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Tolerance studies of the Mu2e Transport Solenoid (Magnetic Design Version 7)

Abstract

This document summarizes the magnetic performance of the Mu2e Transport Solenoid when the position of the coils is different from the nominal one. Two types of errors were studied: Systematic and Random.

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History of Changes

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V1	2011/09/09	67	Initial release
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V3	2012/08/22	65	Updated study using the Magnet Design Version 7

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1. INTRODUCTION

The version 7 of the magnetic design of the Transport Solenoid (TS) is described in [1]. In the present report we summarize the changes in the magnetic performance due to misalignment errors in the coils.

Two types of errors are studied: systematic and random. Systematic errors are the ones occurring when a group of coils belonging to the same section (TS1, TS2 etc.) has known misalignment errors. Random errors are the ones occurring when each individual coil has an unpredictable deviation from its nominal position.

In the case of random errors, each coil is allowed to move in one particular direction. The field is calculated for each geometrical configuration. The process is repeated 100 times, with different individual displacement. The maximum displacements of the coils are limited to a value specified in each case.

The results of the tolerance studies are presented in terms of the longitudinal field component and of the gradient along the axial coordinate.

The coordinate system used for the following analysis is the same of reference [1].

The next set of plots summarizes the magnetic performance results when the coils are at the nominal position. In some of the plots, the requirements for the absolute field and longitudinal gradient values are specified by a black line according to [2].

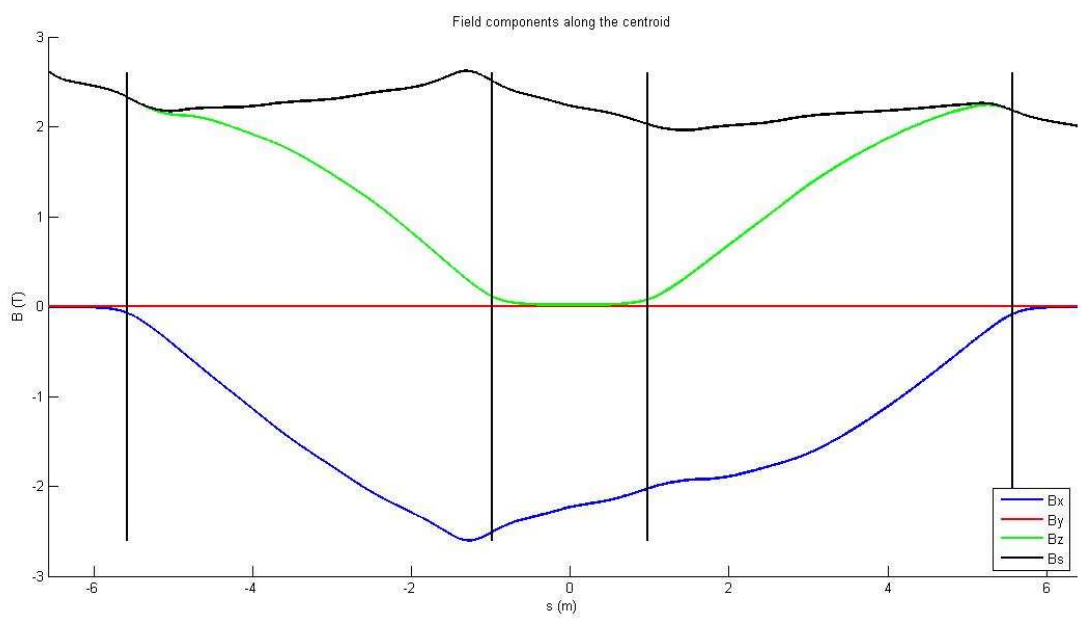

Figure 1 - Magnetic field components along the axis of TS. The vertical black lines represents the geometric interfaces between the straight and curve sections.

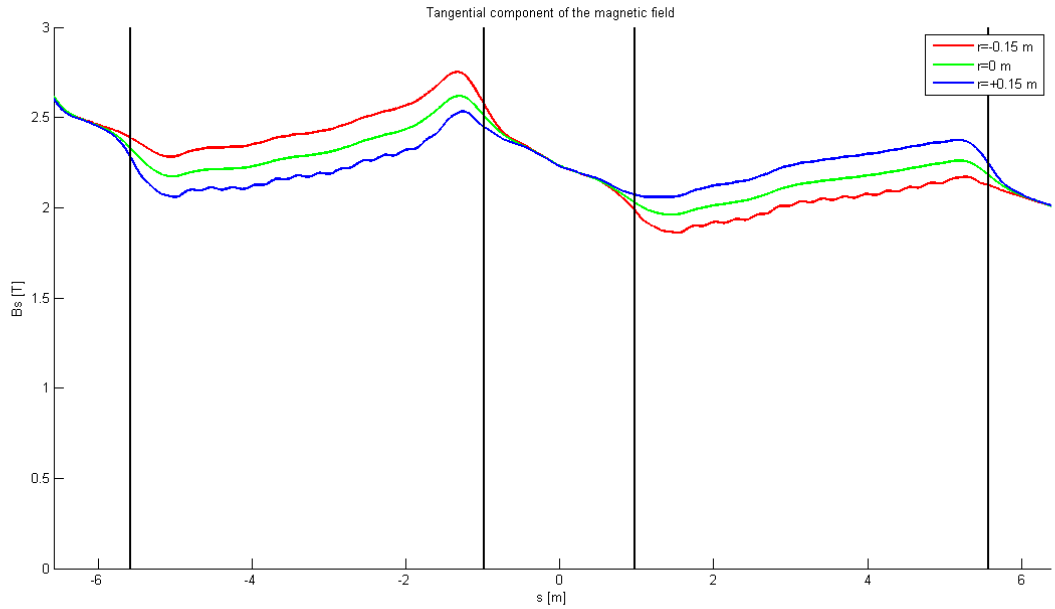

Figure 2 – Longitudinal component of the magnetic field along TS, calculated in 3 different points of the section (centre and ±0.15 m in radial direction).

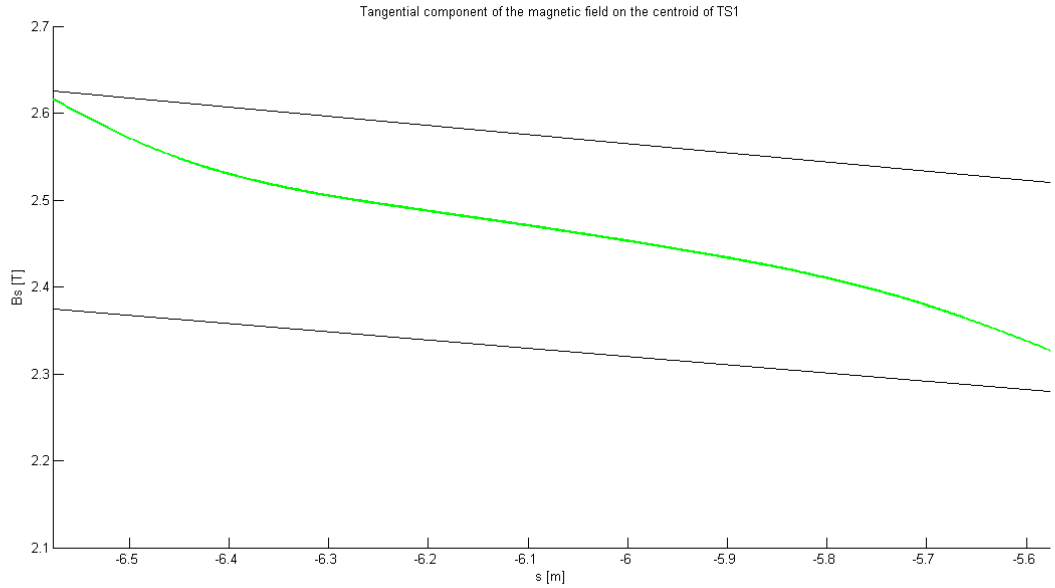

Figure 3 - Longitudinal magnetic field component in TS1.

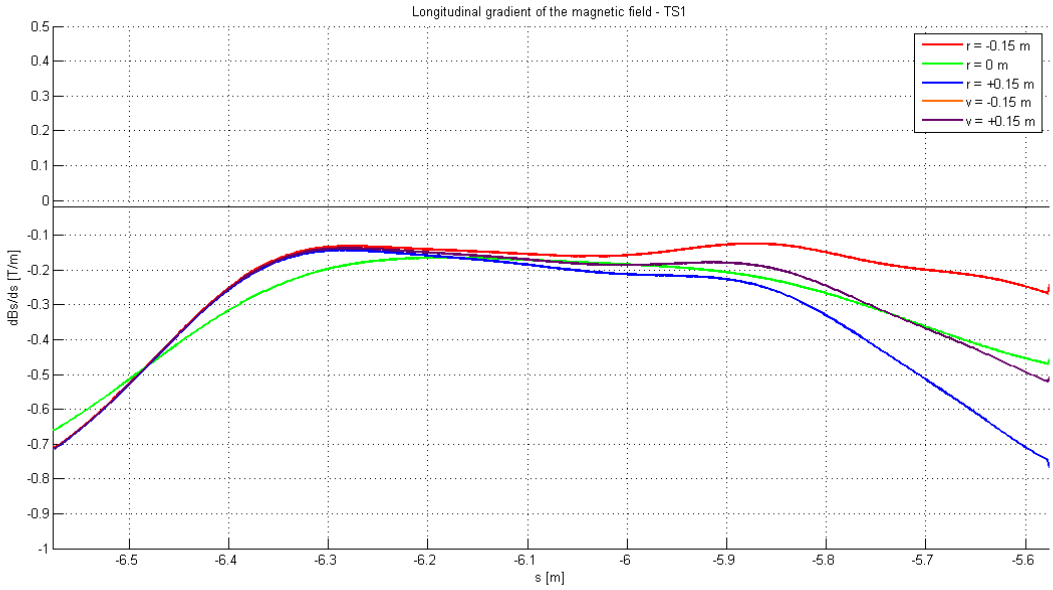

Figure 4 - Longitudinal field gradient in TS1.

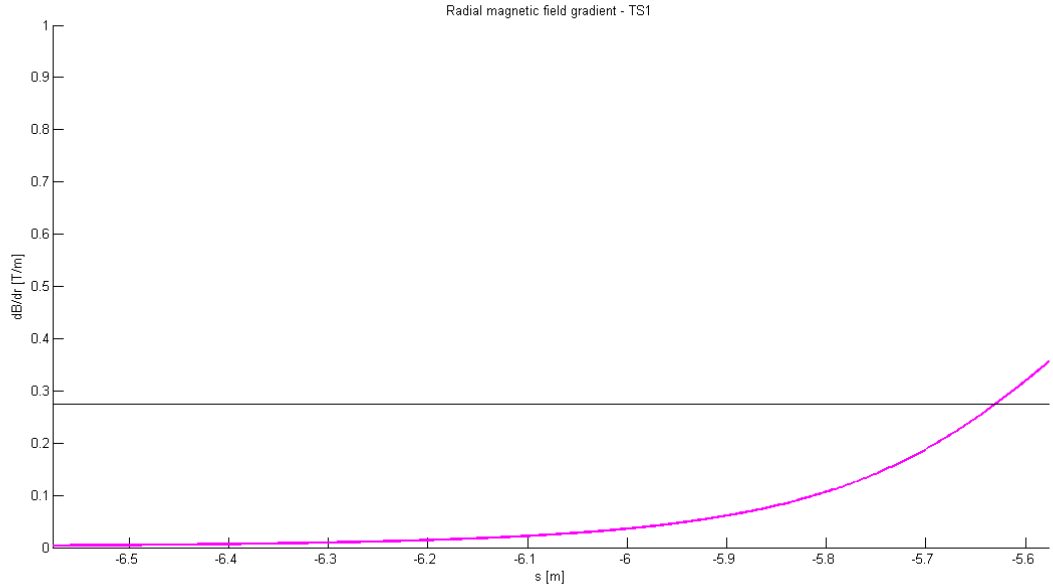

Figure 5 – Radial field gradient in TS1.

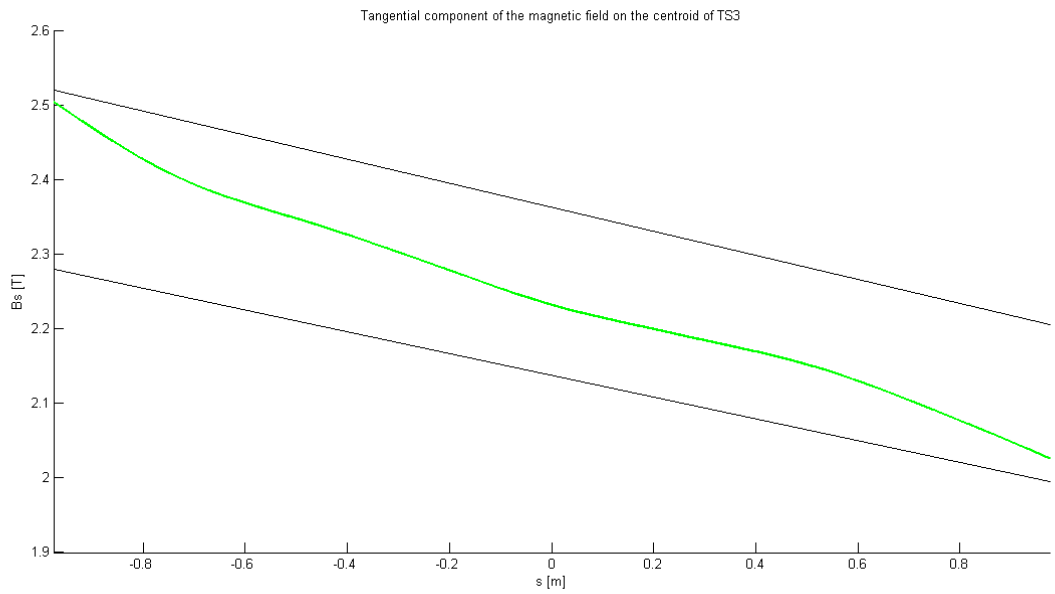

Figure 6 - Longitudinal magnetic field component in TS3

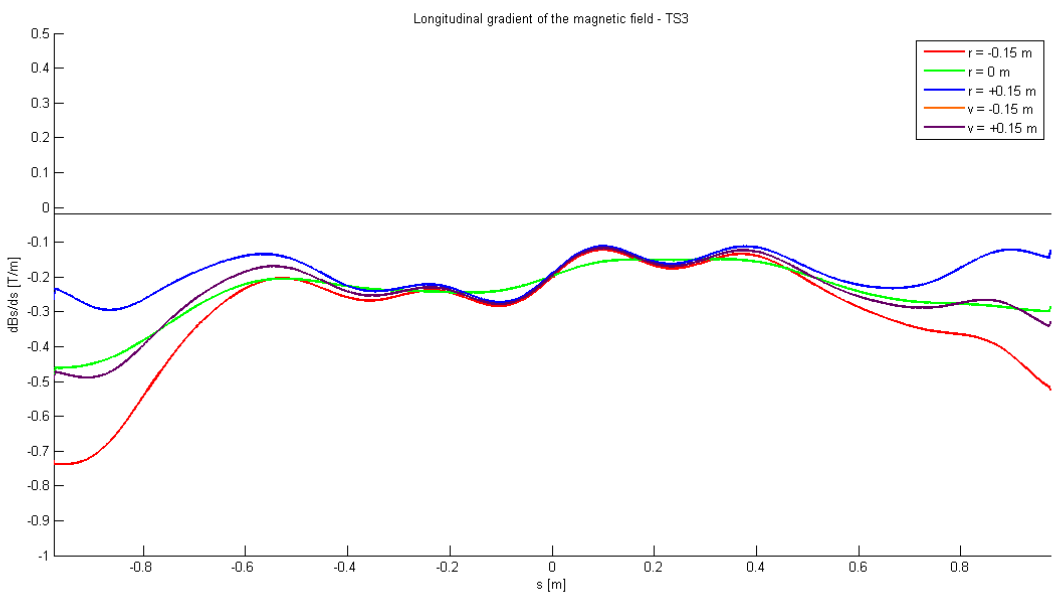

Figure 7 - Longitudinal field gradient in TS3.

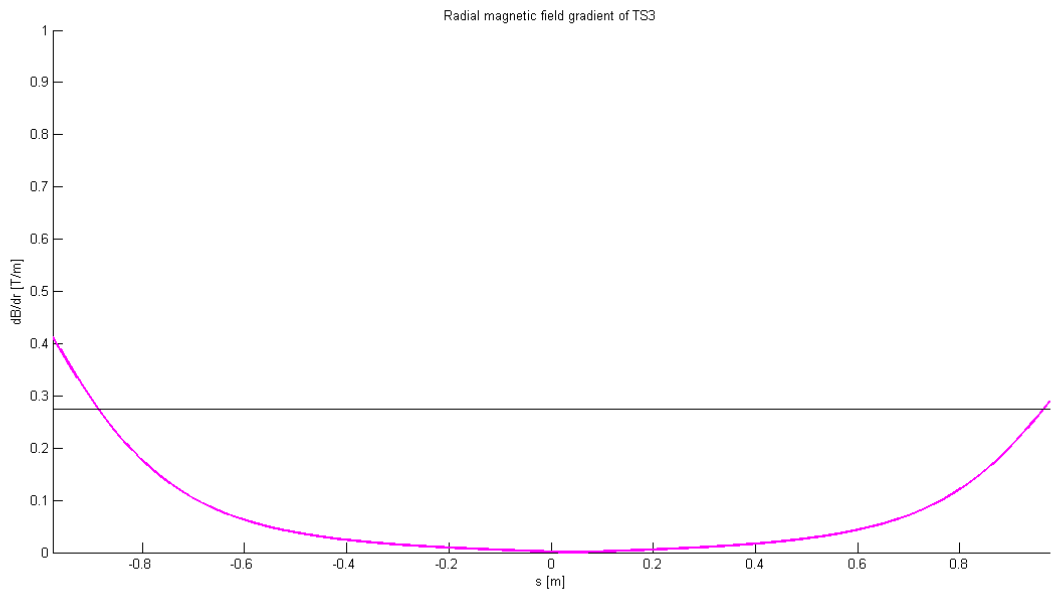

Figure 8 – Radial gradient in TS3.

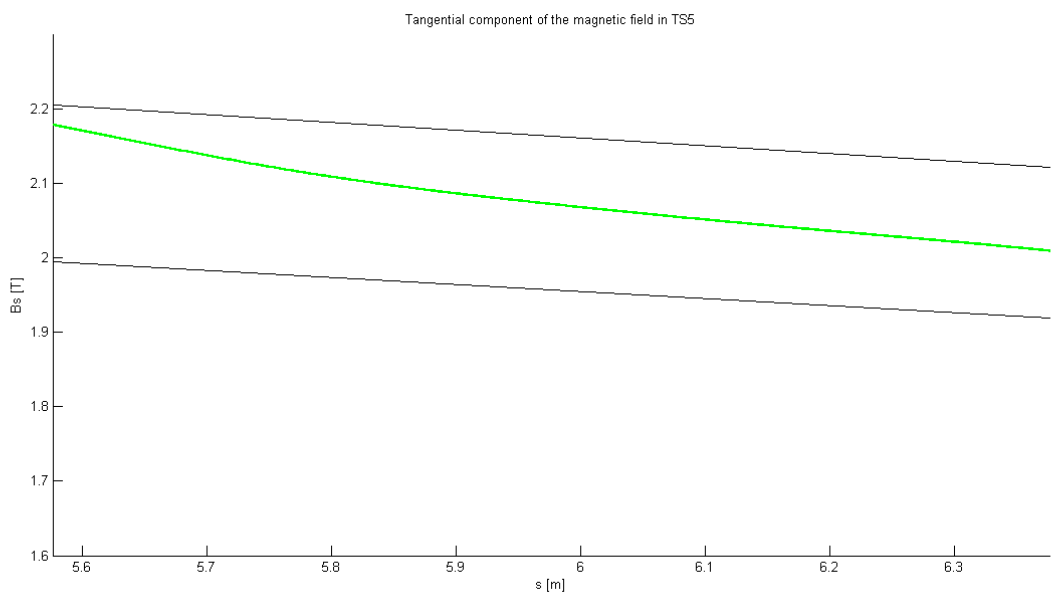

Figure 9 - Longitudinal magnetic field component in TS5

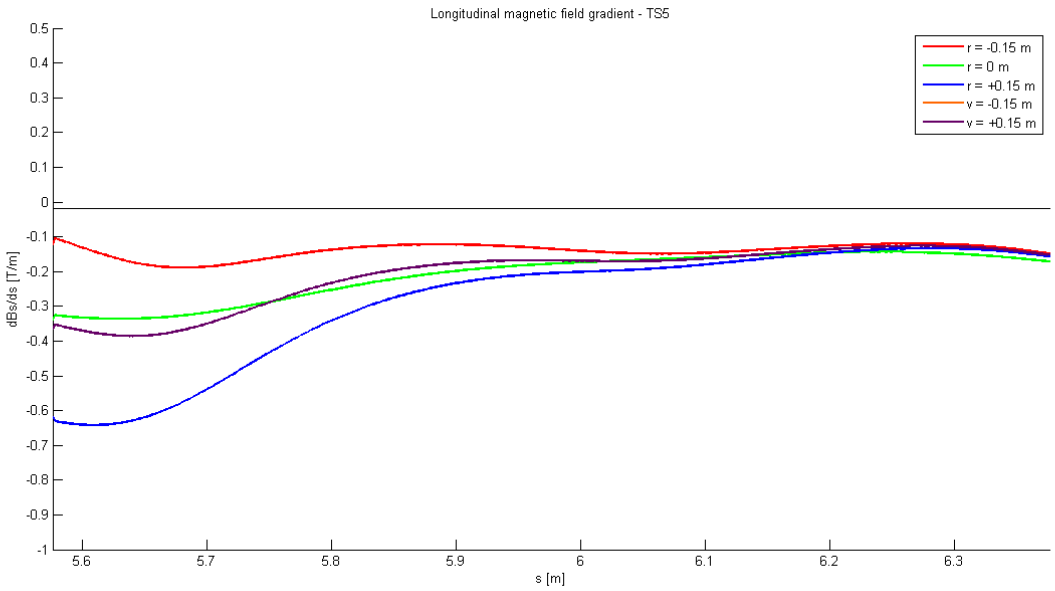

Figure 10 - Longitudinal field gradient in TS5.

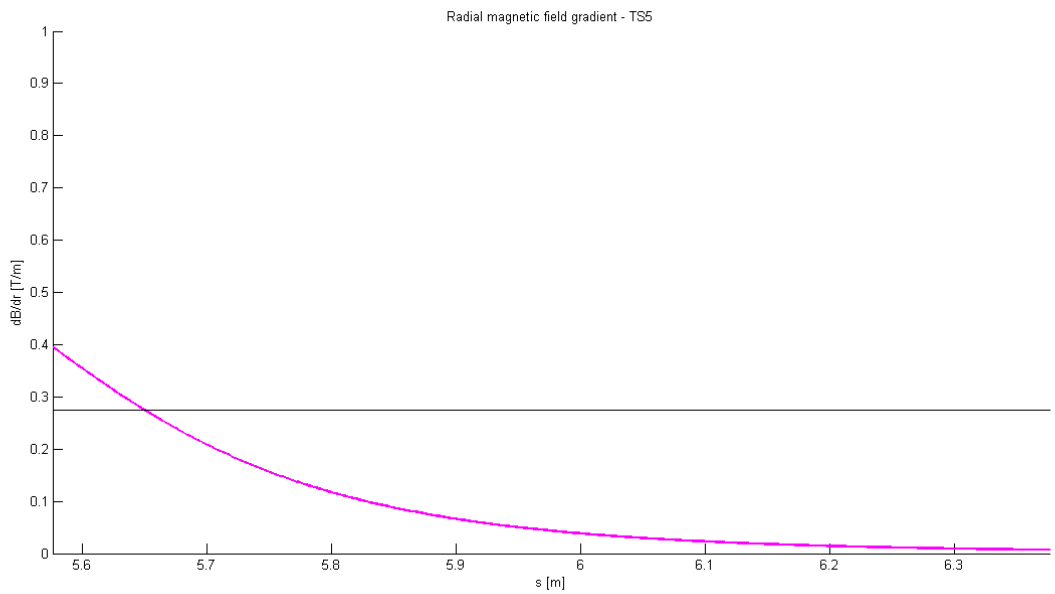

Figure 11 – Radial gradient in TS5.

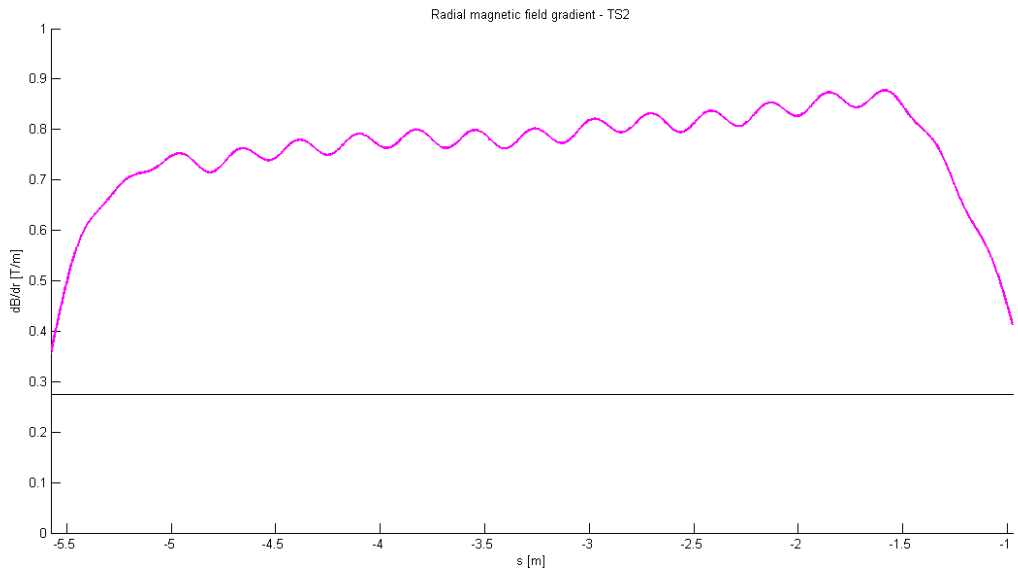

Figure 12 – Radial gradient in TS2.

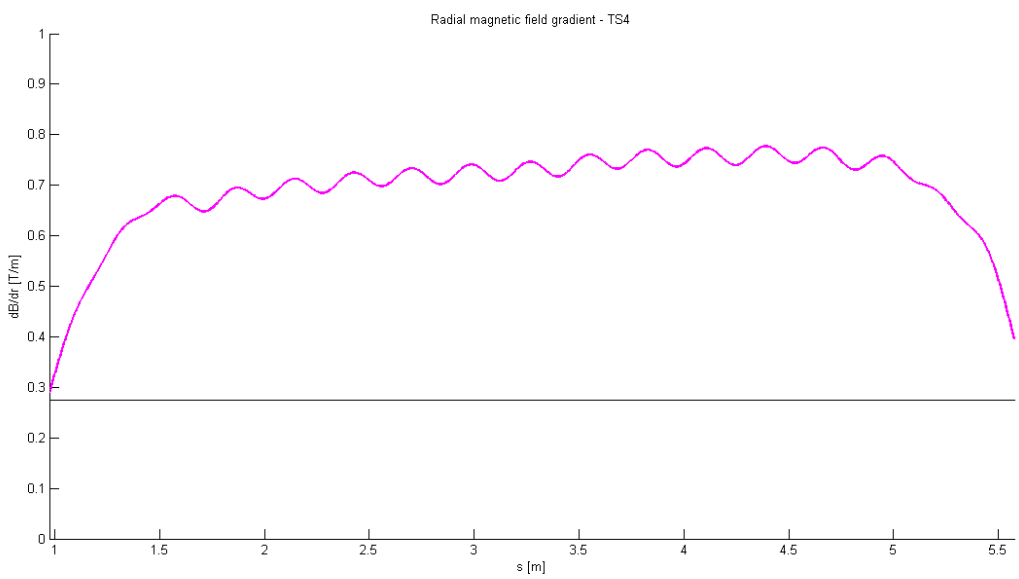

Figure 13 - Radial gradient in TS4

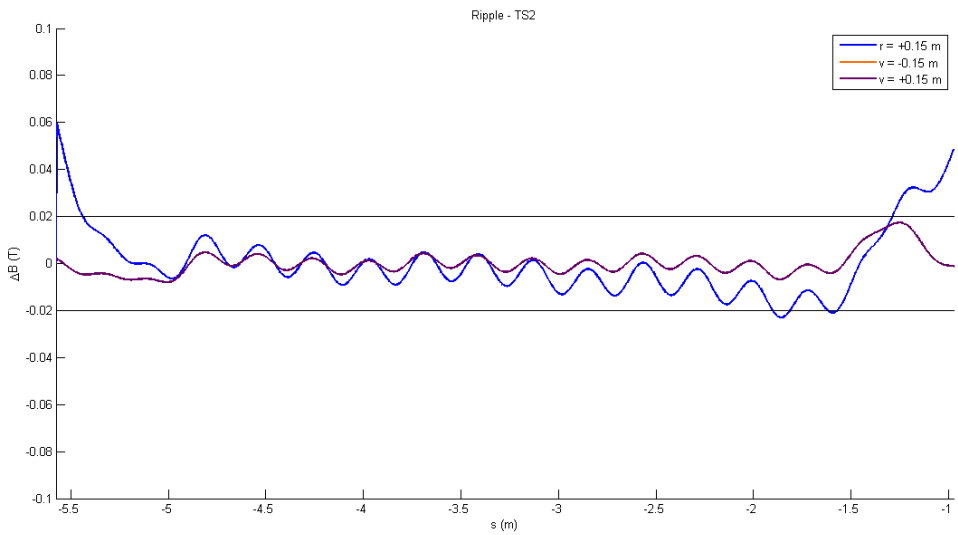

Figure 14 – Ripple in TS2

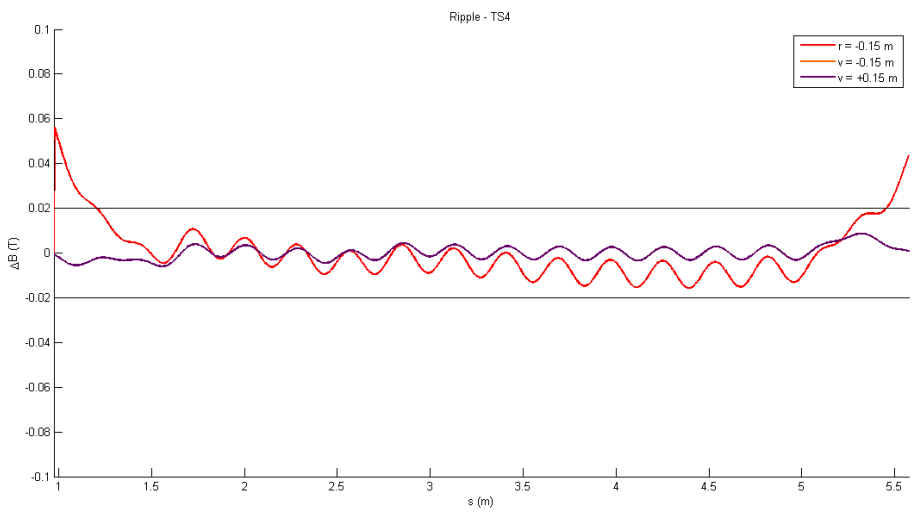

Figure 15 - Ripple in TS4

2. RANDOM ERRORS

The random errors were sub-divided into two different classes: Translation and Rotational errors. Translational errors include radial, vertical and longitudinal displacements. Rotational errors include Pitch and Yaw angles (due to the cylindrical symmetry, Roll angles are not considered). In each case, only one movement at time is allowed.

The results are presented as the average over the 100 results, with error-bars having a width equal to the standard deviation.

2.1 TRANSLATIONAL

2.1.1 RADIAL DISPLACEMENTS

2.1.1.1 ΔR = 10 mm

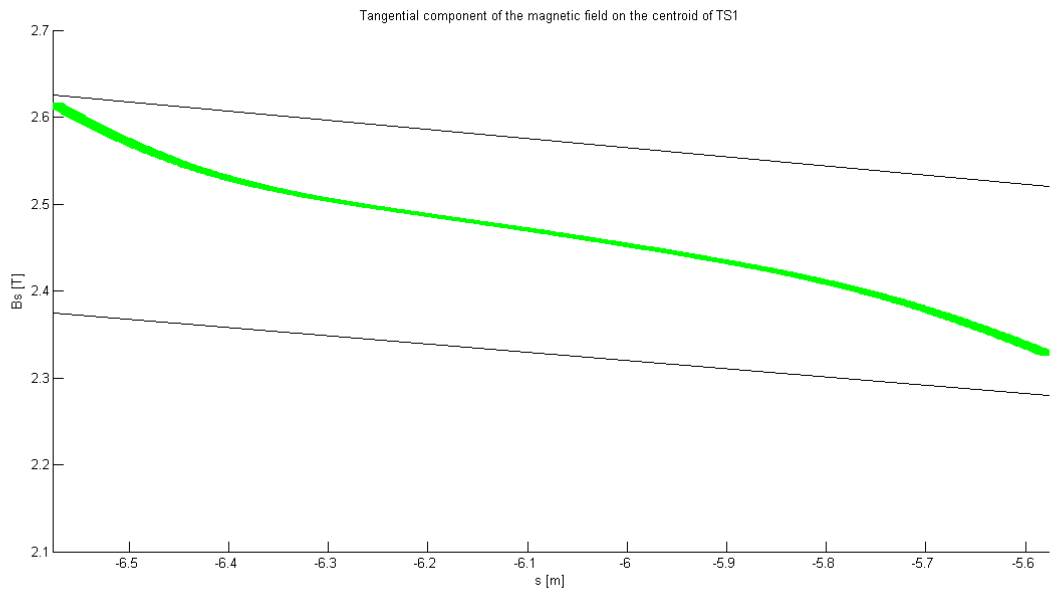

Figure 16 - Longitudinal magnetic field component in TS1.

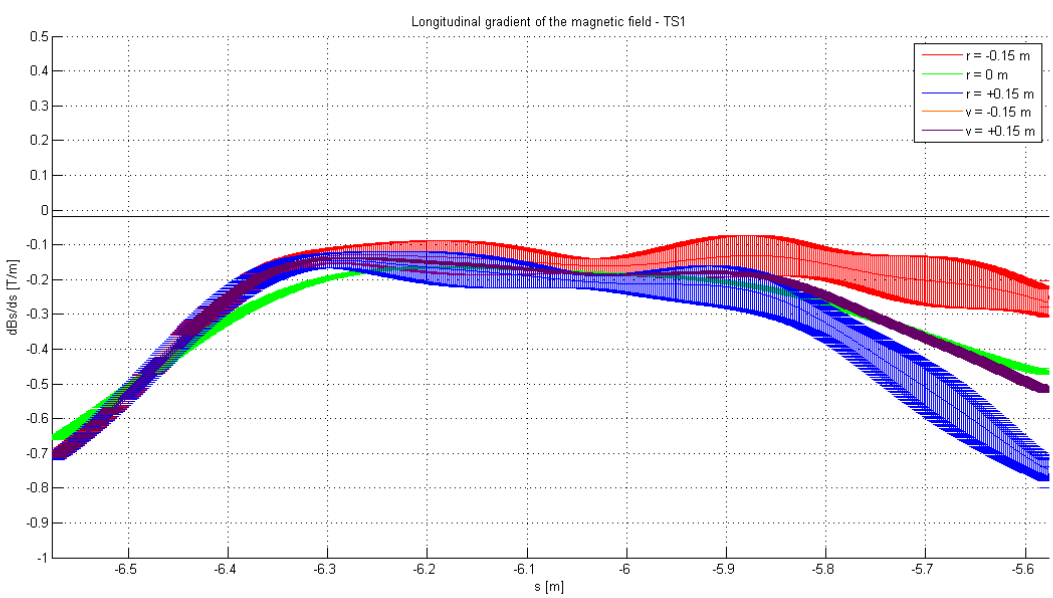

Figure 17 - Longitudinal field gradient in TS1.

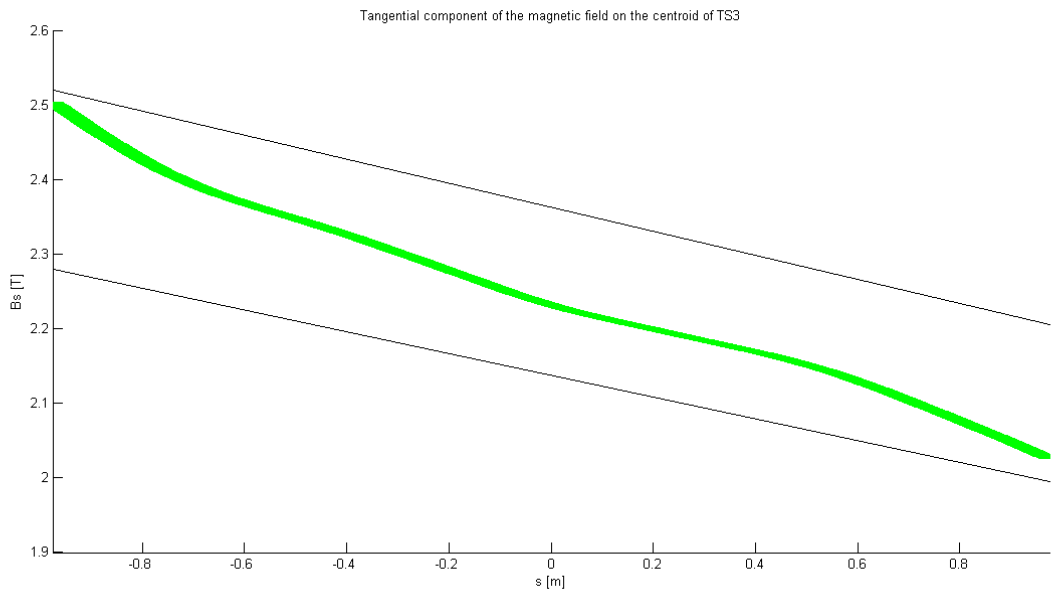

Figure 18 - Longitudinal magnetic field component in TS3

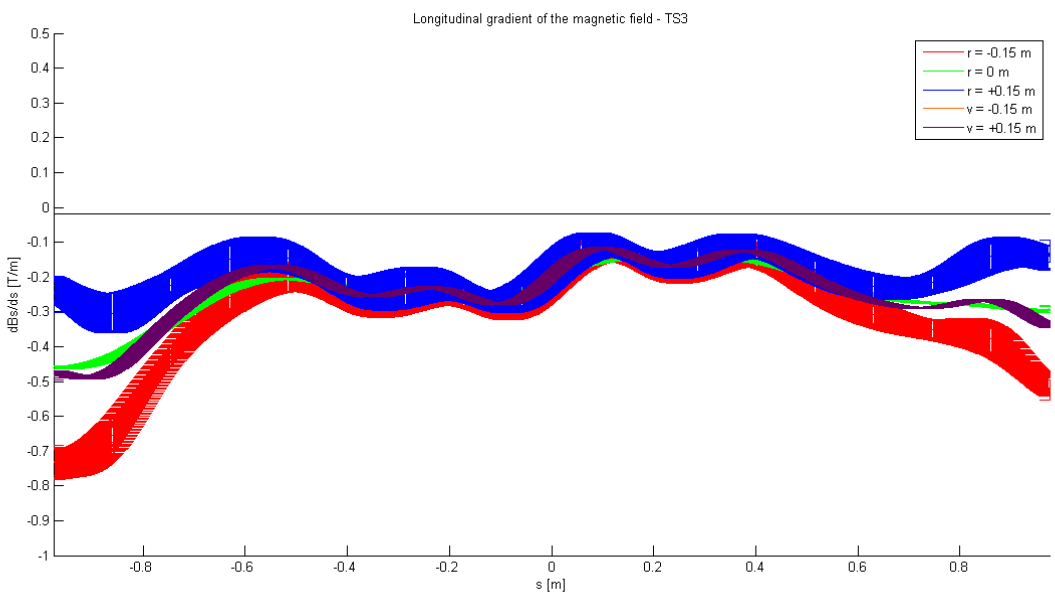

Figure 19 - Longitudinal field gradient in TS3

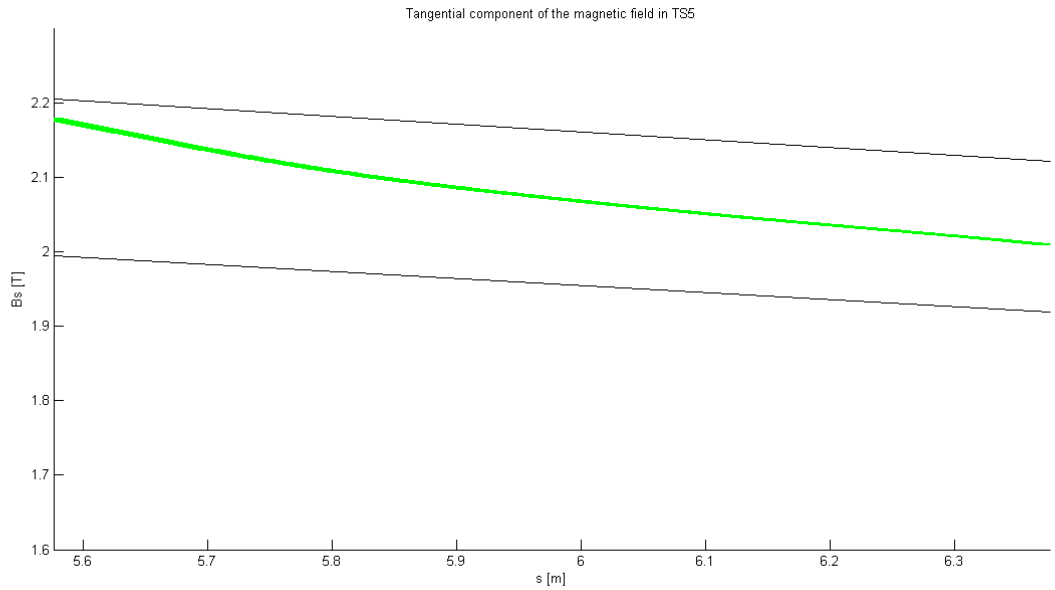

Figure 20 - Longitudinal magnetic field component in TS5

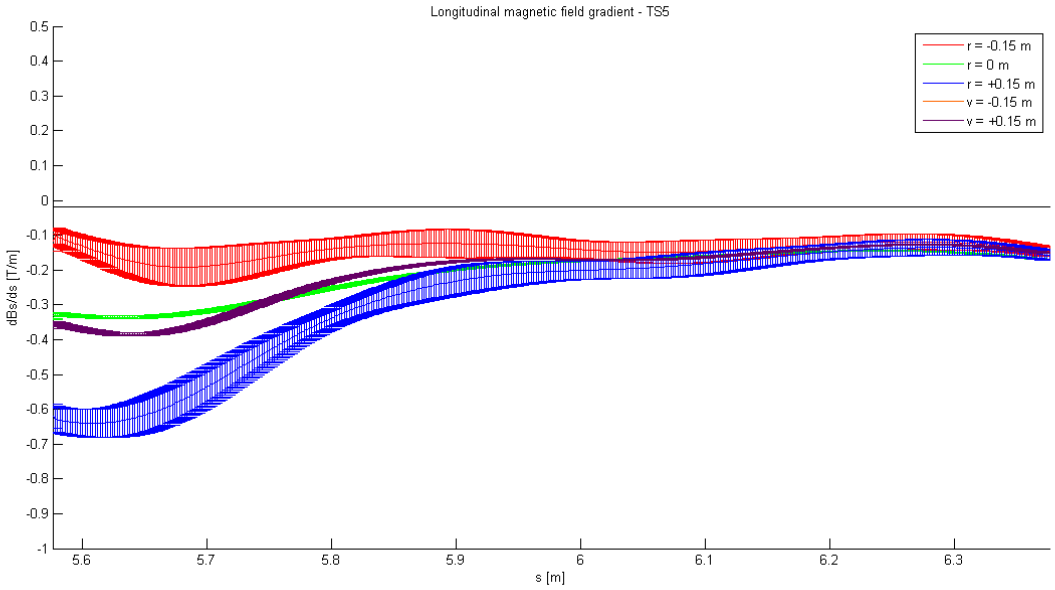

Figure 21 - Longitudinal field gradient in TS5.

2.1.1.2 ΔR = 2 mm

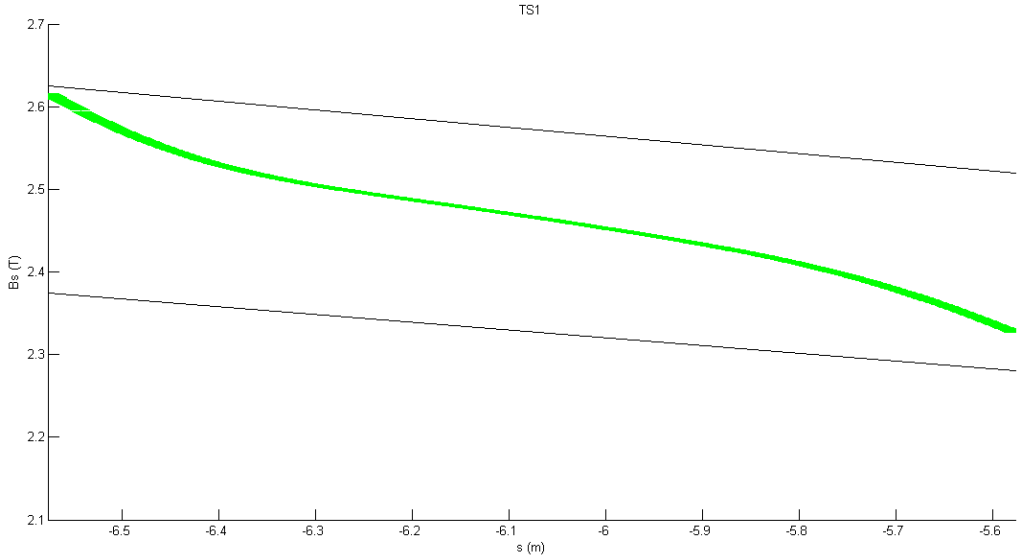

Figure 22 - Longitudinal magnetic field component in TS1.

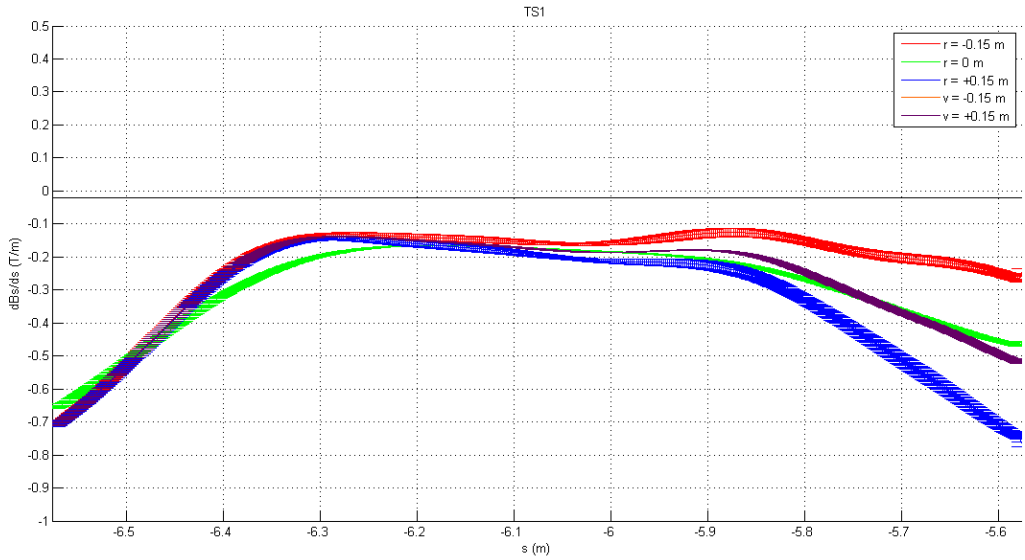

Figure 23 - Longitudinal field gradient in TS1.

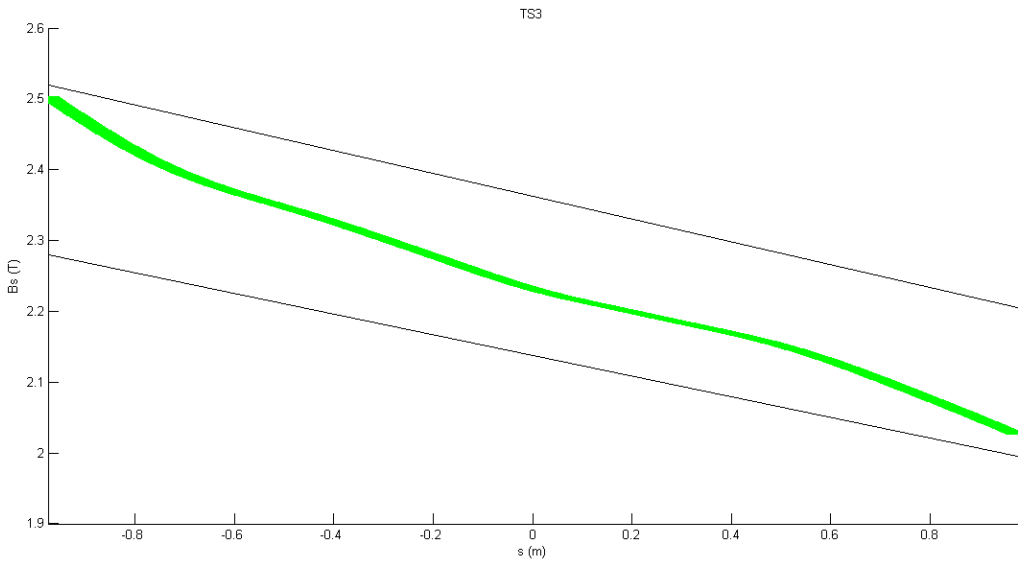

Figure 24 - Longitudinal magnetic field component in TS3

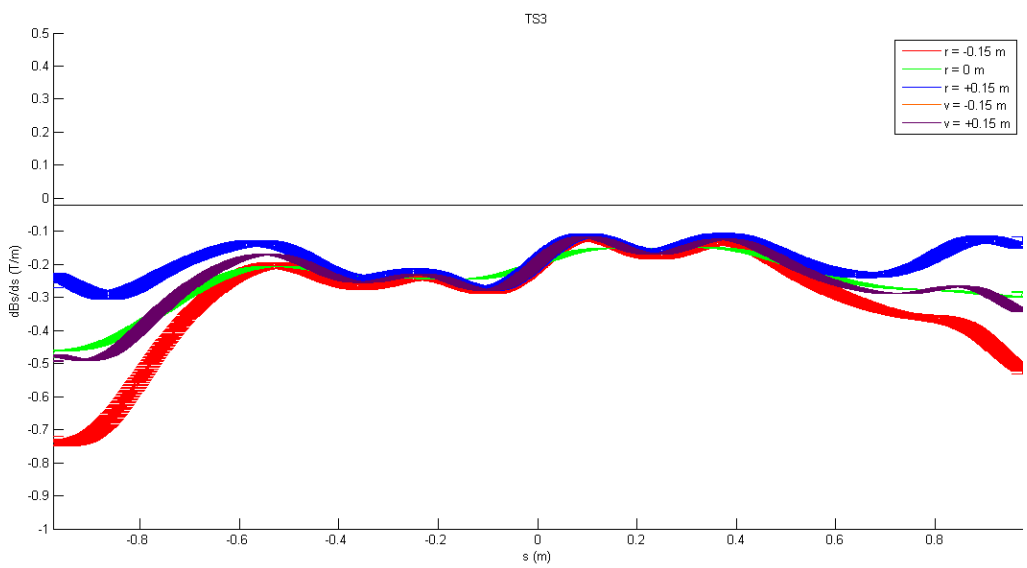

Figure 25 - Longitudinal field gradient in TS3.

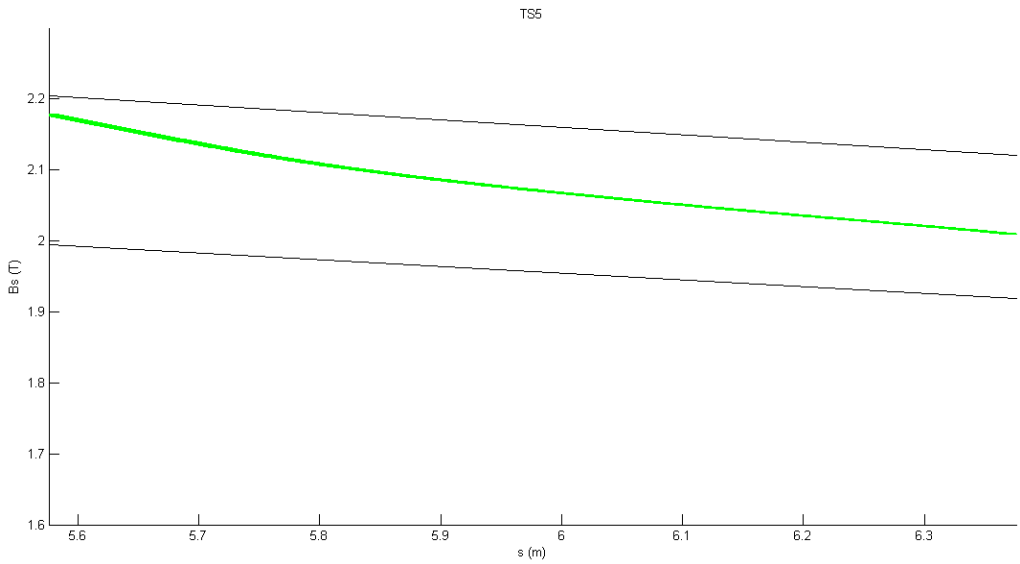

Figure 26 - Longitudinal magnetic field component in TS5

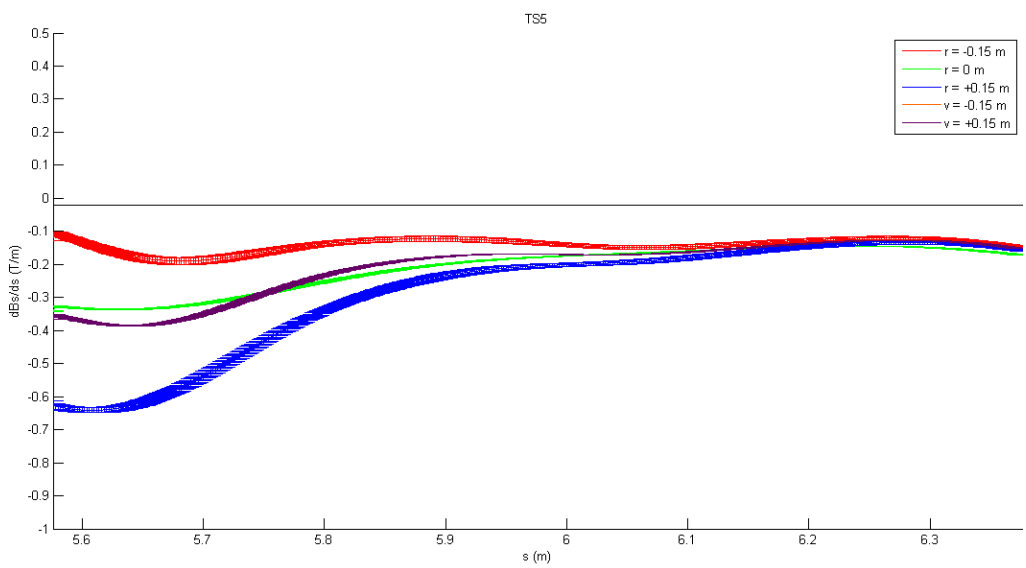

Figure 27 - Longitudinal field gradient in TS5.

2.1.2 VERTICAL DISPLACEMENTS

2.1.2.1 ΔV = 10 mm

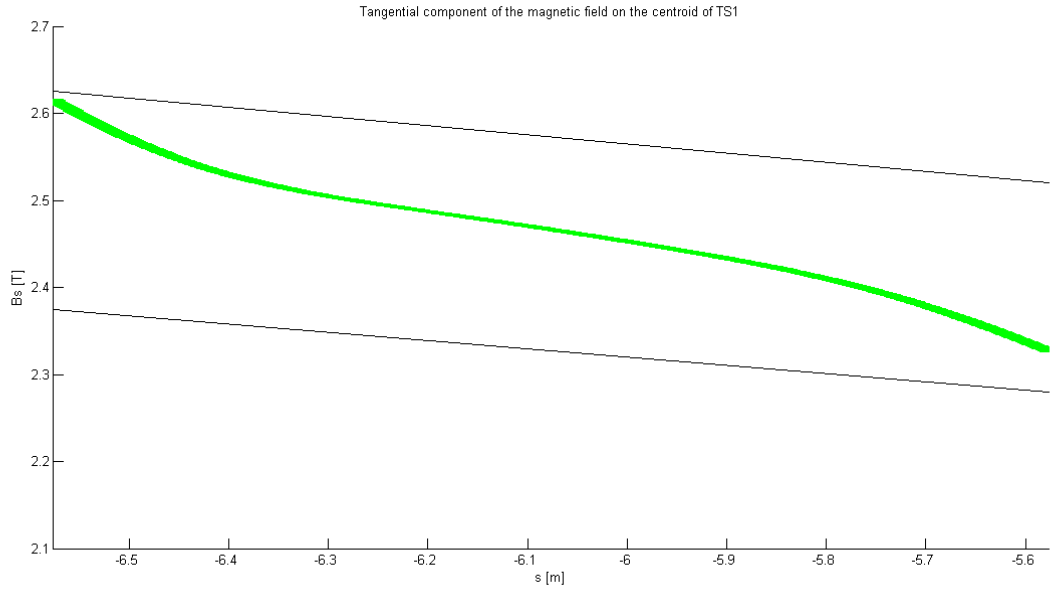

Figure 28 - Longitudinal magnetic field component in TS1.

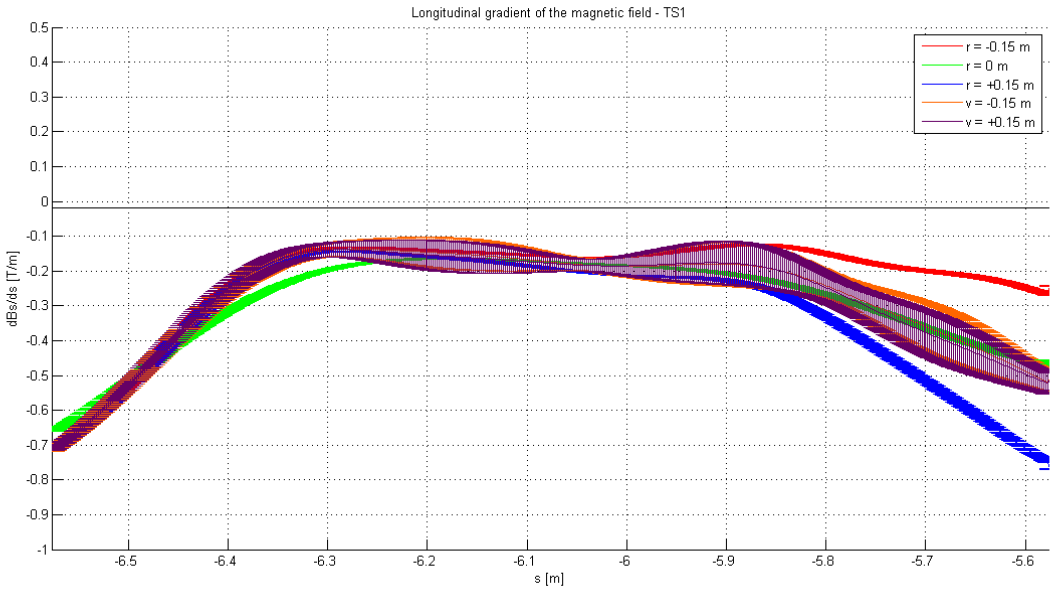

Figure 29 - Longitudinal field gradient in TS1.

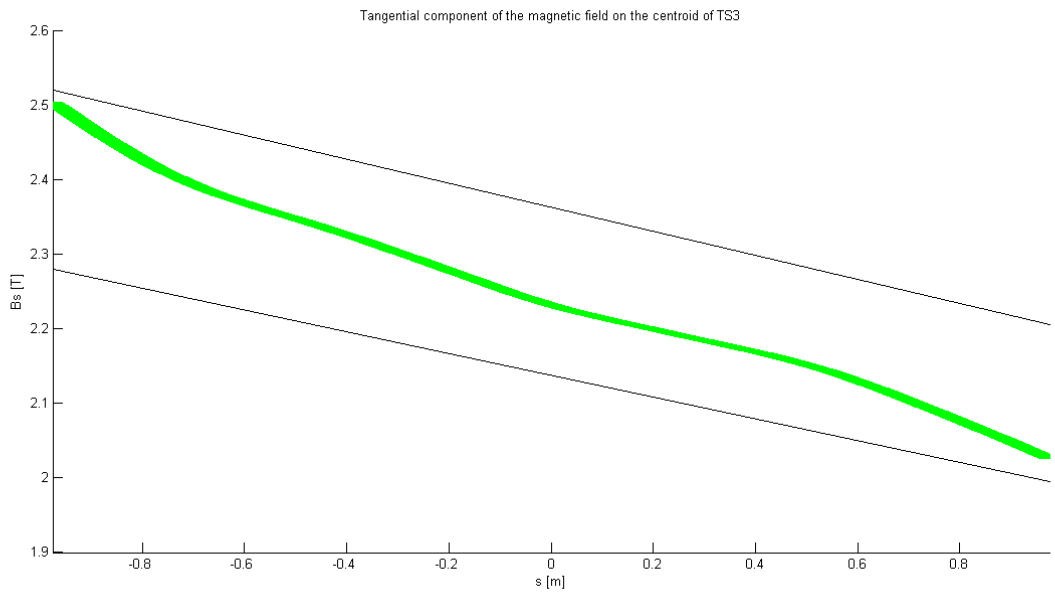

Figure 30 - Longitudinal magnetic field component in TS3

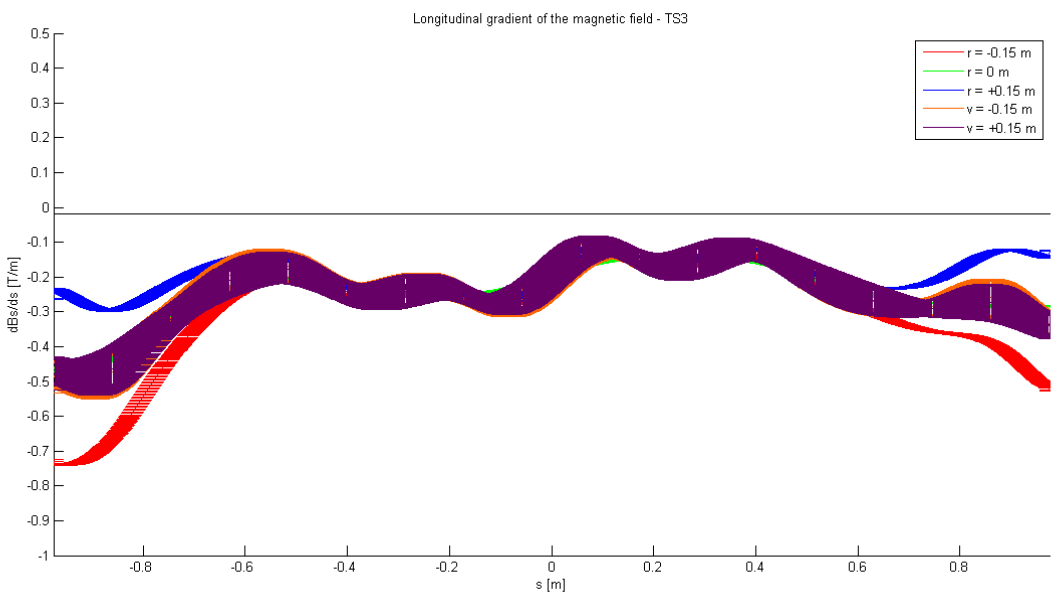

Figure 31 - Longitudinal field gradient in TS3.

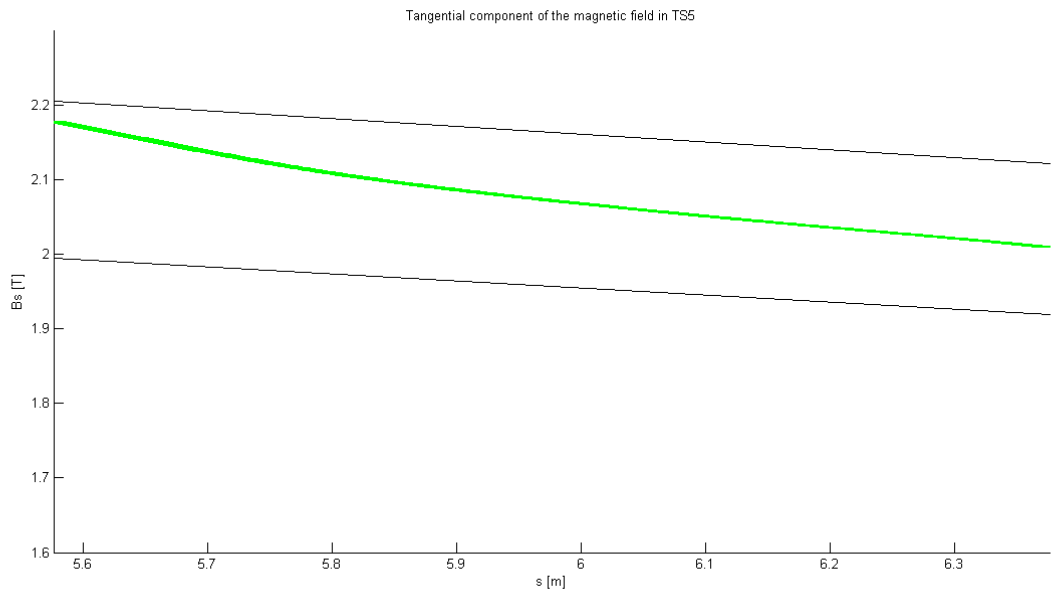

Figure 32 - Longitudinal magnetic field component in TS5

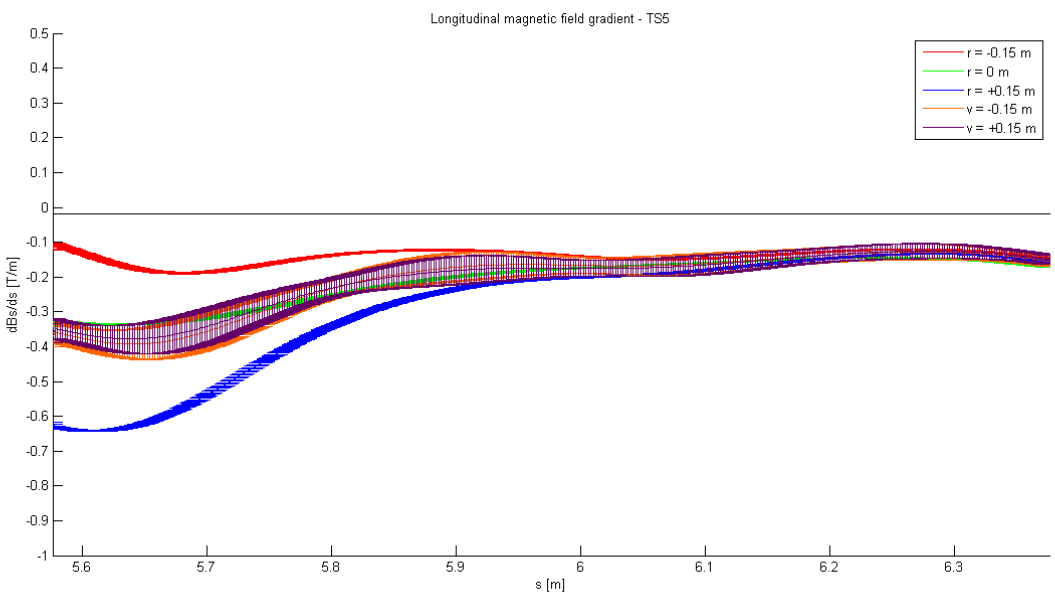

Figure 33 - Longitudinal field gradient in TS5.

2.1.3 LONGITUDINAL DISPLACEMENTS

2.1.3.1 ΔL = 10 mm

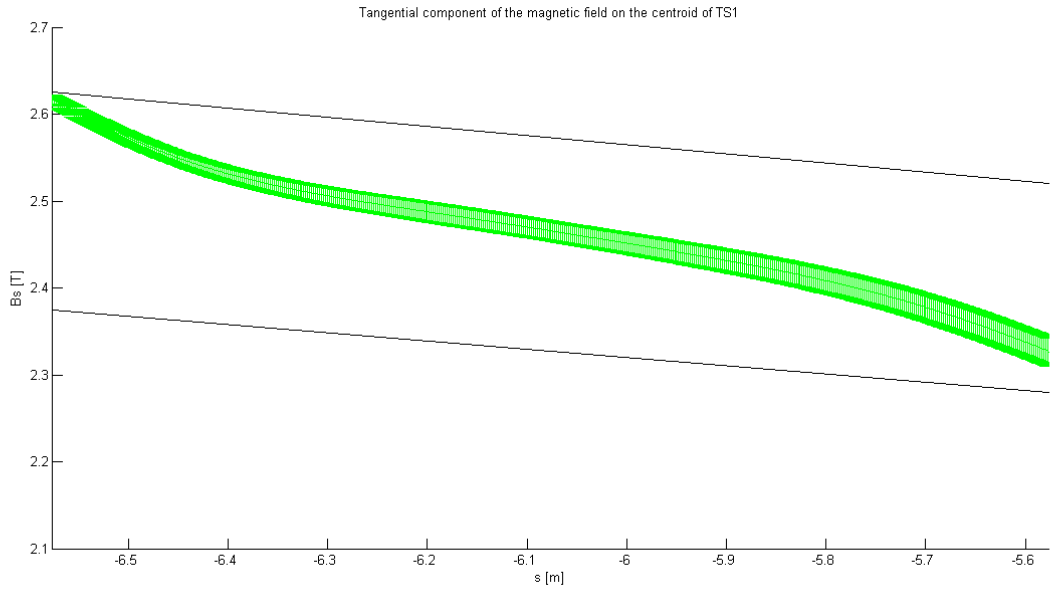

Figure 34 - Longitudinal magnetic field component in TS1.

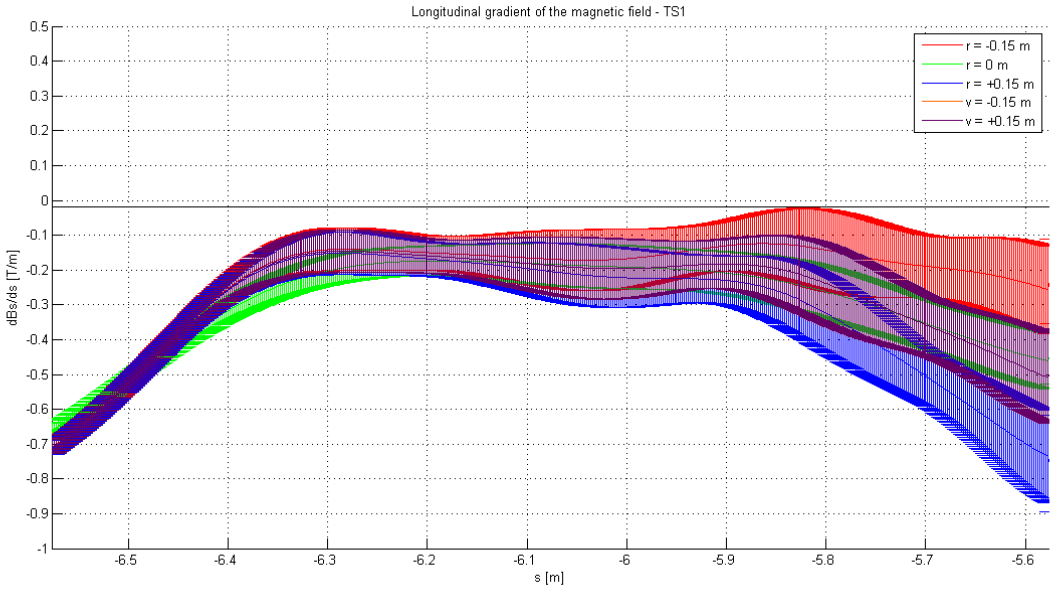

Figure 35 - Longitudinal field gradient in TS1.

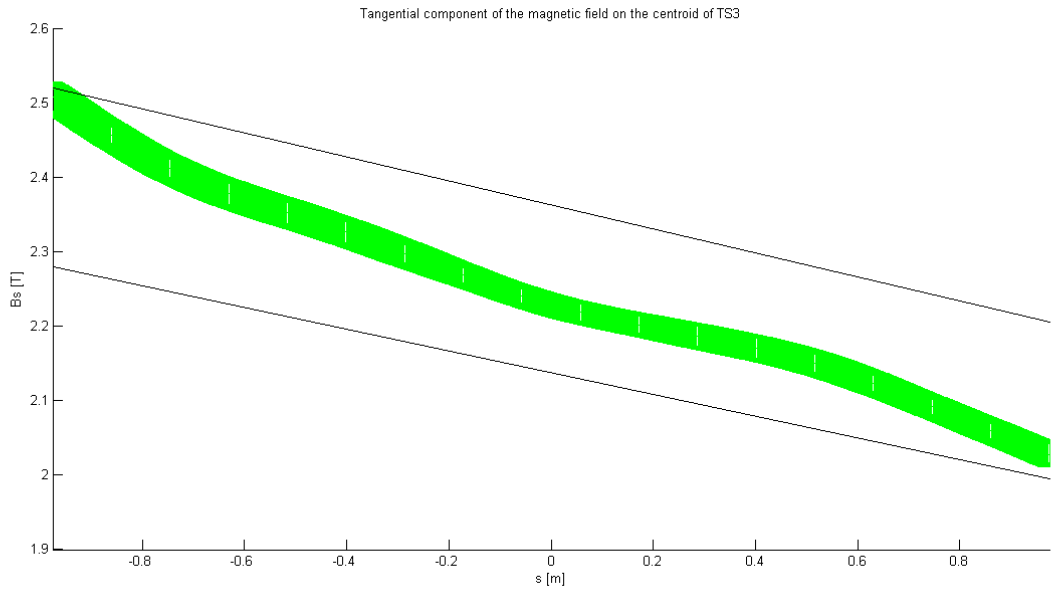

Figure 36 - Longitudinal magnetic field component in TS3

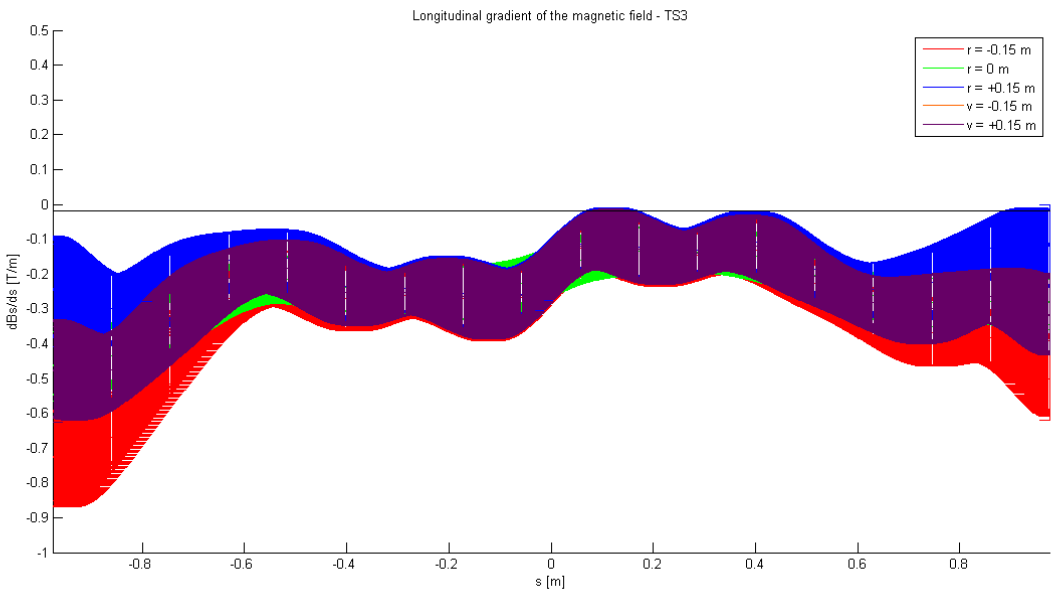

Figure 37 - Longitudinal field gradient in TS3.

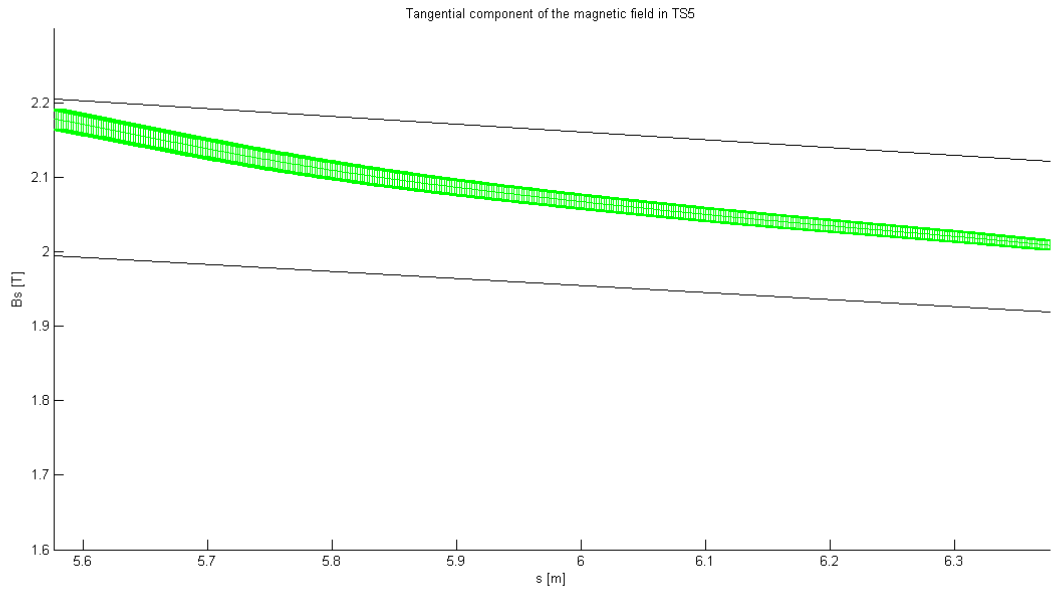

Figure 38 - Longitudinal magnetic field component in TS5

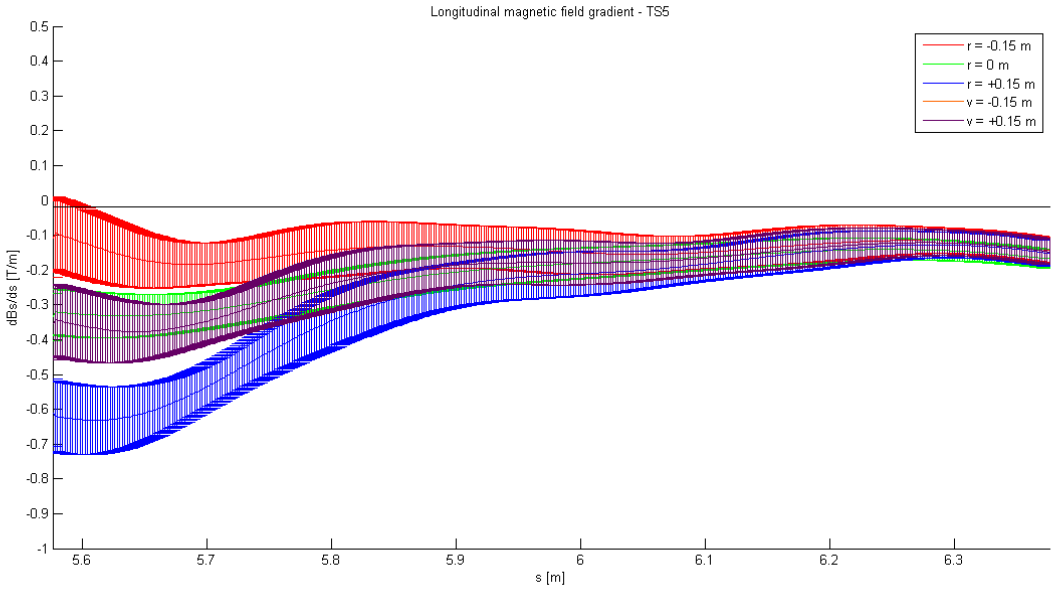

Figure 39 - Longitudinal field gradient in TS5.

2.1.3.2 ΔL = 2 mm

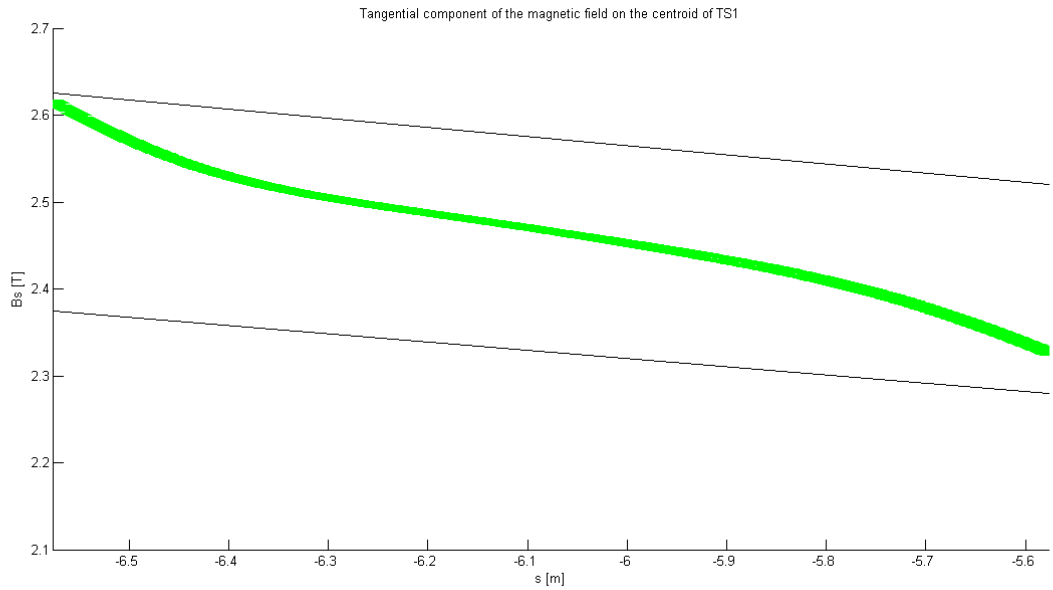

Figure 40 - Longitudinal magnetic field component in TS1.

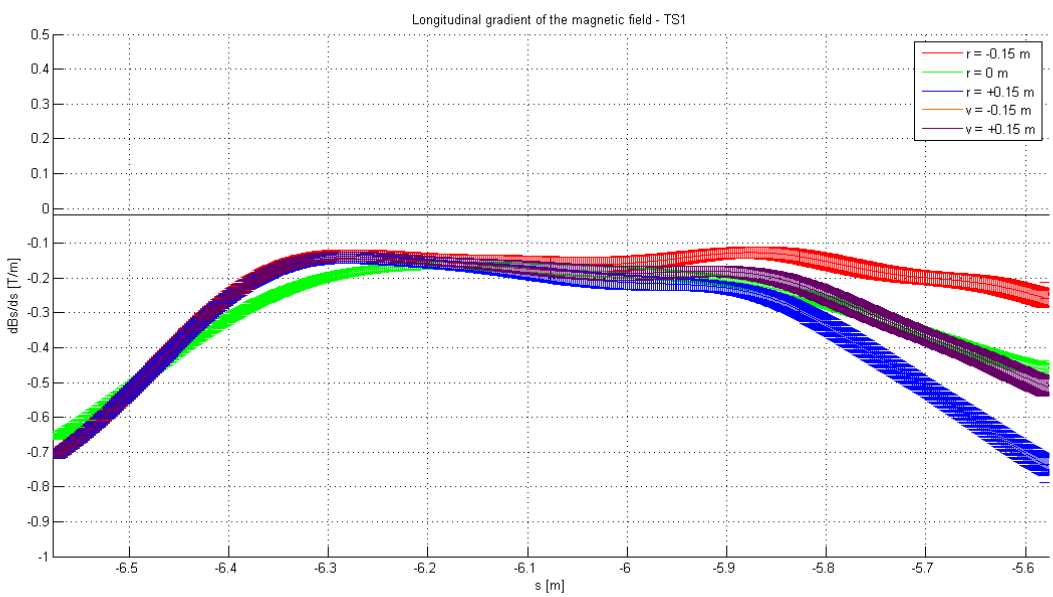

Figure 41 - Longitudinal field gradient in TS1.

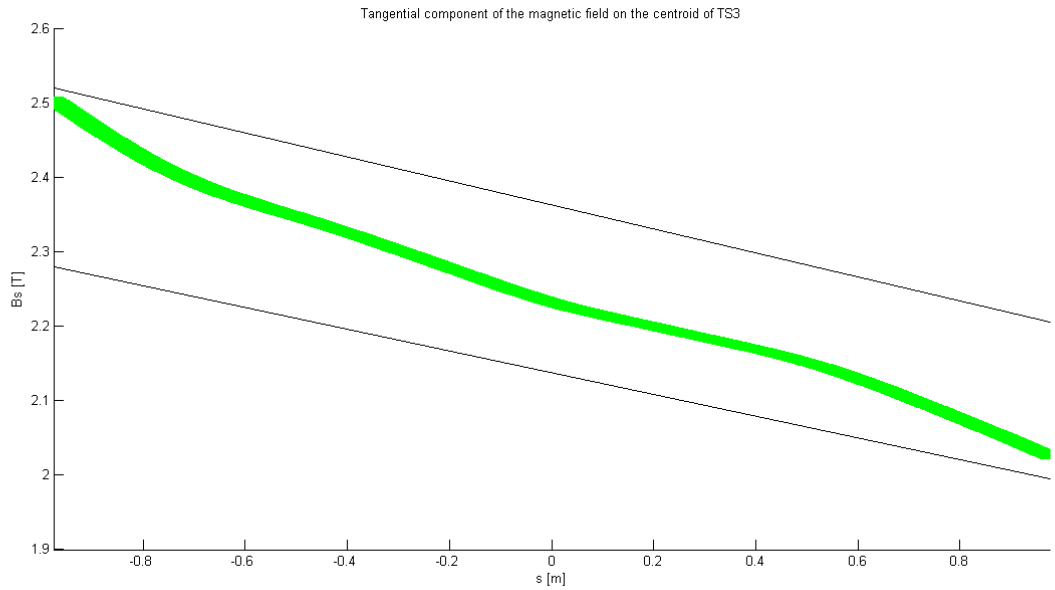

Figure 42 - Longitudinal magnetic field component in TS3

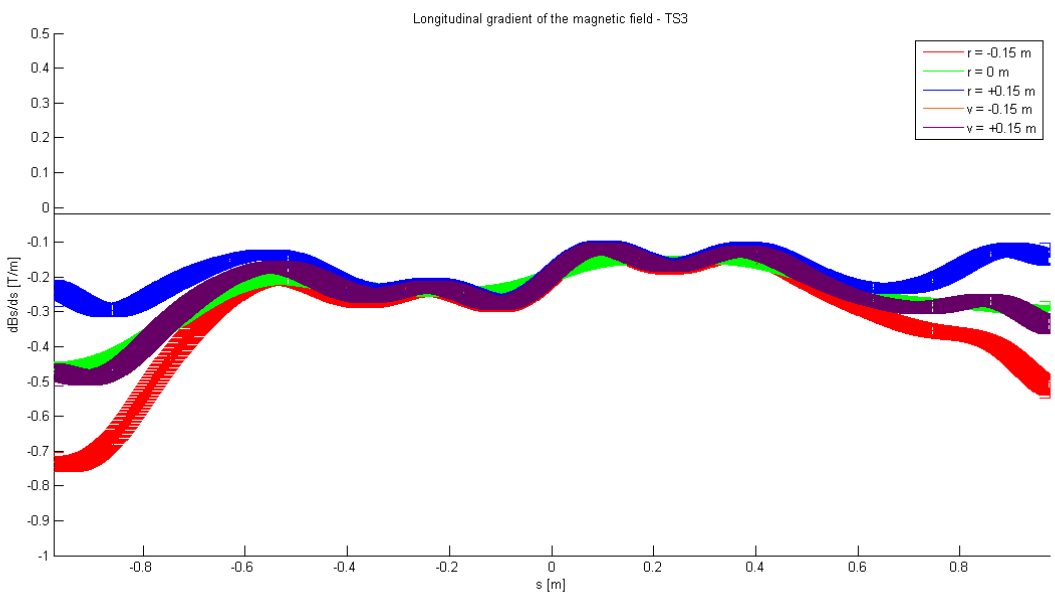

Figure 43 - Longitudinal field gradient in TS3.

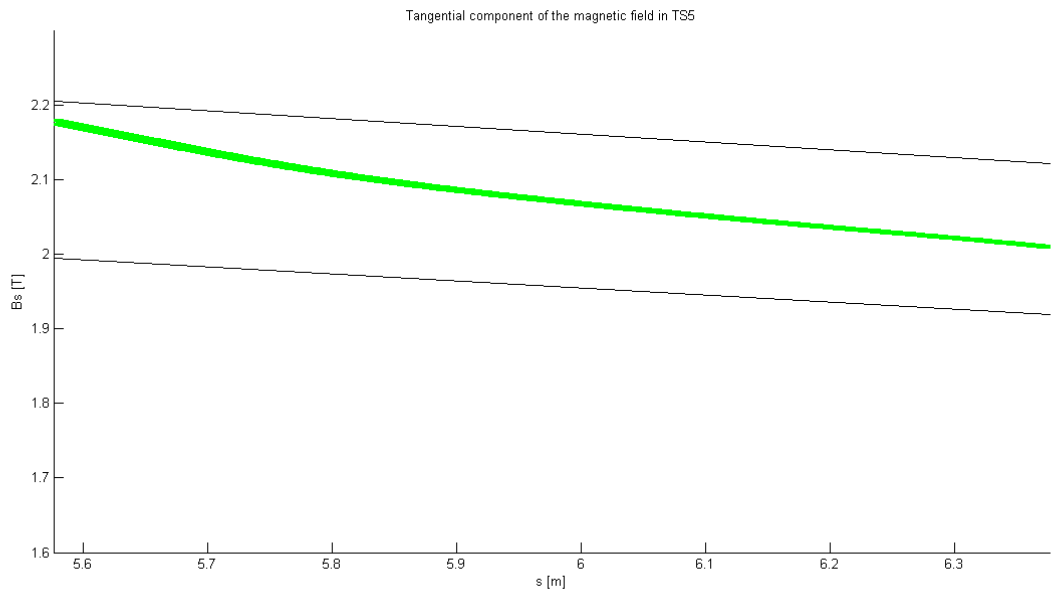

Figure 44 - Longitudinal magnetic field component in TS5

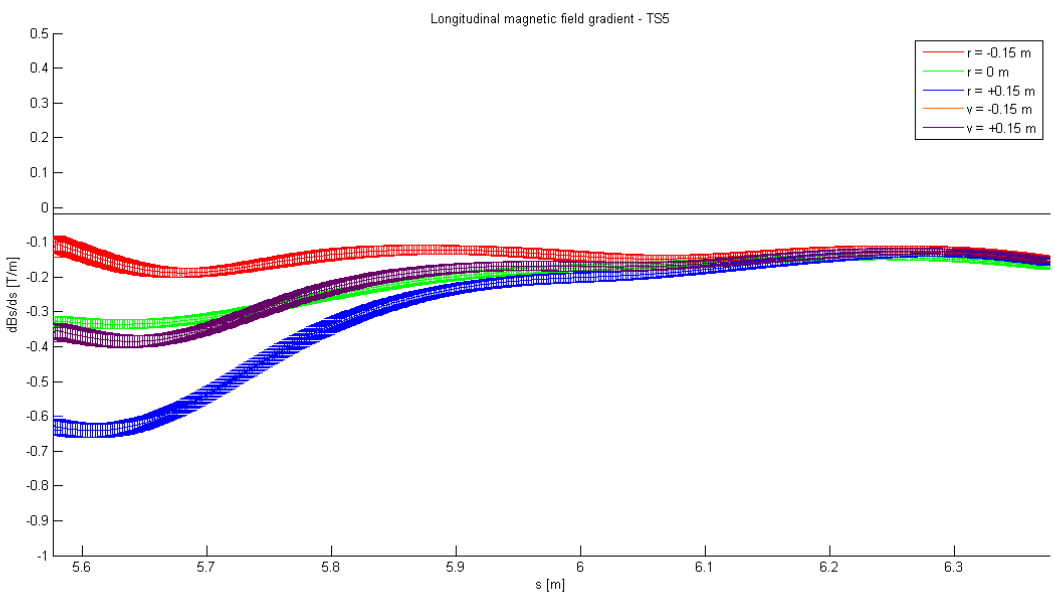

Figure 45 - Longitudinal field gradient in TS5.

2.2 ROTATIONAL

2.2.1 PITCH ROTATION

2.2.1.1 ΔP = 10 mrad

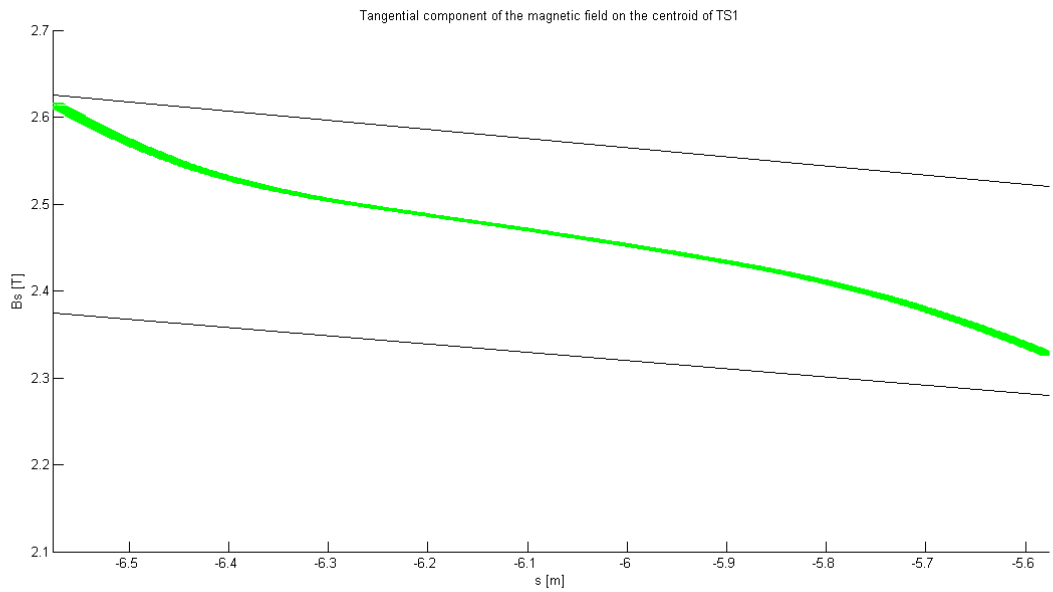

Figure 46 - Longitudinal magnetic field component in TS1.

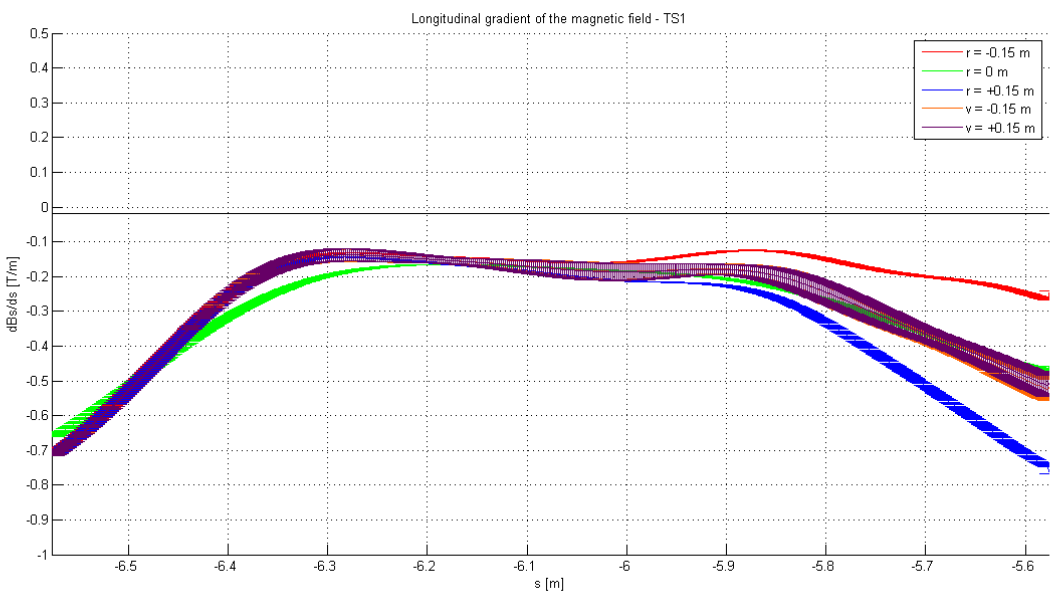

Figure 47 - Longitudinal field gradient in TS1.

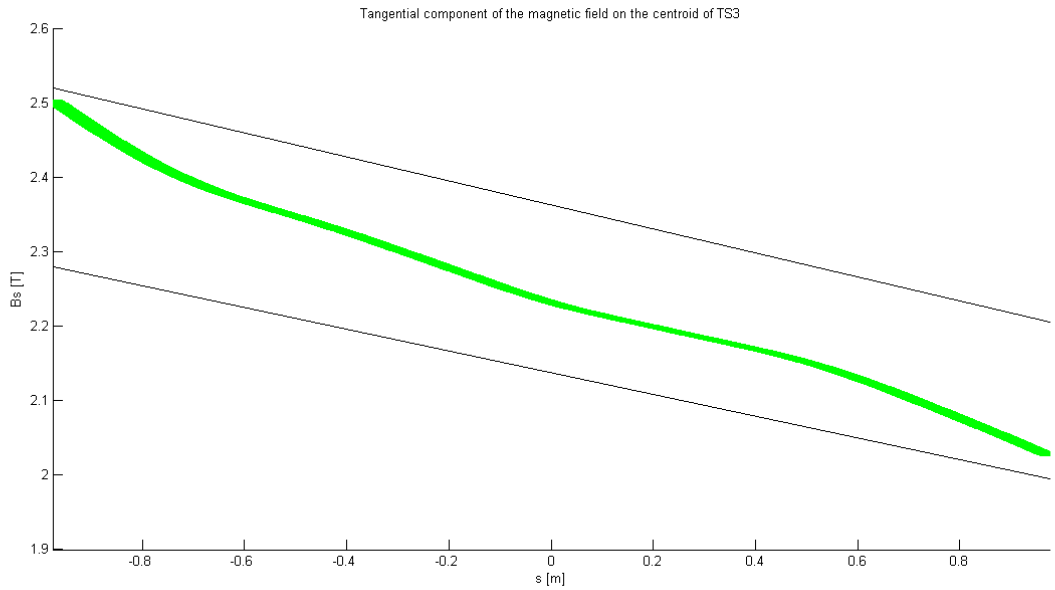

Figure 48 - Longitudinal magnetic field component in TS3

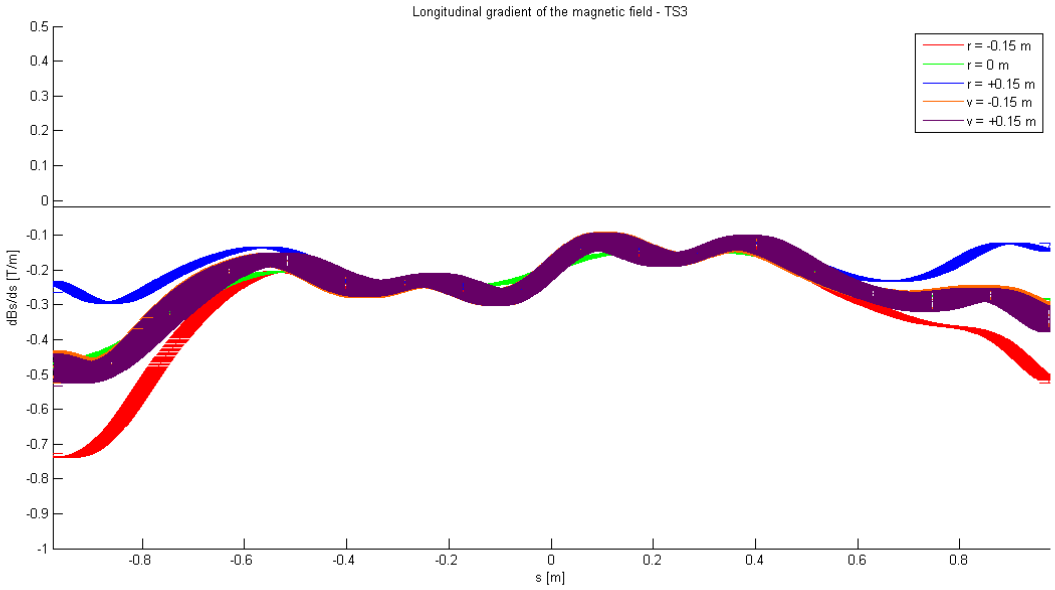

Figure 49 - Longitudinal field gradient in TS3.

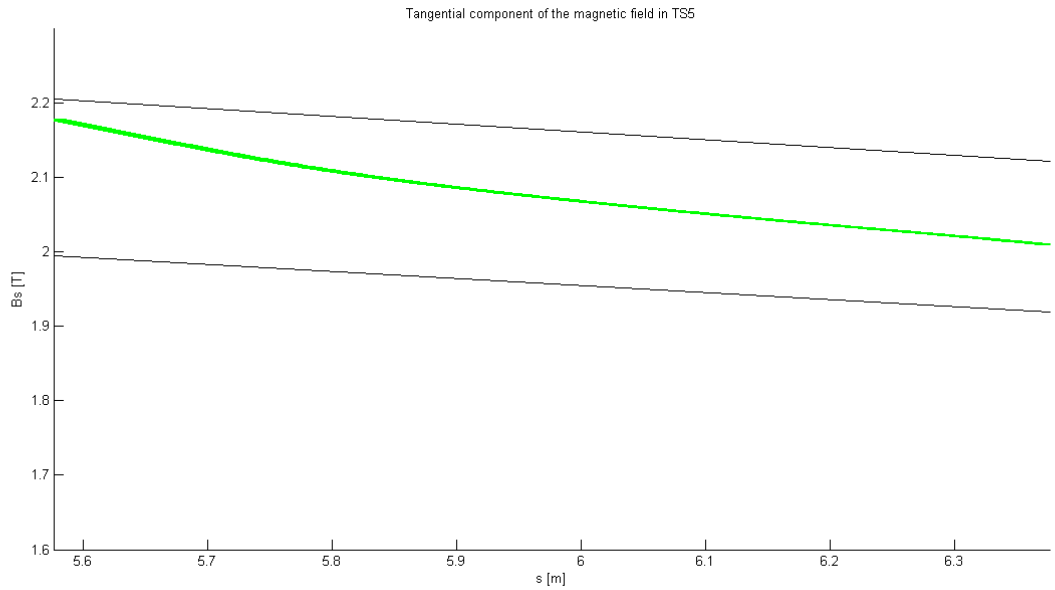

Figure 50 - Longitudinal magnetic field component in TS5

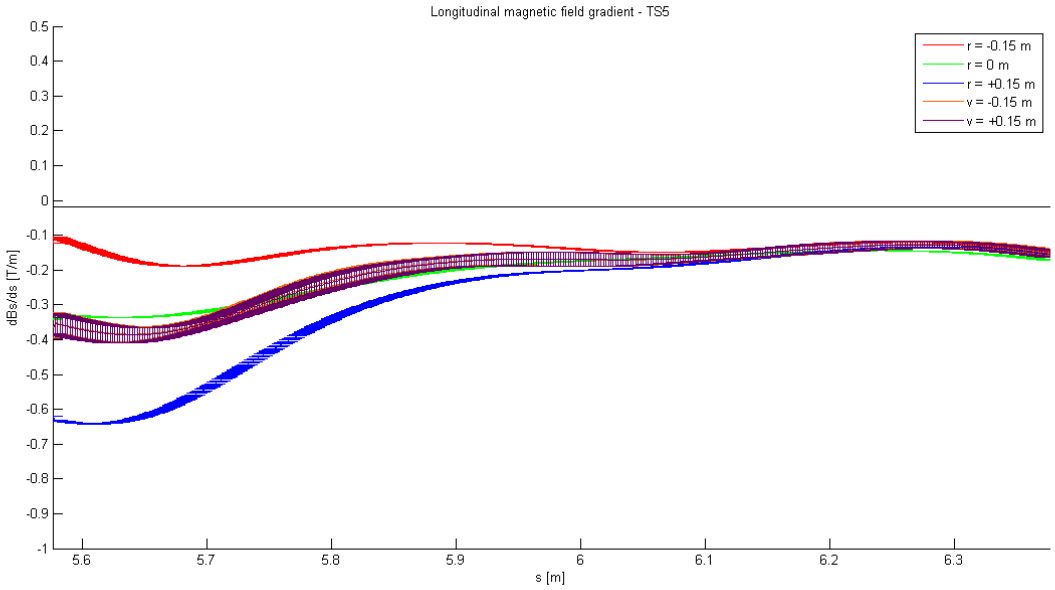

Figure 51 - Longitudinal field gradient in TS5.

2.2.1.2 ΔP = 2 mrad

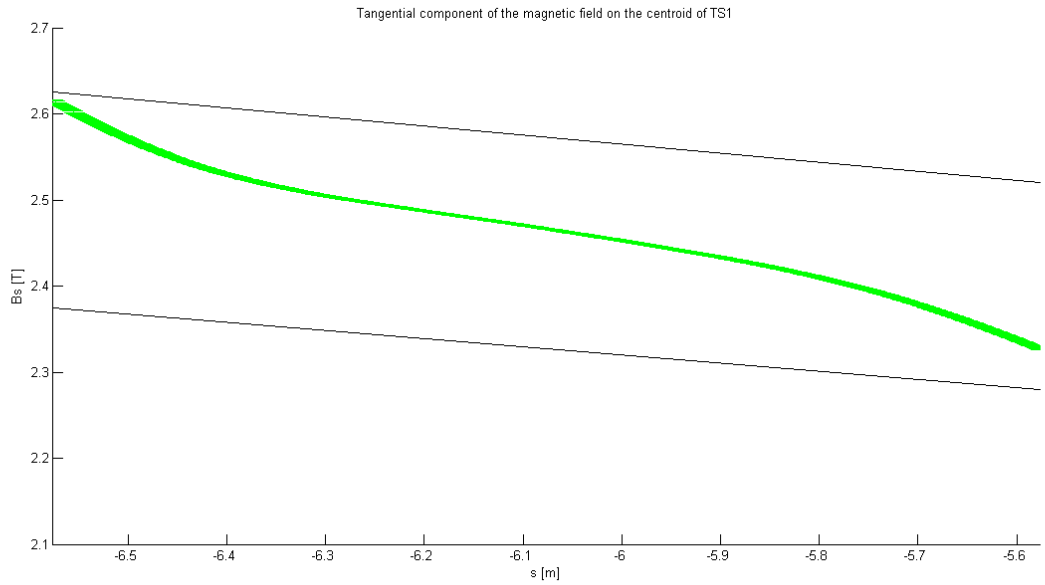

Figure 52 - Longitudinal magnetic field component in TS1.

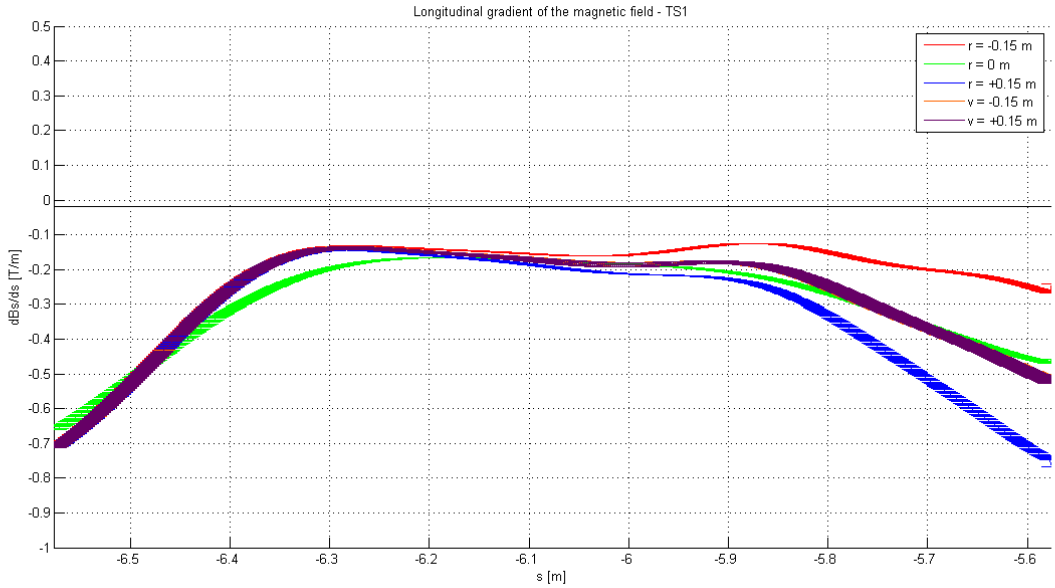

Figure 53 - Longitudinal field gradient in TS1.

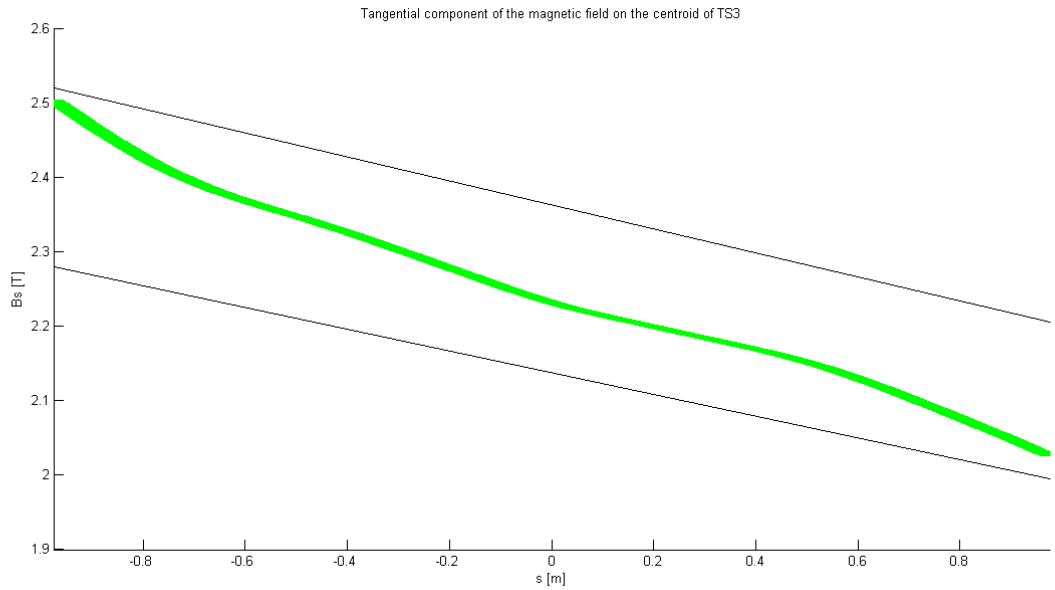

Figure 54 - Longitudinal magnetic field component in TS3

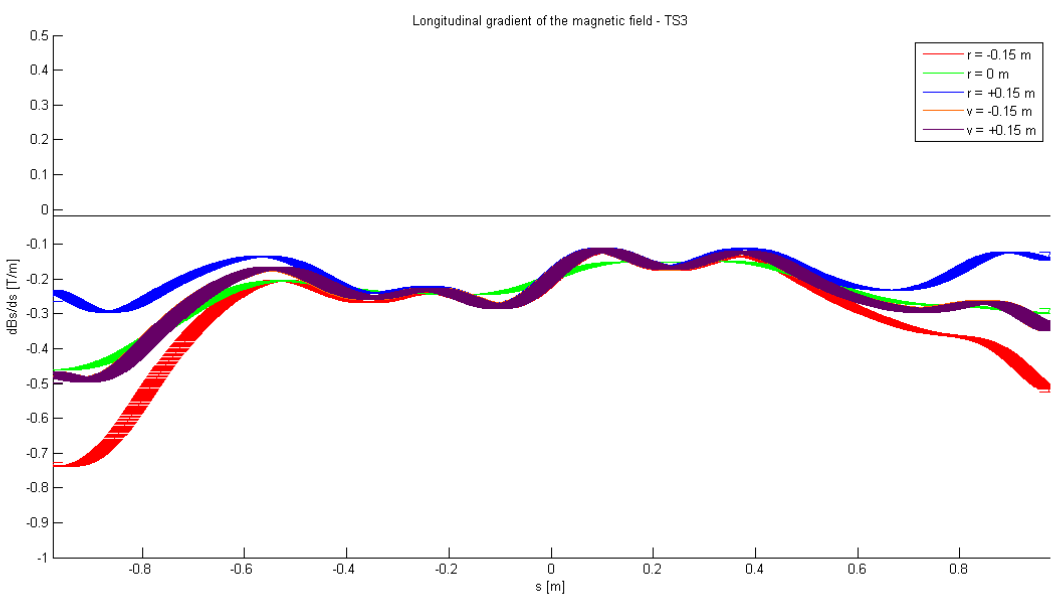

Figure 55 - Longitudinal field gradient in TS3.

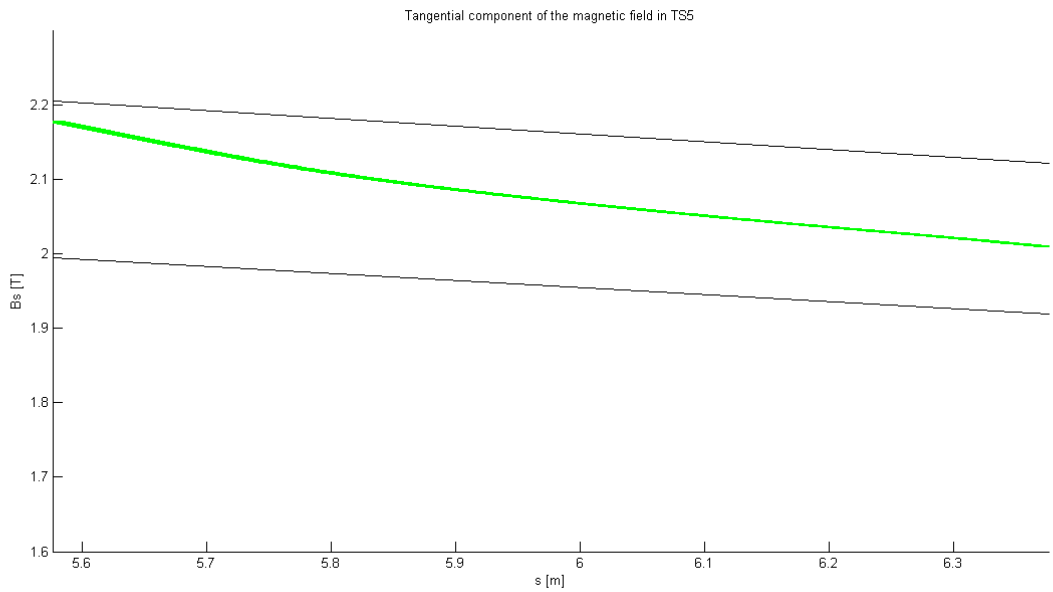

Figure 56 - Longitudinal magnetic field component in TS5

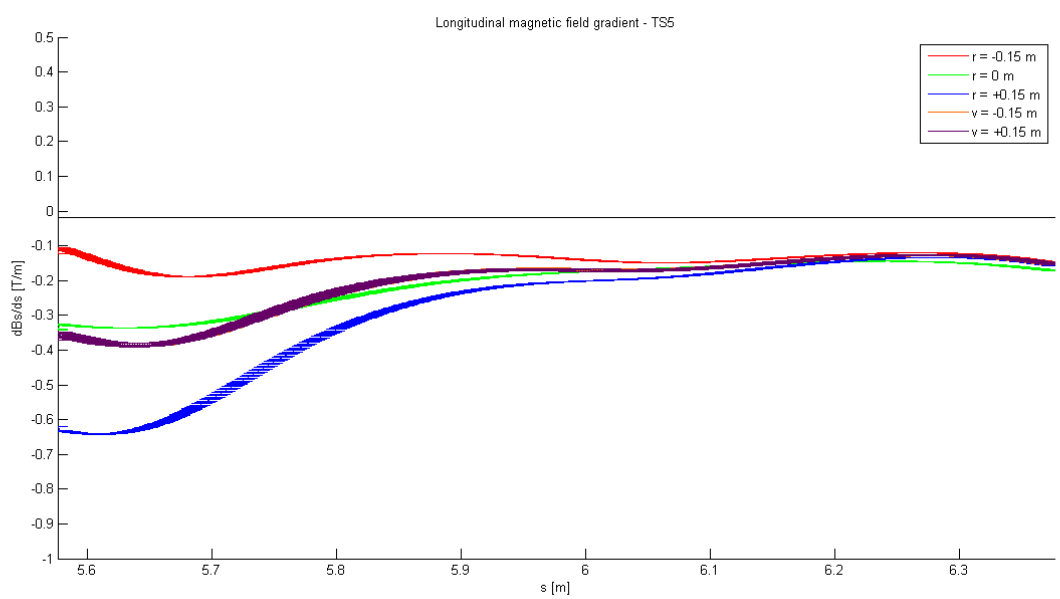

Figure 57 - Longitudinal field gradient in TS5.

2.2.2 YAW ROTATION

2.2.2.1 ΔY = 10 mrad

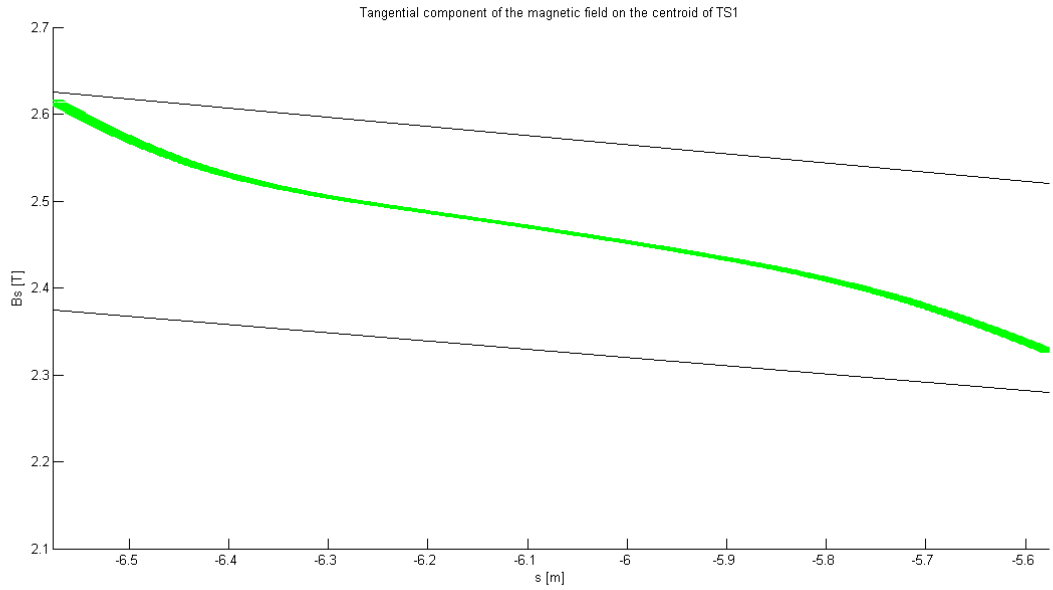

Figure 58 - Longitudinal magnetic field component in TS1.

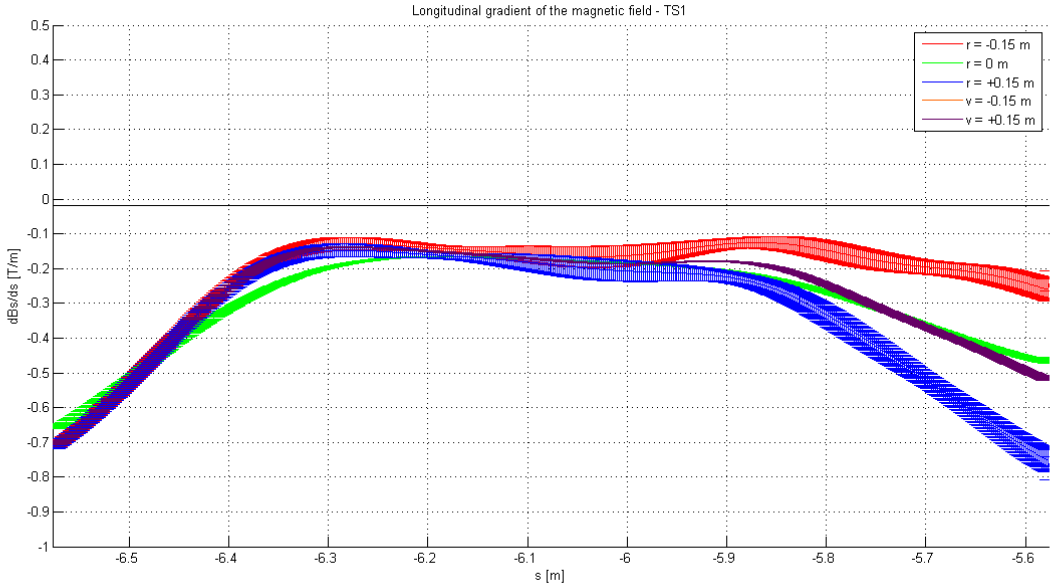

Figure 59 - Longitudinal field gradient in TS1.

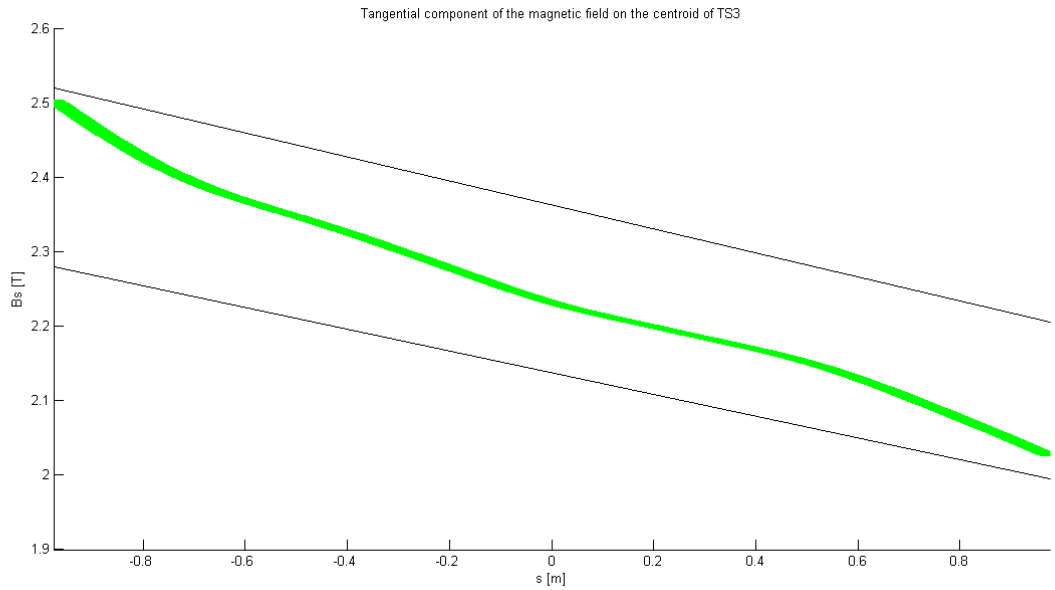

Figure 60 - Longitudinal magnetic field component in TS3

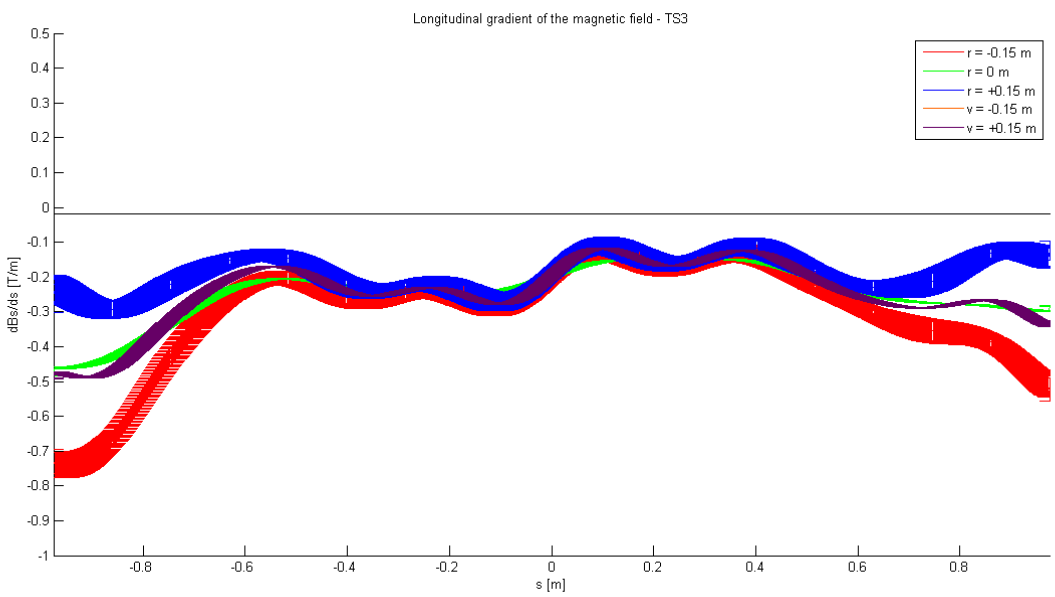

Figure 61 - Longitudinal field gradient in TS3.

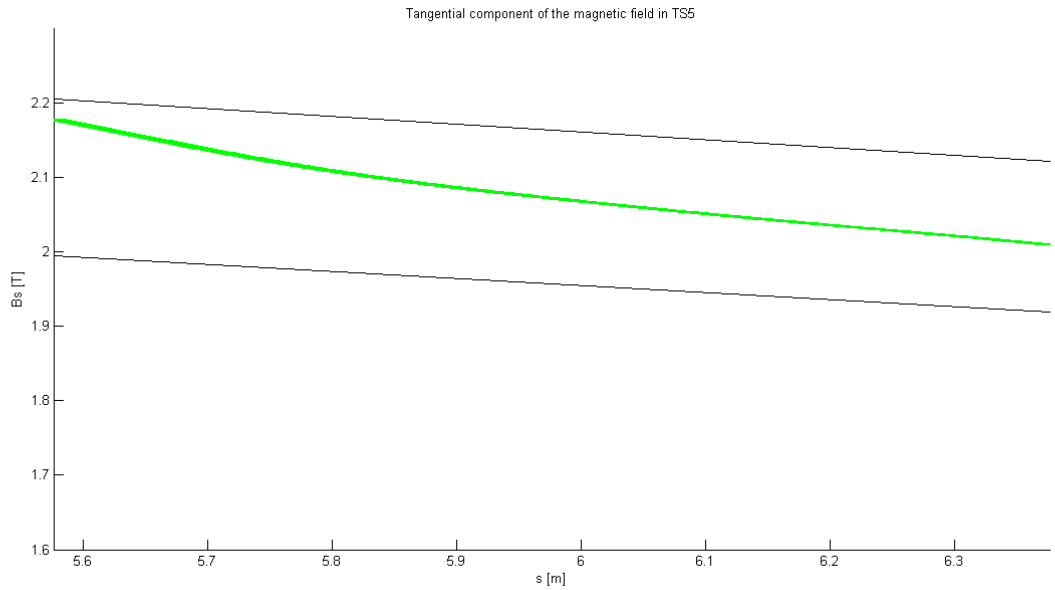

Figure 62 - Longitudinal magnetic field component in TS5

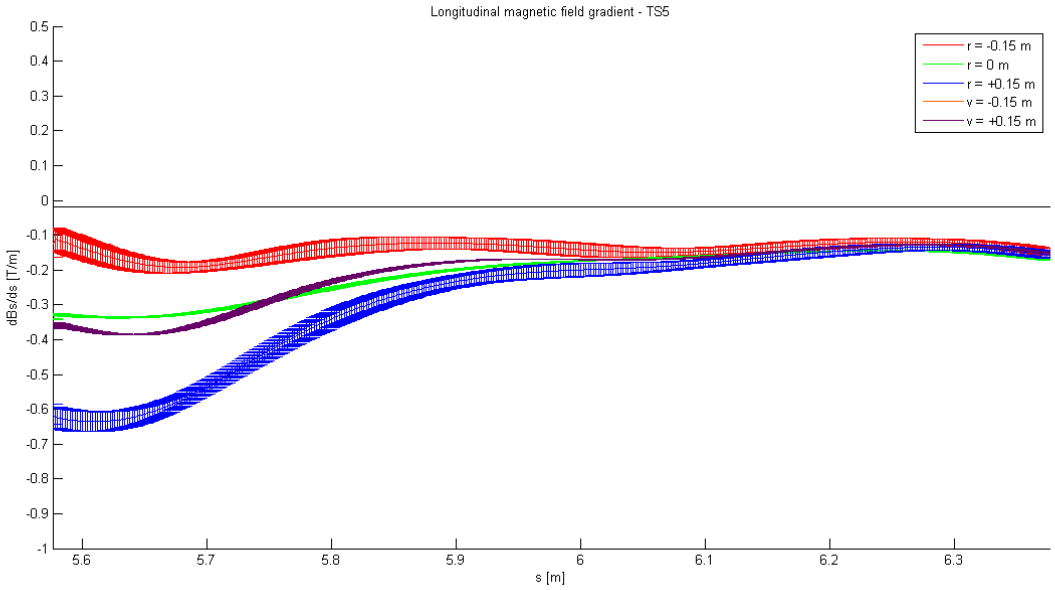

Figure 63 - Longitudinal field gradient in TS5.

2.2.2.2 ΔY = 2 mrad

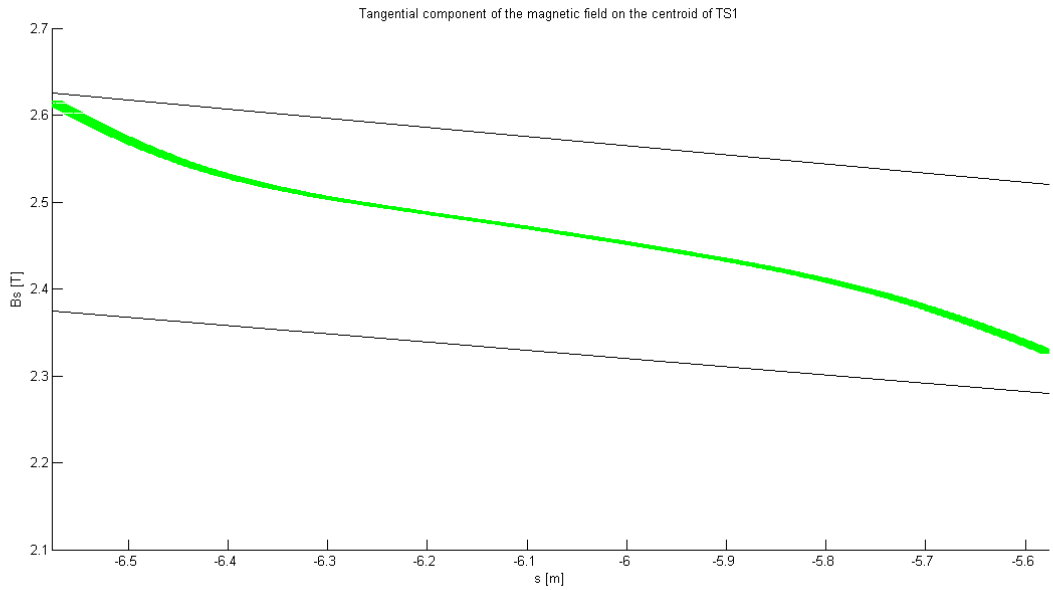

Figure 64 - Longitudinal magnetic field component in TS1.

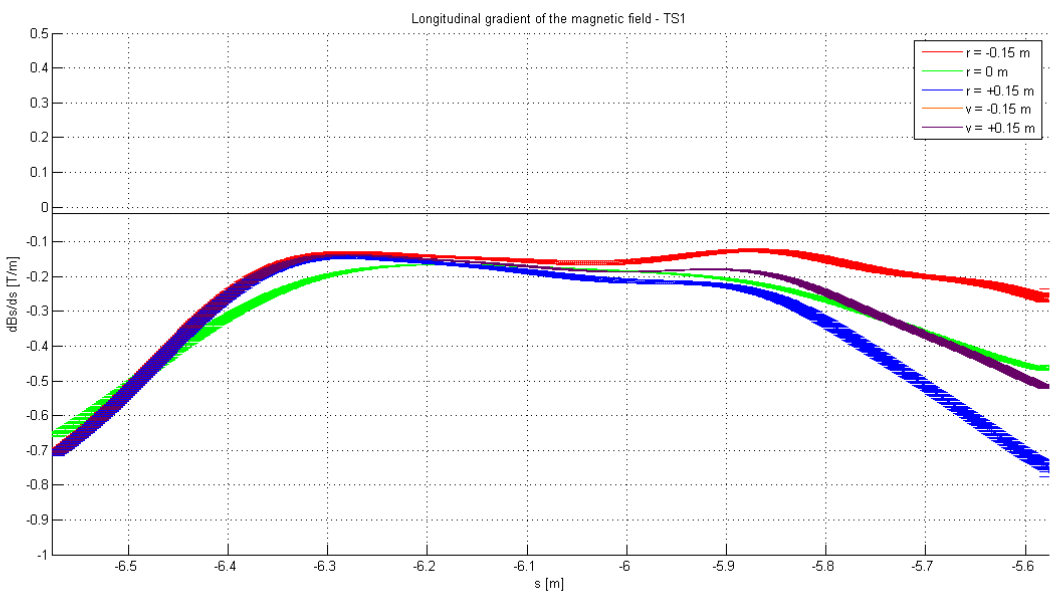

Figure 65 - Longitudinal field gradient in TS1.

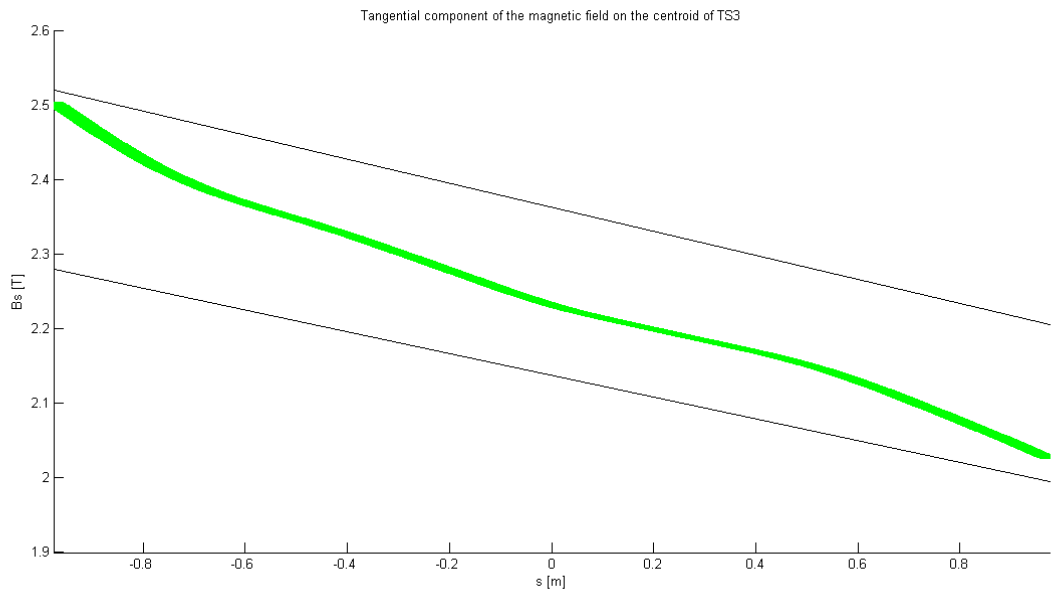

Figure 66 - Longitudinal magnetic field component in TS3

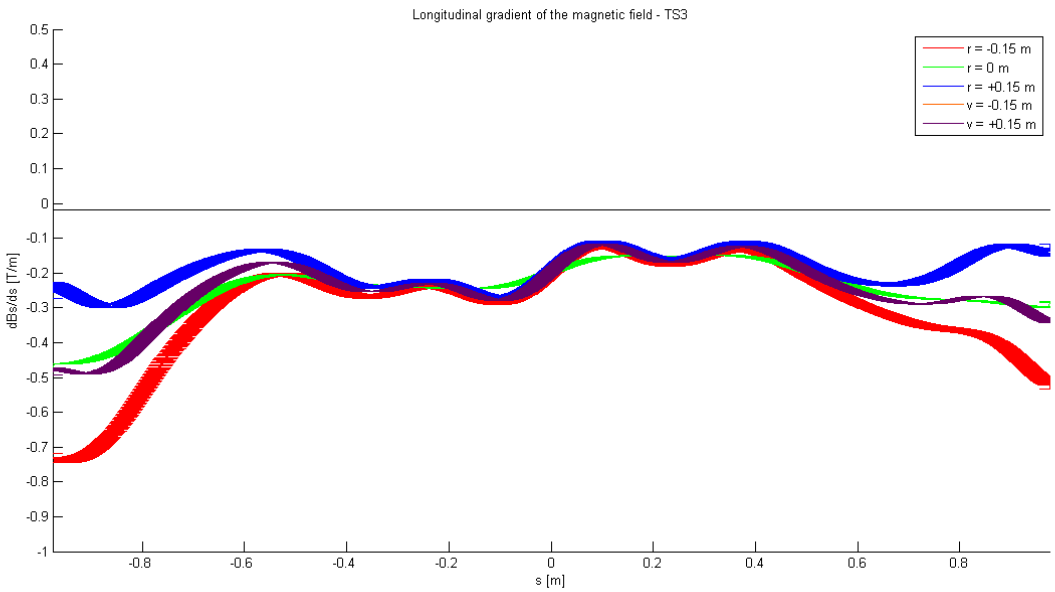

Figure 67 - Longitudinal field gradient in TS3.

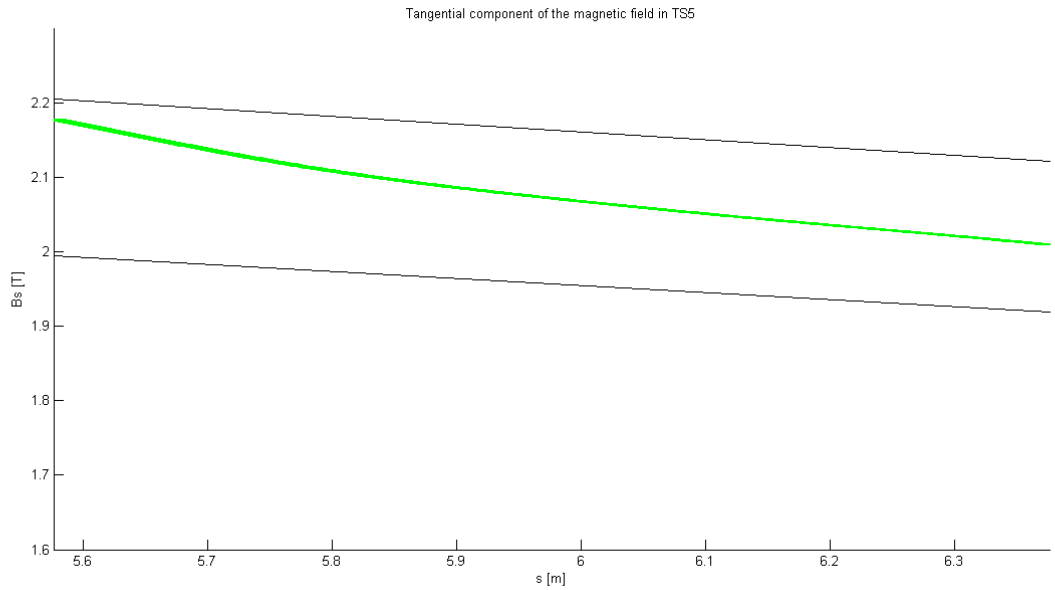

Figure 68 - Longitudinal magnetic field component in TS5

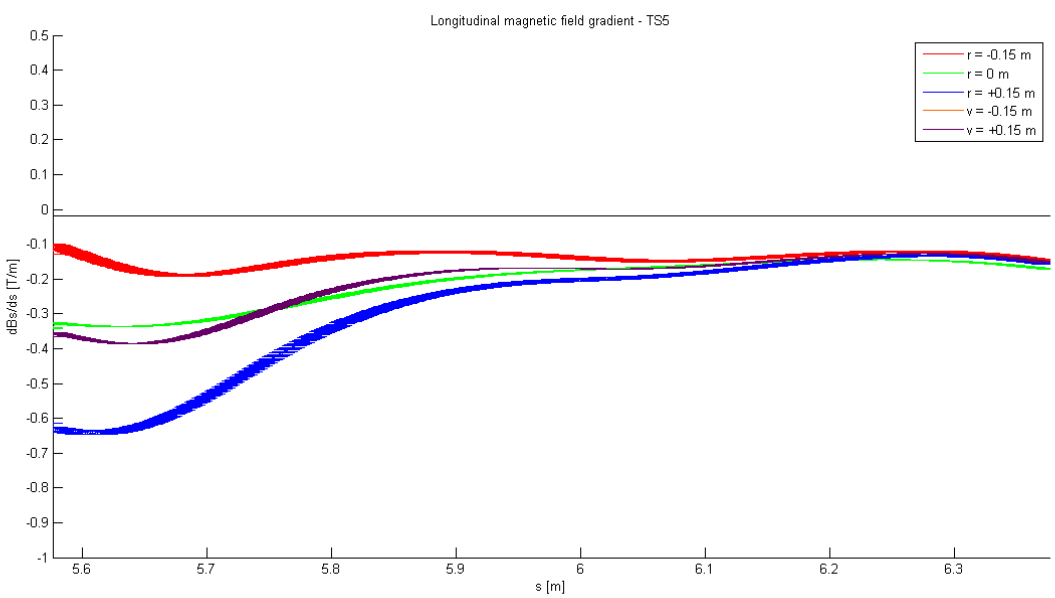

Figure 69 - Longitudinal field gradient in TS5.

3. SYSTEMATIC ERRORS

Since the most critical part of the TS is the first straight section (TS1) due to the fact that this has the highest field, the systematic analysis is mainly focused on the study of this section.

3.1 CASE 1 - TS1 IS BENT 1° TOWARDS +X

Figure 70 describes the type of geometrical deviation taken into account. Here the represented bending angle has been taken much higher than 1° for major clearness of the picture

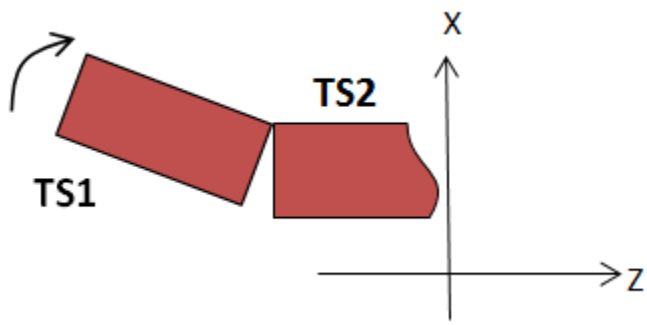

Figure 70 - TS1 bent towards +x

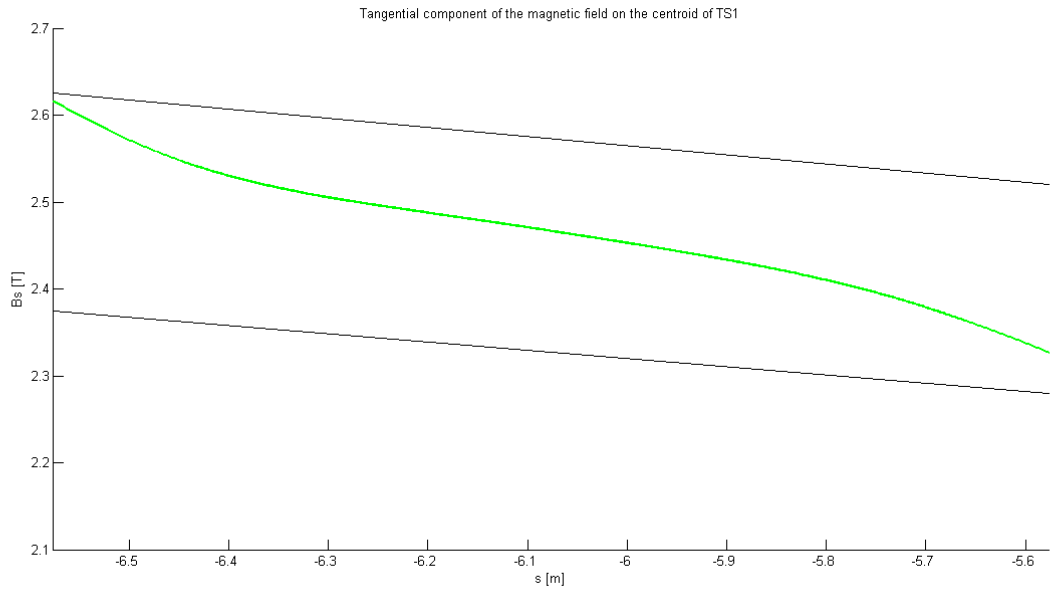

Figure 71 - Longitudinal magnetic field component in TS1.

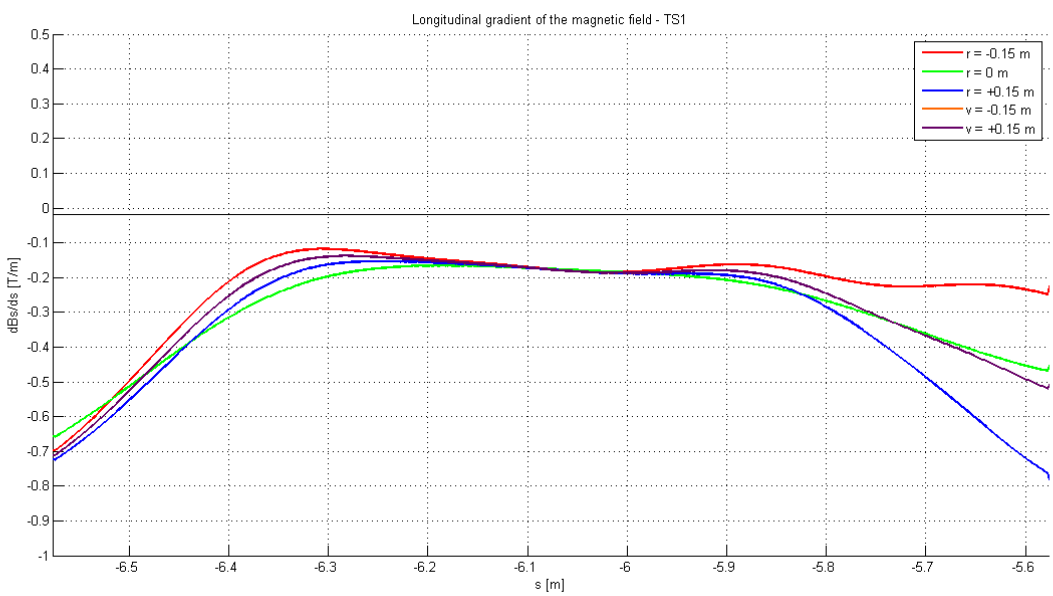

Figure 72 - Longitudinal field gradient in TS1.

3.2 CASE 2 - TS1 IS BENT 1° TOWARDS +Y

Figure 73 describes the geometrical deviation taken into account. Notice that, again, the bending angle has been taken much higher than 1° for major clearness of the picture.

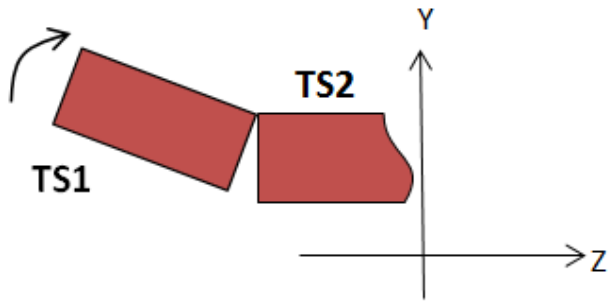

Figure 73 - TS1 bent towards +y

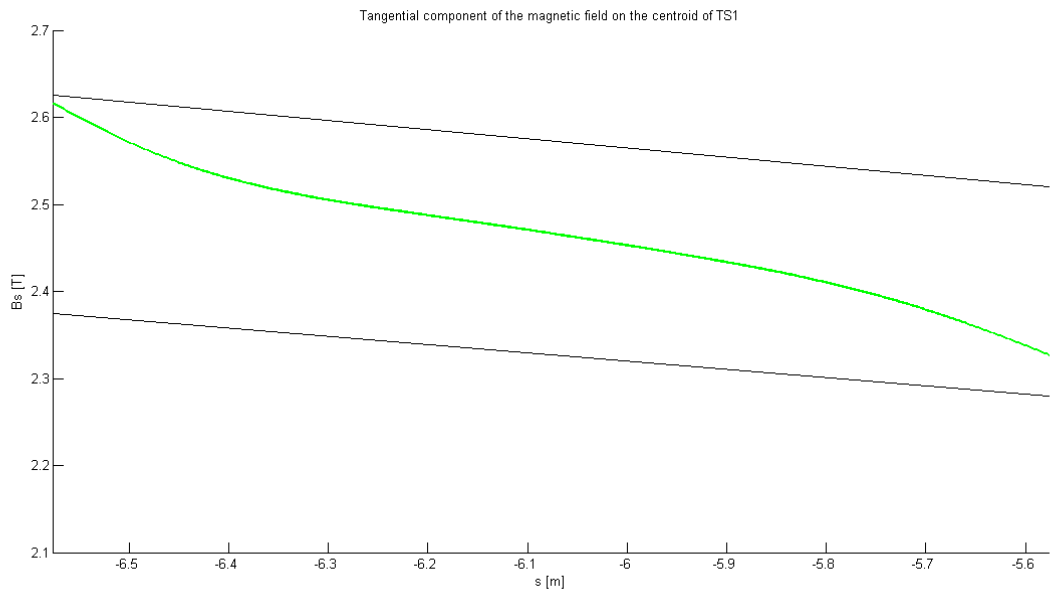

Figure 74 - Longitudinal magnetic field component in TS1.

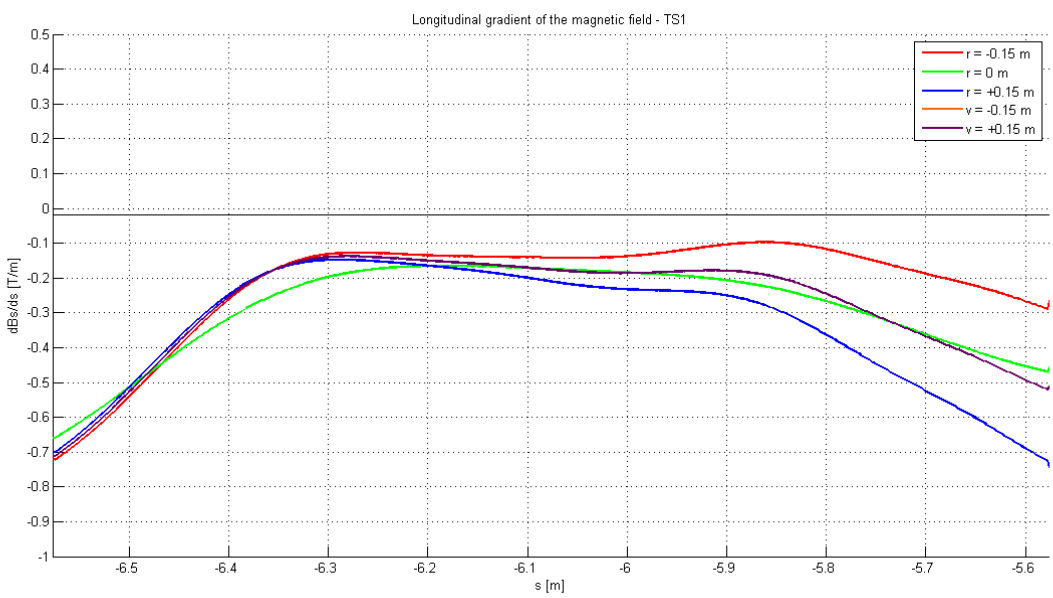

Figure 75 - Longitudinal field gradient in TS1.

3.3 CASE 3 - TS1 IS DISPLACED 10 mm IN +Z DIRECTION.

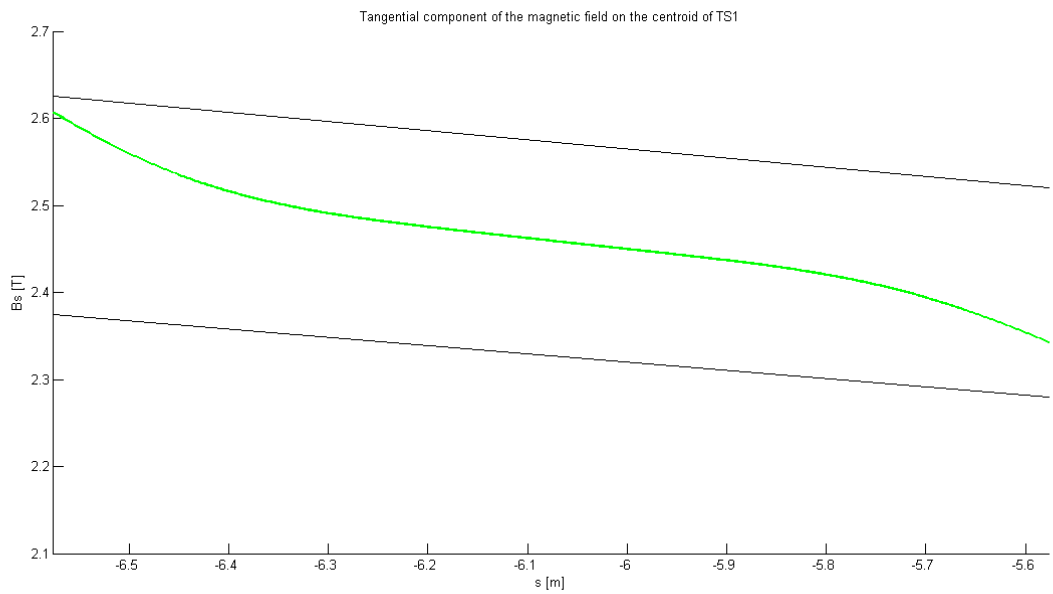

Figure 76 - Longitudinal magnetic field component in TS1.

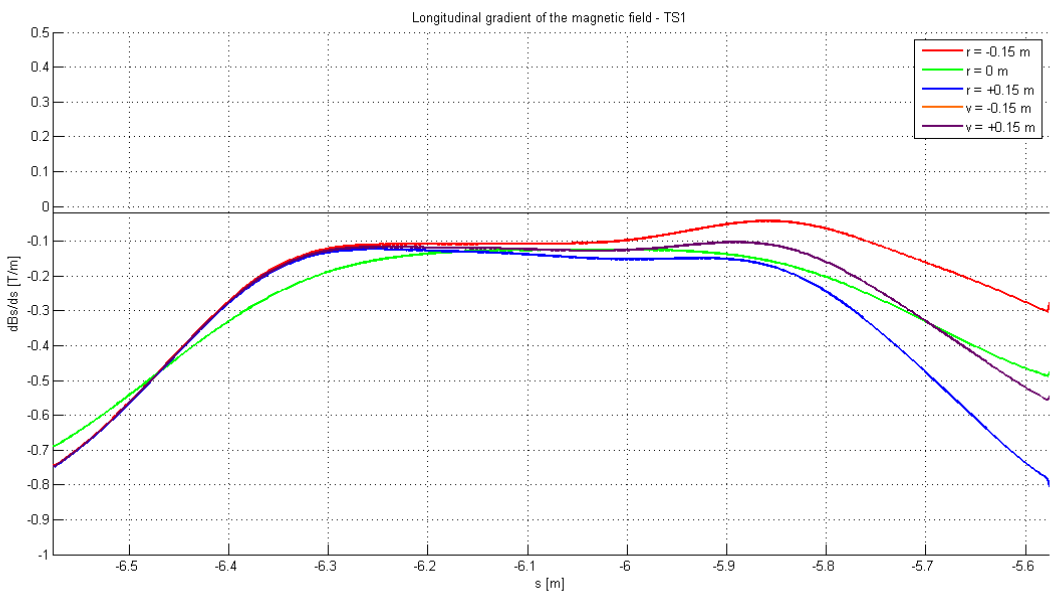

Figure 77 - Longitudinal field gradient in TS1.

3.4 CASE 4 - TS1 IS DISPLACED 10 mm IN -Z DIRECTION.

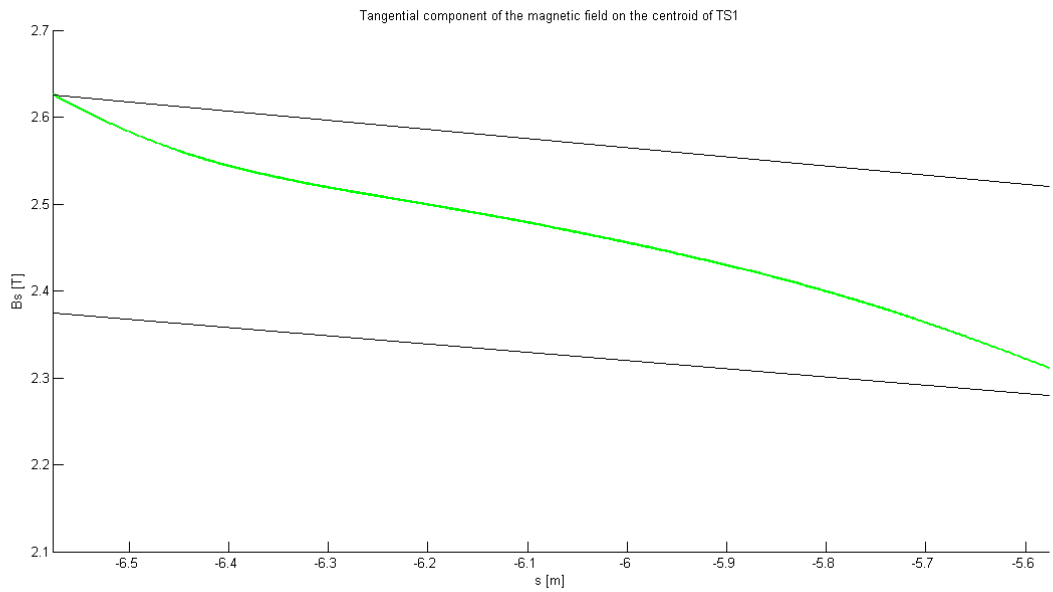

Figure 78 - Longitudinal magnetic field component in TS1.

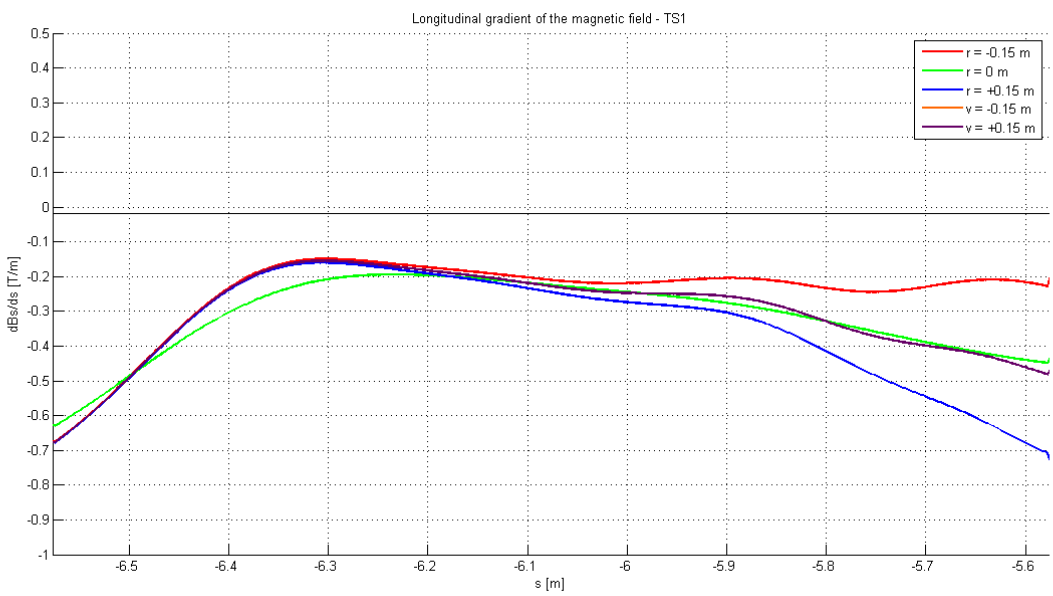

Figure 79 - Longitudinal field gradient in TS1.

3.5 CASE 5 - TS1 IS DISPLACED 10 mm IN +X DIRECTION.

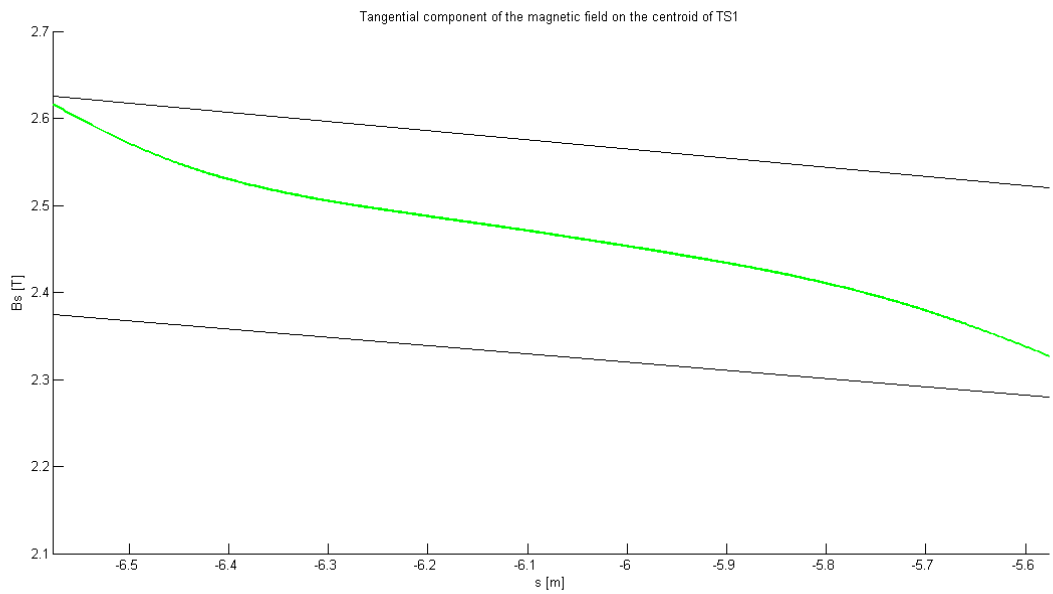

Figure 80 - Longitudinal magnetic field component in TS1.

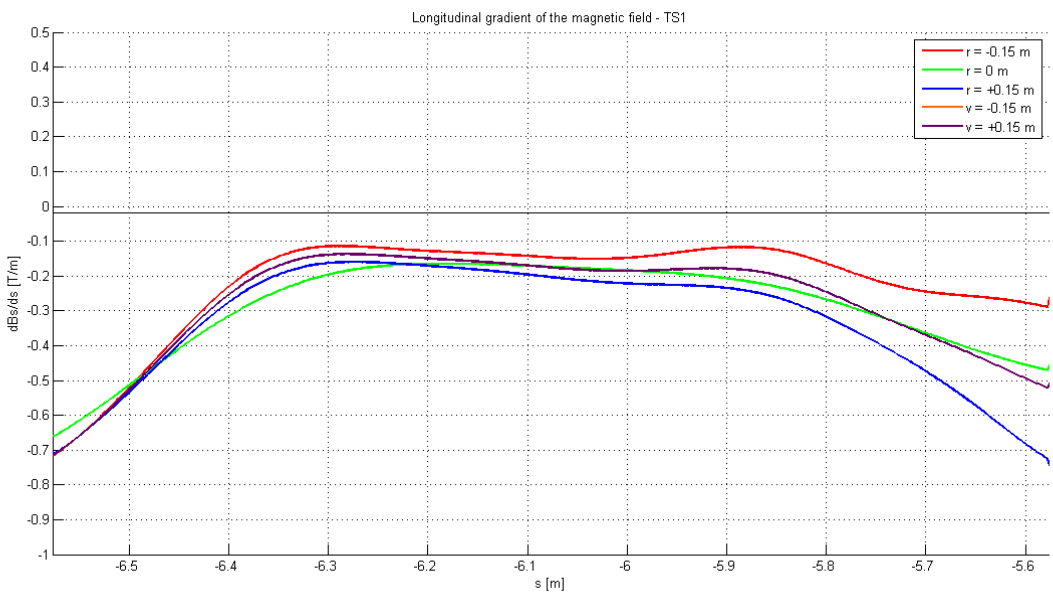

Figure 81 - Longitudinal field gradient in TS1.

3.6 CASE 6 - TS1 IS DISPLACED 10 mm IN -X DIRECTION.

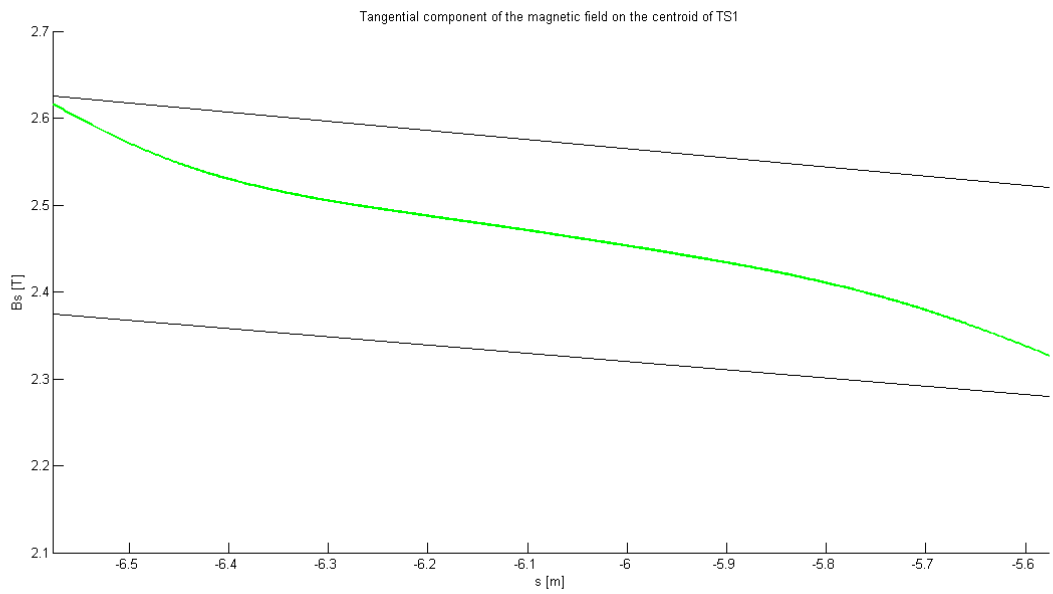

Figure 82 - Longitudinal magnetic field component in TS1.

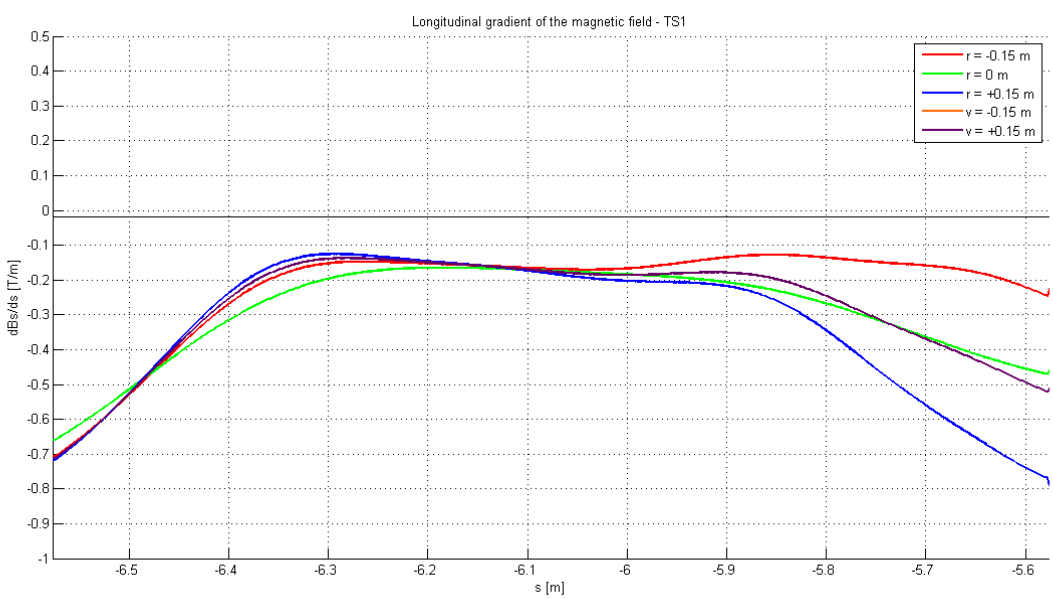

Figure 83 - Longitudinal field gradient in TS1.

3.7 CASE 7 – TS3u COILS ARE MOVED 10 mm IN -X DIRECTION, TS3d COILS ARE MOVED 10 mm IN +X DIRECTION.

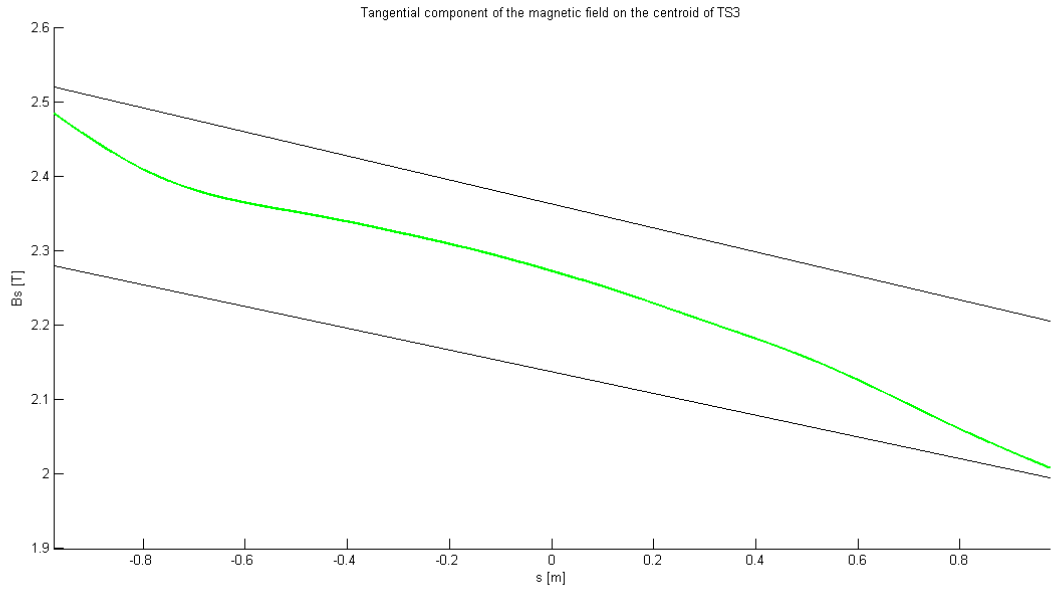

Figure 84 - Longitudinal magnetic field component in TS3.

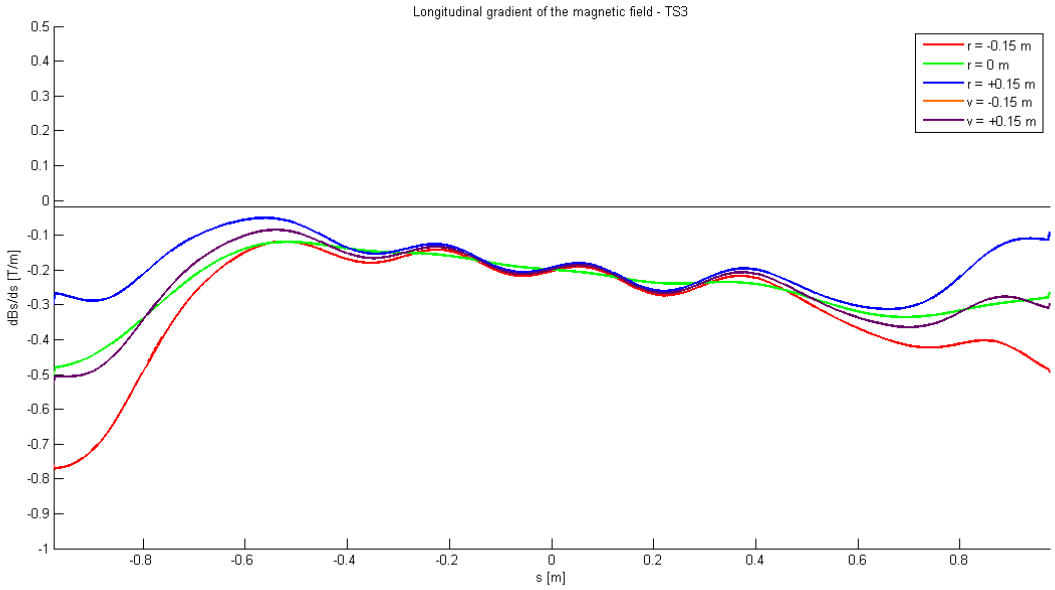

Figure 85 - Longitudinal field gradient in TS3.

3.8 CASE 8 - TS3u COILS ARE MOVED 10 mm IN +X DIRECTION, TS3d COILS ARE MOVED 10 mm IN -X DIRECTION.

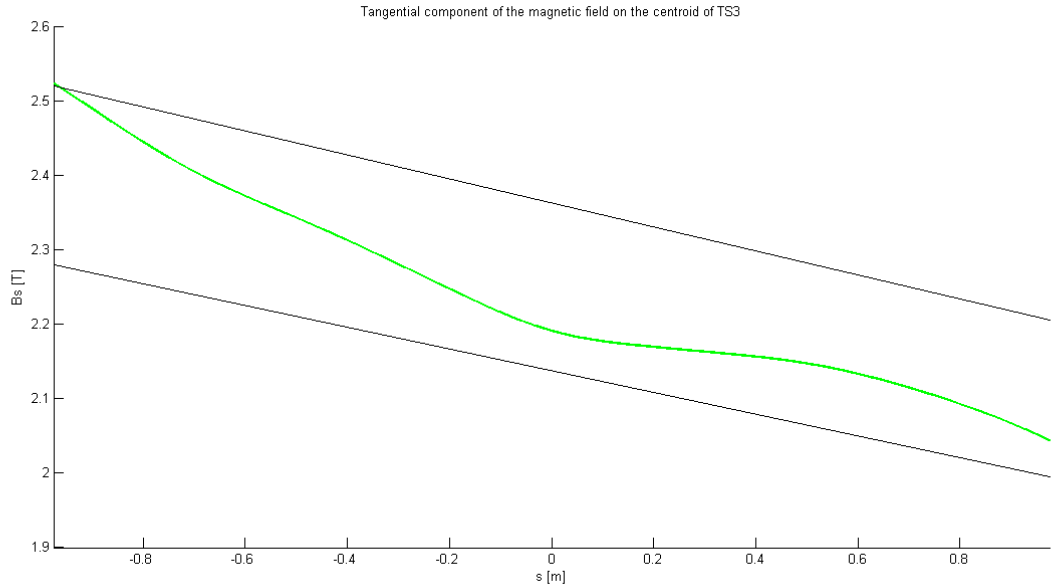

Figure 86 - Longitudinal magnetic field component in TS3.

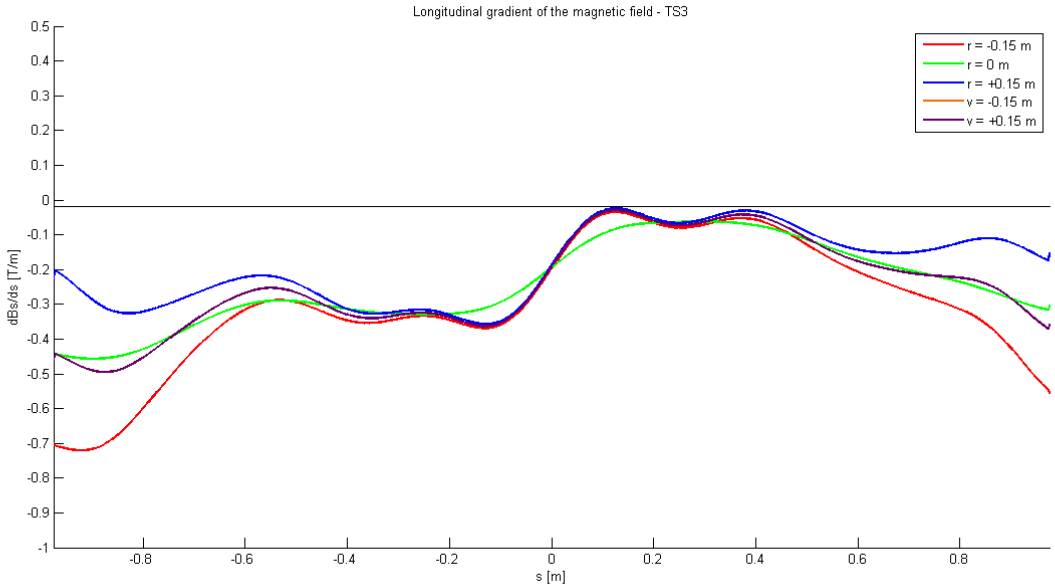

Figure 87 - Longitudinal field gradient in TS3.

3.9 CASE 9 – TS3u COILS ARE MOVED 2 mm IN +X DIRECTION, TS3d COILS ARE MOVED 2 mm IN -X DIRECTION.

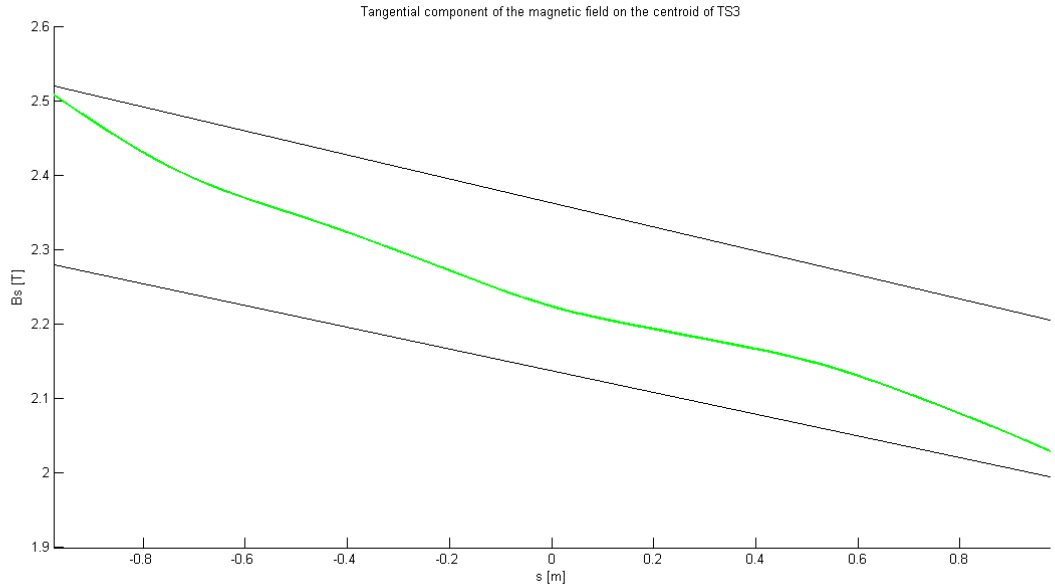

Figure 88 - Longitudinal magnetic field component in TS3.

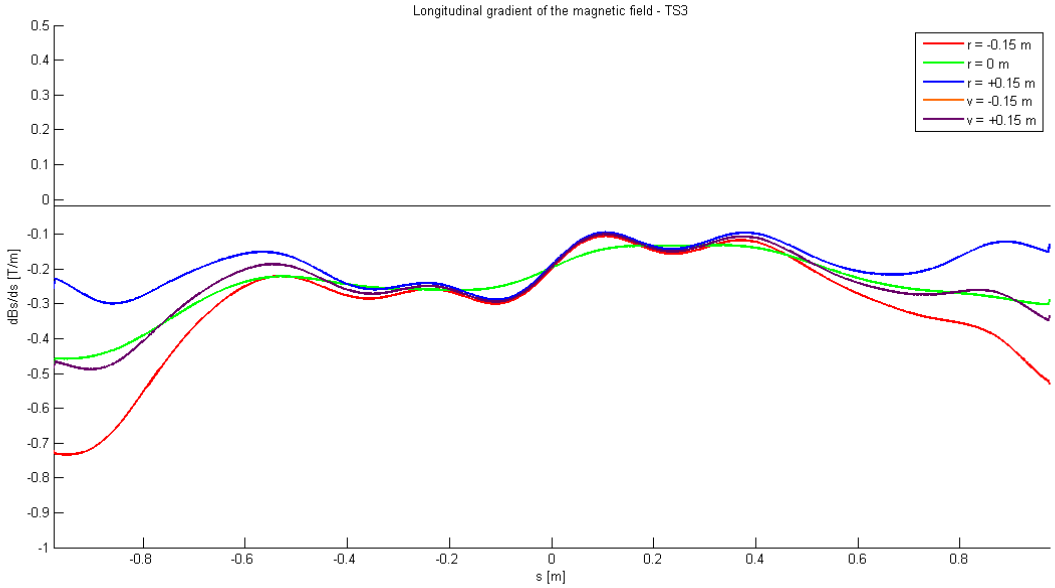

Figure 89 - Longitudinal field gradient in TS3.

3.10 CASE 10 - TS3u IS BENT 1° TOWARD –Z, TS3d IS BENT 1° TOWARD +Z

Figure 90 shows the deformation in exam; as usual, the angles in the picture are emphasized respect to the ones in the calculation.

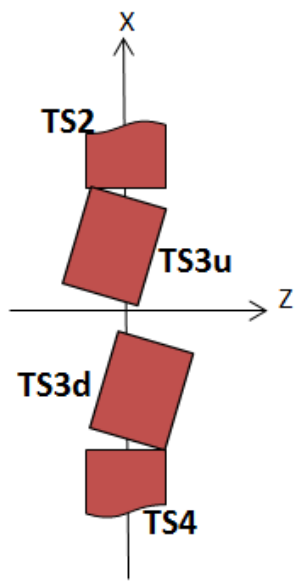

Figure 90 - TS3u bent toward -Z; TS3d bent in the opposite direction

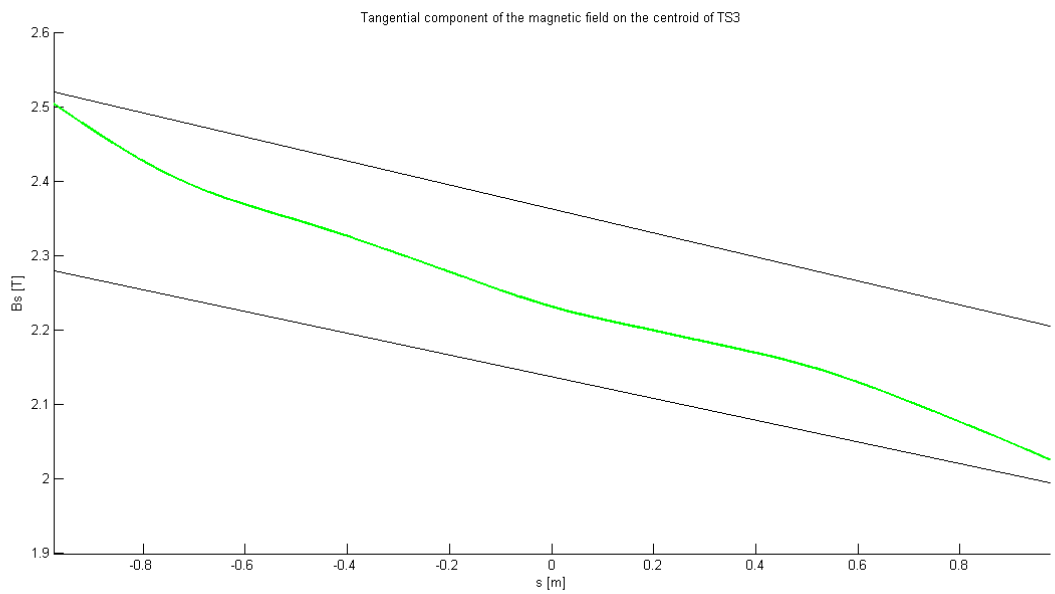

Figure 91 - Longitudinal magnetic field component in TS3.

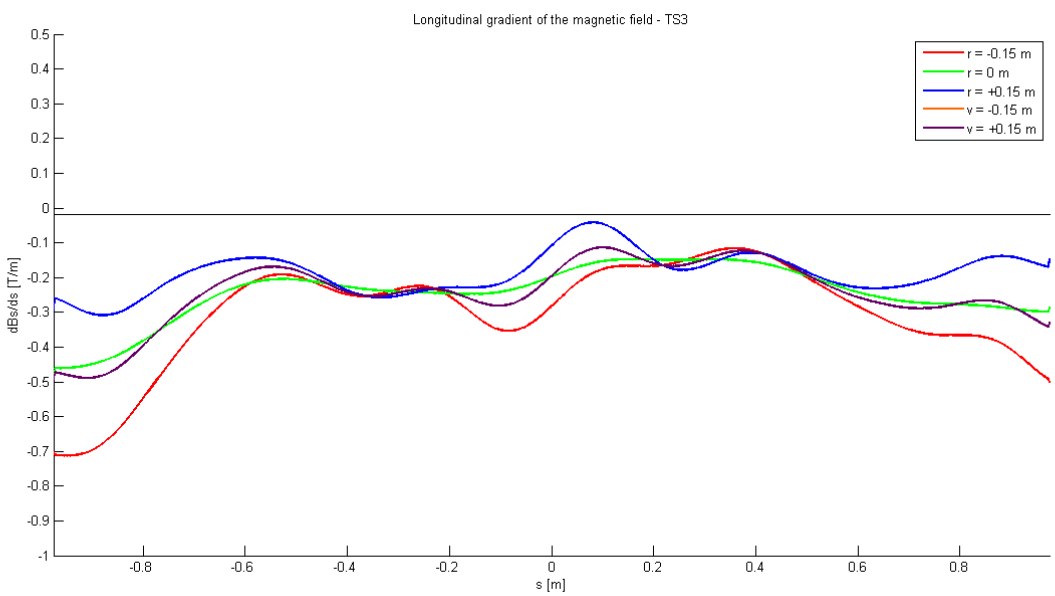

Figure 92 - Longitudinal field gradient in TS3.

3.11 CASE 11 - TS3u IS BENT 0.5° TOWARD –Z, TS3d IS BENT 0.5° TOWARD +Z

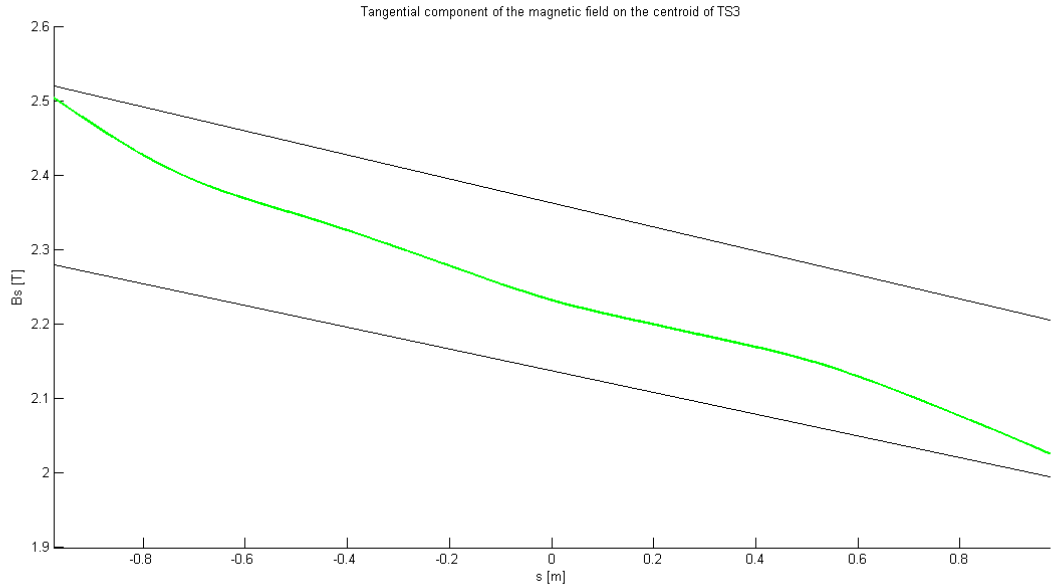

Figure 93 - Longitudinal magnetic field component in TS3.

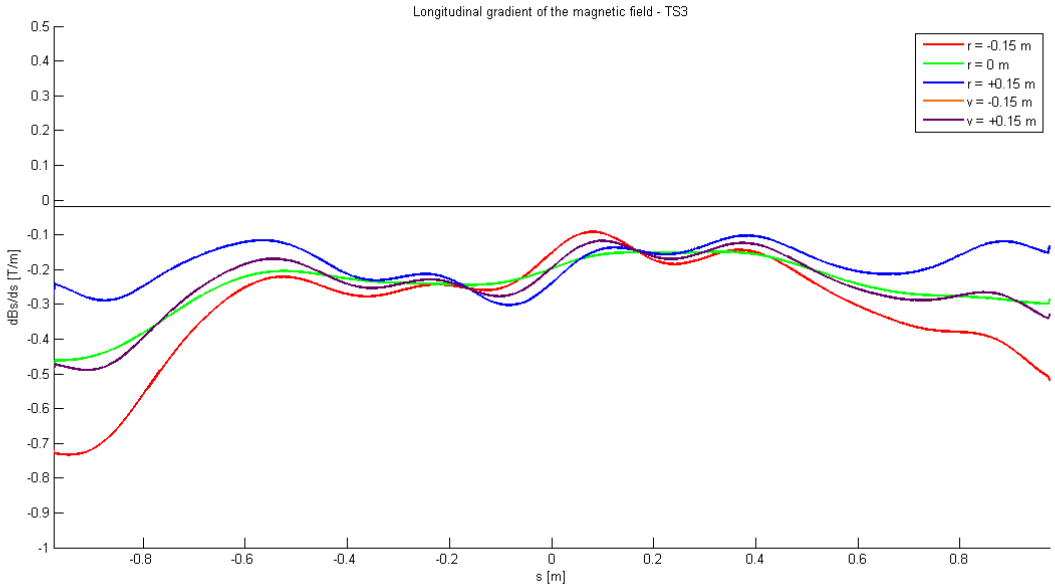

Figure 94 - Longitudinal field gradient in TS3.

3.12 CASE 12 – TS3 u IS BENT 1° TOWARD +Y, TS3d IS BENT 1° TOWARD +Y

Figure 95 shows the geometrical deviation considered, with emphasized angular displacements

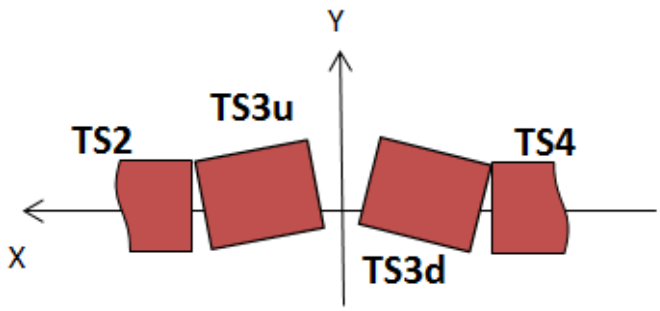

Figure 95 - TS3u and TS3d bent toward +Y

The other following cases (13-15) correspond to similar configurations, with the TS3u and TS3d bent in the specified direction.

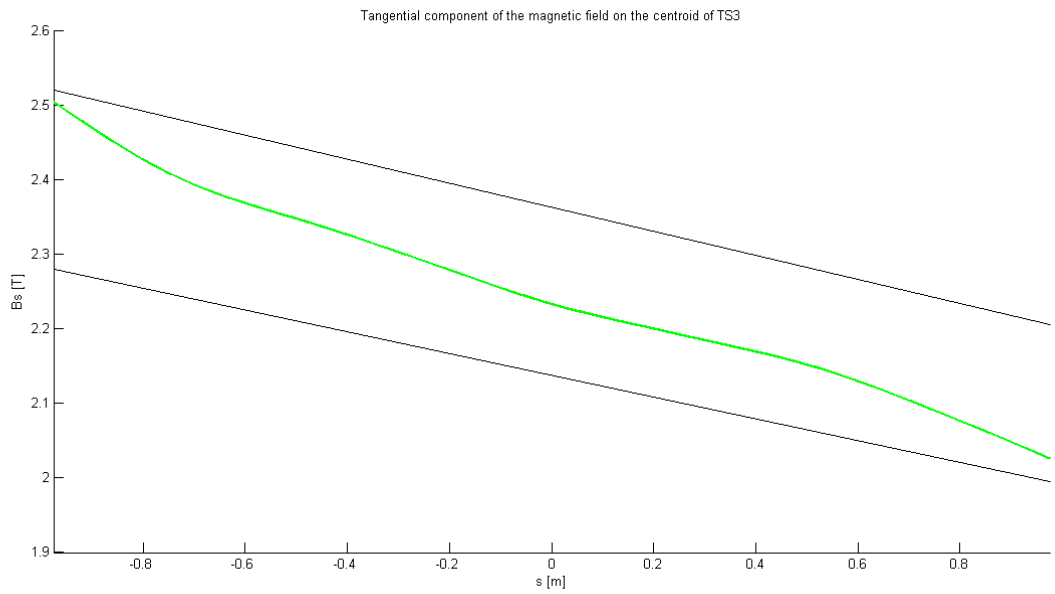

Figure 96 - Longitudinal magnetic field component in TS3.

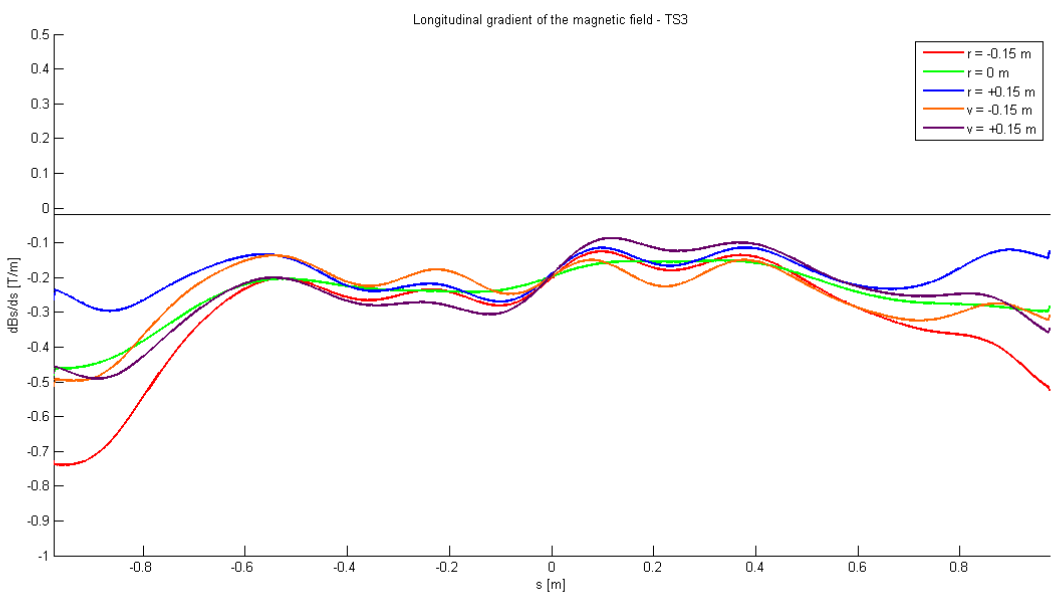

Figure 97 - Longitudinal field gradient in TS3.

3.13 CASE 13 – TS3 u IS BENT 1° TOWARD -Y, TS3d IS BENT 1° TOWARD -Y

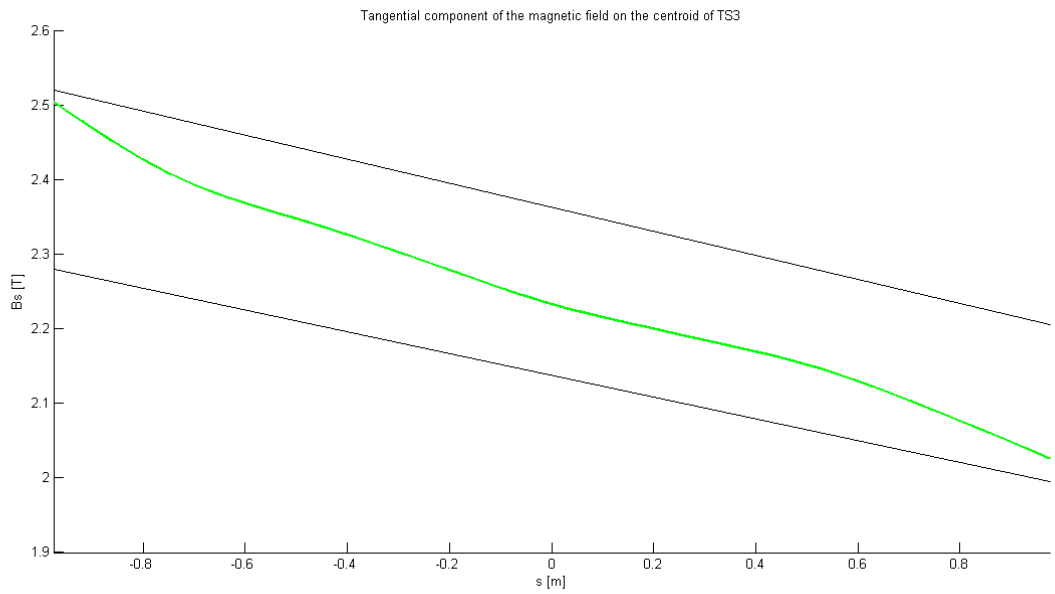

Figure 98 - Longitudinal magnetic field component in TS3.

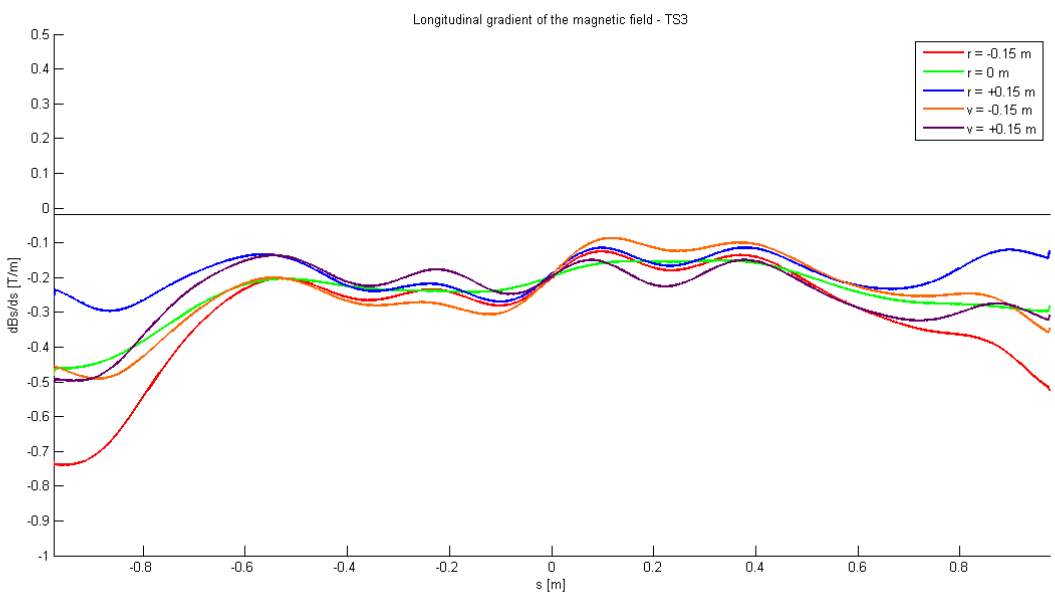

Figure 99 - Longitudinal field gradient in TS3.

3.14 CASE 14 – TS3 u IS BENT 1° TOWARD +Y, TS3d IS BENT 1° TOWARD –Y

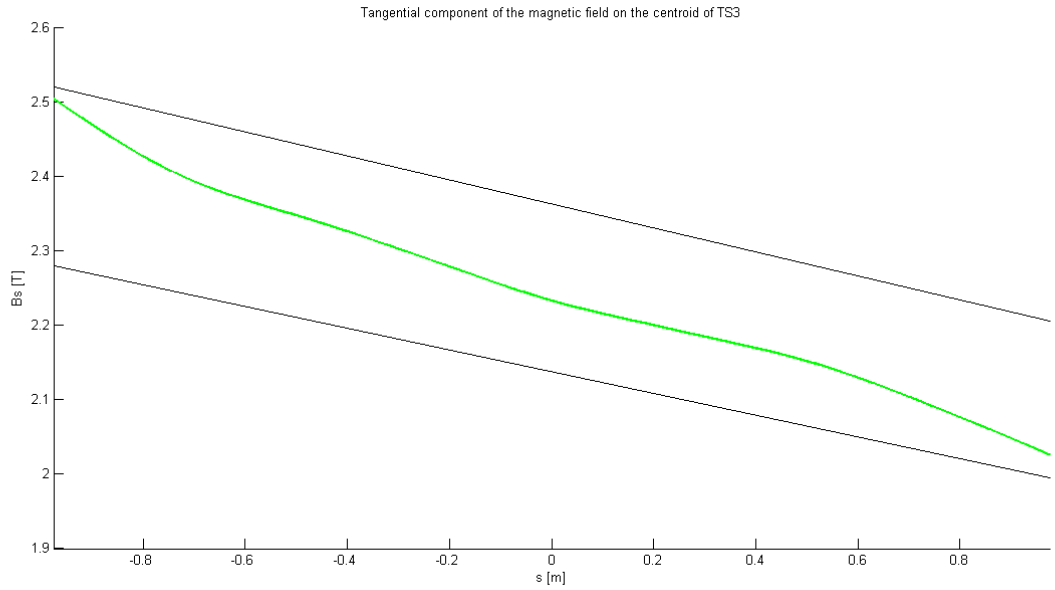

Figure 100 - Longitudinal magnetic field component in TS3.

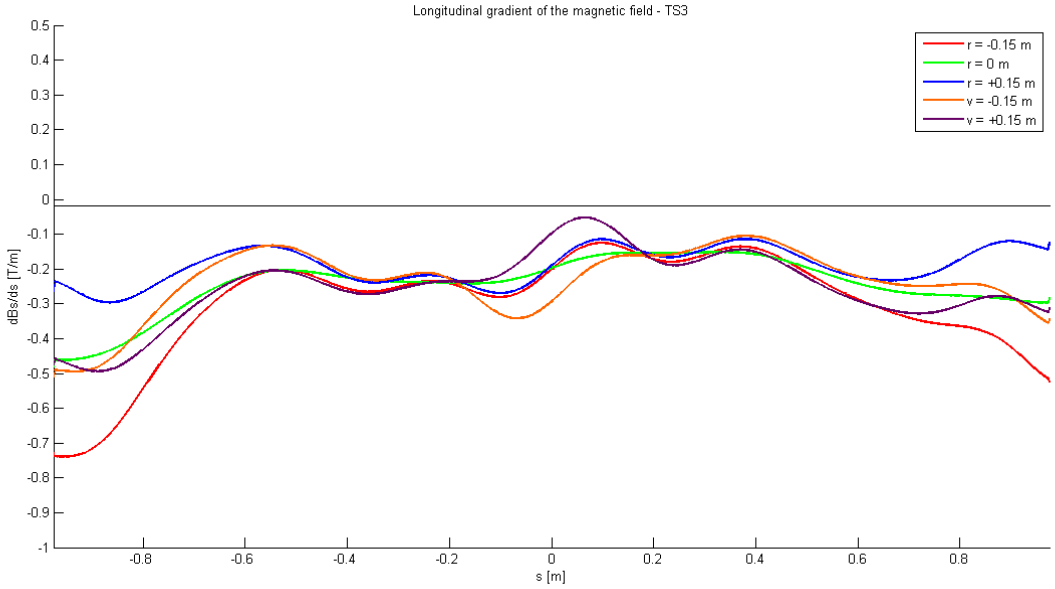

Figure 101 - Longitudinal field gradient in TS3.

3.15 CASE 15 – TS3 u IS BENT 1° TOWARD -Y, TS3d IS BENT 1° TOWARD +Y

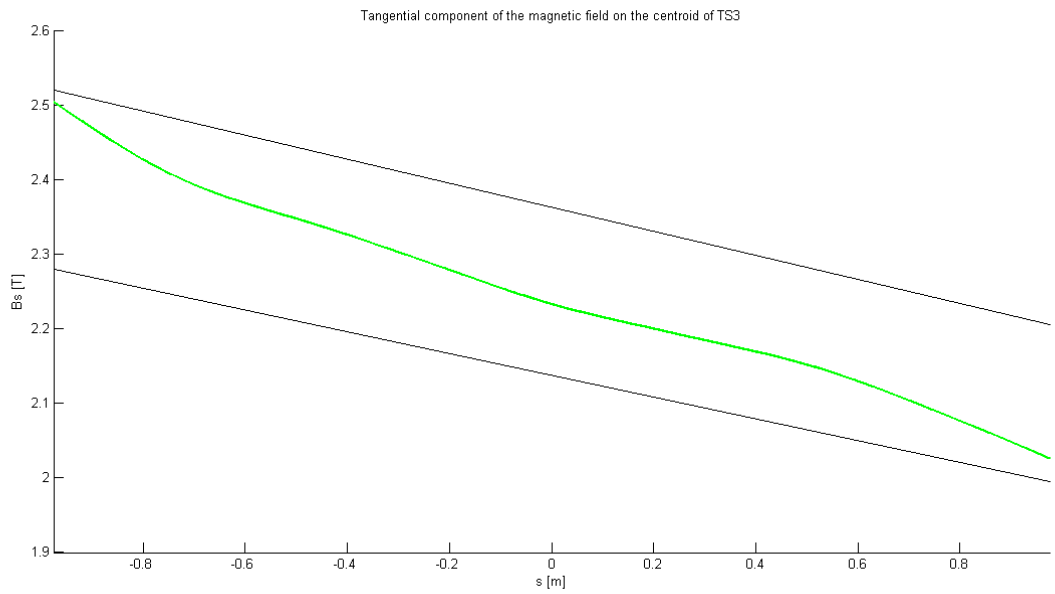

Figure 102 - Longitudinal magnetic field component in TS3.

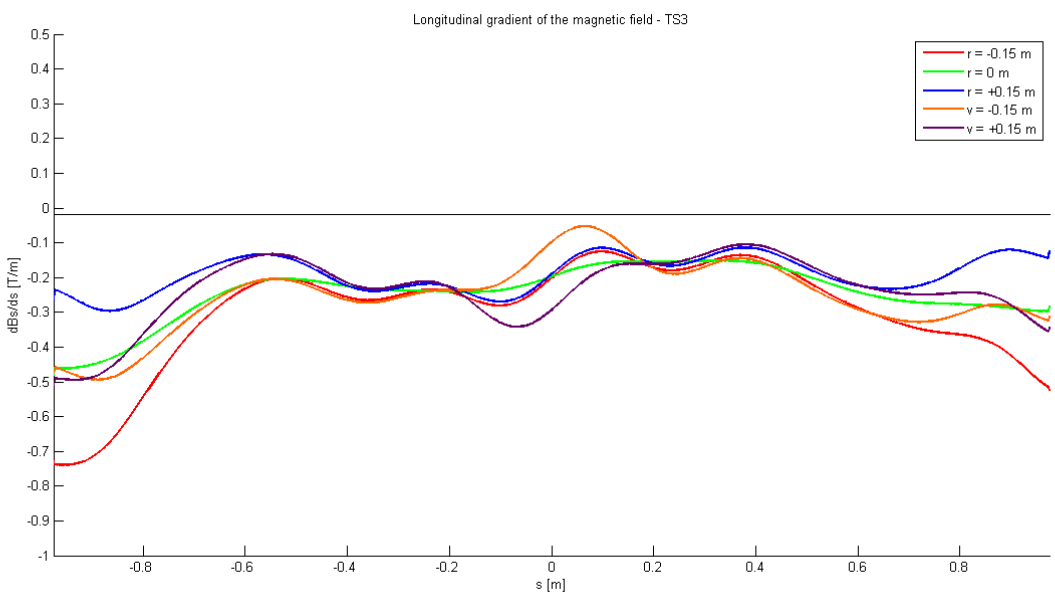

Figure 103 - Longitudinal field gradient in TS3.

3.16 CASE 16 – TS5 COILS ARE DISPLACED 10 mm IN +Z DIRECTION

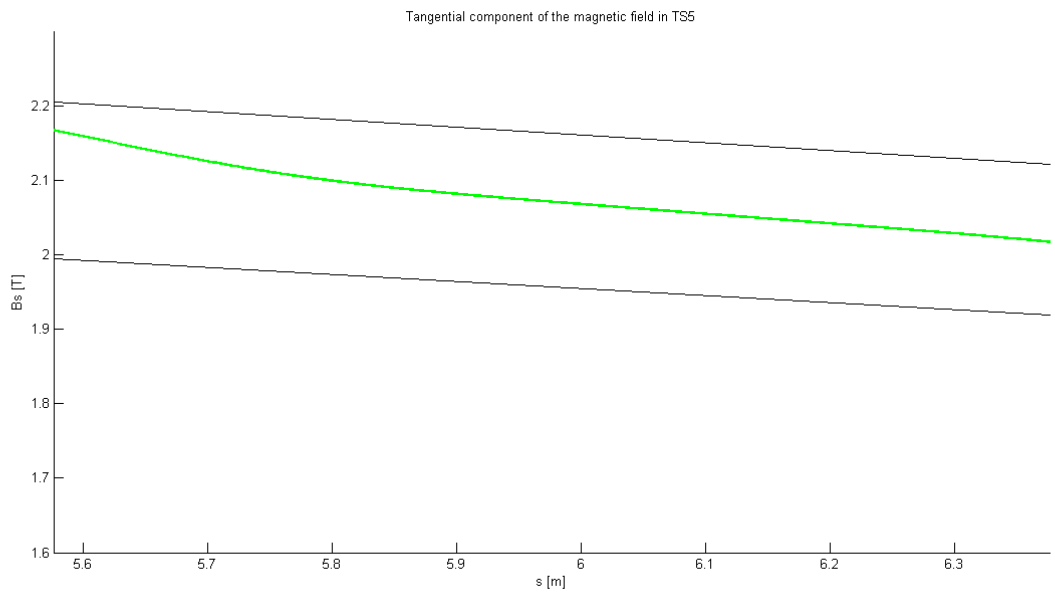

Figure 104 - Longitudinal magnetic field component in TS5.

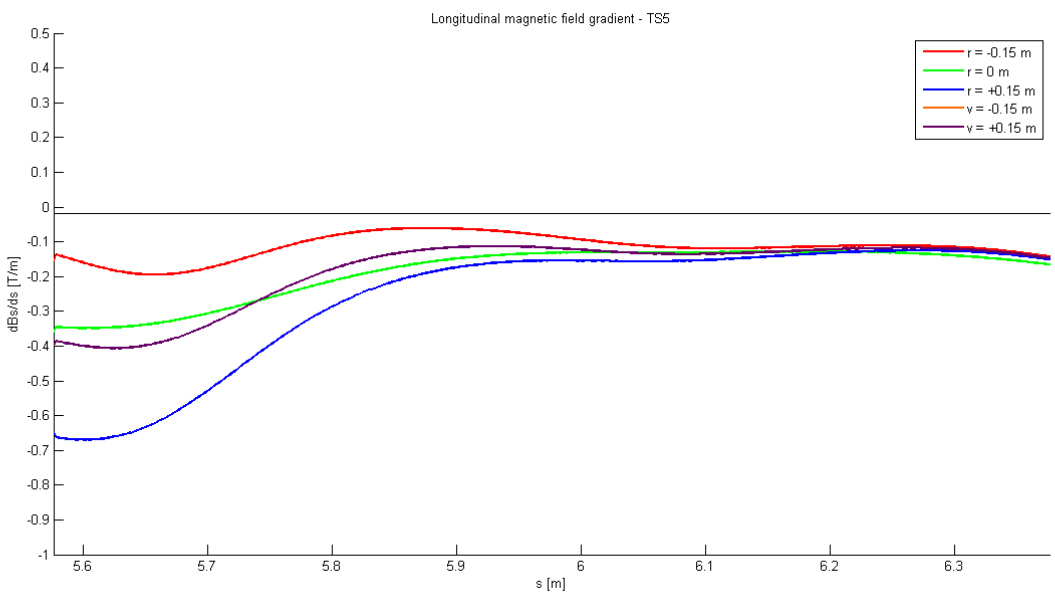

Figure 105 - Longitudinal field gradient in TS5.

3.17 CASE 17 – TS5 COILS ARE DISPLACED 10 mm IN -Z DIRECTION

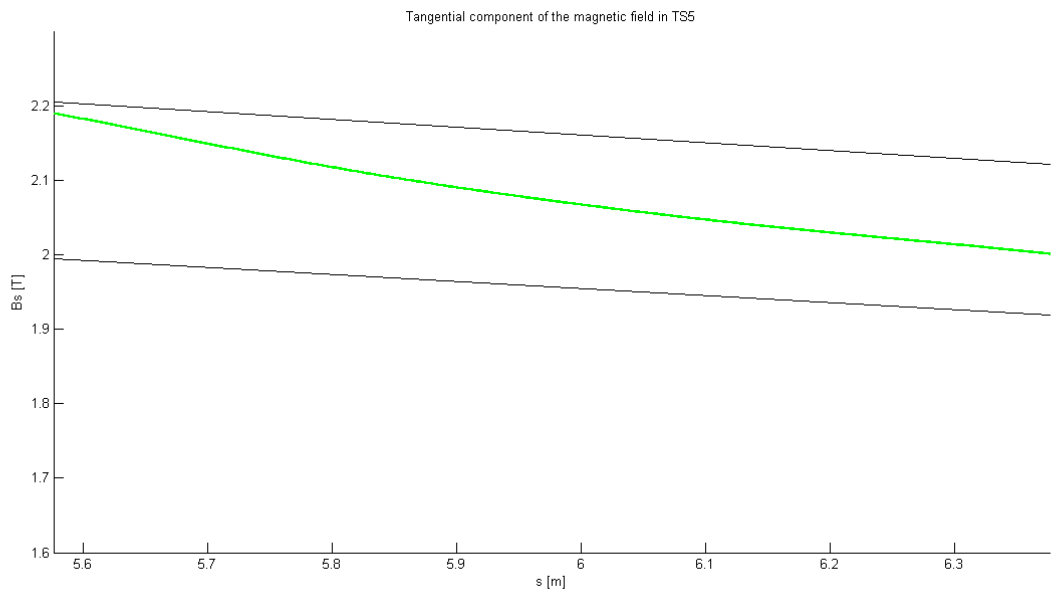

Figure 106 - Longitudinal magnetic field component in TS5.

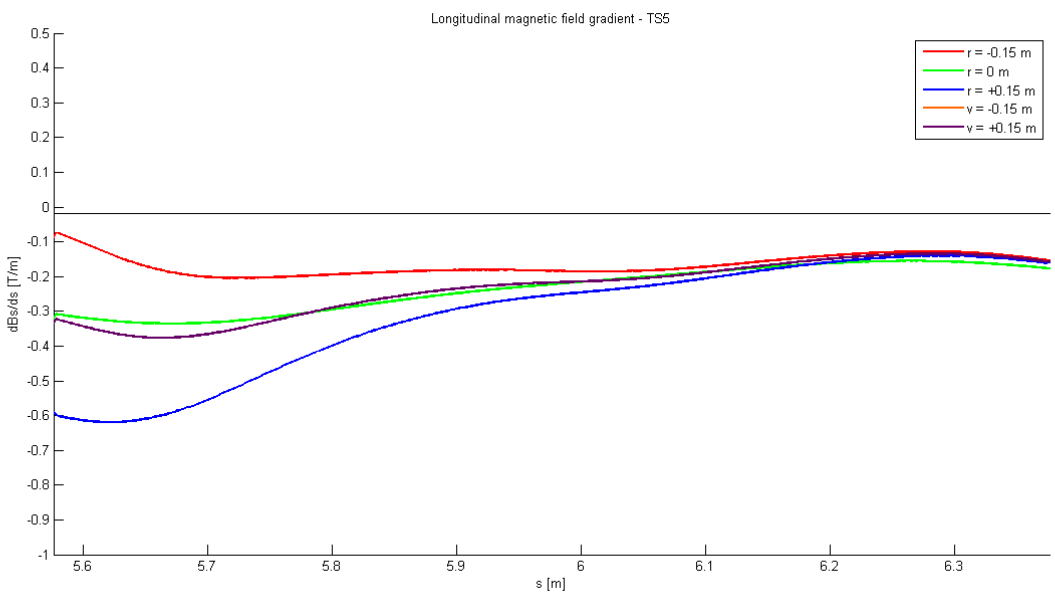

Figure 107 - Longitudinal field gradient in TS5.

3.18 CASE 18 – TS5 IS BENT 1° TOWARDS +X

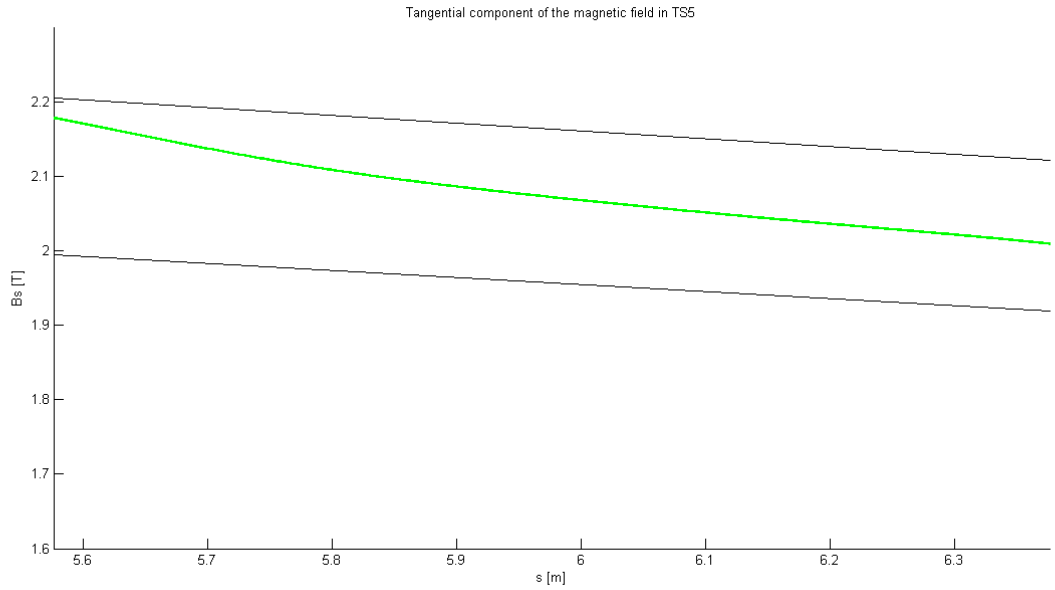

Figure 108 - Longitudinal magnetic field component in TS5.

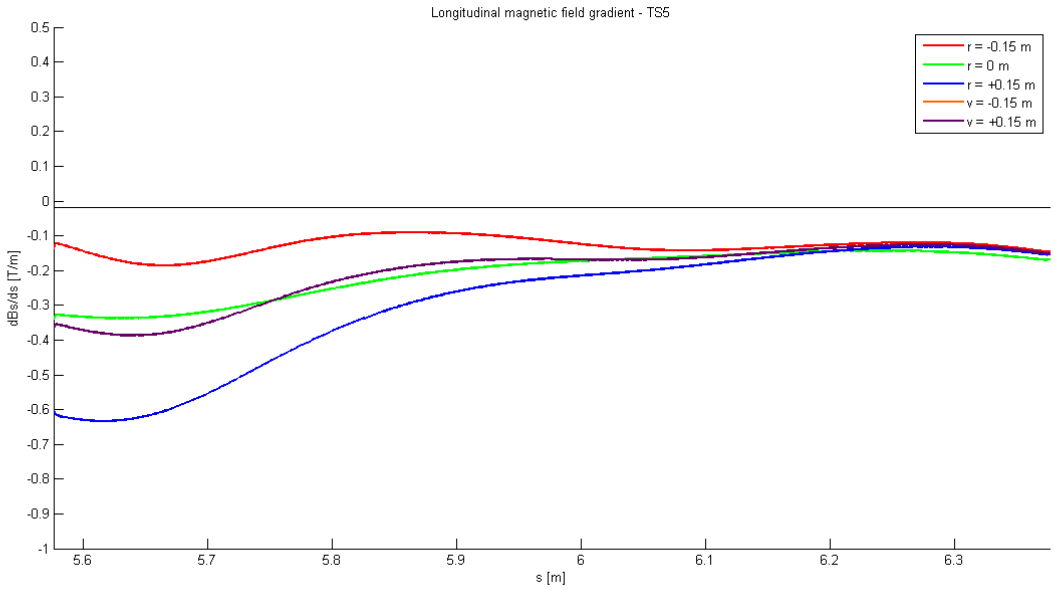

Figure 109 - Longitudinal field gradient in TS5.

3.19 CASE 19 - ESTIMATED RADIAL DISPLACEMENTS APPLIED TO TSu AND TSd

For this section of the systematic analysis, it was considered the displacements from the mechanical analysis of the support structure of the coils [3].

Figure 110 represents the estimated module of the radial displacement of the first 25 coils of the solenoid (TSu).

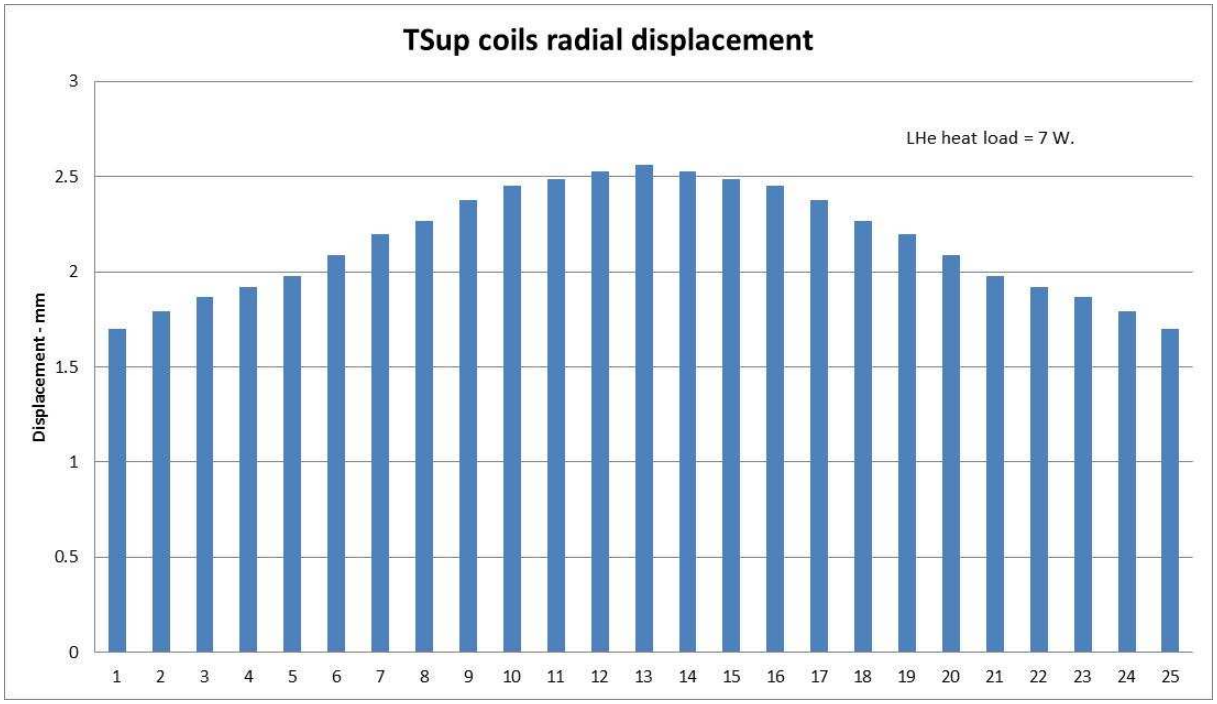

Figure 110 - Estimated radial displacements for the first 25 coils

These same displacements are applied symmetrically also to the second part of the TS (coils 26-50), but in opposite direction: that means that coils of TS3 lying on different sides of the gap slide in opposite directions; the coils of TS2 and TS4 move toward the centre of curvature respectively of the first and of the second bend. These movements are summarized in Figure 111.

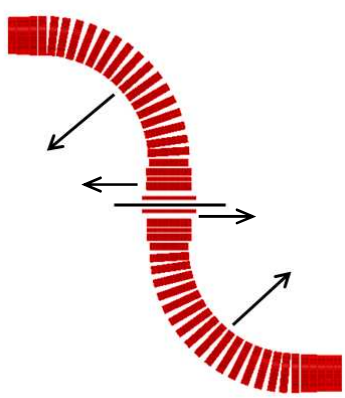

Figure 111 - Coils radial displacement directions

Values of the histogram in Figure 110 have been multiplied by 2 in order to obtain the following graphs.

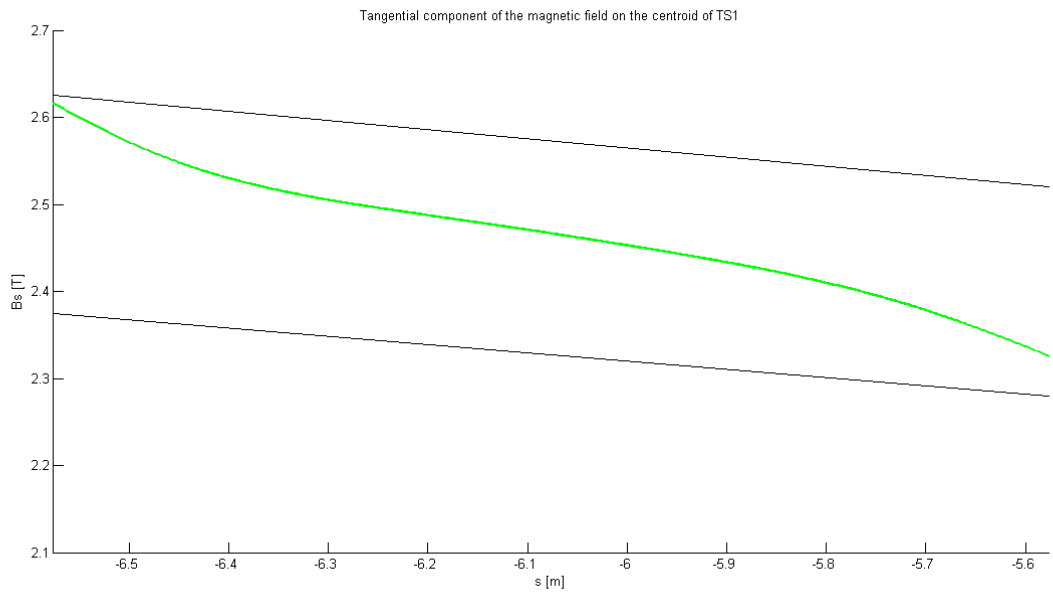

Figure 112 - Longitudinal magnetic field component in TS1.

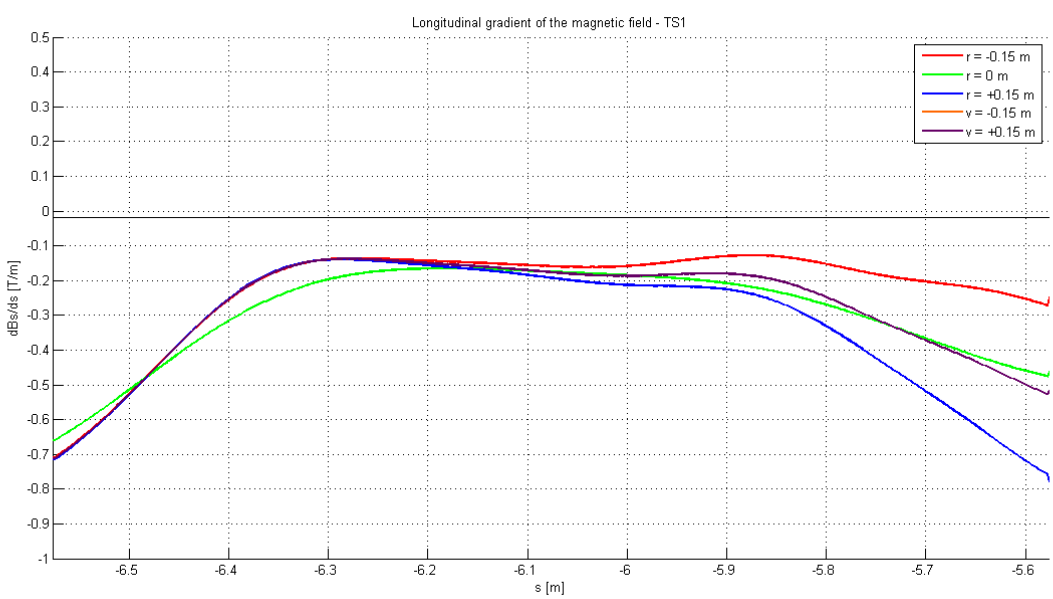

Figure 113 - Longitudinal field gradient in TS1.

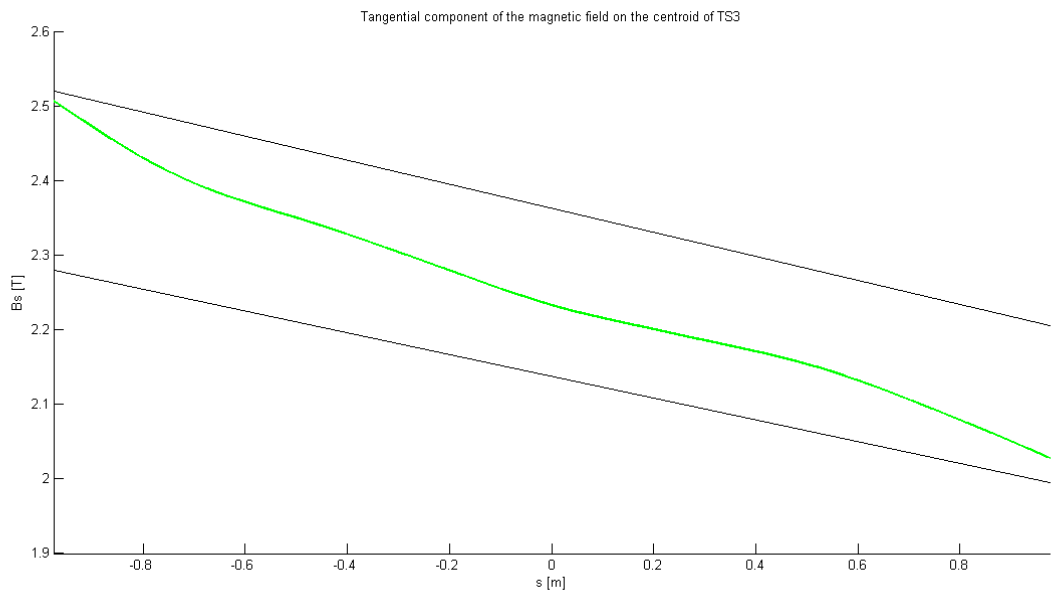

Figure 114 - Longitudinal magnetic field component in TS3

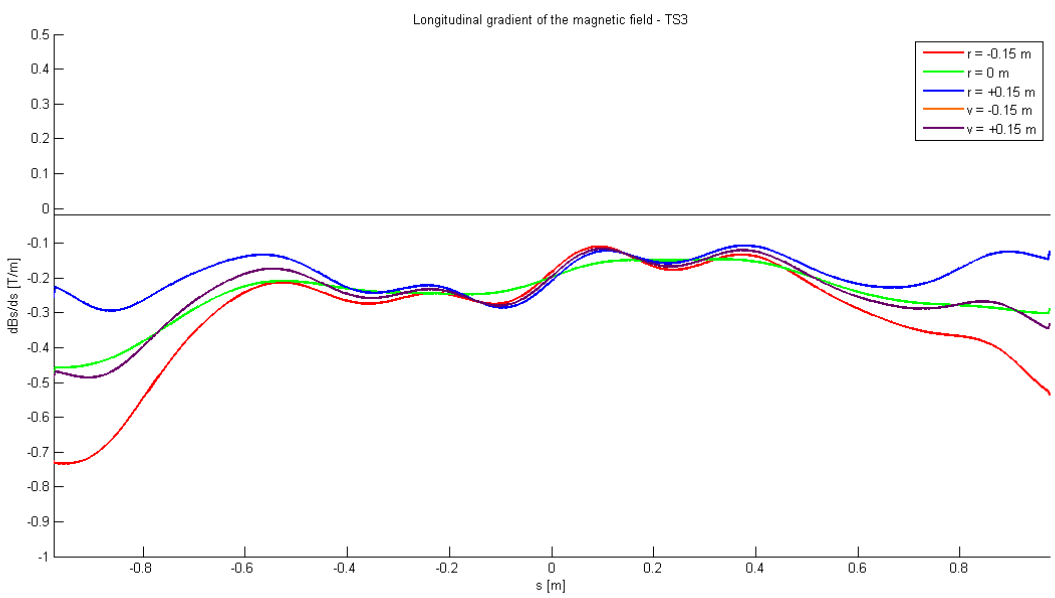

Figure 115 - Longitudinal field gradient in TS3.

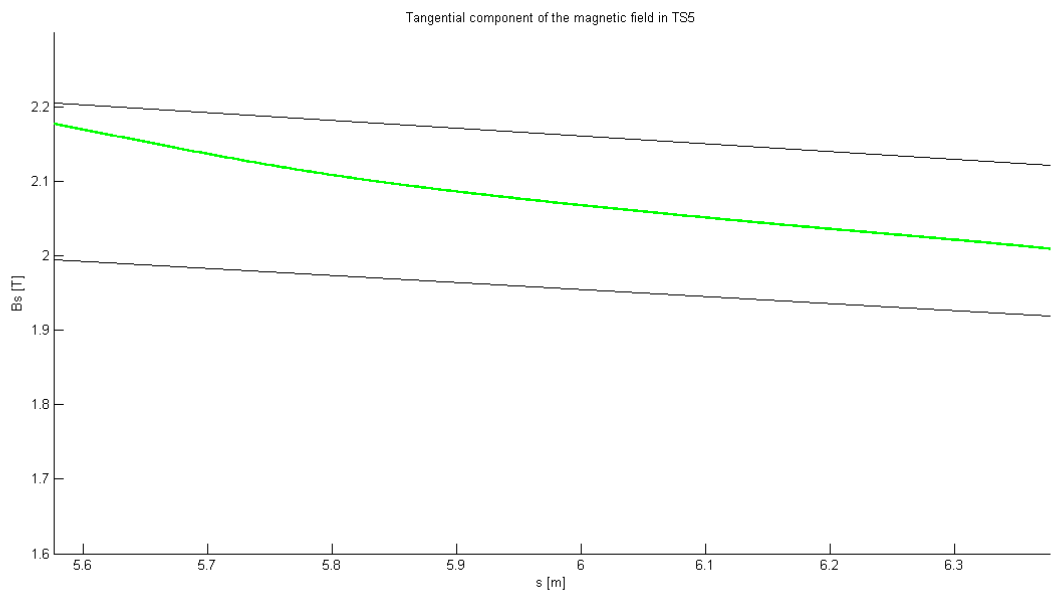

Figure 116 - Longitudinal magnetic field component in TS5

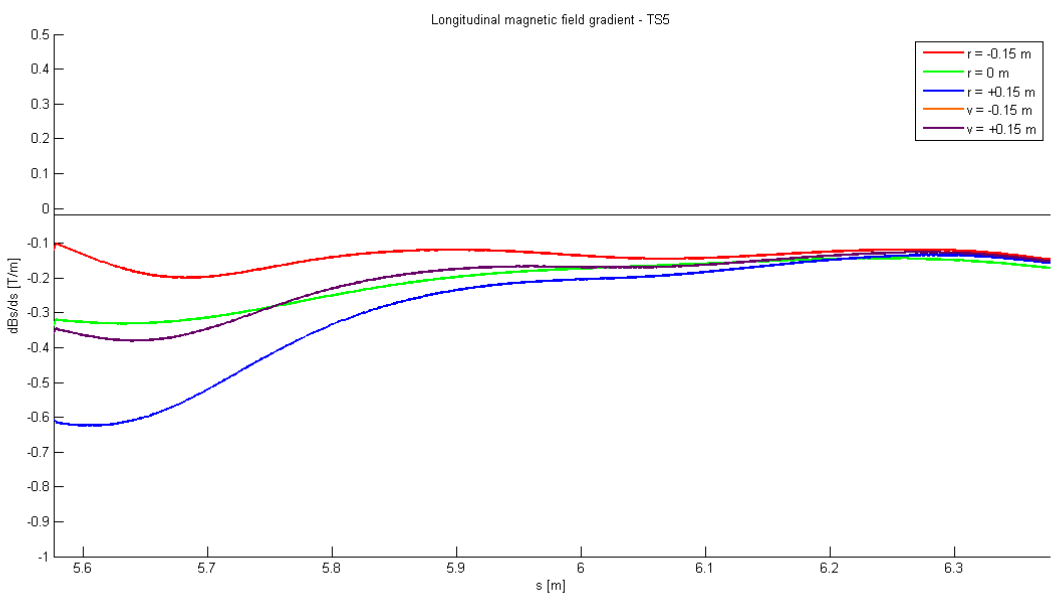

Figure 117 - Longitudinal field gradient in TS5.

4. COILS ROUNDNESS

In all of the analysis above, the coils were assumed to be perfectly round. The figure bellow shows some different possible orientations for the roundness.

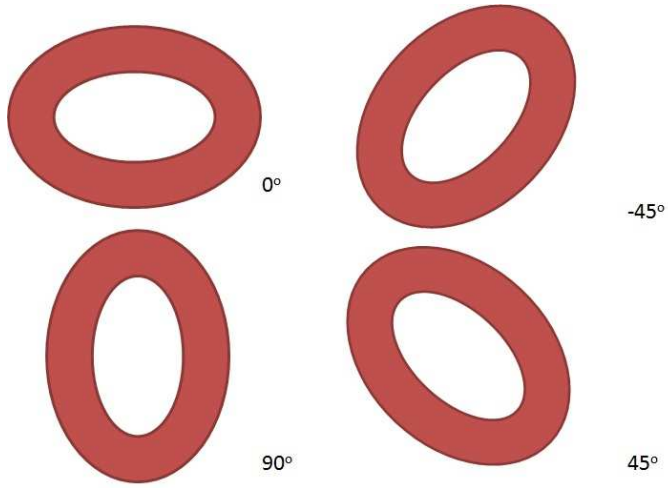

Figure 118 - Coil roundness different orientations

For version 7, no calculations on the cases above have been made. Results available from simulations on version 5 show that some rare violations of the condition on the longitudinal gradient are possible in TS1 section with roundness lower than 0.98, that is a value generally lower respect to the real expected one.

5. CONCLUSIONS

A study of the coil position tolerance was done. Two different scenarios were considered: random and systematic errors.

The errors considered in this study are relatively big compared to the ones expected in the real case.

The results show that, in general, the magnetic design version 7 is very robust. No particular violations are detected for the cases examined.

This study can be used to indicate positions for improvements in the magnetic design.

6. REFERENCES

[1] M. Lopes, "Mu2e Transport Solenoid Magnetic Design (Magnetic Design Version 7)", Mu2e-DocDB-1233

[2] R. Coleman et al., "Mu2e Magnet Field Specifications", Mu2e-DocDB-1266

[3] G. Ambrosio et al., "Mu2e TSu Design Study", Mu2e-DocDB-2075