STUDY OF THE C SHAPED VARIANT OF THE TRANSPORT SOLENOIDS SYSTEM FOR Mu2e EXPERIMENT.

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INTRODUCTION

The goal of the project is to make a solenoids system with a C shape by modifying the S shaped one and to study the characteristics of the resulting magnetic field. The solenoid system is a part of the Mu2e experimental apparatus. The purpose of the system is to create a field configuration that meets a series of requirements. The S shaped solenoids system is already optimized and meets these requirements. We need to study the C shape configuration in order to verify if it does the same.

ANALYSIS OF THE C SHAPED SYSTEM

For the modeling and analysis of the C shaped system we used the model of the S shaped one and the programs and methodologies already used for its study. The magnetic design of the original TS is described in [1]. The finite element method analysis of the magnetic field of the original system was performed by using the program "OPERA". So the first step was to convert the original OPERA model to a C shaped one. This was done by flipping all the coordinates of the points of the coil sections TS4, TS5

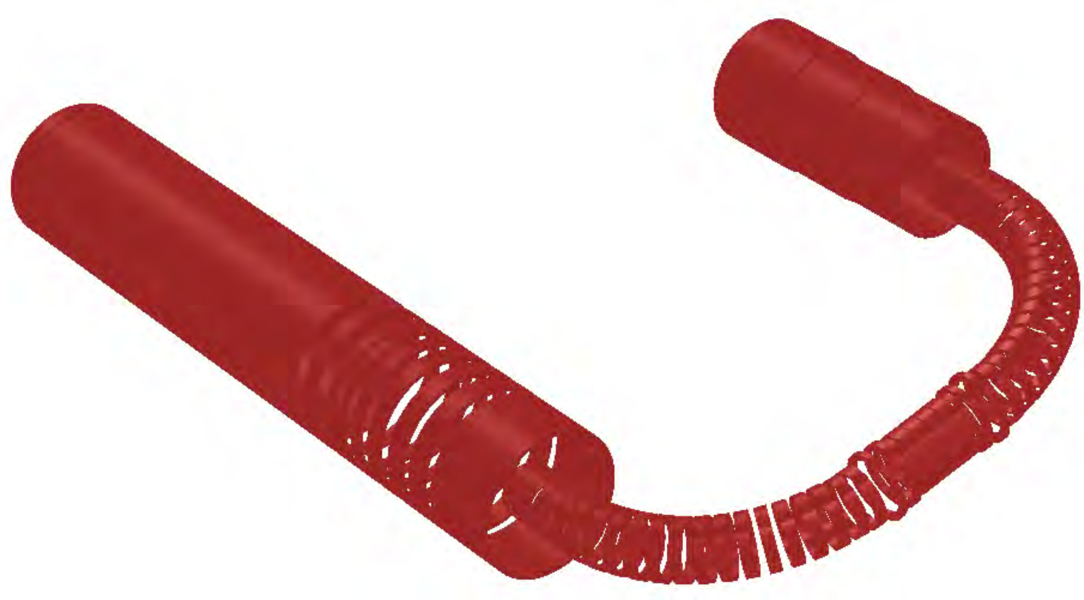
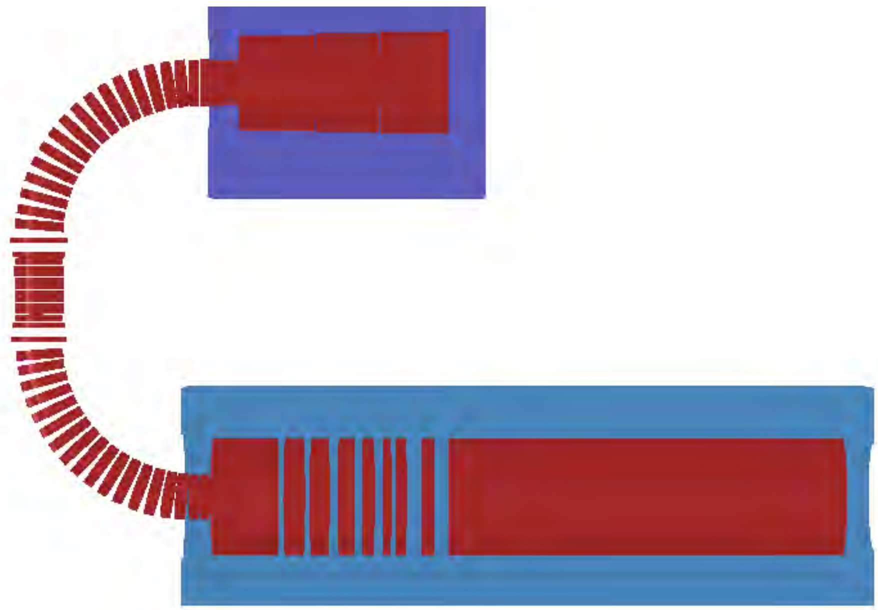


Figure 1: OPERA model of the solenoid system

Figure 2: OPERA model of the coil system with iron



and DS and the DS Iron around the axes of TS3 section and adjusting the yaw angles forming the second curved section. By this way we created the new model that is shown in **Error! Reference source not found.** and **Error! Reference source not found.**. Using the same parameters of the original system we analyzed the magnetic field using OPERA. The results have been processed by means of a Matlab program. The program calculates the field value in a series of points along the axial trajectory and two equally spaced (+/- 150 mm) parallel lines that follow this trajectory. With this set of data we computed the characteristics of the field and verified by plotting the fulfillment of the requirements. The field requirements are described in [2] and summarized in **Error! Reference source not found.**.

Table 1: Field uniformity requirements.

REGION	UNIFORMITY REQUIREMENTS
TS1	- |dBs/Bs| < 0.05 about an uniform negative axial gradient; - dBs/ds<0.02 T/m for a radii r<0.15 m.
TS2	- Field ripple |Bsmax-Bsmin| < 0.02 T; - Radial gradient dBs/dr> 0.275 T/m.
TS3	- |dBs/Bs| < 0.05 about an uniform negative axial gradient; - dBs/ds<0.02 T/m for a radii r<0.15 m.
TS4	- Field ripple |Bsmax-Bsmin| < 0.02 T; - Radial gradient dBs/dr> 0.275 T/m.
TS5	- |dBs/Bs| < 0.05 about an uniform negative axial gradient; - dBs/ds<0.02 T/m for a radii r<0.15 m.

The results of the simulation compared with the limits posed by the requirements are shown in Figure - Figure .

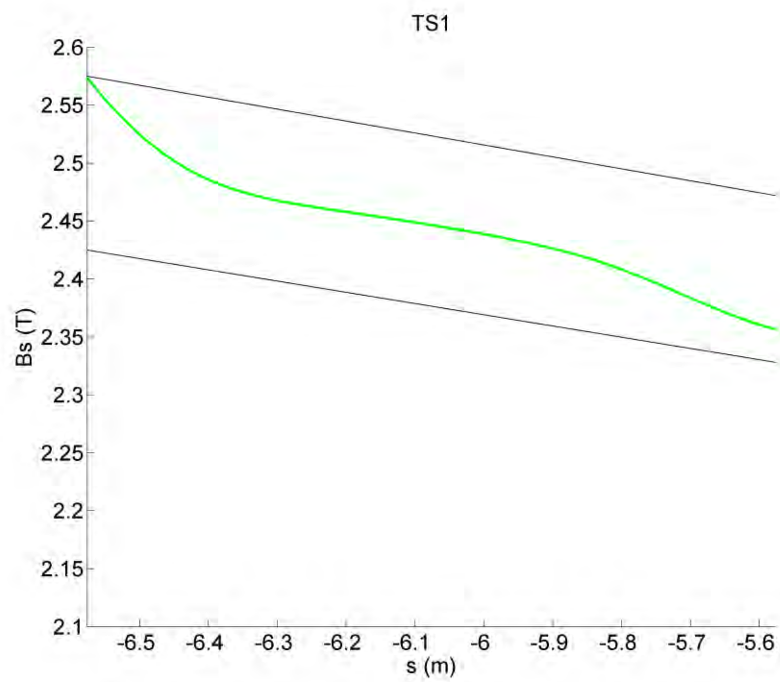


Figure 3: TS1 axial field along the axis

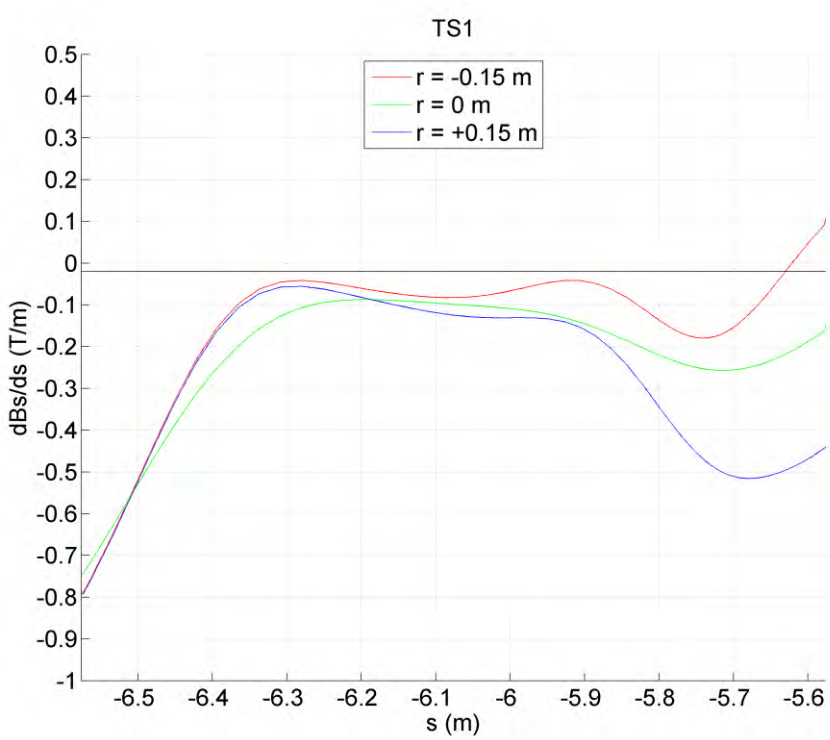


Figure 4: TS1 axial field gradient

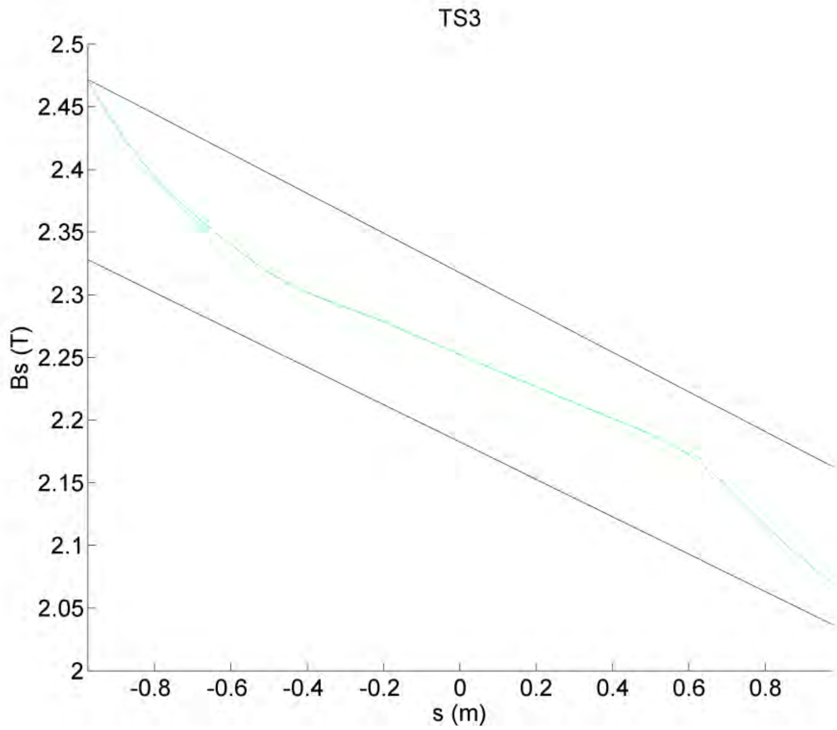


Figure 5: TS3 axial field along the axis

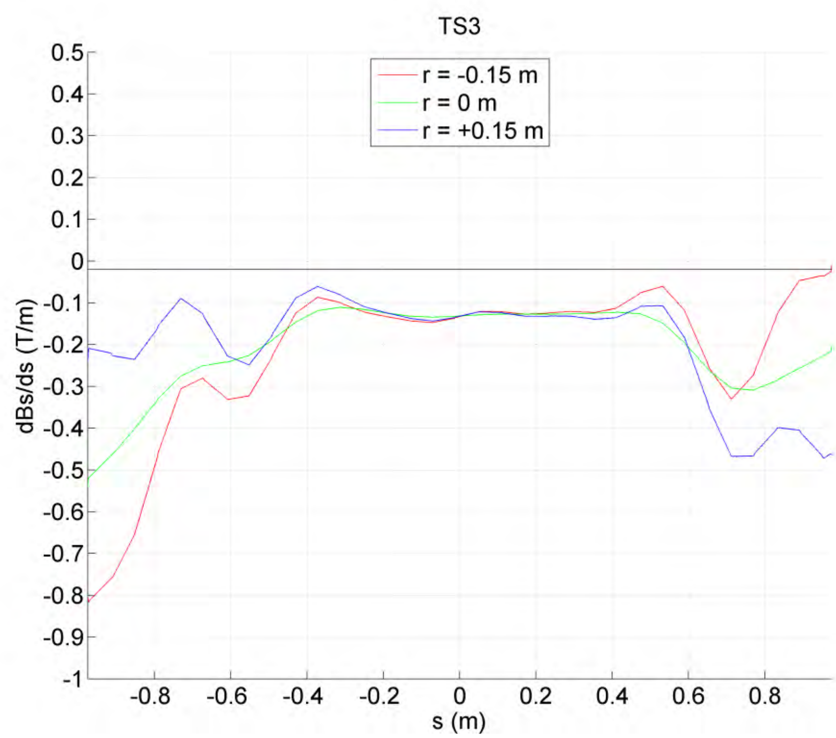


Figure 6: TS3 axial field gradient

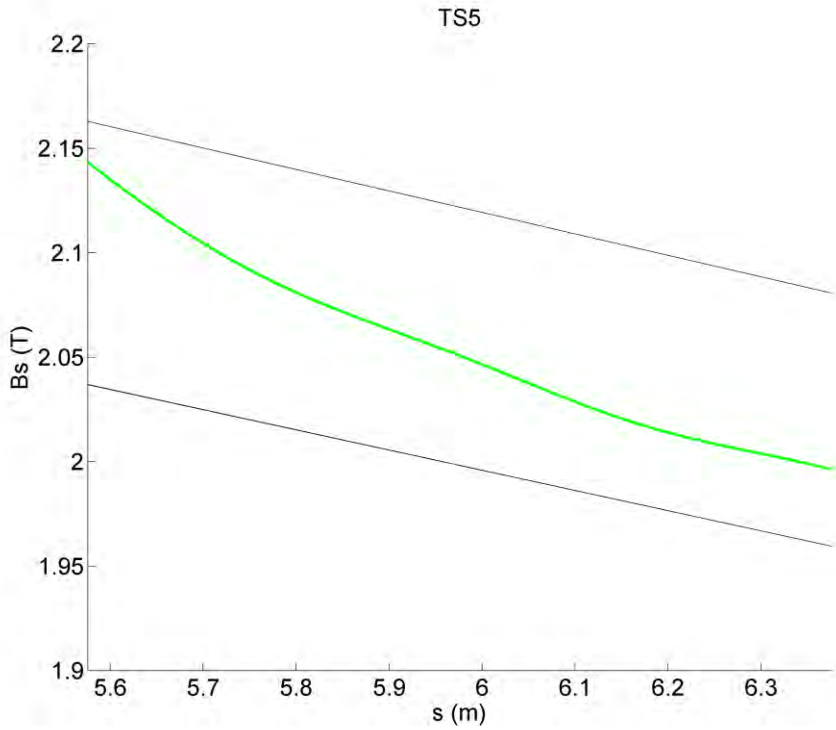


Figure 7: TS5 axial field along the axis

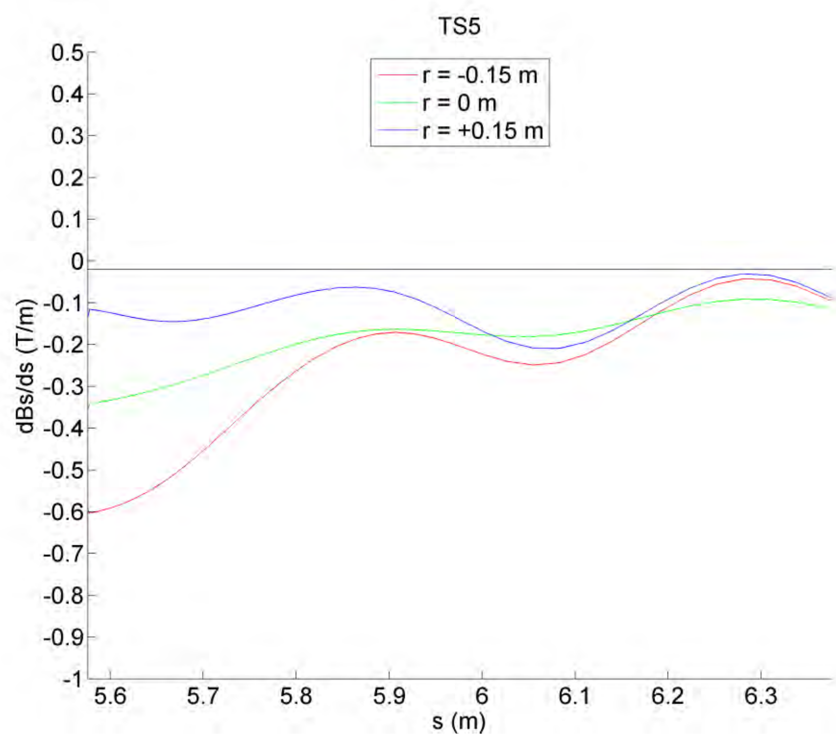


Figure 8: TS5 axial field gradient

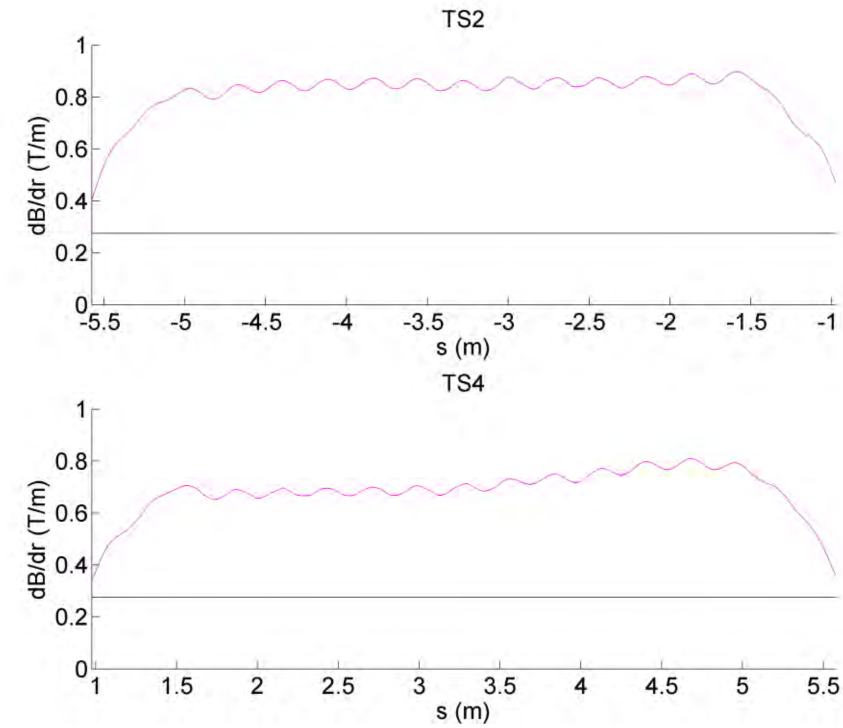


Figure 9: TS2 and TS4 axial field radial gradient

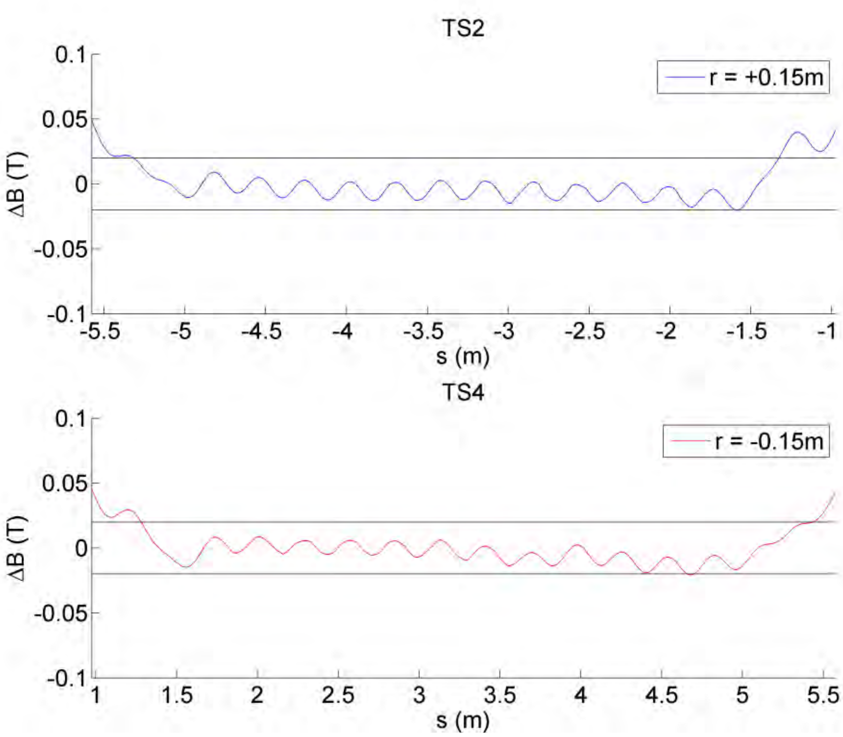


Figure 10: TS2 and TS4 axial field max ripple

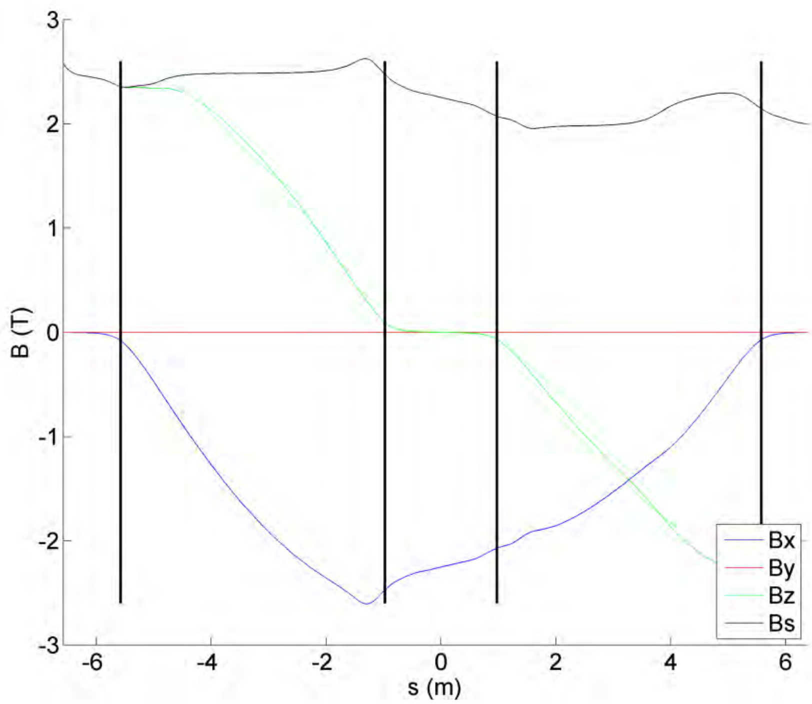


Figure 11: Magnetic field components along the TS axis

As we can see from the preceding figures, all the requirements are met. We can also notice that the field is about the same of the S shape version. This means that a correction of the current densities is not necessary to maintain the field characteristics when shifting from the S shape to the C shape.

STUDY OF THE FIELD EFFECT IN THE TRAJECTORY OF A CHARGED PARTICLE

An important difference between the fields produced by the C shape system and the S shaped one is that in the TS4 section the field radial gradient is opposite because the curvature is opposite. This is a problem as spiraling particles (like particles that are going to flow through the coil system) tend to drift up or down depending on the sign of their charge when there's a radial gradient. In the S shape system the vertical displacement of a particle produced by the TS2 section is compensated from the displacement produced by TS4. In the C shape system a charged particle drifts in the same direction both in TS2 and TS4 sections. Consequently the particle arrives off-axis in the Detector solenoid. To avoid this effect a correction field is needed. A possible solution is to add a series of vertical coils in the TS2 and TS4 sections to compensate the effect of the radial gradient. A preliminary study of this system has been done. The model used for this study has the subsequent characteristics:

- A vertical coil is placed inside or outside every coil of the TS2 and TS4 sections of the system;
- A multi-turn solution with concentric coils is studied;
- Every coil has the same section and current density;
- The two solutions with correction coils inside and outside the TS coils were investigated.

The base OPERA model for the study of correction coil system is showed in Figure 1. The software OPERA allow the user to simulate the trajectory of a charged particle in a magnetic field. In order to understand the influence of the size and number of turns of coils in the particle trajectory several simulations have been done. In every simulation the section and the number of turns were modified and the needed current density was computed. The characteristics of the coils and the results are shown in Table 3 and Table 2. The particle used for the simulation was an electron with energy of 100 MeV[1] with a path starting on the PS interface with TS1.

Table 2: Geometric characteristics of correction coils

Radial distance between correction coils and TS coils	30 mm
Angle of aperture	120 degree
Total width	Same as the TS coil
Turns, Section	See Table 3

Table 3: Results of the correction coils simulation

Case #	Position	Number of turns	Section dimensions [mm]		Current density [A/mm^2]
			Width	Thickness	
1	IN	1	10	10	1100
2	IN	2	30	10	200
3	IN	2	40	10	165
4	IN	4	10	15	235
5	IN	4	10	20	180
6	IN	4	10	30	114
7	OUT	1	10	10	1450
8	OUT	2	30	10	252
9	OUT	2	40	10	206
10	OUT	4	10	15	300
11	OUT	4	10	20	226
12	OUT	4	10	30	155

As we can see from the table above the current density needed for the OUT configuration is about 25% greater than the current for the IN configuration. Furthermore we can infer that when augmenting the coil area it is better to increase the section's Thickness than increasing the Width. The current density is reasonable only with a total area of about 100 mm^2 so the correction coils are going to be voluminous. The effect of the correction field in the particle trajectory is showed in Figure , Figure and Figure . As we can see the negative charged particle's path oscillates around the TS axis. The path of a positive charged

[1] 100 MeV is a very high energy for the particle so in reality the particle will be affected less strongly by the field.

particle instead tends to diverge from the axis. So a selection of positive or negative particles can be done using a collimator and changing the current direction in the coils.

Another important feature to be analyzed is the effect of the correction coils in the axial field. The main question is if the resulting magnetic field still meets the requirements. A new OPERA model of the TS

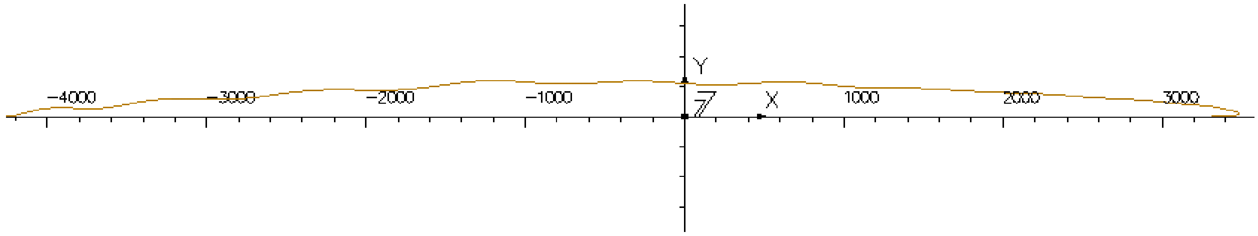


Figure 12: Particle trajectory in the S shape system.

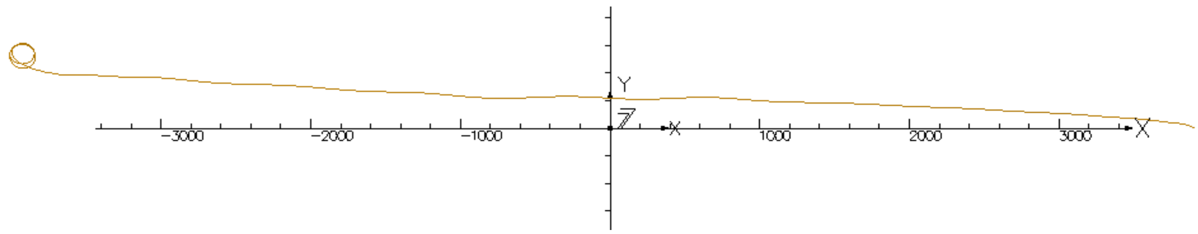


Figure 13: Particle trajectory in the C shape system without correction coils.

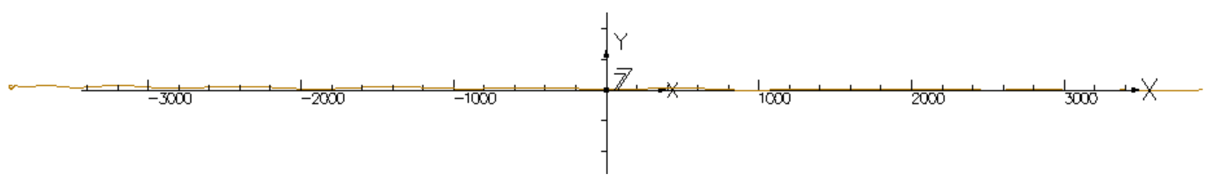


Figure 14: Particle trajectory in the C shape system with correction coils.

system with the correction coils has been done. For this simulation different coil dimensions have been used. The geometric characteristics of this coil are showed in Table 4.

Table 4: Geometric characteristics of the coil used for the field simulation

Radial distance between correction coils and TS coils	30 mm
Angle of aperture	180 degree
Total width	Same as the TS coil
Turns	1
Section Width	Max possible with a 20 mm central gap
Section Thickness	10 mm

Two different configurations of the system have been simulated:

- With correction coils outside the TS coils;
- With correction coils inside the TS coils.

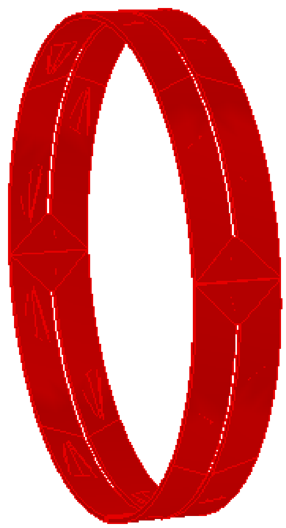


Figure 15: Model of the correction coil used for the field simulation

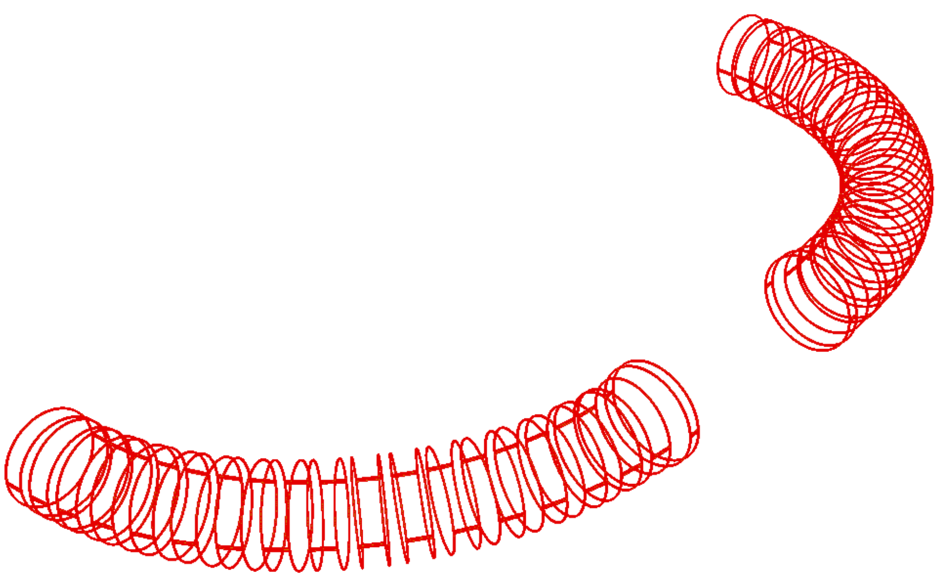


Figure 16: OPERA model of the corrector coils

We made the same analysis as for the previous model and the results are showed in the graph **Error! Reference source not found.**7. The two configurations create the same field components. The difference between the two configurations is only the current density that is 30% higher for the outside configuration. Doing a comparison with the field of the TS model without correction solenoids we see that only the By component changes significantly. The other components are about the same with or without the correction coils. So the requirements are met also with the correction coils .

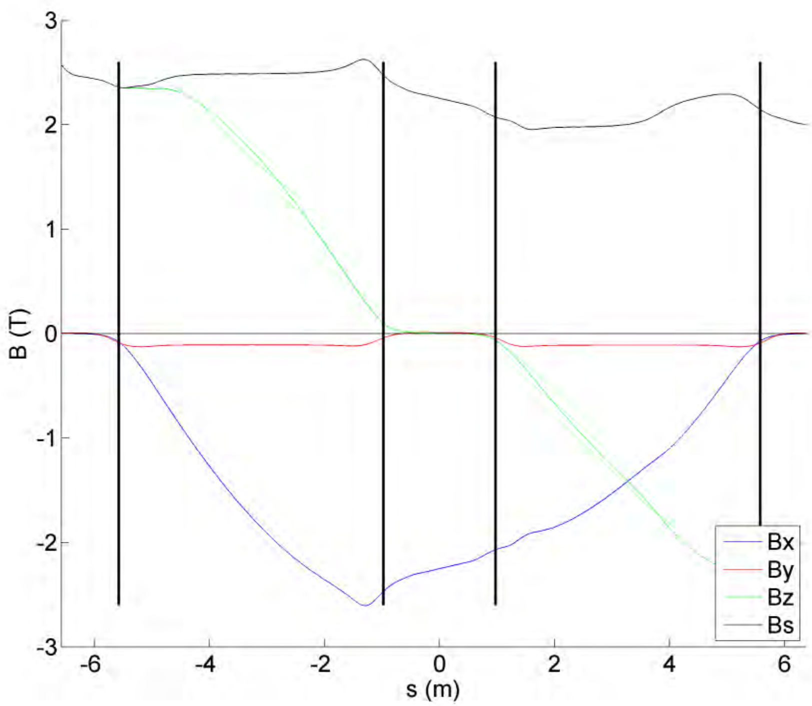


Figure 17: Magnetic field components in the axis of TS system with correction coils

SUMMARY

In this work a preliminary study of the magnetic field configuration in the C shape TS has been done. A model for system has been done using OPERA and the magnetic field has been simulated. We have seen that the field characteristics in the C shape TS are the same as in the S shape TS. So the field requirements are met until they are met in the original TS design.

A series of correction coils has been added in order to correct the particle vertical displacement in the curved sections. A simulation has shown that the vertical coils do not modify the axial field profile.

The average energy of the particle in the TS system is about 50 MeV. The preceding study has been done with a particle energy of 100 MeV, so the value of the current density for the correction coils is about double the value they need in reality.

REFERENCES

[1] Mu2e Transport Solenoid Magnetic Design (Magnetic Design Version 5) – DocDB 1233-v9

[2] Mu2e Magnet Field Specifications – DocDB 1266-v3