STUDY OF A SYSTEM OF CORRECTION COILS FOR TS COIL SYSTEM.

Marco Menchicchi

INTRODUCTION

The goal of the project is to investigate the effectiveness of a system of correction coils placed in the TS system. This correction system is needed because of the positioning errors that cannot be avoided during the assembly of the experimental apparatus. These errors cause the path of the particle to be different from the desired one. In this study we try to minimize the effect of the assembly errors using the minimum number of coils and the minimum value of current density.

ANALYSIS OF THE PROBLEM

The study of the assembly errors has already been done in [1]. This study considers the effects of both systematic and random errors in the track of charged particles trough TS system. The considered errors are a displacement of the coils up to 10 mm and rotation along pitch and yaw angles up to 10 mrad. A part of the study is the analysis of the effect of these misalignment errors in the path of 1 MeV charged particle. The 1 MeV energy has been chosen because the amplitude of the spiraling trajectory of the particle is relatively small. The errors produced in the path are measured with respect of a nominal track. The nominal track is the track of the particle in the ideal (with no assembly errors) system. An example of the effect of a random displacement error is showed in Figure 1. With the correction coils system we tried to minimize the displacement caused by the errors considered in the previous study.

CORRECTION COILS GEOMETRY

For a first study of the system we decided to make every correction coil as showed in Figure 2. The dimensions are showed in Table 1.

Table 1: dimensions of the correction coils

GAP [mm]	WIDTH [mm]	HEIGTH [mm]	APERTURE ANGLE	ID [mm]
10	Equal to the coaxial TS coil	10	174	ID of coaxial TS coil + 10

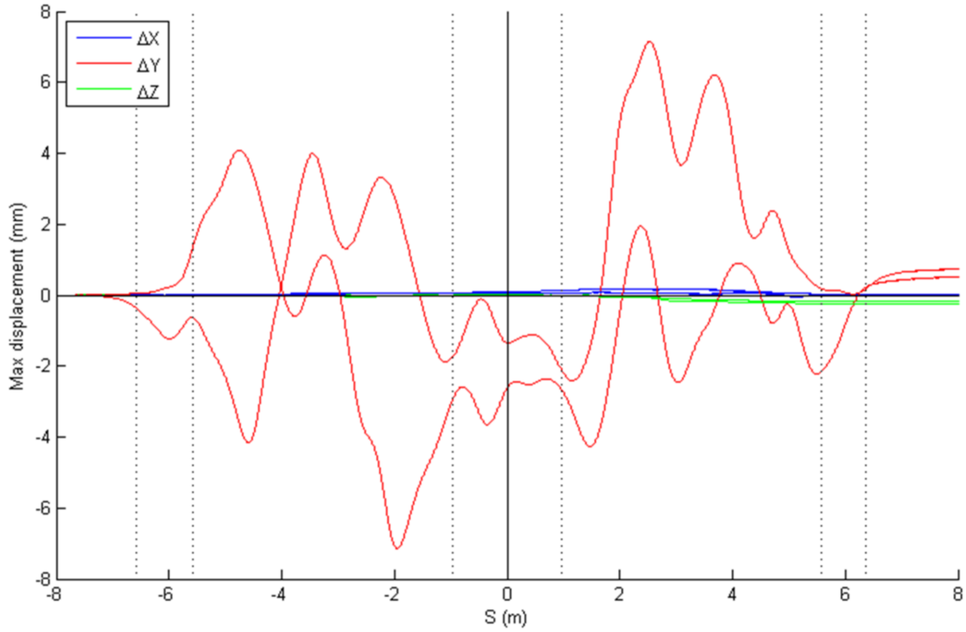


Figure 2: Path displacement caused by a random vertical displacement error.

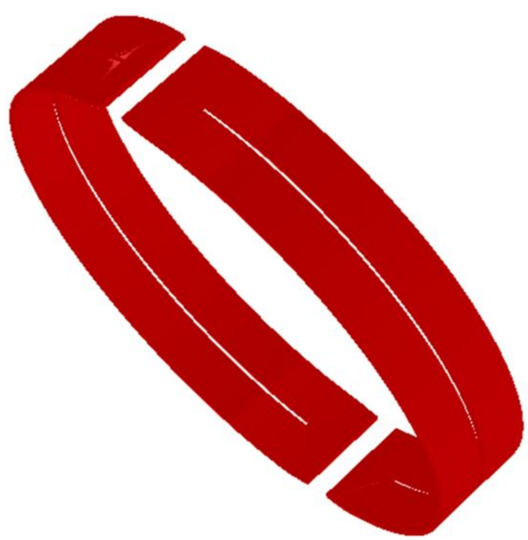


Figure 1: OPERA model of a correction coil.

We decided to place each correction coil in the intern or outer side of a TS coil. The width of the correction coil is the same as the width of the TS concentric coil in order to simplify the configuration of the support structure. There are 2 types of correction coils: vertical and horizontal. The vertical coils produce a vertical field that make the particle drift in vertical direction. The horizontal coil instead produces a horizontal field. The 2 types of coils are identical, except that the horizontal one is rotated by 90 degree along the axis with respect to the vertical one. When both the vertical and horizontal coils are placed in the same TS coil, the vertical coil is placed in the outer part of the horizontal one at a distance of 10 mm. We assumed that any value between 2 user defined limits can be assigned to the current density of each coil. This is not realistic because each current density would require a different generator. We allow that hypothesis because it simplifies the study and because we are doing a first approximation of the system. An example of the disposition of the correction coils is showed in Figure 3.

STUDY OF A PROGRAM FOR THE AUTOMATIC CURRENT DENSITY ASSIGNMENT

The study of the correction system needs the correction coils current to be optimized and the particle

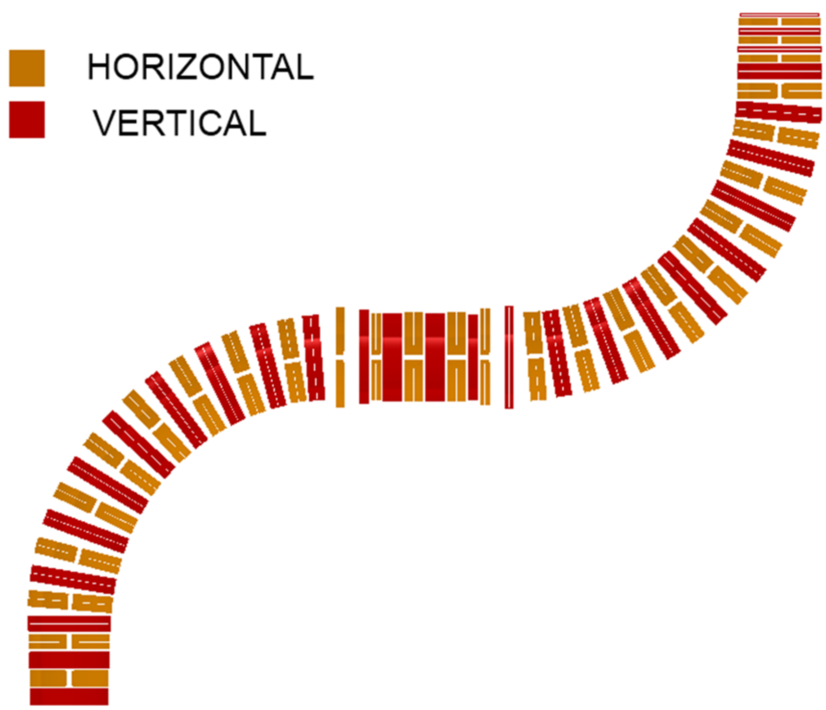


Figure 3: Opera model of the correction coils system.

track to be simulated several times. Given a correction coils configuration, the optimization process consist of:

- Assigning the current density to each coil;
- Simulating the particle path;
- Evaluating the error;
- Correcting the current density in order to minimize the error.

The last 3 steps have to be repeated until the error is below the needed tolerance. The main problems of doing the procedure manually are:

- The optimization is not guaranteed;
- A large amount of time may be needed to reach a good result.

To avoid these problems a program that carries on the optimization automatically has been done. The structure of the program is in Figure 5. The 4 steps of the code consist of:

- Generate correction coils: a file with the position, name and geometric features of each correction coils is generated based on the input of the user;
- Generate the OPERA model: a model containing both TS coils (eventually with alignment errors) and correction coils is generated and the configuration is saved to a file;
- Simulate the particle initial track: the program runs a simulation of 1 MeV particle with the current densities of the correction coils all set to 0 and evaluates the errors;
- Optimize the current densities: the current density of each correction coil is assigned in a way that minimizes the path error.

The core part of the program is the last section. The goal of this section is to minimize the error with the minimum use of current. The error is defined as:

ERROR: maximum distance between the track of the particle and the nominal track measured along the line perpendicular to the coils axis. The error is made of 2 components that are the projection of the distance vector in the plane where the coils axis lie (horizontal error) and in the perpendicular plane (vertical error).

To be useful, the program should find a solution in a reasonable amount of time. The major time consuming process is the simulation of the particle track by OPERA. The amount of time needed depends on:

- Number of conductors in the model;
- Precision of the simulation;
- Length of the path to be simulated.

So to speed up the process it is necessary to limit the number of simulations and their complexity. A first approach to this problem is showed in Figure 5. The program implementing this process takes

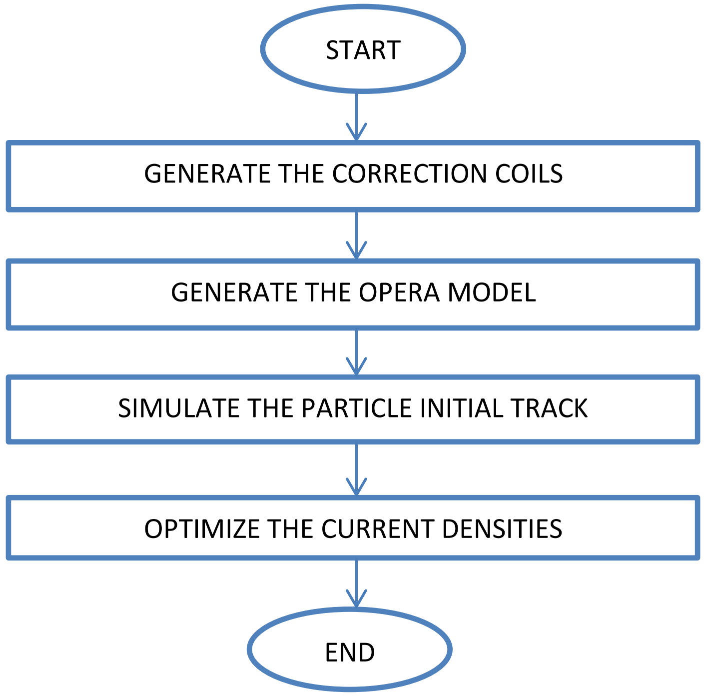


Figure 5: Structure of the optimization program

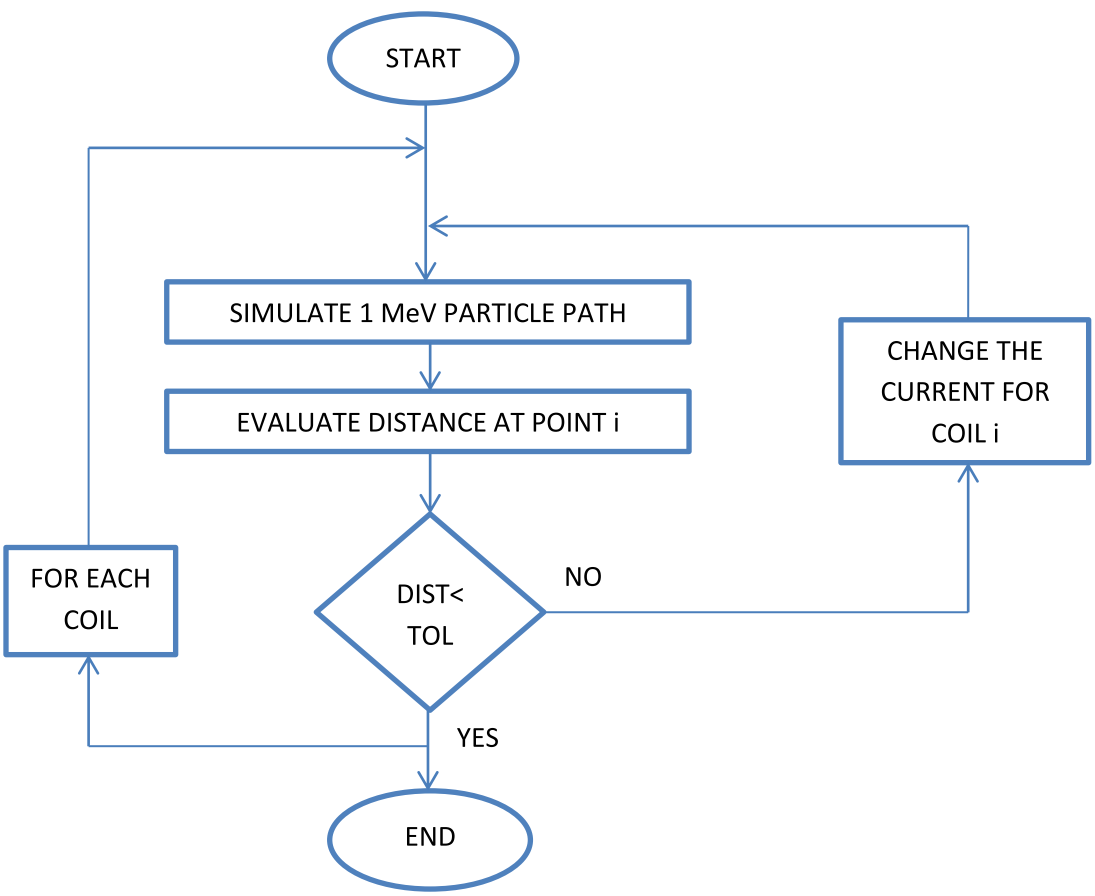


Figure 5: Optimization process

each coil and adjusts the current density to make the track of the particle be as close to the axis as possible. The main assumptions of this program are:

- The track vertical and horizontal errors are class C1 functions (both the nominal track and the particle track are class C1 functions);
- The corrector coils influences the particle only on a limited part of its path.

Because of the second assumption, when a coil current density changes, the track influenced is not the whole track. We verified with some simulations that the track going from the starting point to a certain distance from the coil's center is not influenced by the coil current. So to speed up the process the program simulates the particle track starting from a point preceding the optimized coil. The speed and position of the particle at that point are taken from the previous simulation. The coils are optimized starting from the first one crossed by the particle to the last one. For each coil a point along the TS centroid is defined. The optimization changes the value of the current only if the error in this point is above a user define tolerance. If it is, the secant method is used to find the zero of the function error =f(current). This is possible because the error is a C1 class function also with respect to the current density and it has only one root. The choice of the optimization point influences the result. To simplify the process we decided to take as optimization points the points between the optimized coil and the next one of the same type.

Some simulations have been done using this program and the results are showed in Figure 7-18.

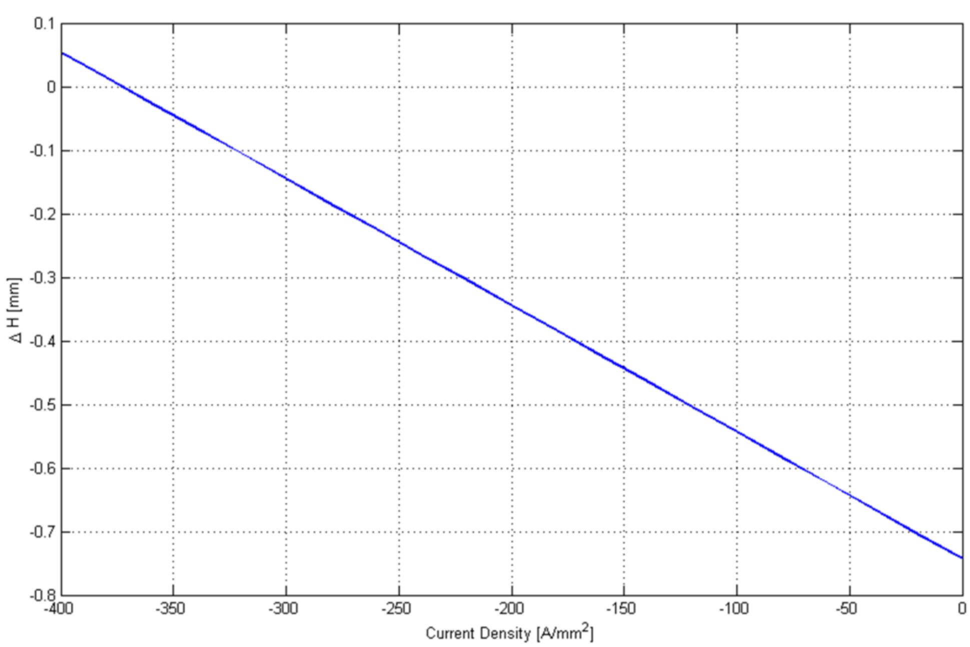
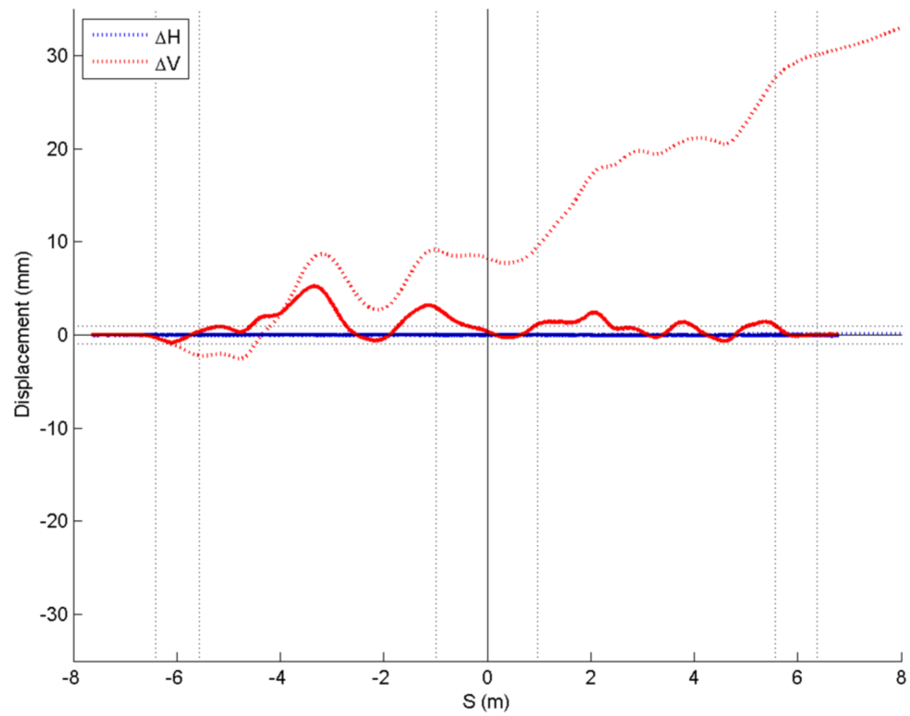


Figure 6: Variation of the horizontal error with the optimized coil current density.



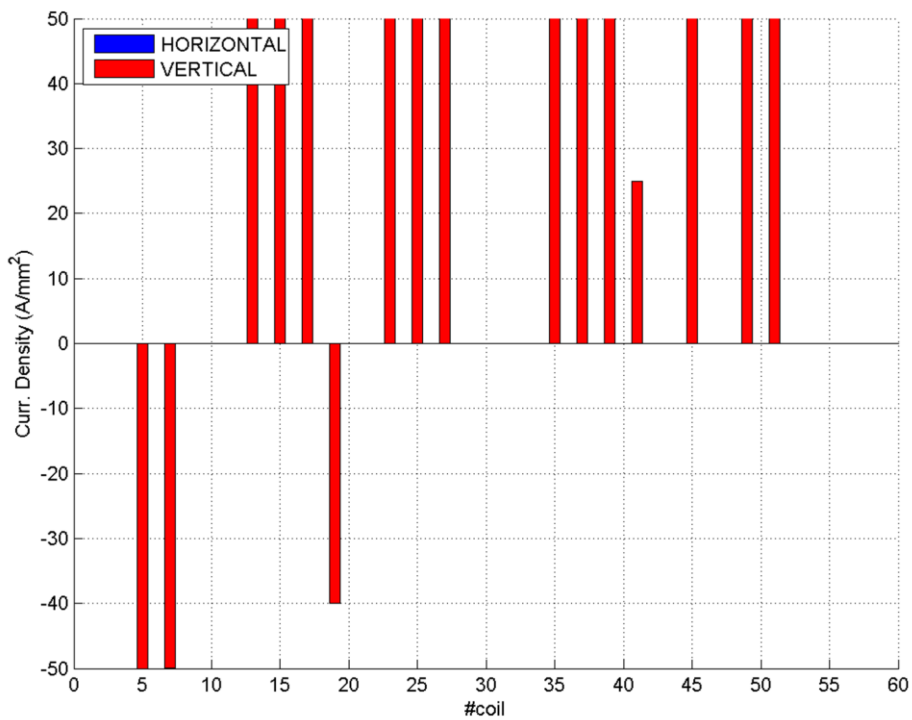
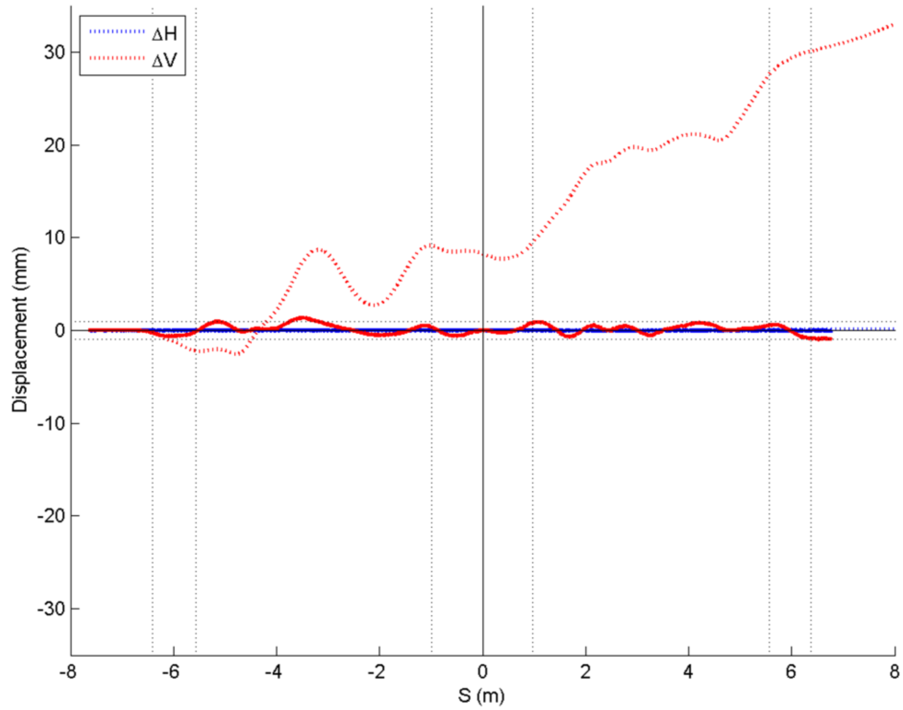


Figure 7: Errors and correction coils current density for the Random case 1 with MaxCurd=50 and 1 correction each 2 TS coils.



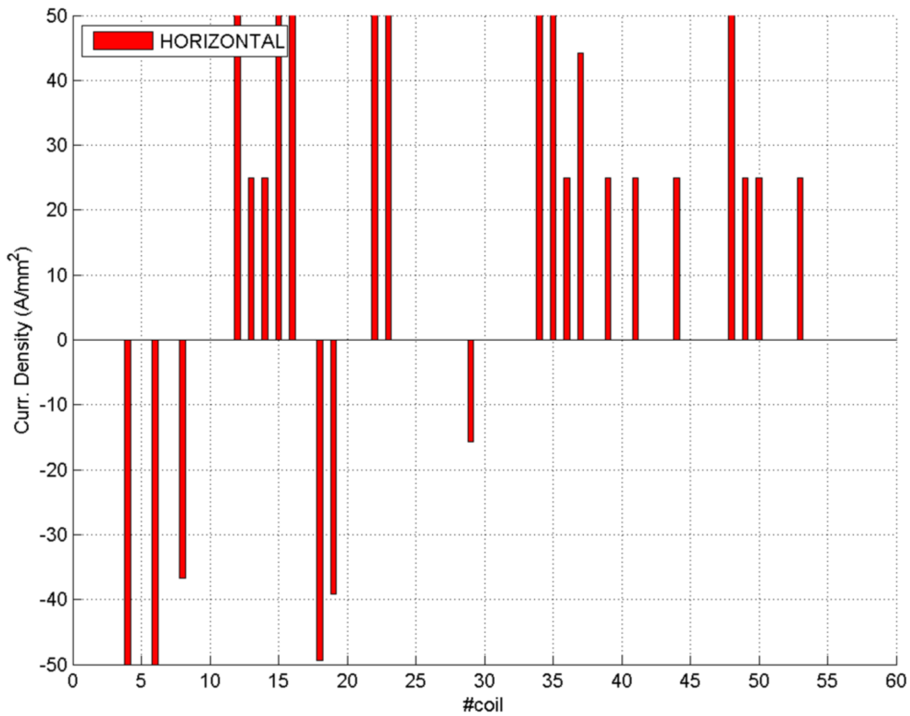


Figure 8: Errors and correction coils current density for the Random case 1 with MaxCurd=50 and 1 correction each TS coils.

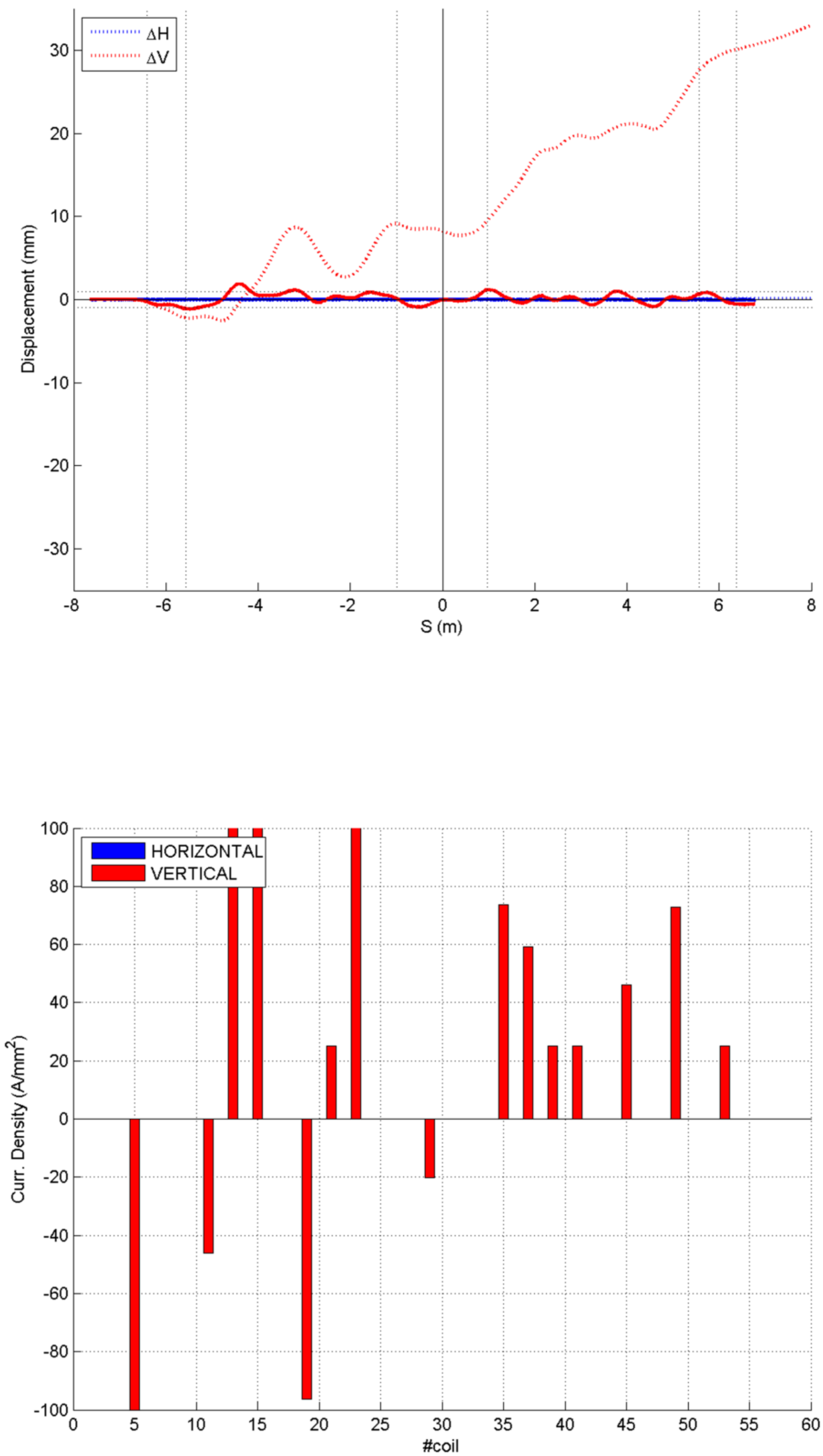
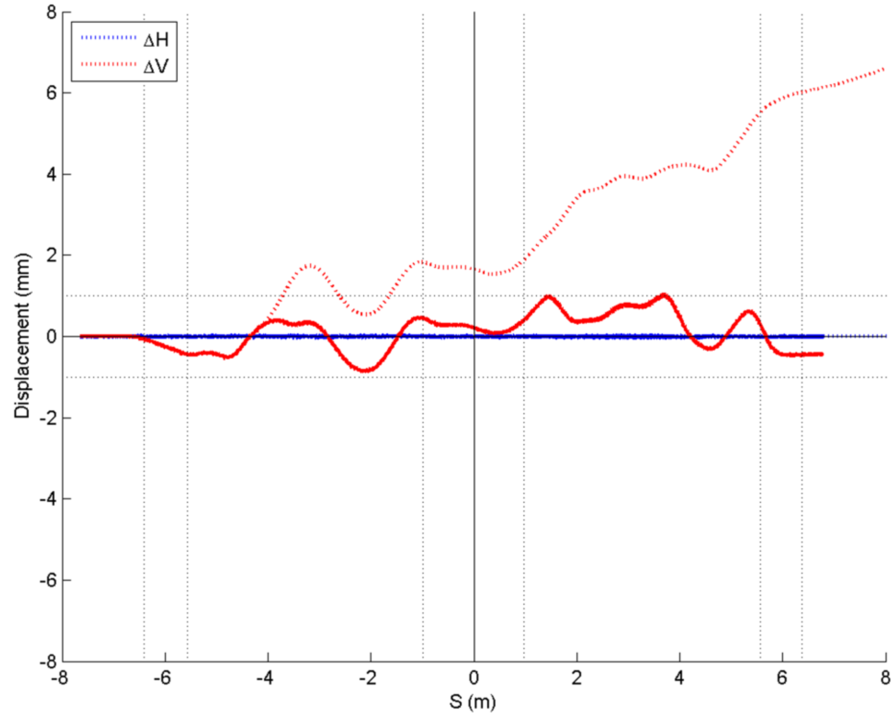


Figure 9: Errors and correction coils current density for the Random case 1 with MaxCurd=100 and 1 correction each 2 TS coils.



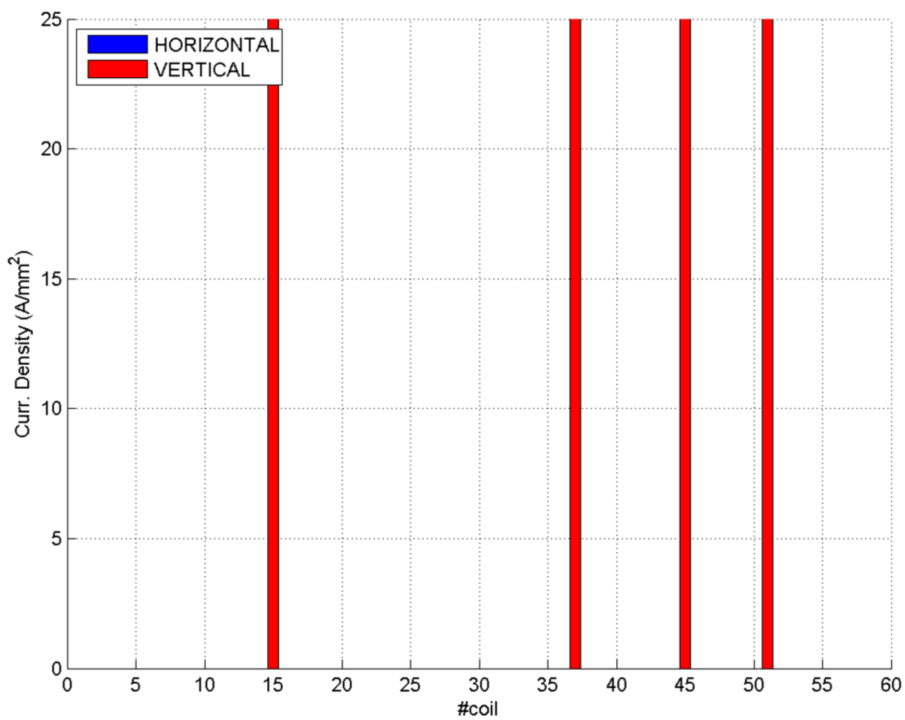
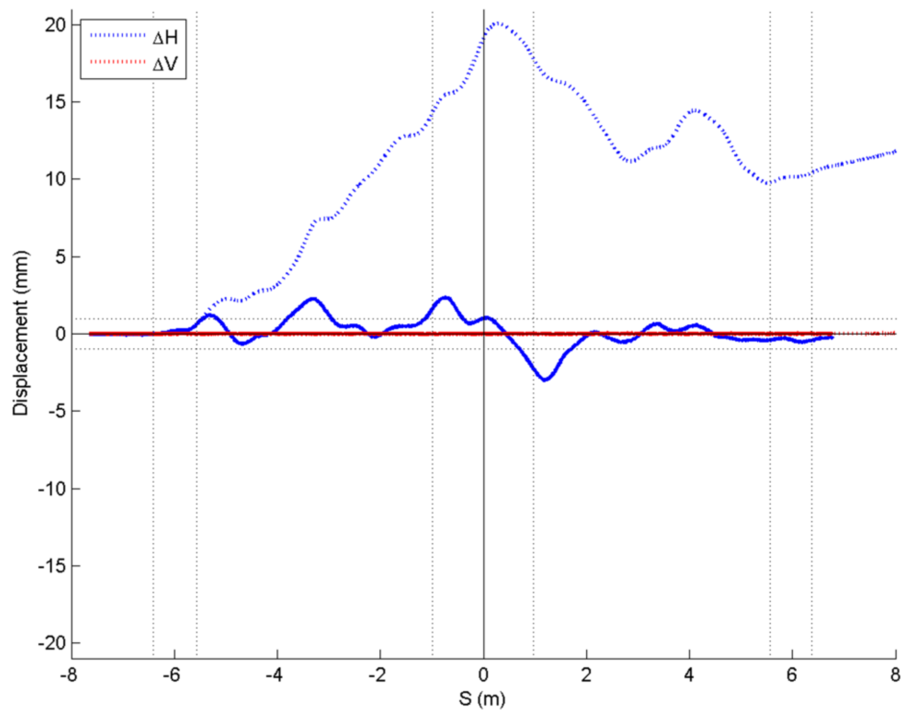


Figure 10: Errors and correction coils current density for the Random case 2 with MaxCurd=50 and 1 correction each 2 TS coils.



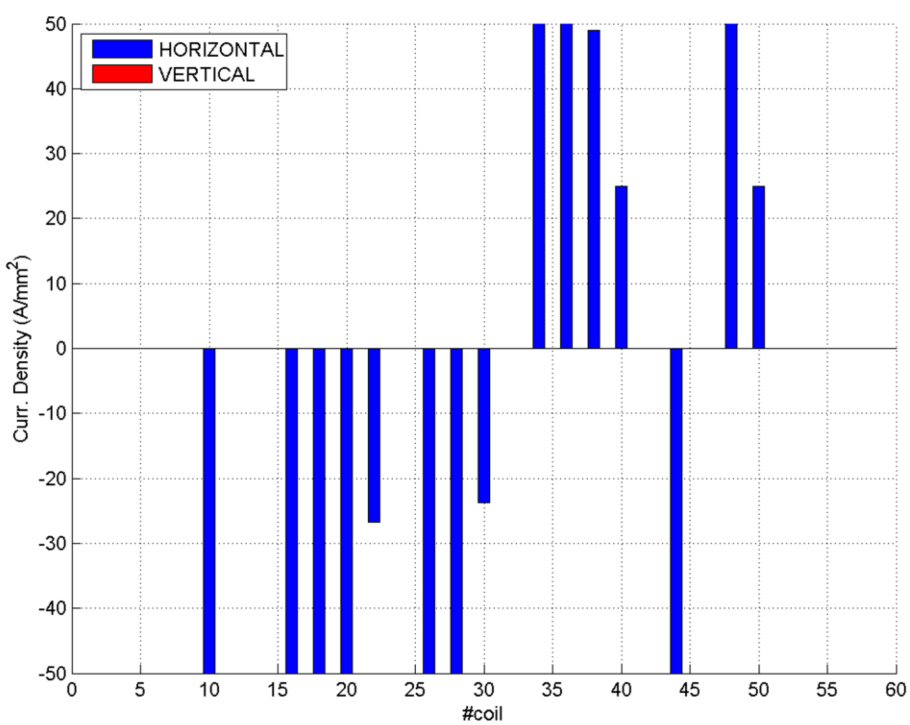
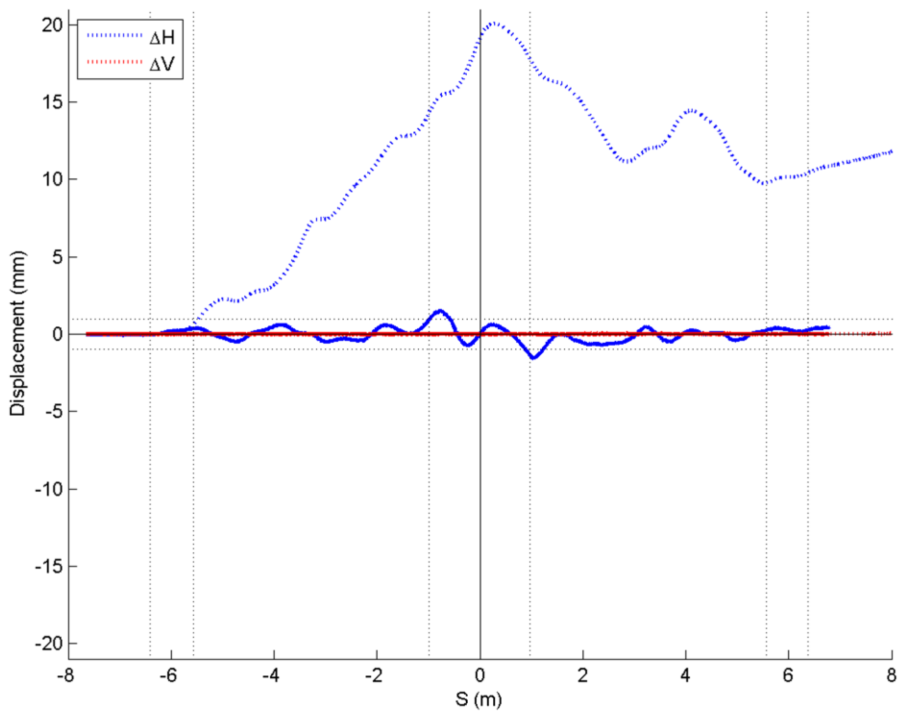


Figure 11: Errors and correction coils current density for the Random case 3 with MaxCurd=50 and 1 correction each 2 TS coils.



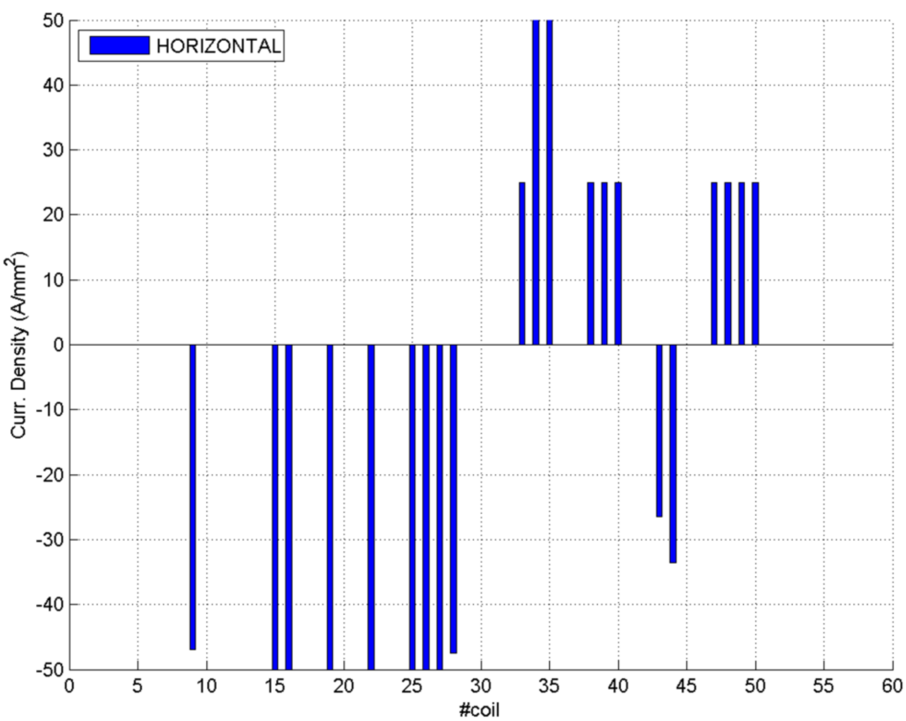


Figure 12: Errors and correction coils current density for the Random case 3 with MaxCurd=50 and 1 correction each TS coils.

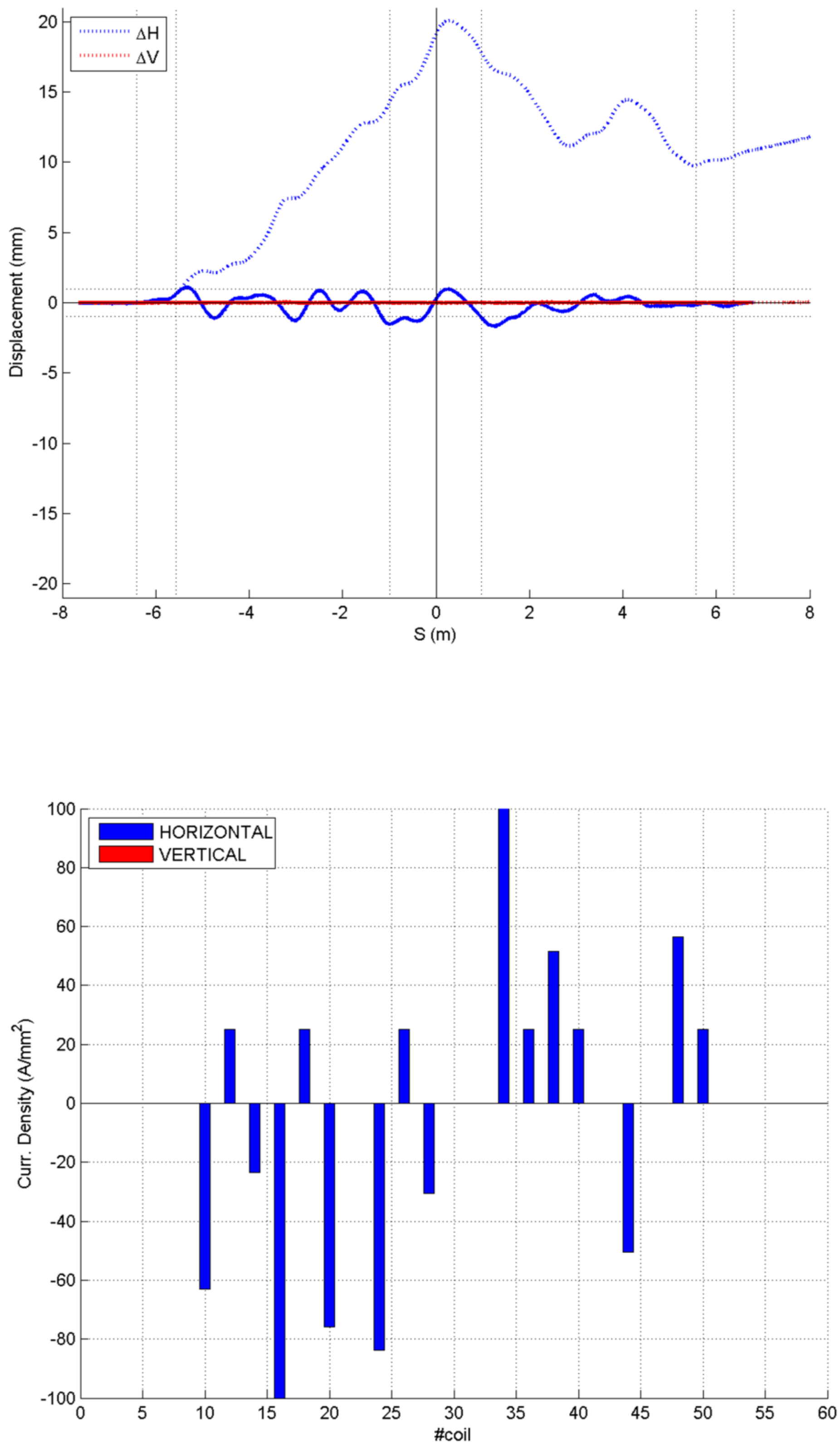
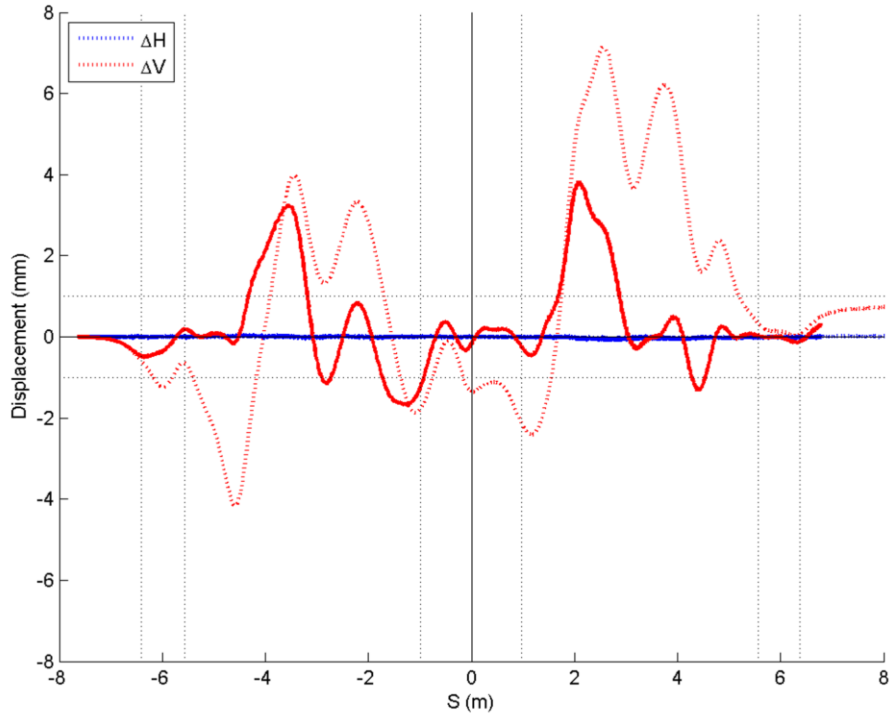


Figure 13: Errors and correction coils current density for the Random case 3 with MaxCurd=100 and 1 correction each 2 TS coils.



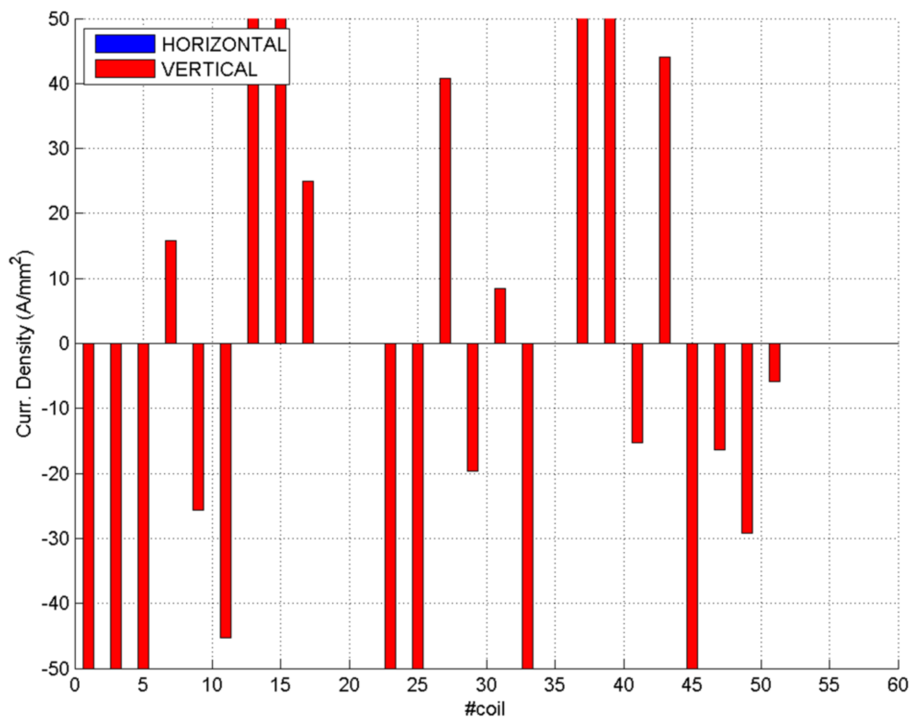
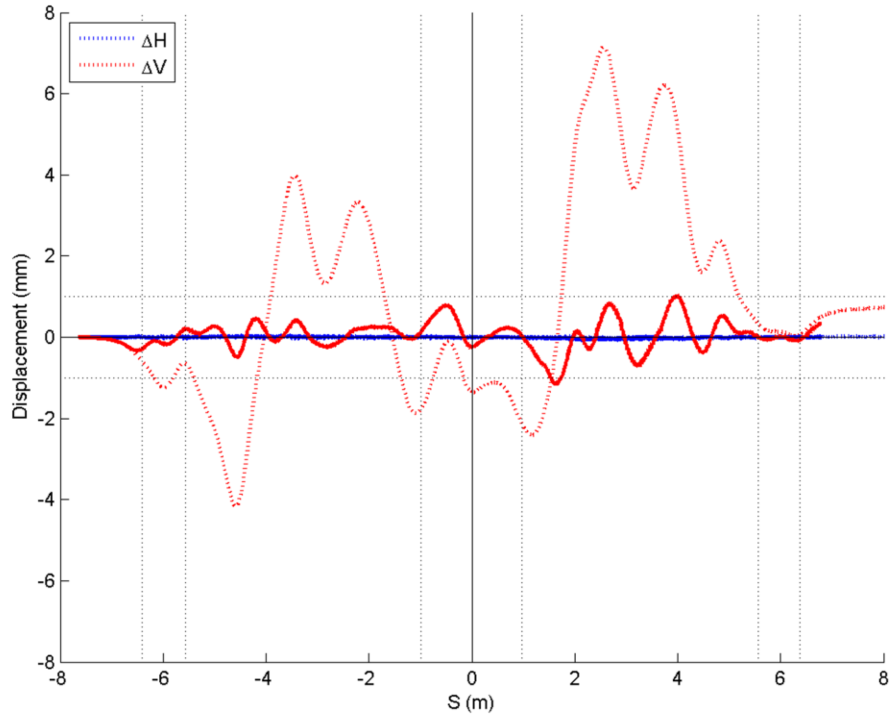


Figure 14: Errors and correction coils current density for the Random case 4 with MaxCurd=50 and 1 correction each 2 TS coils.



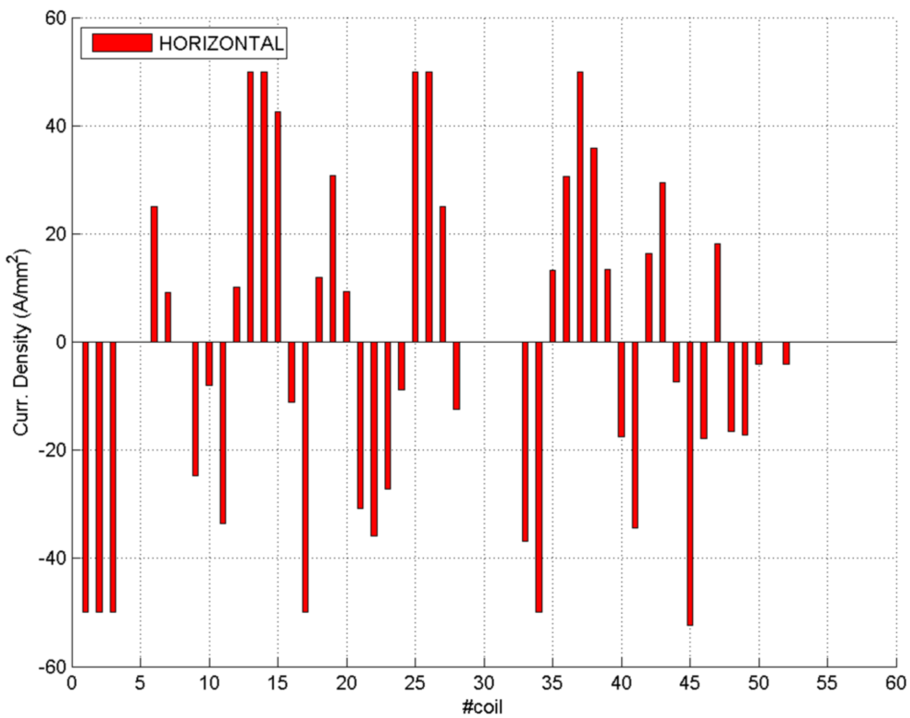
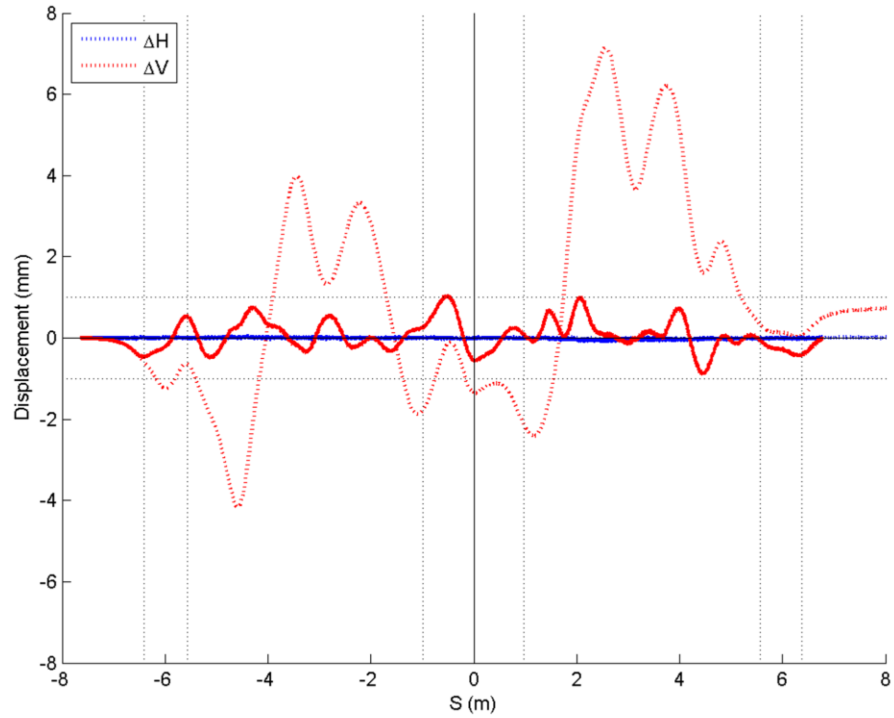


Figure 15: Errors and correction coils current density for the Random case 4 with MaxCurd=50 and 1 correction each TS coils.



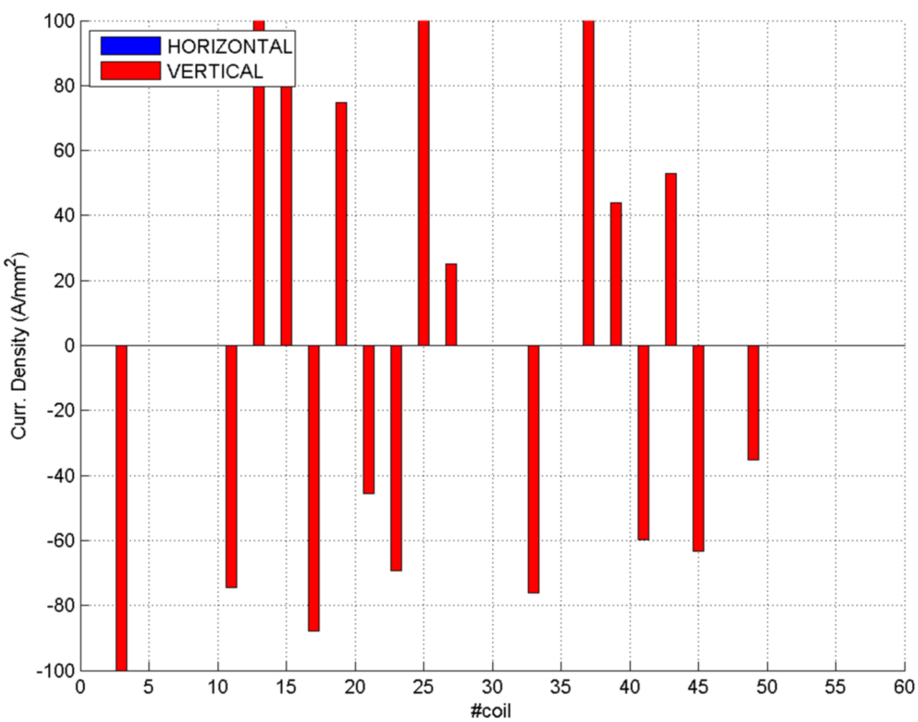


Figure 16: Errors and correction coils current density for the Random case 4 with MaxCurd=100 and 1 correction each 2 TS coils.

The simulations are based on the worst cases given by the alignment errors study [1]. The cases are:

- Case 1: random pitch rotation up to 10 mrad;
- Case 2: random pitch rotation up to 2 mrad;
- Case 3: random yaw rotation up to 10 mrad;
- Case 4: random vertical displacement up to 10 mm.

For each case[1] 3 different configurations of the correction coils are used. The parameter MaxCurd is the maximum absolute value of the current density of each coil. The configurations are:

- With a correction coil of the same type each 2 TS coils and MaxCurd=50 A/mm^2;
- With a correction coil of the same type each TS coil and MaxCurd=50 A/mm^2;
- With a correction coil of the same type each 2 TS coils and MaxCurd=100 A/mm^2.

For all simulation a tolerance of 1 mm has been set. The optimization took about 40 minutes for each studied case. As we can see from the graphs the critical cases are Case 1 and Case 4. Indeed it is not possible to reduce the error below the limit of 1 mm with the less expensive solution. We can also see that the 2nd and 3rd configurations can fix the particle path in all the 4 cases.

The simulations showed the positive features of the program:

- The simulation time is relatively small when no iron is in the model;
- The error is reduced in each studied situation.

And some weaknesses:

- The optimization is not the best possible because a part of the error in a coil is produced by the optimization of the preceding coils (it's a local optimization);
- After the optimization there are many different current intensities needed by different coils.

SUMMARY

In this work a preliminary study of the correction coil system has been done. A first configuration of the coils has been created and modeled with OPERA. A program to automatically set the current densities of each coil has been created and used to simulate some critical cases. The results showed that the program can minimize the error but cannot optimize the current distribution. In the configuration with 1 coil each 2 correction coils a maximum current density of 50 A/mm^2 has been verified to be not sufficient. The next step in this study is to create a program to optimize the coils globally and to distribute the current densities in a way that minimizes the number of different current intensities. The critical cases need to be further investigated.

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[1] For Case 2 the 2nd and 3rd , simulations results have not be shown because they are identical to the one of the 1st simulation. Indeed the 1st configuration is sufficient to make the particle remains into the tolerance.

REFERENCES

[1] Studies of the Alignment Tolerances of the Transport Solenoid of the Mu2e Experiment – TD-09-017

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

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