Target Station T4 Wobbling - Explained

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Summary

The target station T4 wobbling is described in detail. The different settings of the magnets around the T4 target allow the creation of a variety of beam configurations/energies for the three output beam lines: P0, H8 and H6. The constraints and inter-relations between the beams are also discussed.

1. T4 station geometry

The T4 target in the north area receives the primary protons from SPS and produces the two general-purpose beams H8 (high energy) and H6 (medium energy) for the north experimental area hall EHN1. The attenuated protons from the target typically form the P0 beam, which is transported to the experimental hall EHN3 [**1**]. The T4 target station geometry is shown in **Figure 1**.

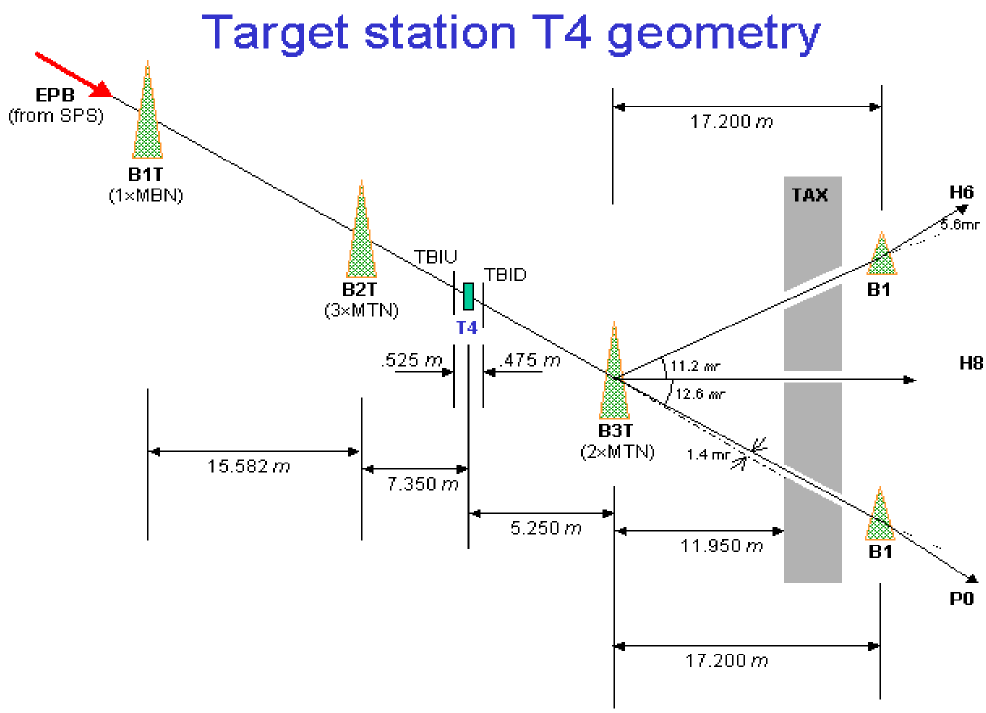

Figure 1: *The T4 target station geometry. B1T, B2T, B3T are the three wobbling magnets. The B1 in P0 and H6 are strong septum magnets. TBIU and TBID are upstream and downstream beam monitors.*

A set of three magnets B1T, B2T, and B3T around the target allows different energies in each beam line to be selected, what is referred to as "T4 wobbling". P0 and H6 have both a septum magnet following the TAX, which allows accepting particles with a skew or production angle different from zero. H8 does not have this option, therefore can only accept particles which are centered in the B3T magnet, a condition which is typically satisfied selecting particles with zero production angle. In **Table 1** the characteristics for the magnets involved are listed.

Table 1: *The main parameters of the magnets related to the T4 wobbling.*

Bend	Type	ID	Aperture *(H×V)*	Position *(m)*	I_{max}*(A)*	$B\ell_{max}$*(T.m)*	Deflection *(mrad)*
1	MBNH	241107	130 × 60	-22.932	1510	10.0053	variable (SPS)
2	MTNH	241128 241135 241142	240 × 60	-7.350	1365	7.3303	variable (SPS)
3	MTNH	040003 040007	240 × 60	3.150 7.350	1365	7.3303	2 × 7.000 (H8) 2 × 12.60 (H6)
H6-B1	MSNH	041022	114 × 60	22.450	1465	4.8281	5.6 (H6)
P4-B2	MSNH	043022	114 × 60	22.450	1465	4.8281	1.4 (P0)

Downstream the target station magnets and before any of the beam line elements, are located the TAX blocks, whose principal function is to control the beam passage (angle and therefore momentum, as well as intensity), and serve as beam dump whenever access is required in any of the beams or when the beams is not operational. In **Table 2** the different options available for the TAX blocks are listed. Selecting different combination for holes in the two blocks allows different conditions to be selected for the three beams.

Table 2: *Target station T4 TAX configurations after the 2001 upgrade.*

H8 & H6 beams	ID	Composition	TAXMOT	Length in beam	Surface (*x* × *y*)
	XTAX042018	Al-Cu-Cu-Fe	5	4× 40 cm	
	XTAX042020	Cu-Cu-Fe-Fe	6	4× 40 cm	

<u>H8 beam:</u>

	XTAX042018		**XTAX-042020**		
Pos. *(mm)*	**Hole-size** *(mm)*	**Material**	**Hole-size** *(mm)*	**Material**	
-140	Ø = 80	empty	Ø = 80	empty	
-40			Ø = 12	2×W (Ø=*2mm)*	Condition for μ-beam
0	Ø = 12	2 × Be			
+60			Ø = 12	3 × Be	Condition for μ beam
+140	none	dump	none	dump	

At each position, there is a corresponding 80 × 42*mm* hole for H6

P0 beam	ID	Composition	TAXMOT	Length in beam	Surface (*x* × *y*)
	XTAX 043018	Al-Cu-Cu-Fe	7	4 × 40 cm	
	XTAX043020	Cu-Cu-Fe-Fe	8	4 × 40 cm	

	XTAX043018		**XTAX-043020**	
Pos. *(mm)*	**Hole-size** *(mm)*	**Material**	**Hole-size** *(mm)*	**Material**
-140	40 × 20		40 × 20	

-100			30 × 15	
-80	Ø = 14			
-60			20 × 15	
-20	Ø = 7.5	W insert	Ø = 12	
+20			Ø = 10	W insert
+40	Ø = 12	1 × Be		
+60			Ø = 4	W insert
+90	Ø = 12	2 × Be		
+100			Ø = 2	W insert
+145	none	dump	none	dump

The different inserts are used as attenuators for the primary proton beam in order not to reach the radiation security limits in the experimental area zones. Each TAX motor can move independently, however there are several constraints and inter-relations between the three beam lines so any movement needs to be scheduled and agreed among the users.

2. Solving the T4 wobbling puzzle

In this section the detailed calculations for solving the T4 wobble puzzle and find out whether or not a given configuration is possible or allowed, are described. The procedure can be summarized in the following steps:

i. Check if the selected combination of P0 and H8 options (beam momentum and polarity) is valid. Verify that the primary proton beam from the target is well treated (either used for P0 or correctly dumped in the TAXs).

ii. Find the bending power required for the B3T magnet to satisfy the requested beam conditions. This also defines the incident angle for the primary proton beam to the T4 target.

iii. Evaluate the bending power for the B2T and B1T magnets to steer the SPS beam into the T4 target with an angle as calculated before.

iv. Finally, the current for the H6-B1 and P0-B1 magnet can be determined. For H6 in particular, the beam can have a non zero production angle, which allows a wide spectrum of possible beam momentum for a given H8 and P0 settings.

Simple geometry is used, along with the basic formula for the beam deflection by a magnet as shown below:

$$\vartheta(mrad) = \frac{299.79}{p(GeV/c)} \cdot B\ell(T \cdot m), \qquad (1)$$

The convention is that ϑ is positive (negative) for positive beams bending left (right). In the following equations the same units as here are assumed.

2.1. T4 wobbling options

There are two basic options for the T4 wobbling, depending on how many beams are active in addition to the primary proton beam. For the presently used SPS energies above 400

GeV/c, with the available bending power of the wobbling magnets, the H8 and H6 beams have to have the same polarity, and the ratio of momentum P_6/P_8 is in the range of 1/3 to 2/3, depending of the production angles.

<u>Three beam option: attenuated protons (typically in P0), H8 and H6</u>

3A. *P0 set for protons; H8 and H6 set for secondary hadrons at different production angles.*

This is the most frequently used condition.

3B. *P0 set for electrons; H8 and H6 set for secondary hadrons.*

This is a special case used for detector calibration of the experiments in the P0 line. The primary beam has to come along the nominal P0 direction and B3T is used as a sweeping magnet for all the charged particles, leaving the neutrals (photons) to the P0, which are converted in a plate upstream of B1 magnet. The incident angle to the T4 target is fixed to –1.4mr, and H8 runs at zero production angle. The primary proton beam is dumped somewhere in the TAX blocks.

3C. *P0 is off; H8 and H6 set for secondary hadrons at different production angles.*

In this case the P0 TAX is at the "dump" position. It is a similar setup as case 3A, but very rarely used since there are always experiments in the P0 line. It offers maximum flexibility in selecting the H8 and H6 momentum and production angles.

<u>Two beam option: attenuated protons(H8) and H6</u>

2A. *P0 set for electrons, H8 receives the primary proton beam, and H6 is set for secondary hadrons at different production angles.*

This configuration is similar to the 3B one. Due to the limit in the strength of B3T magnet, it can be feasible only for SPS energies below 350 GeV.

2B. *P0 is off, H8 uses the protons and H6 set for hadrons at different production angles.*

This configuration is similar to the 3C one.

<u>Single beam option: primary protons(or ions) in H8 or P0</u>

1A. *Primary proton/ion beam to H8 or P0*

In this option the T4 target head is out and the primary proton beam from SPS is directed to either H8 or P0, selecting the appropriate TAX positions. It is the case when ion beam is put in SPS.

More information on the possible wobbling settings can be found in [**2**], along with the constraints involved. In the next sections the basic formulas involved are described.

2.2. B3T magnet setting

2.2.1. Three beam option

A general case for this configuration is shown in **Figure 2** where the attenuated primary proton beam is drawn to an arbitrary angle. For the most frequent use of this configuration the proton beam goes to P0 direction, which means that the d_0 parameter in the figure is equal to zero.

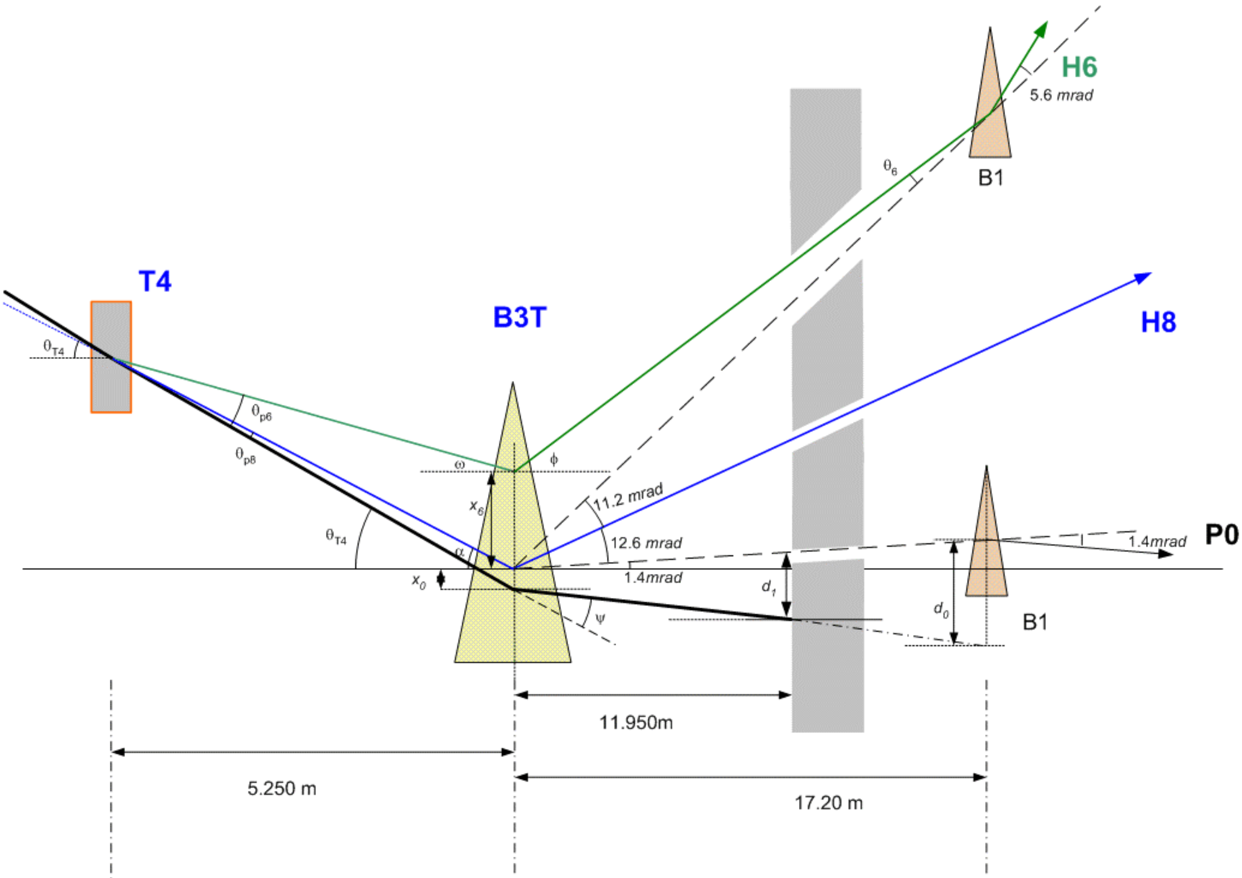

Figure 2: *B3T magnet configuration with three output beams.*

For the proton (or P0) and H8 beams, we can write:

$$P0 : \psi = \frac{299.79}{P_{SPS}} B\ell_3 \qquad (2) \qquad\qquad H8 : \alpha + 14 = \frac{299.79}{P_8} B\ell_3 \qquad (3)$$

where $P_{SPS}(=P_0)$ is the primary SPS momentum, P_8 is the H8 beam line momentum and $B\ell_3$ is the bending power of the B3T magnet. ψ and α are the angles as defined in the figure. In the sign convention used, angles "above" the nominal direction are considered as positive, and the primary SPS beam is also positive.

Following simple geometry calculations we can write:

$$d_0 = l_{B3T-B1} 1.4 + x_0 + \tan(\vartheta_{T4} - \psi)\, l_{B3T-B1} \qquad (4)$$

$$x_0 = -l_{T4-B3T}\,\vartheta_{p8} \tag{5}$$

$$\vartheta_{T4} = \alpha + \vartheta_{p8} \tag{6}$$

resulting to: $$\psi = \alpha + 1.4 + \frac{(l_{B3T-B1} - l_{T4-B3T})\vartheta_{p8} - d_0}{l_{B3T-B1}} \tag{7}$$

Solving the system of these equations we can write:

$$B\ell_3 = \frac{P_0 P_8}{P_0 - P_8} \frac{12.6 + \frac{d_0}{l_{B3T-B1}} + \frac{l_{T4-B3T} - l_{B3T-B1}}{l_{B3T-B1}}\vartheta_{p8}}{299.79} = f(P_0, P_8, d_0, \vartheta_{p8}) \tag{8}$$

An important angle to evaluate is the "skew" in P0 beam, which is defined as the angle between the beam and it's nominal beam direction for P0. Following **Figure 2** we have:

$$P0\,skew: \vartheta_{P0} = 1.4 + \vartheta_{T4} - \psi \tag{9}$$

If the proton beam is dumped then because of safety it has not to be closer than 30-40mm from any of the TAX holes. Following **Figure 2** we have:

$$d_1 = \frac{l_{B3T-TAX}}{l_{B3T-B1}} d_0 \tag{10}$$

Table 3 summarizes the allowed ranges for the beam. Typically, when the P0 beam is OFF, the corresponding TAX is moved to the "dump" position, which removes part of the constraint.

Table 3: *Allowed beam dump position for the primary beam in the TAXs. A distance of ±30mm from the holes has been taken as safety margin.*

Beam	TAX hole center *(mm)*	Allowed range for d_1 *(mm)*
H6	301.14	$d_1 > 331.14$ $d_1 < 271.14$
H8	167.30	$d_1 > 197.30$ $d_1 < 137.30$
P0	16.73	$d_1 > 46.73$ $d_1 < -13.27$

2.2.2. Two beam option

Figure 3 shows this configuration. The proton beam is directed to H8, so we have:

$$H8: P_8 = P_{SPS}, \vartheta_{T4} + 14 = \frac{299.79}{P_{SPS}} B\ell_3 \tag{11}$$

This equation has two parameters, therefore not a unique solution. The problem is further constrained from the H6 beam momentum and/or production angle requirements. Following eq.(23) we have:

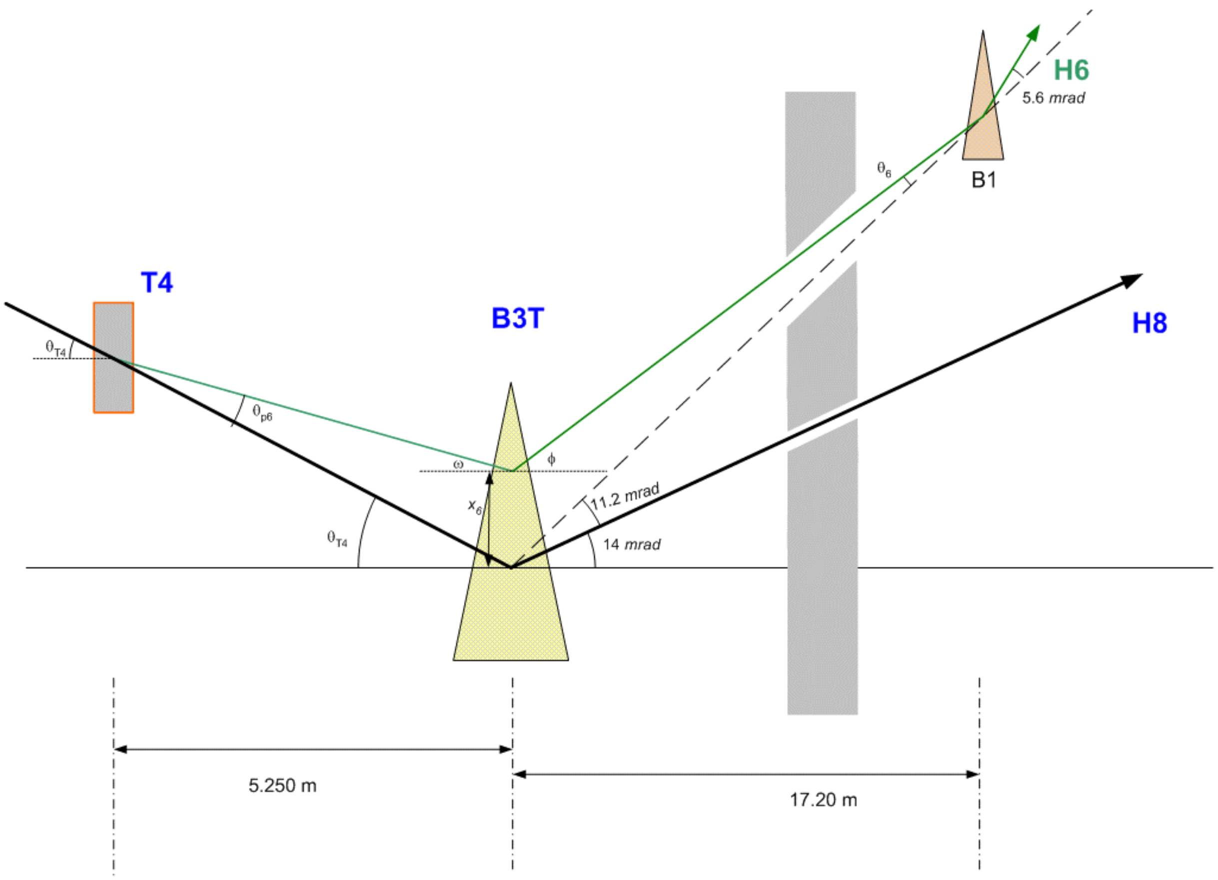

Figure 3: *B3T magnet configuration with two output beams.*

$$B\ell_3 = \frac{11.2 - \frac{l_{T4-B1}}{l_{B3T-B1}}\vartheta_{p6}}{299.79}\frac{P_0 P_6}{P_0 - P_6} \Rightarrow B\ell_3 = f(P_{SPS}, P_6, \vartheta_{p6}) \qquad (12)$$

2.2.3. Single beam option

Depending on which beam is serviced we have:

$$\begin{aligned} P0: B\ell_3 &= \frac{P_{SPS}}{299.79}(\vartheta_{T4} + 1.4), \text{ or} \\ H8: B\ell_3 &= \frac{P_{SPS}}{299.79}(\vartheta_{T4} + 14) \end{aligned} \qquad (13)$$

Since the bending power of B3T magnet is not enough to sufficiently deflect the primary proton beam for the high SPS energies, a combined deflection of all B1T, B2T and B3T magnets is needed, taking into account the apertures in each magnet.

2.3. B2T and B1T magnet setting

In **Figure 4** the two possible beam deflections between B1T and B2T are shown. It basically follows from the sign and value of the ϑ_{T4} angle as defined above. The B2T magnet has to bend the beam to the sum of the angles in B1T and B3T:

$$\vartheta_2 = \vartheta_1 + \vartheta_{T4} \tag{14}$$

From simple geometry calculations and for the general case where the proton beam arrives to P0 with a non zero skew (or in other words when H8 has a non zero production angle), we can write:

$$\left.\begin{aligned} x_2 &= x_{T4-B3T} + x_{B2T-T4} \\ x_{T4-B3T} &= l_{T4-B3T}\alpha = l_{T4-B3T}(\vartheta_{T4} - \vartheta_{p8}) \\ x_{B2T-T4} &= l_{B2T-T4}\vartheta_{T4} \end{aligned}\right\} \Rightarrow x_2 = l_{B2T-B3T}\vartheta_{T4} - l_{T4-B3T}\vartheta_{p8} \tag{15}$$

And also:

$$x_2 = l_{B1T-B2T}\vartheta_1 \tag{16}$$

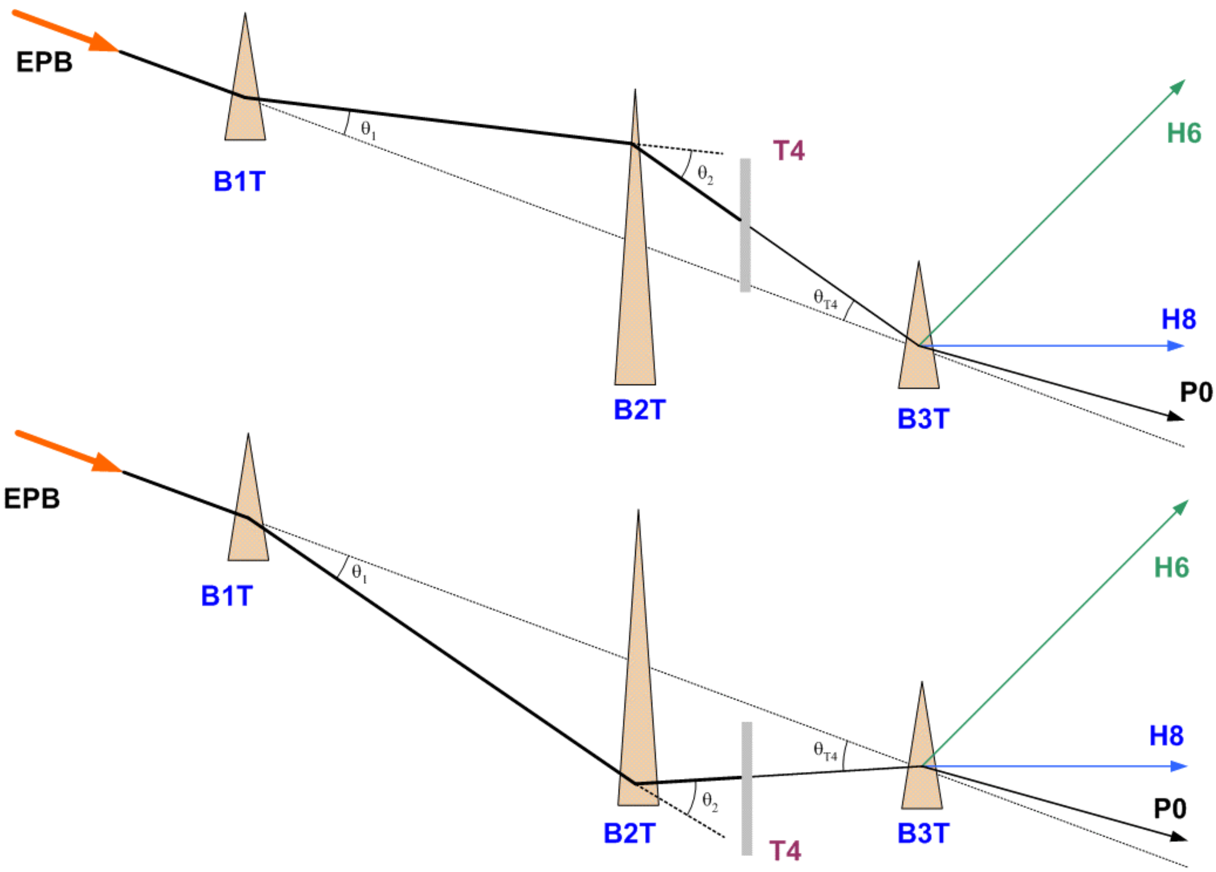

Figure 4: *Definition of angles and direction in the beam deflection by B1T and B2T magnets. The positive direction is the one from "above" the nominal beam axis.*

So finally:

$$\vartheta_1 = \frac{l_{B2T-B3T}\vartheta_{T4} - l_{T4-B3T}\vartheta_{p8}}{l_{B1T-B2T}} \tag{17}$$

$$\vartheta_2 = \frac{l_{B1T-B3T}\vartheta_{T4} - l_{T4-B3T}\vartheta_{p8}}{l_{B1T-B2T}} \tag{18}$$

The sign of ϑ_2 is negative (positive) if the displacement x_2 is positive (negative). For the bending strengths of the magnets we have:

$$B\ell_1 = \frac{P_0}{299.79}\vartheta_1 \tag{19}$$

$$B\ell_2 = \frac{P_0}{299.79}\vartheta_2 \tag{20}$$

2.4. H6 beam momentum selection

The presence of the H6-B1 magnet in the beam gives additional freedom to select particles with different production angles and thus have a wide momentum range possible for a given H8 and/or P0 beam configuration. Using the angles as defined in **Figure 2** (or **Figure 3**) we can write:

$$\omega = \vartheta_{T4} - \vartheta_{p6}, \quad \varphi = 25.2 - \vartheta_6 \tag{21}$$

Using the small angle approximation, we can write:

$$\left.\begin{aligned} x_6 &= l_{B3T-B1}\vartheta_6 \\ x_6 &= l_{T4-B3T}(\vartheta_{p6} - \vartheta_{p8}) \end{aligned}\right\} \Rightarrow \vartheta_6 = \frac{l_{T4-B3T}(\vartheta_{p6} - \vartheta_{p8})}{l_{B3T-B1}} \tag{22}$$

So finally for the H6 beam momentum we have:

$$P_6 = \frac{299.79}{\varphi + \omega} B\ell_3 = \frac{299.79}{25.2 + \vartheta_{T4} - \frac{l_{T4-B1}}{l_{B3T-B1}}\vartheta_{p6} + \frac{l_{T4-B3T}}{l_{B3T-B1}}\vartheta_{p8}} B\ell_3 \tag{23}$$

The strength of the B1 septum magnet in H6, given by:

$$B\ell_{B1} = \frac{P_6(\vartheta_6 + 5.6)}{299.79} \tag{24}$$

3. Examples

A set of fortran routines and PAW kumac files to run the examples and produce the plots can be found in: `/afs/cern.ch/user/e/efthymio/public/t4wobbling`

3.1. <u>Option 3A</u>: P0 beam ON, H8/H6 secondary hadrons

This is the case, d_0 in eq.(8) is zero, and from eq.(23) the H6 beam momentum can be determined as a function of P_{SPS}, P_{H8}, ϑ_{p8}, and ϑ_{p6}. The result for the present SPS energy is shown in **Figure 5** and summarized in **Table 4**. Typically in this configuration H8 runs with zero production angle, and there is strong interest to have H6 running with the smallest production angle possible, in particular for electron beams.

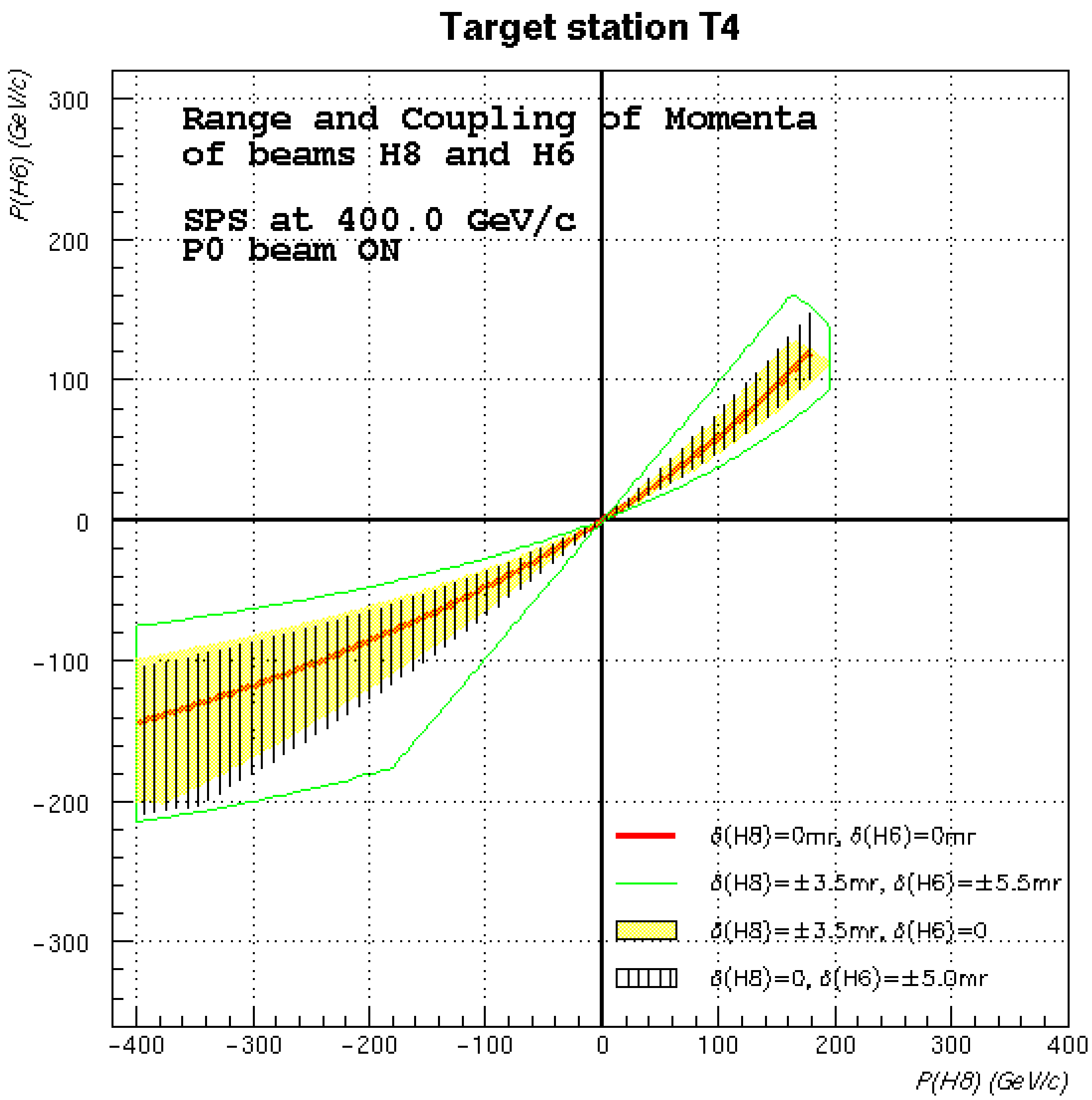

Figure 5: *H8 and H6 beam momentum relationship.*

Table 4: *H6 beam momentum and production angle for few typical cases.*

P0	H8(ϑ_{p8}=0)	H6				
		ϑ_{p6}=-3 mr	ϑ_{p6}=3mr	ϑ_{p6}=0mr	ϑ_{p6}=-5mr	ϑ_{p6}=5mr
400	+180	108.4	136.0	120.9	101.5	148.8
	+100	52.6	69.8	60.0	48.7	77.8
	+52	23.4	34.6	29.3	23.4	39.0
	-300	-96.8	-149.1	-117.4	-86.7	-179.9
	-250	-85.3	-129.7	-102.9	-76.5	-155.4
	-20	-18.9	-12.4	-10.3	-8.1	-14.3

3.2. Option 2B: P0 electrons, H8/H6 secondary hadrons

In this option the incident angle ϑ_{T4} is fixed to –1.4mr. Although there is a possibility to have H8 with non zero production angle, given the small diameter of the TAX holes for P0 the most typical case is that H8 runs at zero production angle (ϑ_{p8}=0mr). The range of available energies in this configuration is shown in **Figure 6**.

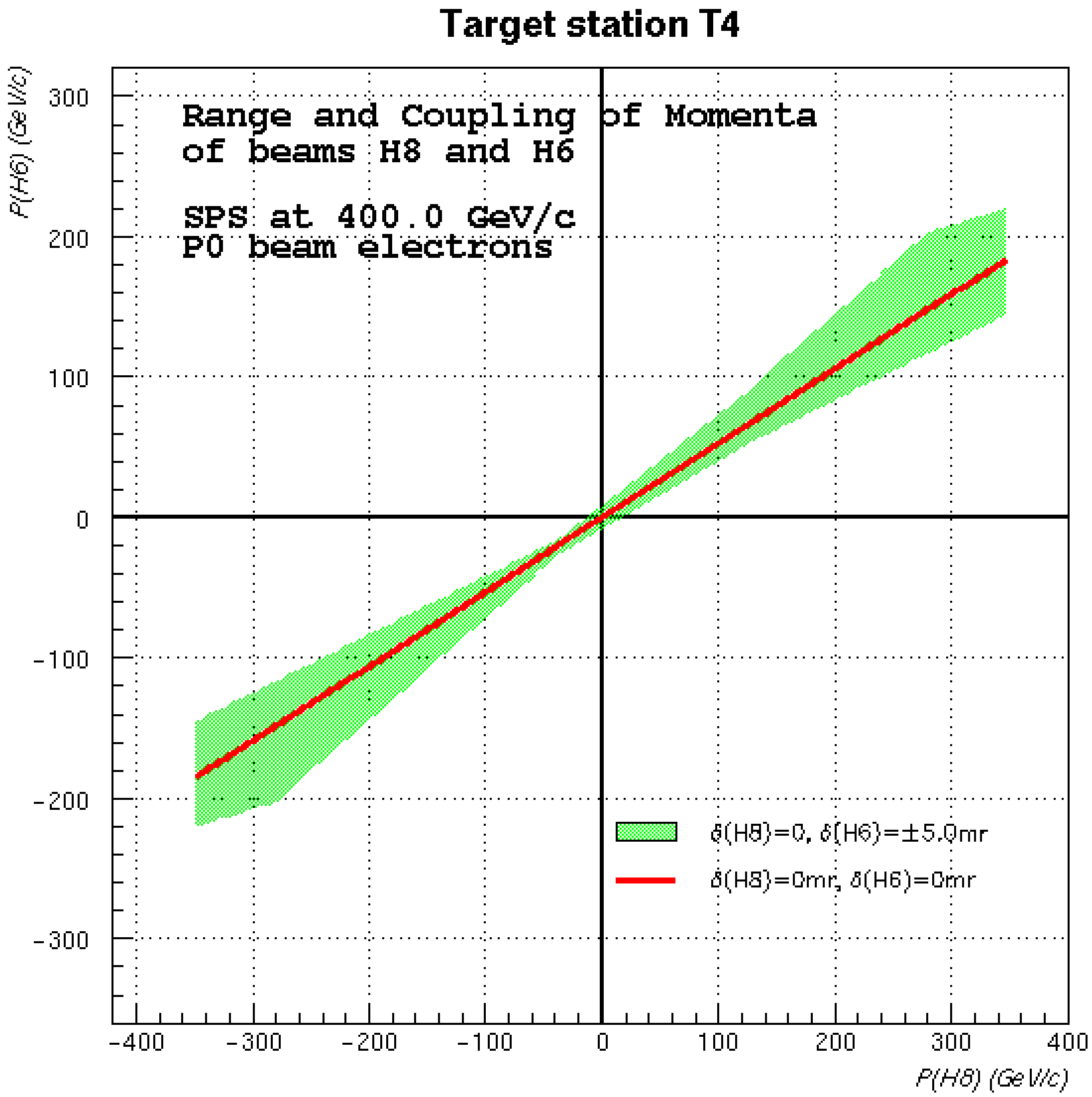

Figure 6: *Possible momentum range for the H6 beam with different production angles.*

3.3. Option 3C: P0 beam OFF, H8/H6 secondary hadrons

This configuration is similar to the two mentioned above. The effect of not having the P0 beam gives more freedom to choose the incident angle for the primary beam and thus have a larger momentum range for the H6 beam with zero production angle which is always preferred.

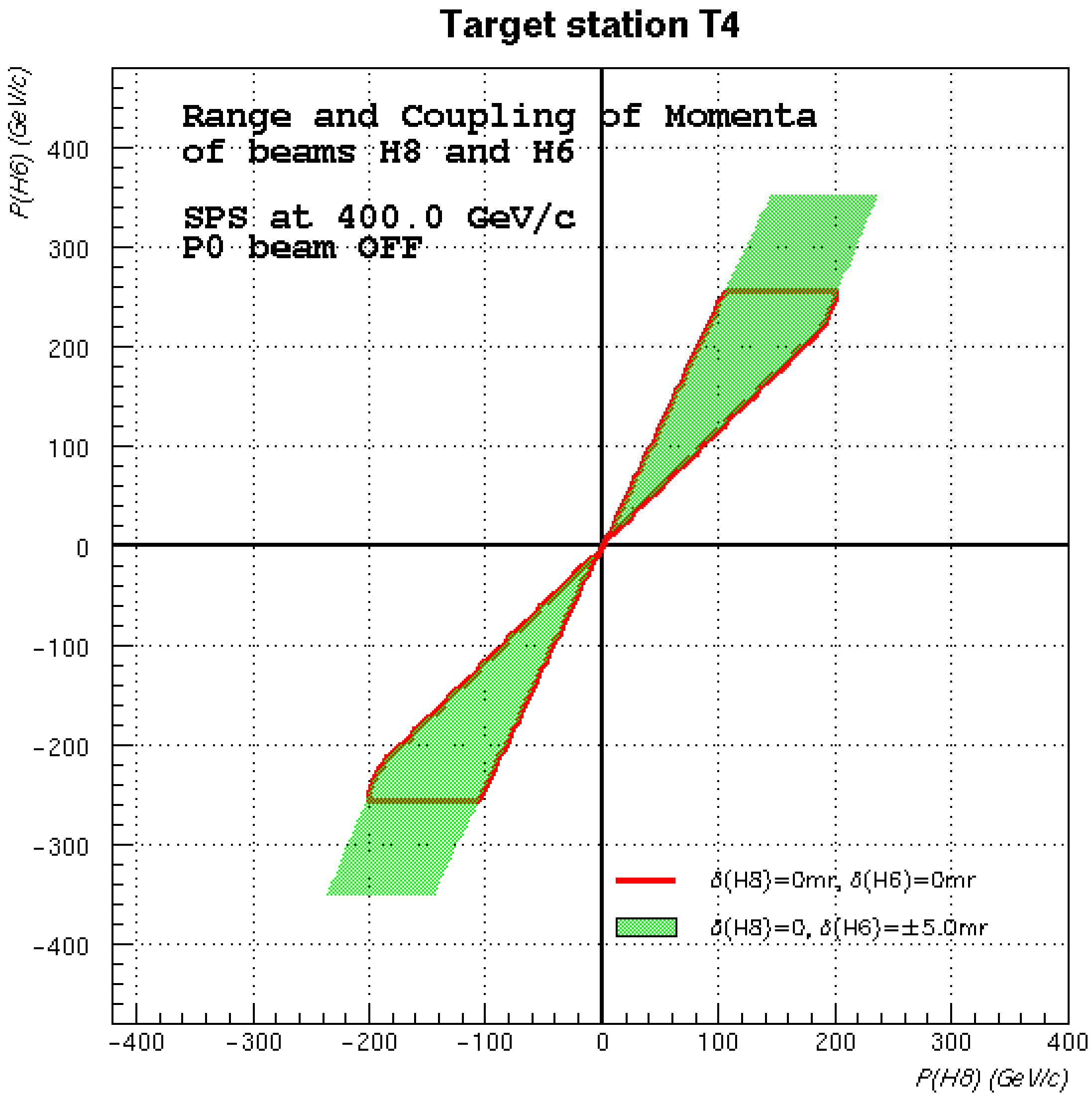

Figure 7: *H8 and H6 beam momentum relation when the P0 beam is not running.*

3.4. <u>Option 2B</u>: P0 beam OFF, H8 protons, H6 hadrons

In this configuration the wobbling settings depend on the choice of H6 beam (momentum and production angle) as shown in eq.(12). For a given production angle of the H6 beam there is a range of possible momentum values, listed in

Table 5: *H6 momentum range for different production angles.*

$P_{H8}=P_{SPS}$ (GeV/c)	ϑ_{p6} (mr)	P_{H6}min (GeV/c)	P_{H6} max (GeV/c)
400	0	124.0	196.0
	±5	88.0	228.0

3.5. Other interesting options

Some non-standard wobbling options are considered here. In particular, if one is allowed to vary the SPS energy some interesting possibilities but also potential problems appear. Two such examples are discussed here.

3.5.1. Pure electrons in H8

A particularly interesting one is when the H8 beam is set for electrons in the same way as the P0 beam in the examples before (i.e. ϑ_{T4} is fixed to –14mr). The primary beam is then deflected towards the P0 line and H6 is set for negative hadrons. As shown in **Figure 8** this configuration is feasible for SPS energies below 250 GeV/c.

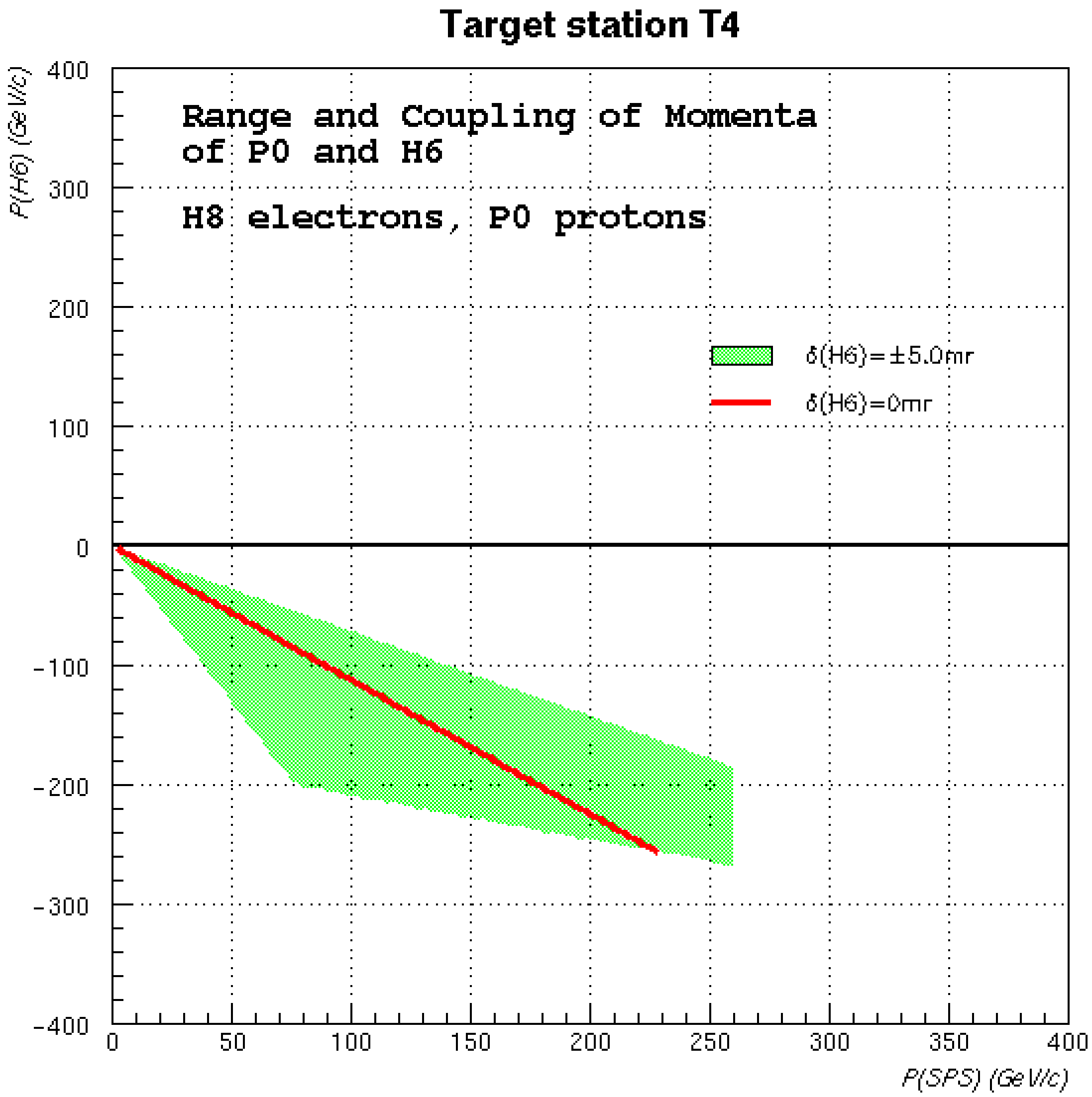

Figure 8: *Momentum range for the H6 beam line as function of the SPS energy, when H8 is set for electrons and P0 receives the primary proton beam.*

In this case the limit to the maximum SPS momentum comes from the strength of the B2T magnet. The area in the figure above indicates the limit in the H6 beam line due to B1 while H8 has always particles as well as P0.

Of course to have pure electrons in H8, a converted has to be added in the beam line upstream of the first quadrupoles, something not so easy to realize.

3.5.2. Primary protons in H6

This option can only happen if SPS runs at very low energies, well below the design value of 400(450) GeV/c.

4. References

[**1**] T4 wobbling and related items from http://gatignon.home.cern.ch/gatignon/T4wobble.html

[**2**] N.Doble, L.Gatignon, K.Elsener: "Operational modes of beam lines from T4 for 1996". SL/EA Memo (http://spsschedule.web.cern.ch/SPSschedule/request/memo_2.html)