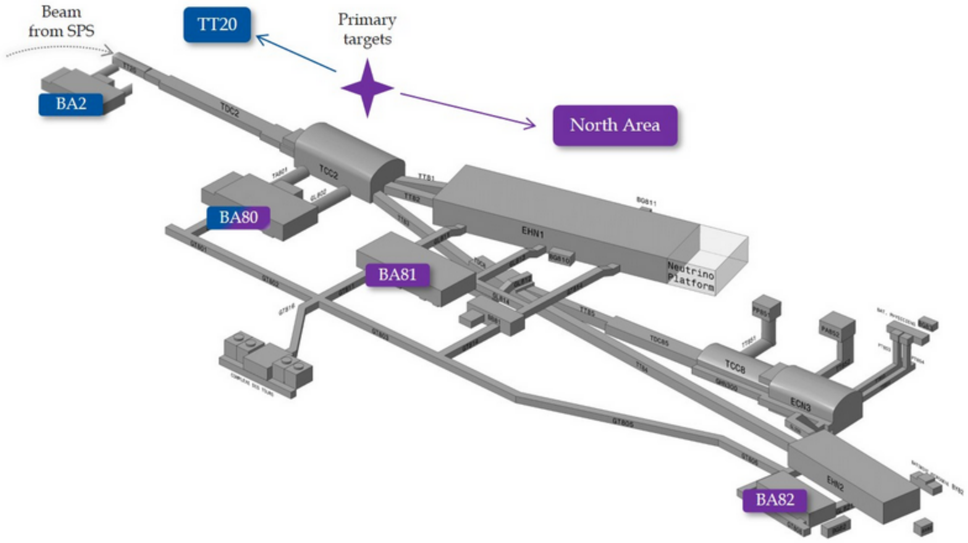


Figure 1: CERN NA layout

As shown in Figure 1, ECN3 is one of the NA experimental areas together with the North Experimental Hall (EHN) 1 and 2. To reach the cavern, protons nowadays are extracted from SPS Long Straight Section (LSS) 2 thanks to a slow-extraction mechanism. The particle beam is then transported along the Transfer Tunnel (TT) 20 with the possibility to be split exploiting the Lambertson septa installed in TDC2. The splitting mechanism allows to simultaneously share beam between all target stations (T2,T4 and T6) in the primary targets area (TCC2) and, consequentially, to serve all primary and secondary lines of the NA.

In detail, the P42 beamline starts at the T4 target. The line transports primary protons along TT80 reaching TCC8. There, another target station is placed in order to generate secondary particles finally detected by the experiments installed in ECN3.

It is part of the ECN3 Beam Delivery Task Force's mandate to evaluate the required infrastructure modifications to the primary and secondary lines up to and including the TDC2/TCC2 areas and P42 transfer line [1]. In this respect, the studies reported in this note aim to assess the transmission efficiency of the P42 transfer line focusing in the sector extending from the T4 target to the associated Target Attenuator eXperimental areas (XTAX).

2 T4/XTAX - FLUKA model

In order to assess the transmission efficiency, the radiation transport capabilities of the FLUKA Monte Carlo code [2] [3] have been exploited. Depending on the beam delivery scenario (Section 2.1), 400 GeV/c protons are sampled from realistic particle distributions and transported in a detailed geometry model for the P42 beamline (Section 2.2) starting from upstream the final vacuum window of TT20 and ending at the exit of the XTAX.

To achieve a proper setup for the simulations, different groups have been involved, both for the beam settings and the geometry description.

SY-ABT provided the beam distributions at the center of the T4 for both analysed beam delivery scenarios [4] while BE-EA advised about the current wobbling settings for T4 target station [5] [6] [7] [8].

Regarding the geometry, TE-VSC has been contacted as responsible for the vacuum windows along the TT20 transfer line, instead BE-EA reported for the remaining vacuum elements (windows and chamber) along the P42 line. In addition, technical drawings, notes and manuscripts have been used in the description of all the devices between the T4 and XTAX. More details about the geometry model are presented in Section 2.2.

2.1 Beam delivery scenarios

Taking into consideration the requirements of the HI experimental physics proposals, two beam delivery scenarios, summarised schematically in Figures 2 and 3, are being considered for increasing the intensity to ECN3 [1]:

1. **Shared**: identical to today's operational scenario using the cycle SFTPRO, as described in Section 1. The beam is split on Lambertson septa in TT20 and delivered simultaneously to all target stations in TCC2, Figure 2.

2. **Dedicated**: a new operational scenario where the beam is transported through TT20 and TCC2 and delivered exclusively onto the experimental target placed in TCC8, Figure 3.

The dedicated scenario assumes that the primary beam can be transported without splitting in TT20, bypassed around T4 and delivered onto target station infrastructure in TCC8. No other NA experiment can receive beam when a dedicated ECN3 scenario is used.

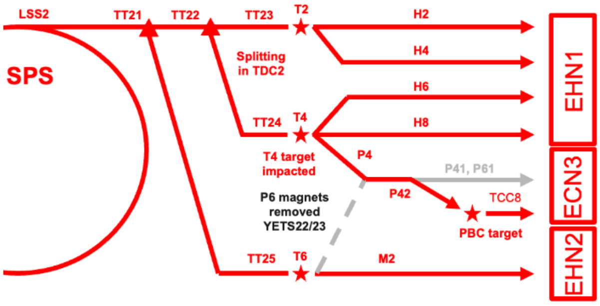


Figure 2: Shared ECN3 scenario

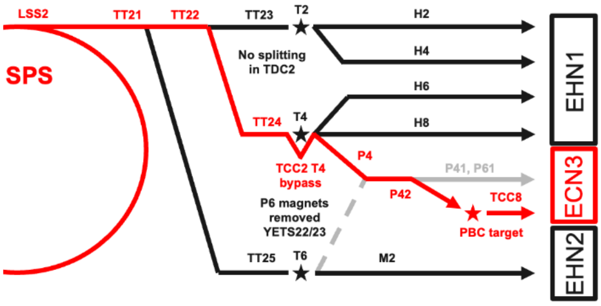


Figure 3: Dedicated ECN3 scenario

	Dedicated	**Shared**
Particles	50'000	7'382
$\sigma(x, y)$	(0.391,0.200) mm	(0.439,0.575) mm
$\sigma(px, py)$	(0.130,0.0618) mrad	(0.162,0.0480) mrad
$\sigma(pt)$	8.16e-04	8.70e-04

Table 1: Properties of beam distribution at the center of T4 for Dedicated and Shared scenarios - provided by ABT

In order to assess the transmission efficiency for both scenarios, primary protons transported along the P42 line modelled in FLUKA have been sampled using the particle distributions that SY-ABT provided for each beam delivery scenario [4]. Table 1 presents the characteristics of the distributions.

The geometry configuration, specifically for the adjustable Beam Intercepting Devices (BIDs) described in the next section, has been adapted depending on the chosen scenario. More detailed description of the study cases can be found in Section 3.

2.2 Geometry

The P42 sector considered for the studies is represented in Figure 4 [9]. The line is ≈20 m long, extending from the T4 target station followed by the two MTNH magnets, the VXSS vacuum chamber [10] [11] and the XTAX assembly.

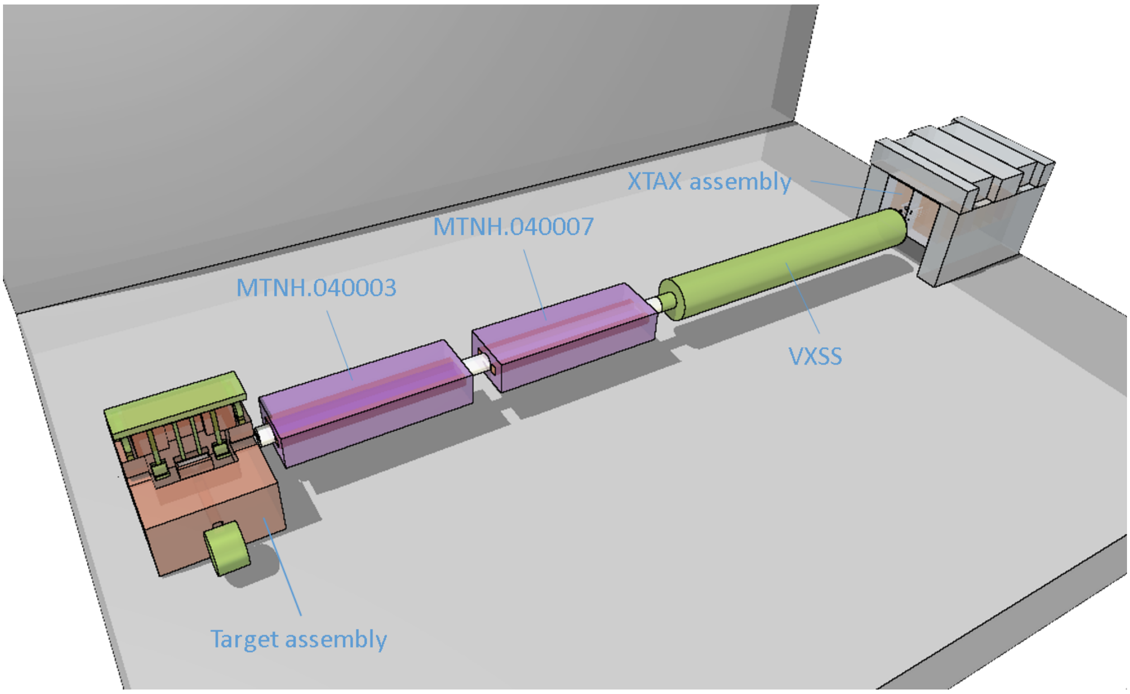


Figure 4: T4/XTAX FLUKA geometry model

2.2.1 Target assembly

The T4 target has been updated in 2014 together with T2, T6 and T10 [12]. The target is now constituted of five Be plates with different lengths going from 500 mm to 40 mm, constant height of 2 mm, 160 mm width and with an inter-plate vertical distance of 40 mm (Figure 5). The target station is equipped with motors to move it vertically. This structure gives the possibility to insert in-beam a specific plate depending on the desired intensity in the primary and secondary beamlines following T4, nominally H6, H8 and P42. Up to today, the 100 mm long plate is the most used.

Two beam instruments are installed in the target assembly together with the target itself, Figure 6: a Target Beam Instrumentation Upstream (TBIU) and one Downstream (TBID) [13]. They give information about the beam and, in particular, the position of the proton impacting on the target and exiting from it [5].

Overall the target assembly is in air for cooling reasons. The beam pipe therefore is interrupted upstream along TT20 with an Al vacuum window of thickness 0.5 mm and it restarts downstream the target with a second Al vacuum window of 0.2 mm. The TBIs however are in vacuum: two Ti windows of thickness 0.25 mm enclose each instrument [14].

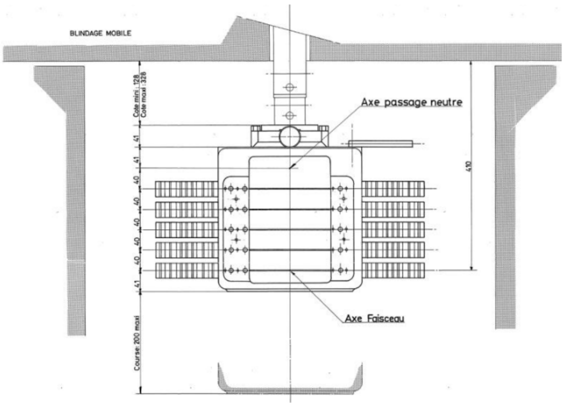


Figure 5: 2D sketch of the target inside the assembly, indicating the "out-of-beam" position in addition to the horizontal plates and the beam axis

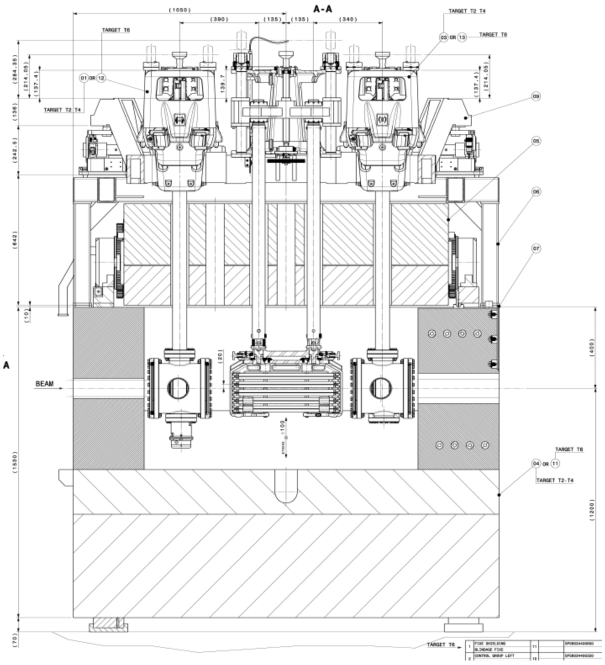


Figure 6: Cross-sectional cut of the target assembly showing also the two TBIs [15]

2.2.2 Magnet and wobbling system

The Target Magnet (MT) series of high field and wide aperture bending magnets have been designed for use around the targets in the experimental areas of CERN. After T4, two MTNH (Target Magnet Normal aperture Horizontal bending) are installed [16] [17]. A simplified

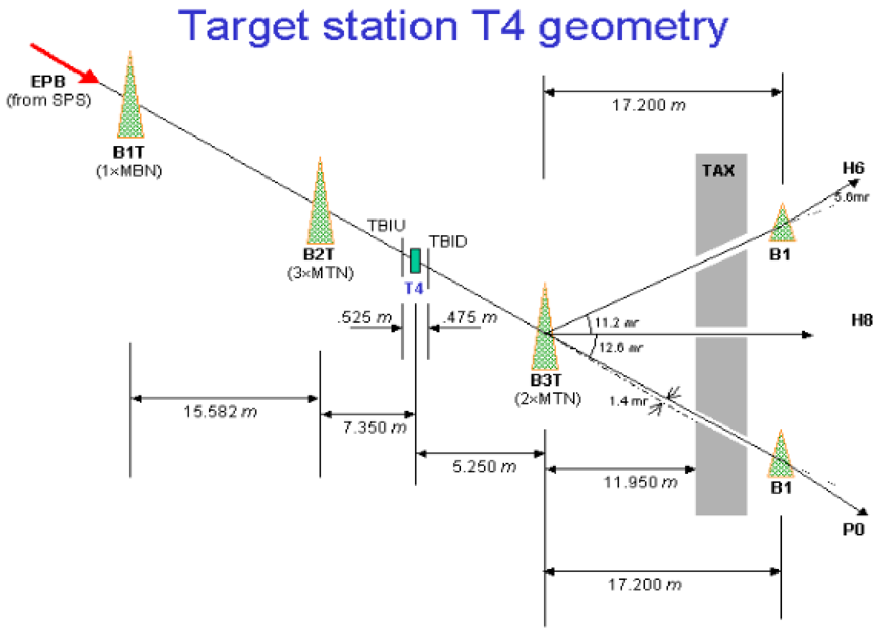


Figure 7: T4 wobbling system [6]

design has been considered for the geometry description of the magnets [18], nevertheless the total magnetic length has been considered.

The two dipoles are part of a wobbling system [6] [7] [8]: around T4 a set of three magnets, called B1T, B2T, and B3T, allows to select different beam energies for each one of the transfer lines (H6, H8 and P42). B1T and B2T are both upstream T4. The first is constituted of one MBNH while the latter is a system of three MTNH. The two dipoles downstream T4 are included in the FLUKA geometry model and form the B3T element.

For the setup of the wobbling system:

1. A valid combination of P42, H8 and H6 beam momentum is selected
2. The bending power required for the B3T magnet system to satisfy the requested beam conditions is calculated. This also defines the incident angle for the primary proton beam to the T4 target.
3. The relative bending power of the B2T and B1T magnets is assessed to steer the SPS beam into the T4 target at the evaluated angle.

Different wobbling scenarios are possible [5]. The FLUKA model is set following the typical wobbling settings where the (attenuated) primary protons of 400 GeV/c go along P42 and hadrons of 180 GeV/c and 120 GeV/c are transported respectively in H8 and H6.

2.2.3 XTAX assembly

The XTAX (Target Attenuator eXperimental areas) is a mobile dump collimator that allows to either dump or limit the acceptance of a primary or a secondary beam along specific beamlines and is always associated to a target [19].

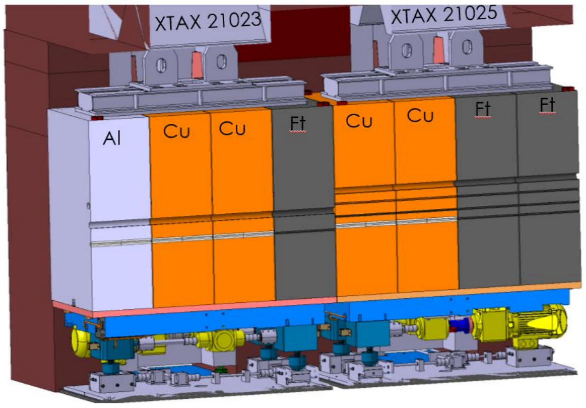


Figure 8: T2 XTAX subassembly CATIA model. Same block configuration and material is used for the T4 XTAX

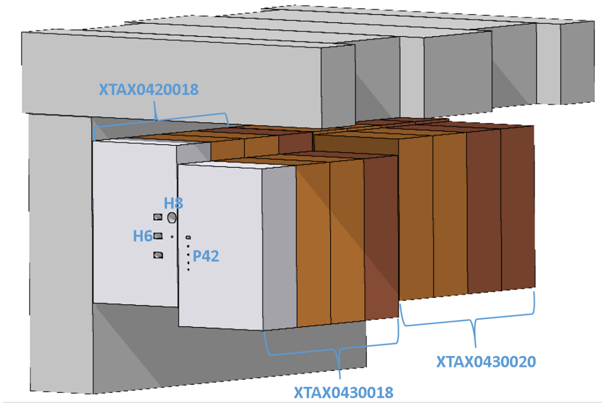


Figure 9: T4 XTAX in FLUKA. Both subassemblies and holes to serve H6, H8 and P42 are shown together with the shielding surrounding the XTAX

The current version of the XTAX is composed of two subassemblies that serve different beamlines. Both of them are made up of two water-cooled tables, each one supporting four blocks of aluminum, iron, or copper, all measuring 800 x 400 x 1200 mm. The tables can be independently moved vertically, enabling different aperture or dump configurations.

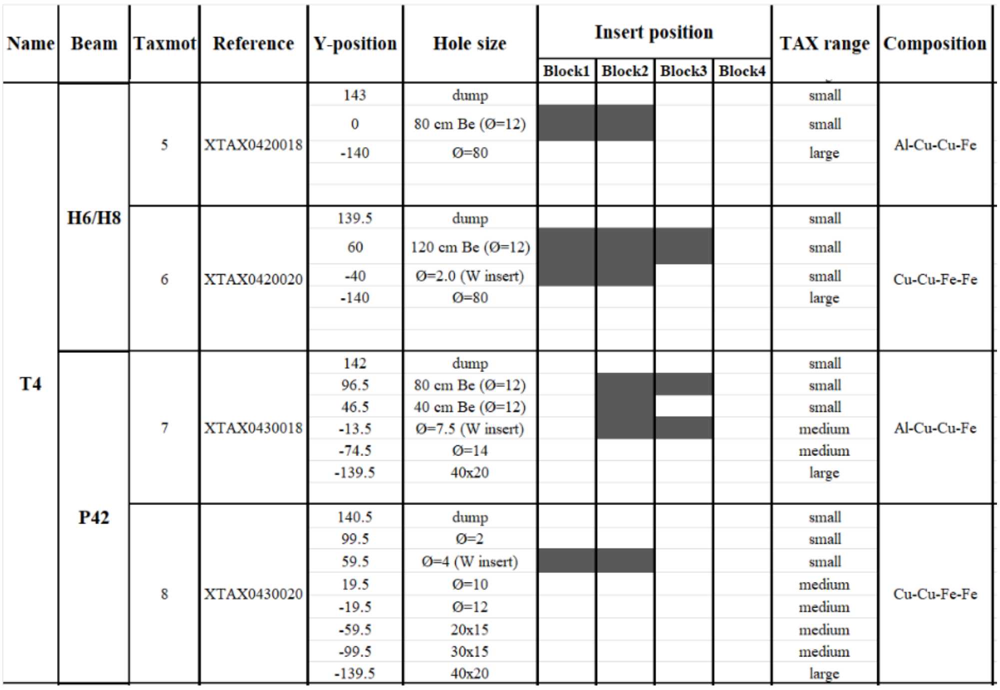
Nowadays the first blocks are made from copper or aluminium, whereas the remaining blocks are made out of iron [20].

Specifically for the T4 XTAX (Figure 9), the first subassembly is constituted by the elements XTAX0420018 and XTAX0420020. These are the reference names for respectively the upstream four blocks (Al-Cu-Cu-Fe) and downstream four blocks (Cu-Cu-Fe-Fe) supported by two different tables. The subassembly serves the H6 and H8 secondary lines, therefore two sets of holes are present in the blocks while the second subassembly (reference name XTAX0430018 and XTAX0430020 with same block's structure) serves the primary line P42.

Holes of different sizes are made at well-chosen vertical positions in the XTAX blocks. These holes enable the transmission of beams of specific sizes and the selection between different beam configurations. In addition, they can be filled with rods of beryllium 40cm long, several of which can be stacked in series to serve as an attenuator or with annular tungsten inserts to trims the beam edges. The position of the XTAX can be moved vertically from +140 mm (Dump) to -140 mm (largest hole).

In the T4 XTAX the holes have a specific angle both respect to the direction of the XTAX itself and respect to the upstream line. The P42 line have an angle respect to target plate of 1.4 mrad, while the H8 holes are bent of 14 mrad, making it parallel to the XTAX blocks, and finally for H6 the deviation is about 25.2 mrad. Position of the holes relatively to the XTAX blocks have been checked following the relative drawings described in Table 4 of [19].

Each XTAX assembly is enclosed by iron or concrete shielding blocks to lower the radiation levels in case of intervention around the element.



Name	Beam	Taxmot	Reference	Y-position	Hole size	Insert position				TAX range	Composition
						Block1	Block2	Block3	Block4		
T4	H6/H8	5	XTAX0420018	143	dump					small	Al-Cu-Cu-Fe
				0	80 cm Be (Ø=12)	■	■			small	
				-140	Ø=80					large	
		6	XTAX0420020	139.5	dump					small	Cu-Cu-Fe-Fe
				60	120 cm Be (Ø=12)	■	■	■		small	
				-40	Ø=2.0 (W insert)	■	■			small	
				-140	Ø=80					large	
	P42	7	XTAX0430018	142	dump					small	Al-Cu-Cu-Fe
				96.5	80 cm Be (Ø=12)		■	■		small	
				46.5	40 cm Be (Ø=12)		■			small	
				-13.5	Ø=7.5 (W insert)		■	■		medium	
				-74.5	Ø=14					medium	
				-139.5	40x20					large	
		8	XTAX0430020	140.5	dump					small	Cu-Cu-Fe-Fe
				99.5	Ø=2					small	
				59.5	Ø=4 (W insert)	■	■			small	
				19.5	Ø=10					medium	
				-19.5	Ø=12					medium	
				-59.5	20x15					medium	
				-99.5	30x15					medium	
				-139.5	40x20					large	

Figure 10: Summary of block composition, holes vertical position and dimension and inserts list for T4 XTAX [19]

3 Transmission efficiency

To address the transmission efficiency for such an intricate beamline, different cases have been investigated, changing the beam scenario and BIDs setup but using a fixed wobbling setting.

3.1 Study cases

As described in Section 2.2.2, for the FLUKA simulations the standard wobbling is followed where 180 GeV/c hadrons are sent to H8 and the 400 GeV/c primary protons feed into P42.

It is possible fixing the wobbling system to identify and to associate the two MTNH with the respective analytical magnetic field. Knowing the magnetic length ($L_{mg} = 3.65$ m [16]) and the bending angle ($\theta = 5.155$ mrad [5]) required for hadrons with specific momentum p and charge q, the magnetic field (B) can be calculated through the formula:

$$B = \frac{p \cdot \theta}{q \cdot L_{mg}}$$

In addition, the angle of the beam impacting on the target plate can be assessed summing the bending angles of the B1T and the B2T magnets, respectively 7.21 mrad and -16.14 mrad [5]: the beam impacts on the target plate with an angle of -8.93 mrad.

Finally, through the measurements with the TBIs installed upstream and downstream the T4, the position of the beam is identified: with the target plate centered in (z,x) = (0,0) cm, the beam passes through the point (0,4.68) cm.

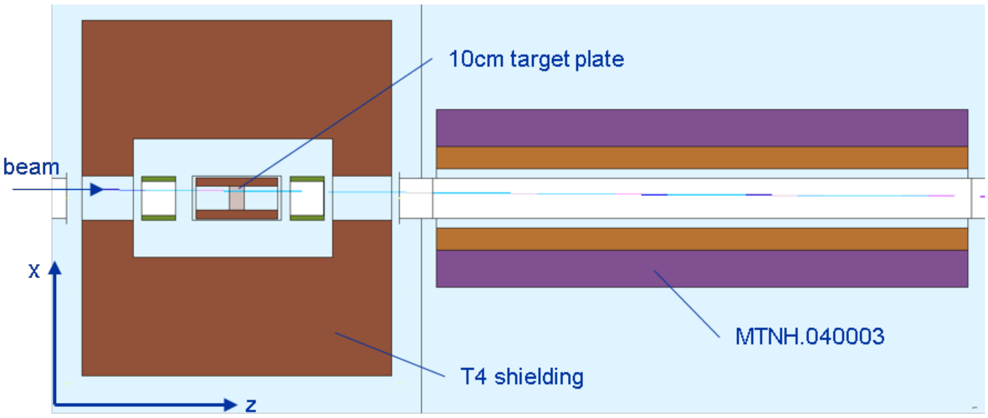


Figure 11: Representation of typical wobbling configuration for T4. Beam impacts 4.68 cm from target center with an angle of -8.93 mrad before being bent by first MTNH dipole towards positive values of x

Once the wobbling setting has been selected and the FLUKA model set up, the beam scenario and the BIDs configuration have been defined for four different study cases, as reported in Table 2.

CASE	**Beam scenario**	**T4 plate**	**XTAX P42 holes**
1	**Dedicated**	Bypass	40x20 mm - 40x20 mm
2	**Shared**	Plate1 - 500 mm	14 mm - 12 mm
3	**Shared**	Plate4 - 100 mm	14 mm - 12 mm
4	**Shared**	Plate5 - 40 mm	14 mm - 12 mm

Table 2: Study cases description for P42 transmission efficiency analyses. Beam scenario and BIDs configuration used are reported for each case

The **Dedicated** beam delivery is defined such that the un-splitted beam bypasses the T4 in order to be completely transmitted to the secondary target system in TCC8. To bypass T4, the target system is lowered 4 cm vertically and the beam passes thorough the "out-of-beam" position, as described in Figure 5. At the same time, the holes with the largest dimension are selected for the XTAX, since it is desired that all beam goes to TCC8 and no collimation is needed. Therefore the 40x20 mm rectangular holes are chosen.

The **Shared** scenario instead is used to simultaneously feed all the experimental areas in NA. Consequently, the beam needs to impact with one of the target plates in order to have characteristic intensity in H6, H8 and P42. In the interaction with the Be target plate a full spectrum of positive hadrons is generated so the beam needs to be collimated to reduce its dimension and to select only particles with the desired momentum. For this reason, standard holes of diameter 14 mm and 12 mm are chosen, respectively for the upstream and downstream blocks of XTAX P42 subassembly.

3.2 Results

The efficiency has been assessed through FLUKA in multiple positions along the beamline in order to be able to evaluate the single losses due to the different BIDs (vacuum windows, XTAX and target when in-beam). Figures 12 and 13 give a description of the scoring positions.

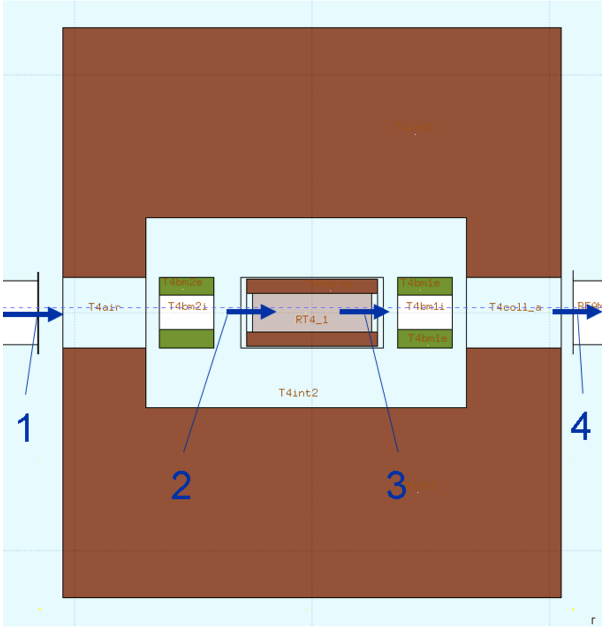


Figure 12: Scoring positions at T4 assembly:
1) $Window\ TT20$,
2) $Target\ In$,
3) $Tareget\ Out$,
4) $Window1$.

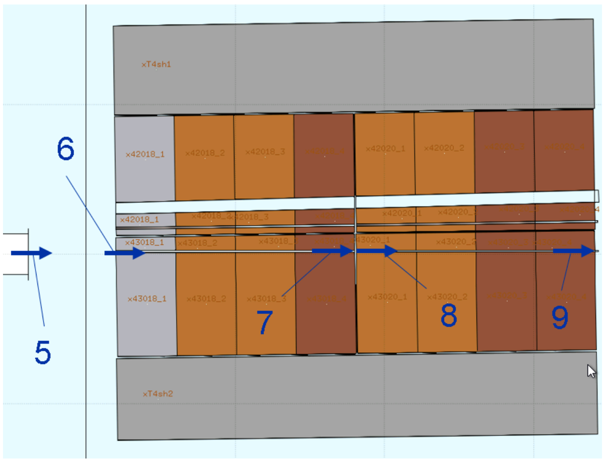


Figure 13: Scoring positions at XTAX:
5) $Window2$,
6) $XTAX\ up\ In$,
7) $XTAX\ up\ Out$,
8) $XTAX\ dw\ In$,
9) $XTAX\ dw\ Out$.

In order to evaluate the efficiency, the USRBDX scoring card has been exploited. USRBDX gives the option to compute a one-direction current through an user-defined surface for a specific scoring particle. As for all FLUKA results, the values scored is normalized per primary particles, in this case represented by the SPS proton: the efficiency is evaluated as (Particle/Primary).

In the simulations, two different FLUKA particles have been scored:

1. **BEAMPART**, it indicates particles which did not have any interaction in the transport. They are primary protons at 400 GeV/c,
2. **PROTON**, any protons transported, primary or secondary.

Scoring both particles helps to distinguish the contribution of the primary and secondary protons since the latter are at lower energy but they could still be in the acceptance of the XTAX holes.

Initially an analytic procedure is followed to calculate the expected losses in the interaction between primary protons and the Be target plate for the **Shared** scenario. The inelastic scattering length (λ_{in}) for proton at 400 GeV/c interacting with Be is well-know and reported in FLUKA to be 40.73 cm. Setting the length of the target plate (L), the probability (P) for a proton to not suffer an inelastic scattering in that region, meaning that the particle survives, is obtained through:

$$P = exp(-\frac{L}{\lambda_{in}})$$

From the formula we can compute the expected values for the efficiency in the cases where a target plate is in-beam. The values reported in the next table can be directly compared with the FLUKA results in position 3 for the BEAMPART particles.

CASE	**T4 plate**	**P**
2	50 cm	0.293
3	10 cm	0.782
4	4 cm	0.906

The outcomes for the transmission efficiency along the P42 line, starting from the T4 and ending at the exit of the XTAX, are reported in Tables 3 and 4.

The result in position 9 indicates the total efficiency for the considered sector of the P42 beamline. In the case of PROTON, only the referred value is reported for a comparison with the BEAMPART analysis: the difference in the results between the two scored particle types is minimal, meaning that the contribute of the low-energy proton tail is minor.

When examining the results for position 2, it is observed that not all primary particles goes into the target plate in the **Shared** cases. This is due to the vertical dimension of the beam, which is higher than the height of the target plate (2 mm), as indicated by the σ value in Table 1.

For this reason, to compare the results for BEAMPART in position 3 with the value calculated in the previous table, the first have been re-scaled considering the particles entering into the target plate. Consequently, the values in position 3 should be considered as (Particles exiting the plate/Particles entering the plate) instead as a total efficiency. This situation explains also the higher values in position 4 respect to the ones in position 3.

In conclusion, the relative error for each of the reported value is in the order of ≈0.01 %.

BEAMPART		**CASE 1**	**CASE 2**	**CASE 3**	**CASE 4**
POS	SURFACE	(Part/Pr)	(Part/Pr)	(Part/Pr)	(Part/Pr)
1	$Window\ TT20$	0.999	0.999	0.999	0.999
2	$Target\ In$	0.000	0.982	0.979	0.978
3	$Tareget\ Out$	0.000	0.297	0.782	0.907
4	$Window1$	0.992	0.304	0.780	0.901
5	$Window2$	0.991	0.304	0.779	0.901
6	$XTAX\ up\ In$	0.990	0.256	0.745	0.877
7	$XTAX\ up\ Out$	0.988	0.247	0.733	0.865
8	$XTAX\ dw\ In$	0.988	0.233	0.707	0.839
9	$XTAX\ dw\ Out$	0.9855	0.2232	0.6882	0.8181

Table 3: Results for transmission efficiency in P42 beamline starting from T4 to the end of associated XTAX holes. Values obtained following FLUKA BEAMPART particles

PROTON		**CASE 1**	**CASE 2**	**CASE 3**	**CASE 4**
POS	SURFACE	(Part/Pr)	(Part/Pr)	(Part/Pr)	(Part/Pr)
9	$XTAX\ dw\ Out$	0.9859	0.2248	0.6894	0.8188

Table 4: Results for transmission efficiency in P42 beamline starting from T4 to the end of associated XTAX holes. Values obtained following FLUKA PROTON particles

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