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Studies of the Alignment Tolerances of the Transport Solenoid of the Mu2e Experiment

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1 Introduction

This technical note summarizes the simulation results of the alignment tolerances for the transport solenoid (TS) of the Mu2e experiment [1]. The TS is composed of 62 "rings" aligned in a s-like shape as show in Figure 1. The simulations consist of introducing random errors in each of the 62 rings by displacing transversally or rotating in yaw and pitch. The methodology of this study is briefly discussed.

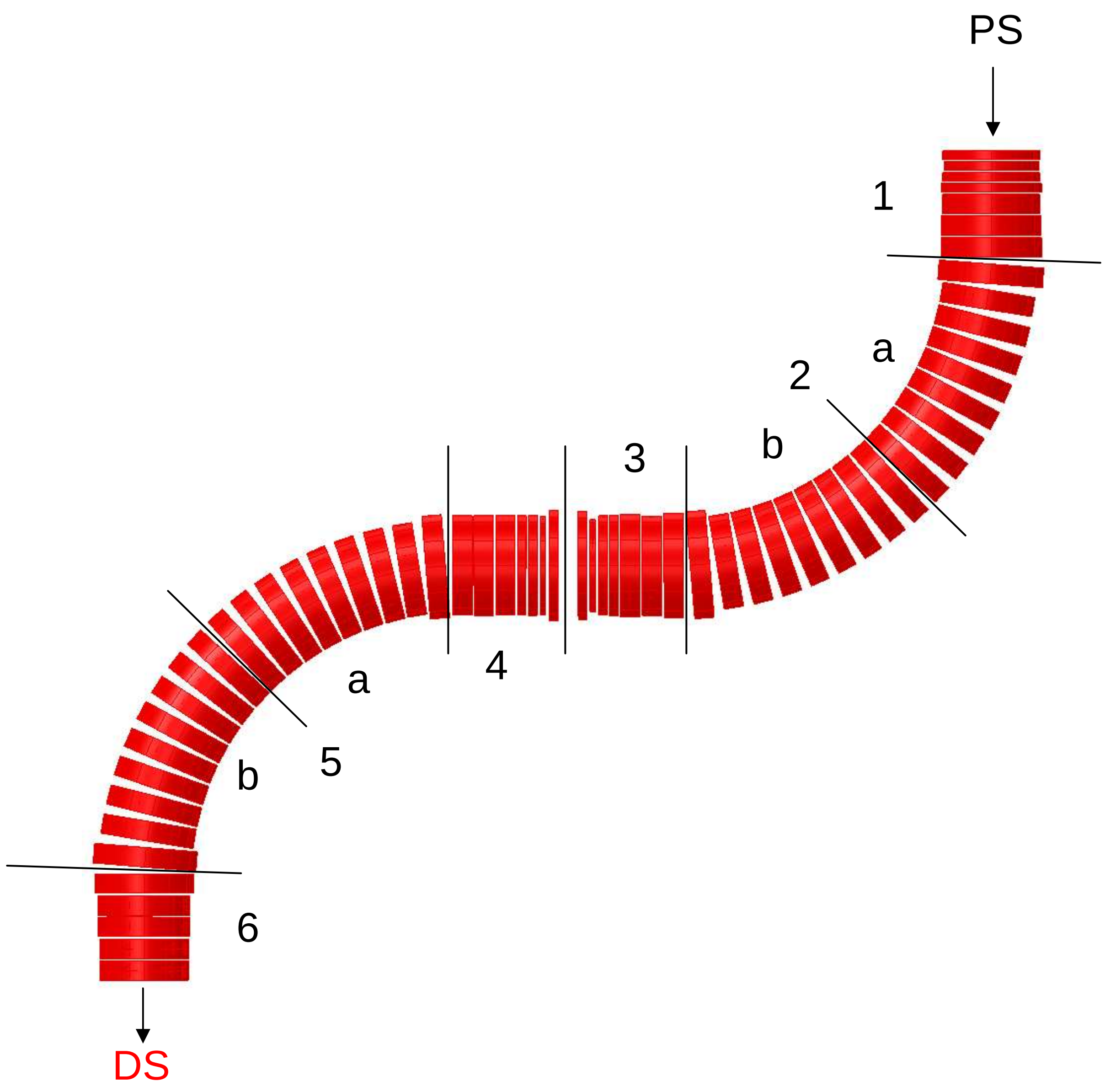


Figure 1 - Transport solenoid for Mu2e experiment

2 Study methodology

The core of the studies consisted in tracking particles through the Mu2e magnet system using G4Beamline (G4B) code. The simulations of G4B tracks 10^6 muons of which approximately 3000 of them are collected by the stopping target at the detector solenoid (DS). In order to speed up the process of tracking 10^6 particles, G4B stores the magnetic fields of the coils in magnetic field map files. Those field maps are separated in 4 sections: Production Solenoid (PS), TS-upstream, TS-downstream and DS.

General Atomic has produced a 3D model (for Opera-3D) of the Mu2e magnet system. The model includes all the 62 coils of TS and PS and DS coils with their surrounding iron. This model could be easily modified in order to generate the equivalent field maps of the TS up and down streams only.

Therefore, to study the alignment tolerance of the TS coils, one can generate a TS field map with the coils slightly moved from their nominal positions. This procedure is repeated 25 times (each time with a different coil perturbation) in order to have some statistics in a reasonable time (it took approximately 33 hours of computation time). Figure 2 shows the basic flowchart of the analysis.

The coils could be misaligned in two different ways: each one of the 62 coils is individually perturbed or coils within the same group receive the same perturbation. The groups correspond to the ones seen in Figure 1. Both are presented in perturbed field maps.

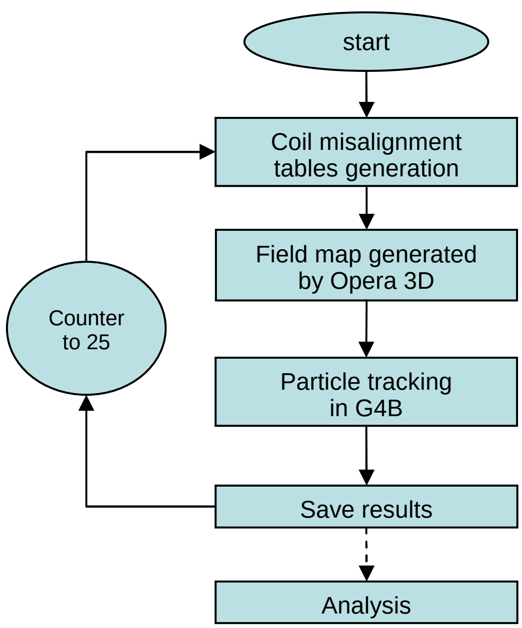


Figure 2 – Basic flowchart for the simulations

Each result from from G4B is then analized by calculating the average of the total momentum (*Ptot*) the momentum spread (*ΔPtot*) the average time (*t*) and time dispersion (*Δt*) and the total number of particles in the stopping target (*N*). The results are then summarized calculating the mean and standard deviation over the 25 simulations for each one of these variables.

3 Simulations results

3.1 Random distributions

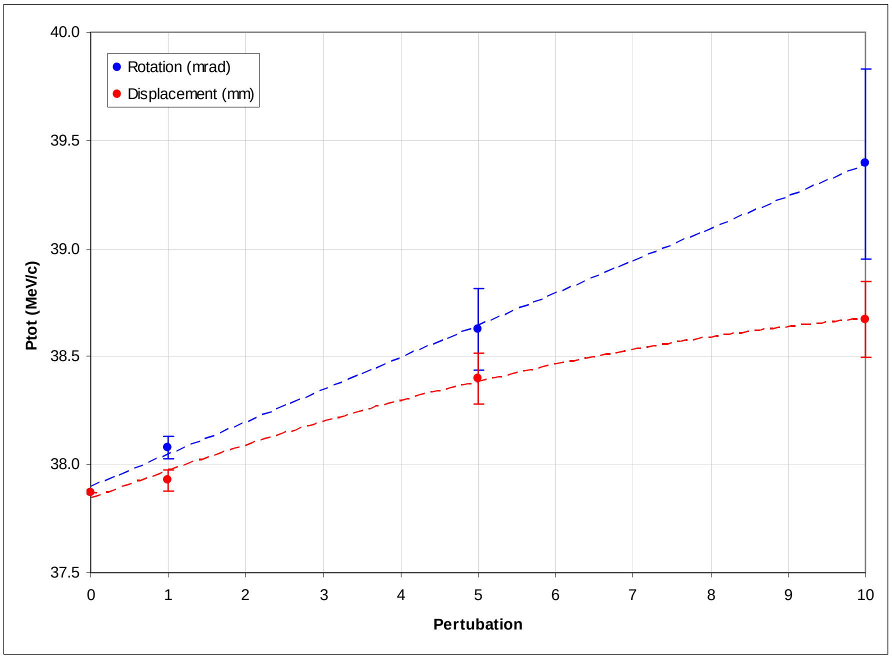
The simulations were divided in two groups: transverse movement (displacement) and rotation (pitch and yaw) of the coils. The results are summarized in Table 1. Figures 3-5 show the behavior of these variables as function of the perturbation amplitude.

Table 1 - Summary of the results of the alignment tolerances

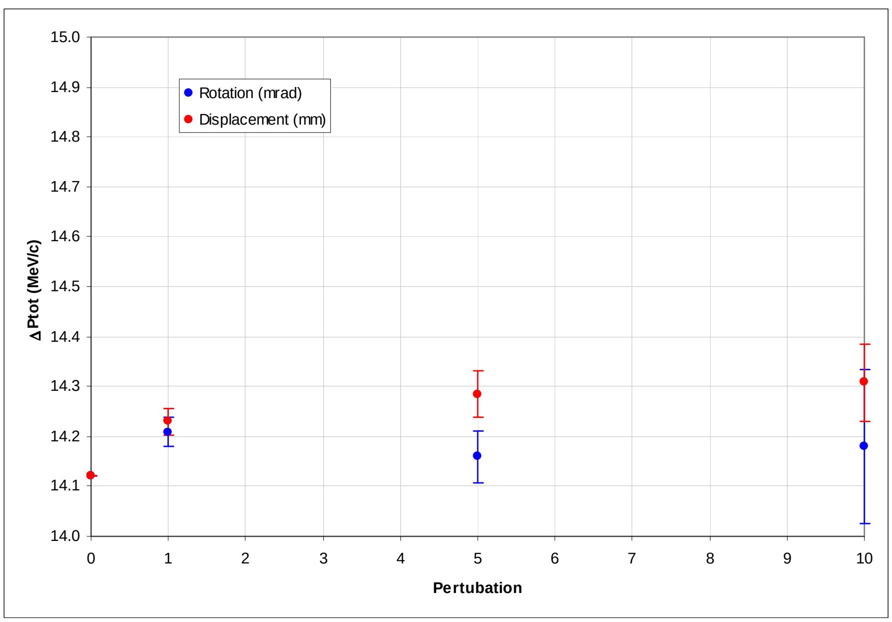
Displacement (mm)	Ptot (MeV/c)	σPtot (MeV/c)	σPtot/Ptot (%)	ΔPtot (MeV)	σΔPtot (Mev)	σΔPtot/ΔPtot (%)	t (ns)	σt (ns)	σt/t (%)	Δt (ns)	σΔt (ns)	σΔt/Δt (%)	N	σN	σN/N (%)
0	37.87	0.00	0.0	14.12	0.00	0.0	306.1	0.0	0.0	190.5	0.0	0.0	3272	0	0.0
1	37.93	0.05	0.1	14.23	0.03	0.2	306.4	0.7	0.2	191.9	1.1	0.6	3177	10	0.3
5	38.40	0.12	0.3	14.28	0.05	0.3	302.4	1.5	0.5	193.1	2.2	1.1	3201	48	1.5
10	38.67	0.18	0.5	14.31	0.08	0.5	300.6	2.3	0.8	197.9	4.1	2.1	3181	94	2.9

Rotation (mrad)	Ptot (MeV/c)	σPtot (MeV/c)	σPtot/Ptot (%)	ΔPtot (MeV)	σΔPtot (Mev)	σΔPtot/ΔPtot (%)	t (ns)	σt (ns)	σt/t (%)	Δt (ns)	σΔt (ns)	σΔt/Δt (%)	N	σN	σN/N (%)
0	37.87	0.00	0.0	14.12	0.00	0.0	306.1	0.0	0.0	190.5	0.0	0.0	3272	0	0.0
1	38.08	0.05	0.1	14.21	0.03	0.2	304.2	0.7	0.2	190.3	1.4	0.8	3182	24	0.8
5	38.63	0.19	0.5	14.16	0.05	0.4	298.4	2.8	1.0	189.0	4.5	2.4	3073	104	3.4
10	39.39	0.44	1.1	14.18	0.16	1.1	289.5	4.7	1.6	190.3	8.6	4.5	2681	166	6.2

As can be seen, the *Ptot* tends to increase with the perturbation amplitude although this increment is very small. The momentum spread tends to be invariant. Higher momentum means faster particles which corroborates the results of timing seen in Figure 4a. The time dispersion, however, does not follow the momentum spread invariance exactly. It can be seen that the errors associated with displacements could slightly increase the time dispersion (Figure 4b). In the other hand, *N* is sensitive to the errors associated with the rotation of the coils (pitch and yaw)

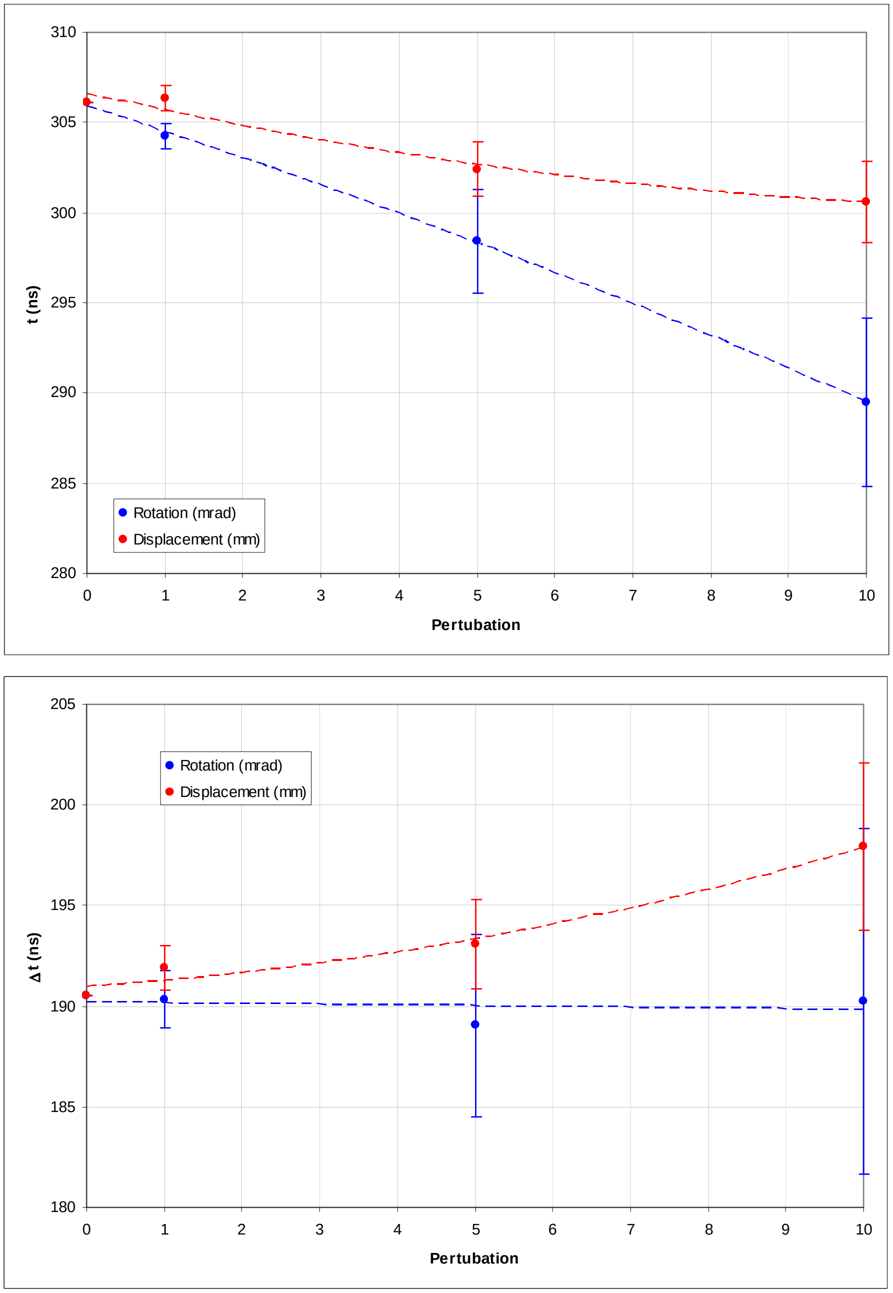


(a)



(b)

Figure 3 - Total momentum (a) and momentum spread (b) as function of the perturbation amplitude



(a)

(b)

Figure 4 - Time (a) and time dispersion (b) as function of the perturbation amplitude

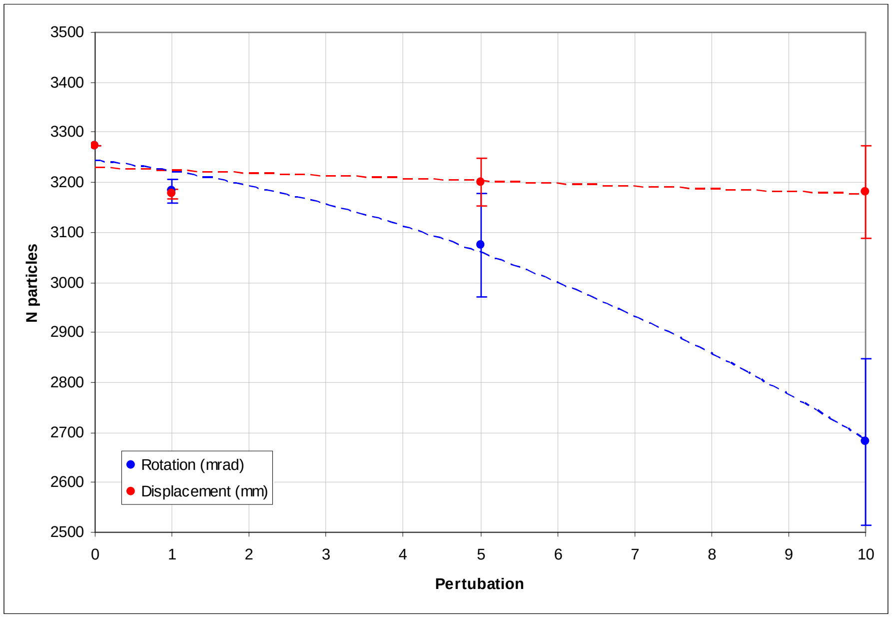


Figure 5 - Total number of particles in the stopping target as function of the perturbation amplitude

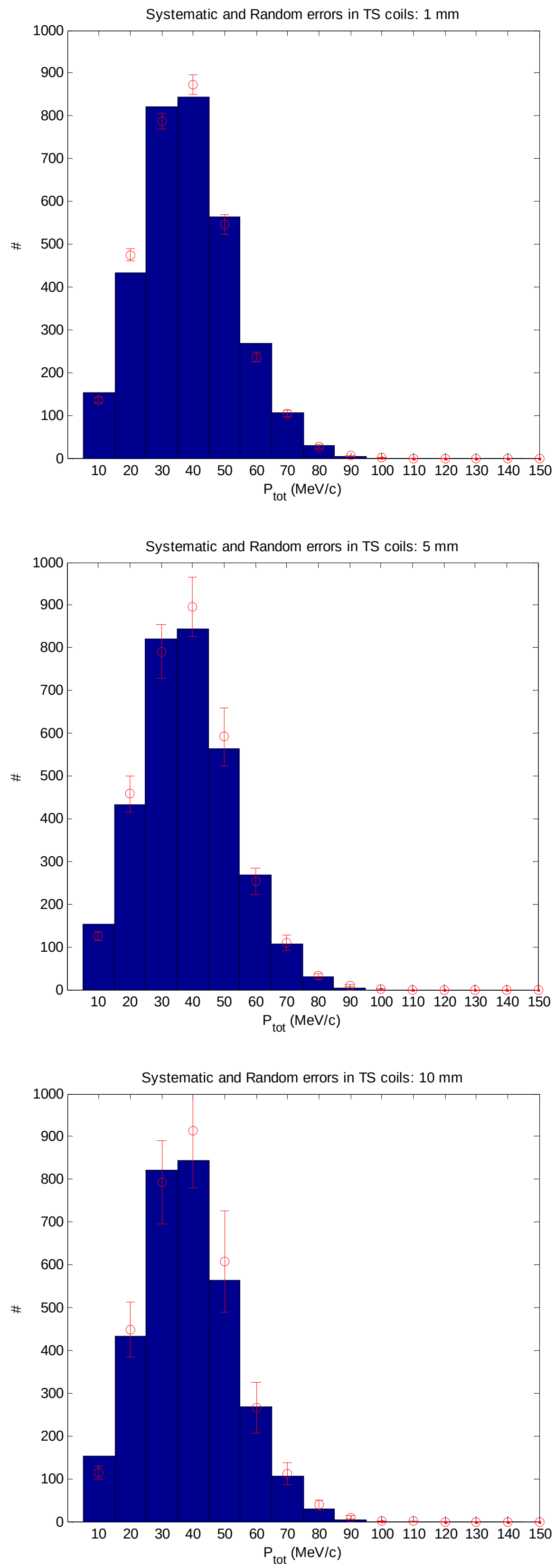
Table 2 shows the percentage of increment or decrement for each one of the considered variables with respect to the results of the TS coils in their nominal positions.

Table 2 – Percentage increment/decrement for each one of the considered variables

Increment / Decrement (%)					
Displacement (mm)	Ptot (%)	ΔPtot (%)	t (%)	Δt (%)	N (%)
1	0.1	0.8	0.1	0.7	2.9
5	1.4	1.2	1.2	1.4	2.2
10	2.1	1.3	1.8	3.9	2.8

Rotation (mrad)	Ptot (%)	ΔPtot (%)	t (%)	Δt (%)	N (%)
1	0.5	0.6	0.6	0.1	2.7
5	2.0	0.3	2.5	0.8	6.1
10	4.0	0.4	5.4	0.1	18.1

Another approach for this analysis is to compare the shape of the *Ptot* and *t* for each perturbation with the coils in their nominal position. In Figures 6-9 the blue histogram represents the nominal distribution and the red data, the correspondent bin mean and standard deviation over the 25 simulations.



(a)

(b)

(c)

Figure 6 – Total momentum distribution for displacements of (a) 1 (b) 5 (c) 10 mm.

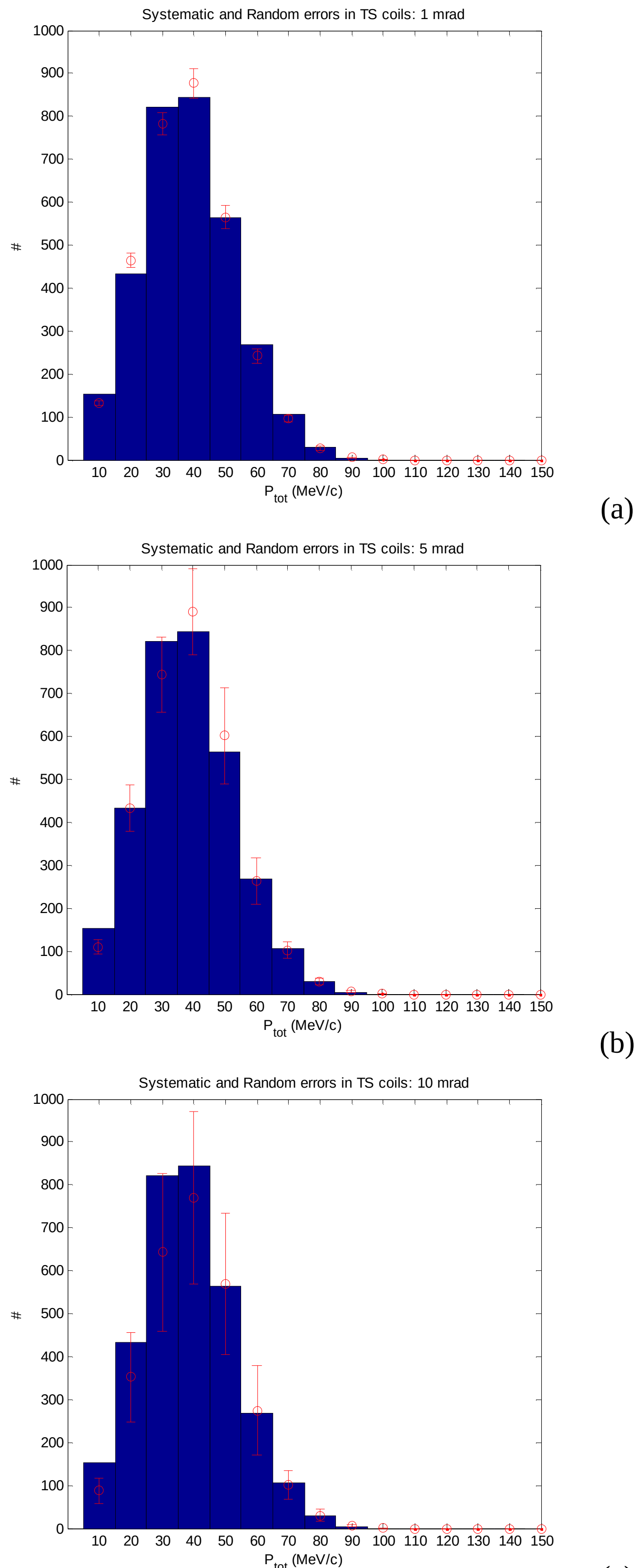
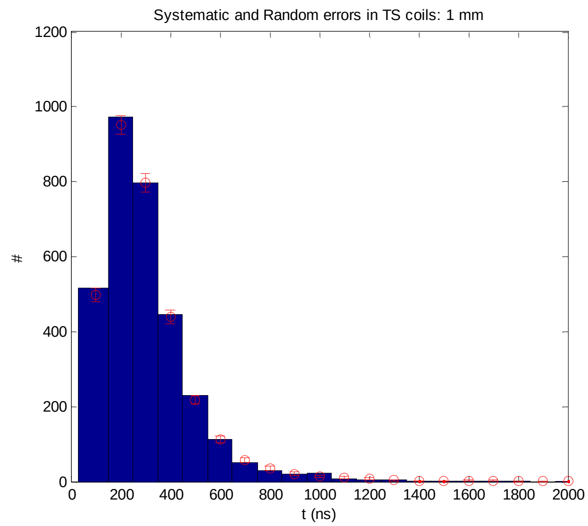
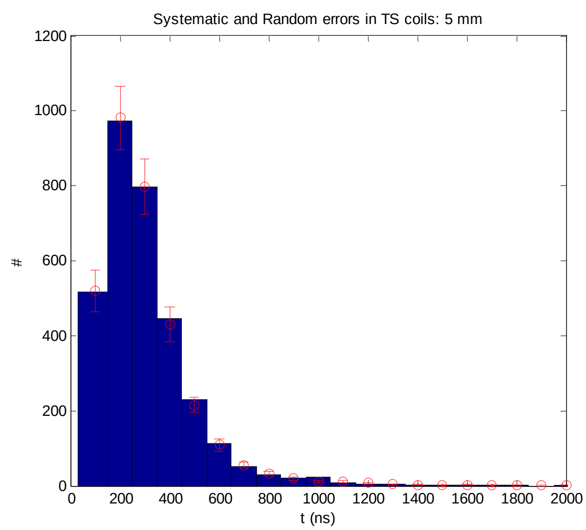


Figure 7 – Total momentum distribution for rotations of (a) 1 (b) 5 (c) 10 mrad.



(a)



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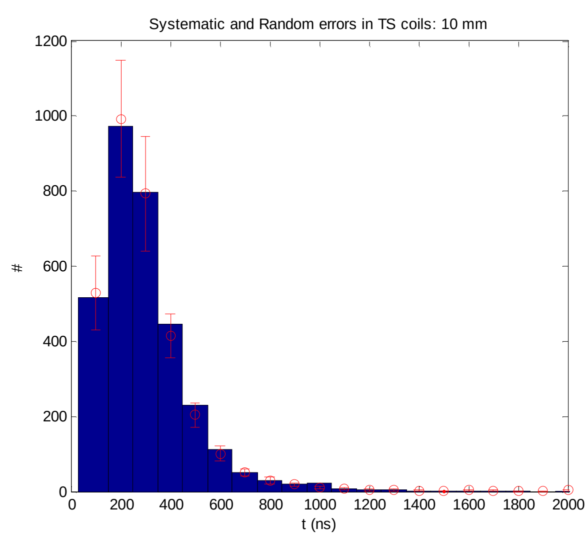
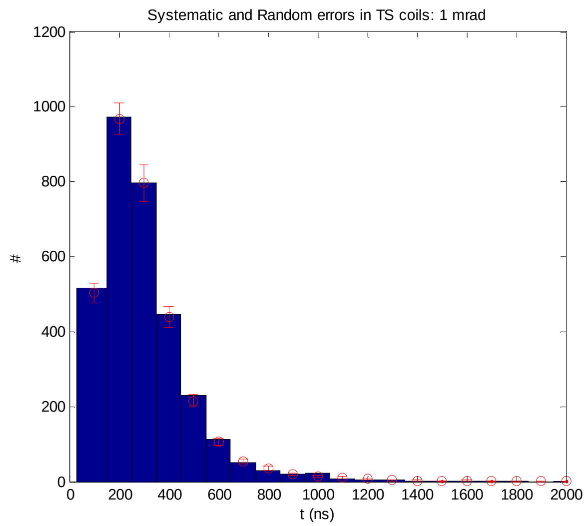
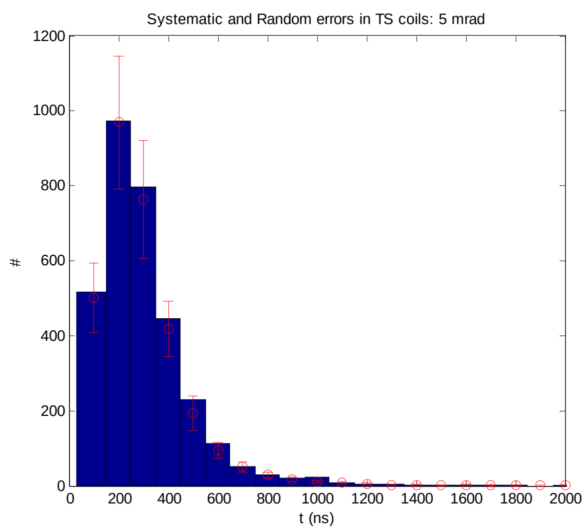


(c)

Figure 8 – Timing distribution for displacements of (a) 1 (b) 5 (c) 10 mm.



(a)



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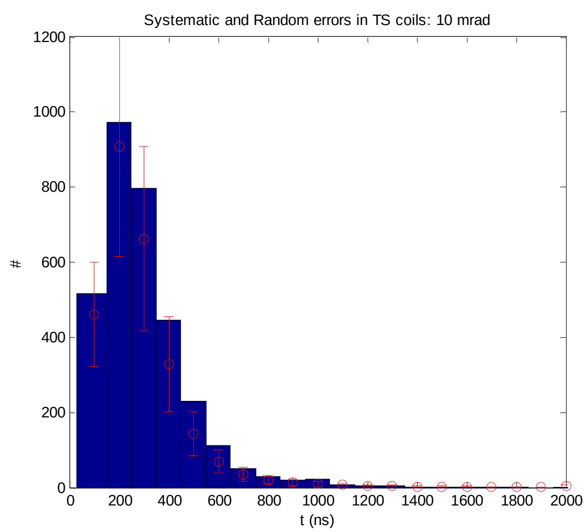

(c)

Figure 9 – Timing distribution for rotations of (a) 1 (b) 5 (c) 10 mrad.

3.2 Systematic rotation errors in the straight sections

In the last section, it was investigated the effects of random errors in the coils. This section is devoted to the analysis of systematic errors on the straight sections. The straight section is refereed according to the number in Figure 1. For that manner, only rotations (yaw and pitch) were considered and the rotation angle applied was ± 5 mrad. The results of these simulations are summarized in the Figure 1. As can be seen, the impact of these changes is small and inconclusive when considered only the variables studied in the previous sections. One may notice, however, a more expressive change (around 20%) in the transversal position of the beam at the stopping target (2.3 and 1.3 mm respectively in x and y).

Therefore, this effect must be taken into account in the tolerance for the TS coils, given that the stopping target is small (few millimeters in diameter [1]).

Table 3 - Summary of the results of the alignment tolerances

Sector	Rotation (mrad)	Rotation type	Ptot (MeV/c)	ΔPtot (MeV/c)	N	t (ns)	Δt (ns)	x (mm)	Δx (mm)	y (mm)	Δy (mm)	Px (MeV/c)	ΔPx (MeV/c)	Py (MeV/c)	ΔPy (MeV/c)	Pz (MeV/c)	ΔPz (MeV/c)
1	5	Yaw	38.3	14.2	3267	300	191	11.2	39.9	-6.1	38.7	-0.1	13.4	-0.1	13.2	33.1	14.7
1	-5	Yaw	38.3	14.2	3176	303	197	11.5	39.8	-7.0	39.2	0.3	13.5	0.3	13.4	33.1	14.6
3	5	Yaw	37.7	14.3	3029	310	195	12.3	39.9	-6.5	38.9	0.0	13.4	-0.2	13.5	32.5	14.5
3	-5	Yaw	37.8	14.2	3272	307	190	10.3	40.3	-6.0	38.4	-0.1	13.4	0.3	13.6	32.6	14.5
4	5	Yaw	37.8	14.2	3047	306	187	12.2	39.7	-6.1	38.5	0.0	13.5	0.3	13.5	32.5	14.5
4	-5	Yaw	37.7	14.2	3271	310	195	10.1	40.2	-6.1	39.3	-0.2	13.4	0.1	13.3	32.5	14.5
6	5	Yaw	37.7	14.2	3093	309	192	11.4	40.1	-6.0	39.6	-0.1	13.4	0.1	13.4	32.5	14.5
6	-5	Yaw	37.8	14.3	3150	309	194	10.3	40.2	-6.8	39.1	0.2	13.4	0.0	13.4	32.6	14.5
1	5	Pitch	38.3	14.1	3146	304	194	10.7	39.7	-6.7	39.3	0.0	13.6	0.0	13.5	32.9	14.5
1	-5	Pitch	37.7	14.1	3166	306	188	11.4	39.7	-7.0	38.9	0.5	13.6	0.2	13.3	32.4	14.4
3	5	Pitch	38.7	14.4	3174	301	196	11.5	39.9	-7.3	38.7	0.0	13.6	0.3	13.5	33.5	14.8
3	-5	Pitch	37.8	14.1	3161	305	190	11.4	40.2	-5.1	38.6	-0.2	13.4	0.3	13.5	32.6	14.3
4	5	Pitch	38.1	14.1	3100	304	193	10.8	40.9	-6.5	38.5	-0.1	13.4	-0.2	13.5	32.9	14.4
4	-5	Pitch	38.0	14.4	3233	307	196	12.0	39.7	-5.8	39.0	0.3	13.4	0.3	13.5	32.8	14.7
6	5	Pitch	37.7	14.2	3168	310	195	11.3	40.1	-6.5	38.9	0.0	13.5	-0.1	13.5	32.4	14.5
6	-5	Pitch	37.7	14.2	3104	310	195	11.4	40.1	-6.1	39.5	-0.1	13.4	0.2	13.3	32.5	14.5
	nominal		**38.1**	**14.5**	**3272**	**306**	**190**	**10.3**	**40.1**	**-6.0**	**39.1**	**0.1**	**13.5**	**-0.1**	**13.2**	**32.6**	**14.6**

3.3 Effect of the gradient in the TS

In an unrelated topic, it was studied (using the same methodology) the effect of the gradient in the TS. According to the MECO report [2], the TS has a gradient to avoid particle trapping as shown in Figure 10.

The studied consisted in eliminate the gradient in the transport solenoid making the field flat at 2.5 T(as in the beginning of the TS) and 2.1 T (as in the ending of the TS). The results are summarized in Table 4.

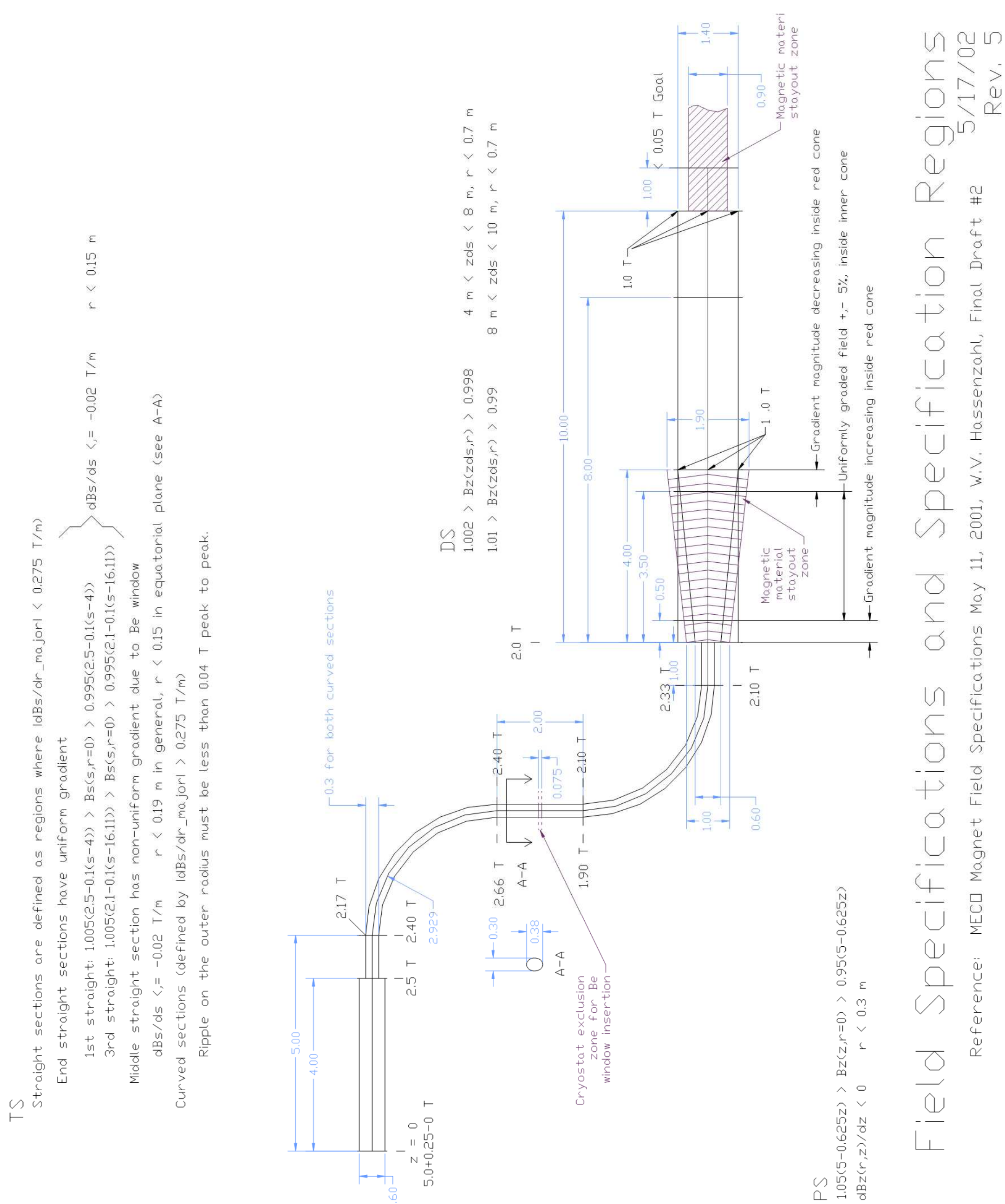

Figure 10 – Field gradient for TS.

Table 4 – Gradient vs. no-gradient in the TS.

	Gradient	No Gradient (2.5 T)	No Gradient (2.1 T)
Ptot (MeV/c)	37.9	41.0	36.4
ΔPtot (MeV)	14.1	15.9	13.4
t (ns)	306.1	291.2	318.1
Δt (ns)	190.5	192.6	201.8
N	3272	4247	2890

As can be seen, at 2.5 T you could have and increment of about 30% in the total number of particles. This is due to the fact the in higher field the particles trajectories are more tide up and therefore, more particles go through the collimators. The same inverse reason for the TS being operated at 2.1 T has about 12% fewer particles collected. The total momentum is increased in 8% at 2.5 T and decreases 4% at 2.1 T.

However in the simulations presented here, it was only considered muons. The settings in the G4B tracking simulations get rid of other particles. This should be modified in the future to include all the particles for a better understanding of the effect of the gradient in TS.

4 Conclusions

This work studied the TS coils misalignments and their effects on the main variables (total momentum, momentum spread, time and time dispersion, and total number of particles at stopping target).

The studied was based on small modifications in each coil of the TS. These modifications were repeated 25 times randomly. This number of repetition gives a reasonable statics within a reasonable computation time.

The results showed the dependence of each variable with the type and amplitude of the perturbation.

For typical the typical values of alignment that can be reached in the production of this coils (few mm and few mrad) the impact in the performance of the experiment (according to the variables studied here) is minimum.

The effect of gradient in TS showed some expressive results, but needs further investigation to include other particles not included in the simulations here.

References

[1] M. Bachman et al., “Muon Electron Conversion (MECO)”, 1997
[2] “MECO Superconducting Solenoid System Conceptual Design Report” Massachusetts Institute of Technology Plasma Science and Fusion Center, 2002