Report on mechanical measurements in the main LHC dipole collared coils: March-April 2004

I.Vanenkov, AT-MAS-MA

This report gives the updated data concerning the mechanical measurements on inner and outer layers of the coils, assembled poles and collared coils.

The dashboard

The available data on coils size by the end of April:

- **Firm 1 (ALSTOM-JEUMONT)** – In total 529 poles have been produced and all measured for coil size (in last 2 months 69 poles, which is a bit less compared to the January – February period, when 80 poles were manufactured and measured). Now all poles are measured with reduced number of measuring sections along the coil (5 instead 15).
- **Firm 2 (ANSALDO)** – In total, more then 416 inner and outer layers have been produced, where 56 layers of each type in the last 2 months (65 layers during January – February period). Up to date, 120 inner and 132 outer have been measured (typically, one inner and one outer layer per magnet are measured).
- **Firm 3 (BNN)** – CERN receives the data on mechanical measurements from BNN by batches with 2÷3 weeks interval. Up to date, the data on 560 inner and outer layers for 180 magnets is available at CERN (last delivery of data mid of April). Following series production specification, the number of measuring coils and the number of measuring sections along the coil has been gradually reduced. Actually, one inner and one outer layer per magnet are measured.

What is new:

Trends in coil sizes. Periodic trends (with positive and negative slopes) are observed in the coils size data from all the firms. Among three firms, the firm 1 is producing the coils with largest amplitude of coil size variation, which often require use of non-nominal polar shims. An action was taken at this firm to reduce the coil size variation. We report the results of this action.

Coil waviness. Due to significant reduction of the measuring points along the coils at firm 3, and firm 1 there is no more possibility to monitor the standard deviation of coil size along the coil for these firms. We present the graph on this parameter only for firm 2, which continues measure the coil size in 15 longitudinal positions along the coil.

Collared coils dimensional data. The data on collared coil dimensional measurements taken over magnets ends shows a significant difference in the CC dimensions between different magnets and between different firms. The investigations are going on in MA section concerning the collars tolerances and their impact on magnet field quality. The preliminary results show that the difference in CC dimensions between magnets of the same firms is not only due to the variation of coil pre-stress, but also related to the collar's tolerances.

Web site. We recall that the web site is available for monitoring the coil size measurements in the production at http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/Obs_coil.html. You need your Nice password to retrieve the information from this web site.

1. Data of coil size measurements

Coil size trends and their impact on the coil pre-stress in the magnets.

Firm 1. The coil size at firm 1 is measured on assembled poles. We recall that, that in order to speed up the production, starting from the poles set 114 the number of measuring sections has been reduced to 5 (from 15). In figure 1 the average of all measuring points is used to show the coil size trends. Due to oversize of the coil, many magnets of firm 1 were collared with non-nominal shims. In order to bring the coil size down, starting from the pole set 115 (blue dashed line in figure 1) the coils are cured with additional curing shim, made of polyimide tape (0.125mm). Moreover, the coils of pole sets 108 and 127 were cured with 2x0.125 mm shims. In order to estimate the efficiency of this action we split the coils of last 33 pole sets (100 ÷ 133) into three batches according to the thickness of curing shims: 0 mm, 0.125 mm and 0.250 mm (see reference table in Appendix A). In figure 2 we have tried to correlate the coil size with the thickness of curing shim, separately for each coil layer. As we can see, there is some correlation, but the effect is rather small: with an additional curing shim 0.125 mm coils become smaller by only ~ 0.04 mm. We should also say that due to random variation of coil components tolerances, the uncertainty on coil size is rather high. Nevertheless, both parameters: the correlation factor and the coil size sensitivity to the curing shim thickness are rather similar to the ones obtained for the coils of MQ magnets at Accel [1].
The difference in coil size between the left and right sides of coils is shown in figure 3. A large random variation in left-to-right side coil asymmetry on the outer layer coil size is related to the problem with the measuring machine, mentioned in a previous report.

In figures 4 and 5, the inner and outer layers coil sizes are plotted together with their E-modulus (notice that the scale for E-modulus axis is reversed).

Firm 2. About 56 inner and 56 outer layers have been produced over last two months, and 28 were measured for coil sizes (14 inner layers and 14 outer layers). In general, the variation in the coil size in the inner and outer layers coils of series production stays in the range of ±0.1 mm (fig. 6). We remind, that at firm 2 starting from the inner layer № 75 (red dashed line in fig. 6) and from the outer layer № 98 (blue dashed line in fig. 6) the coils are cured with extra shims of 0.1 mm in the curing mould. Due to important trend on coil size before introduction of extra curing shims and low statistics (the shims were modified only once) we can't evaluate precisely the effect of curing shims on coil size for this firm. Nevertheless, we have tried to estimate the effect of additional curing shim by comparing the average coil size before and after modification of the curing shims took place. The average coil size of 5 inner and 5 outer layers, produced just before the modifications of curing shims was compared with the average coil size of 5 inner and 5 outer layers produced with additional curing shims. The results are shown in figure 7. The coil size sensitivity to the curing shim thickness is a bit higher compare to the firm 1 results, shown before (fig.2).

At firm 2 each coil is measured in 15 longitudinal positions (the only firm today who has kept all measuring points along the coil, two other firms are measuring at fewer positions). We should say that keeping measure the coils at all positions helps to control the coil production tooling and validate the new one. For example, recently, at this firm a new winding machine was installed, requiring the verification of coil shape quality. Therefore, the first coil produced with this machine was first measured for coil dimensions and then the geometry of this coil was compared with the statistical longitudinal coil profile (see more details in Appendix B). The standard deviation (one sigma) of coil size variation along the coil is shown in figure 8.

The difference in coil size between left and right sides of coils is shown in figure 9.

In figures 10 and 11, the inner and outer layers coil sizes are plotted together with their E-modulus (notice that the scale for E-modulus axis is reversed). Remark: a significant difference in the values of E-modulus between Firm 1 (figures 4 and 5) and Firm 2 (figures 10 and 11), is mostly due to two facts: first, that the coils at Firm 1 are measured in pole configuration, while the shown data for Firm 2 is related to the coil size measurements done on individual coil layers and second, that measuring machines at two firms are of different design.

Firm 3. CERN receives the data on mechanical measurements from BNN by batches with 2 ÷ 3 weeks interval. In last two months CERN has received the data on coil size measurements performed on 60 inner and outer layers, which were used in 30 new magnets. In total, up to date, the data on 560 inner and outer layers for 180 magnets is available at CERN. Following series production specification, the number of measuring coils and the number of measuring sections along the coil has been gradually reduced. For magnets 100 ÷ 180 only half of coils were measured (two inner and two outer coils per magnet). Actually, one inner and one outer layer per magnet are measured.

For most of the coils, the variation in the coil size in the inner and outer layers coils of series production stays in the range of ±0.1 mm (fig. 12). In fact, the coil size variation in the last 80 magnets build by firm 3 is smallest among three firms. Following series production specification, the numbers of measuring coils per magnet and measuring sections along one coil has been gradually reduced. Actually, two inner and two outer layers per one magnet are measured at 5 longitudinal positions along the coil (14 positions in the past, see fig. 12).

Due to reduced number of measuring sections, we removed the graph with standard deviation of coil size variation along the coil.

The difference in coil size between left and right sides of coils is shown in figure 13.

In figures 14 and 15, the inner and outer layers coil sizes are plotted together with their E-modulus (notice that the scale for E-modulus axis is reversed).

2. Measurement data of the collared coil dimensions

Trend graphs (straight part of the coil)

For the details on the procedure of collared coil dimensions measurements at each dipole manufacturer see previous reports.

Firm 1. In figures 16 ÷ 18 the collared coil dimensions (CCD) data for measuring points S2, S4-S6, S8 and S10 are shown (each plot gives the data on two symmetrical points). We remind, that a new machine to measure collared coil dimensions is in use at Firm 1 starting from the CC-51 (the collared coils 44 and 48 are also were measured with the new system). With new machine, the measuring points S1, S3, S7 and S9 are not measured; therefore we removed the corresponding figures.

Firm 2. In figures 19 ÷ 23 the CCD data for measuring points S1-10 are shown (each plot gives the data on two symmetrical points). At firm 2, for the collared coils of the series, the CC dimensions are measured in 11 pre-defined positions along the coil, where 4 positions are taken in the straight part of the coil.

Firm 3. In figures 24 ÷ 28 the CCD data for measuring points S1-10 are shown (each plot gives the data on two symmetrical points). At firm 3, for the collared coils of the series, the CC dimensions are measured in 16 pre-defined positions along the coil, where 8 positions are taken in the straight part of the coil (an agreement was achieved between CERN and firm 3 to add 5 measuring positions in order to have more accurate statistics on this data).

Trend graphs (coil ends)

For the magnets of pre-series, the CC dimensions were taken at 5 longitudinal positions over coil ends: at 0.02 m, 0.06 m, 0.1 m, 0.14 m and 0.18 m away from collared coil extremities. The magnets of series are measured at 3 longitudinal positions over each coil end: at 0.04 m, 0.110 m and 0.18 m away from collared coil extremities. The coil pre-stress is varies along the coil ends. The analysis, carried out in MA section have shown, that the average CCD data of all measuring sections over coil ends can be used to classify the magnets by the level of coil pre-stress in coil ends. More details can be found in the minutes of QWI meeting at http://lhc-div-mms.web.cern.ch/lhc-div-mms/Quench%20working%20unit/. From 10 measuring points S1-S10, the points S3 and S7 are the best to monitor the variation of coil pre-stress, as at these points the collars have maximum vertical deformation due to coil pre-stress. In figures 29÷34 we monitor the average value of CCD data for measurements taken over coil ends.

Firm 1. Due to difference in number of measuring points between old and new measuring machines at firm 1, we split the collared coils into two groups: the collared coils 1÷50, which were measured with use of old machine and collared coils 51÷110, which are measured with the new machine. In figures 29÷30 the CC dimensions for measurements taken over coil ends are shown together with the data on coil straight part. We should notice, that firm 1 is receiving the collars from to suppliers. As can be seen in figures 29 and 30, the magnets, collared with collars from FSG, systematically shows smaller CC dimensions over coil ends. The investigations on the collars shape are going on in collaboration of MA and CC sections, for tracing the source of this variance.

Firm 2. In figure 31 the CC dimensions for measurements taken over coil ends are shown together with the data on coil straight part. Unfortunately, at firm 2 after switching to the measuring procedure of series, for CC from 36 to 63, the measurements over non-connection coil end were taken not at correct longitudinal positions. Later, some of these collared coils were re-measured. In figure 31 only the data from correct measurements is shown. For an easy cross-check with firm 1, in figure 32 the CC dimensions for measurements taken at points S2 and S8 are shown.
In figures 31 and 321 the data on magnet 2023 corresponds to the measurements after re-collaring (this magnet did not pass the cold test at CERN and was re-collared with bigger shims in coil ends).

Firm 3. In figures 33 the CC dimensions for measurements taken over coil ends are shown together with the data on coil straight part. The CC up to 3020 were measured at 5 longitudinal positions over each coil end (measuring procedure of pre-series), then all CC have been measured according to the measuring procedure of series (3 longitudinal positions over each coil end). In figure 34 the CC dimensions for measurements taken at points S2 and S8 are shown. Apart of few first magnets, firm 3 is using the FSG collars. Compare the CCD data for three firms (figures 30, 32 and 34) once again we notice that the CC dimensions taken over coil ends are systematically smaller for the magnets, collared with FSG collars. The difference is in order of 0.1÷0.2 mm.

Asymmetry in collar's deformation

The left-to-right side asymmetry with respect to the aperture axes in collars deformation produces non-allowed multipole b2. In figures 35÷37 the asymmetry in collar's deformation between the lateral and central part of the collars are shown separately for each firm.

In these figures the data not for all magnets is shown due to following reasons:

Firm 1. A new machine and measuring procedure are in use at firm 1 starting from the CC 51 (also CC 44 and 48). For the magnets 32-50 there no measurements had done at the measuring points S2, S4, S6 and S8.

Firm 3. The data on measuring points S2 and S4 from the CC 28 and CC 38-54 is dropped due to the problem with sensor S2 (fixed after CC-54).

Acknowledgments

We wish to acknowledge M. Bajko, M. Cornelis, P. Fessia, A. Musso, M. Modena, G. De Rijk, F. Savary, and W. Scandale for comments, discussions and valuable help.

Reference:

[1] F. Simon , I.Vanenkov, "The MQ magnet mock-up collaring test", AT-MAS Internal Note 2004-01.

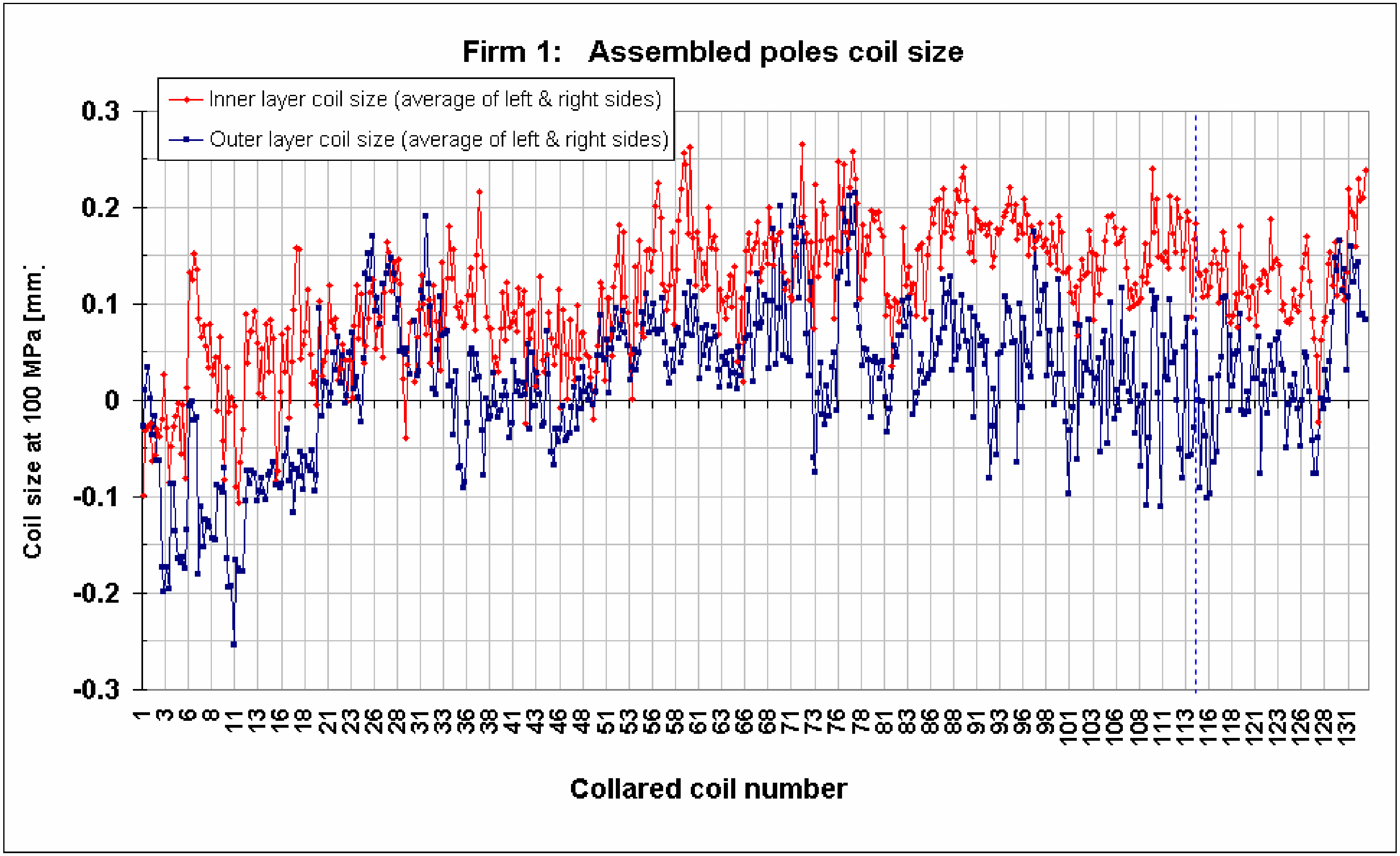
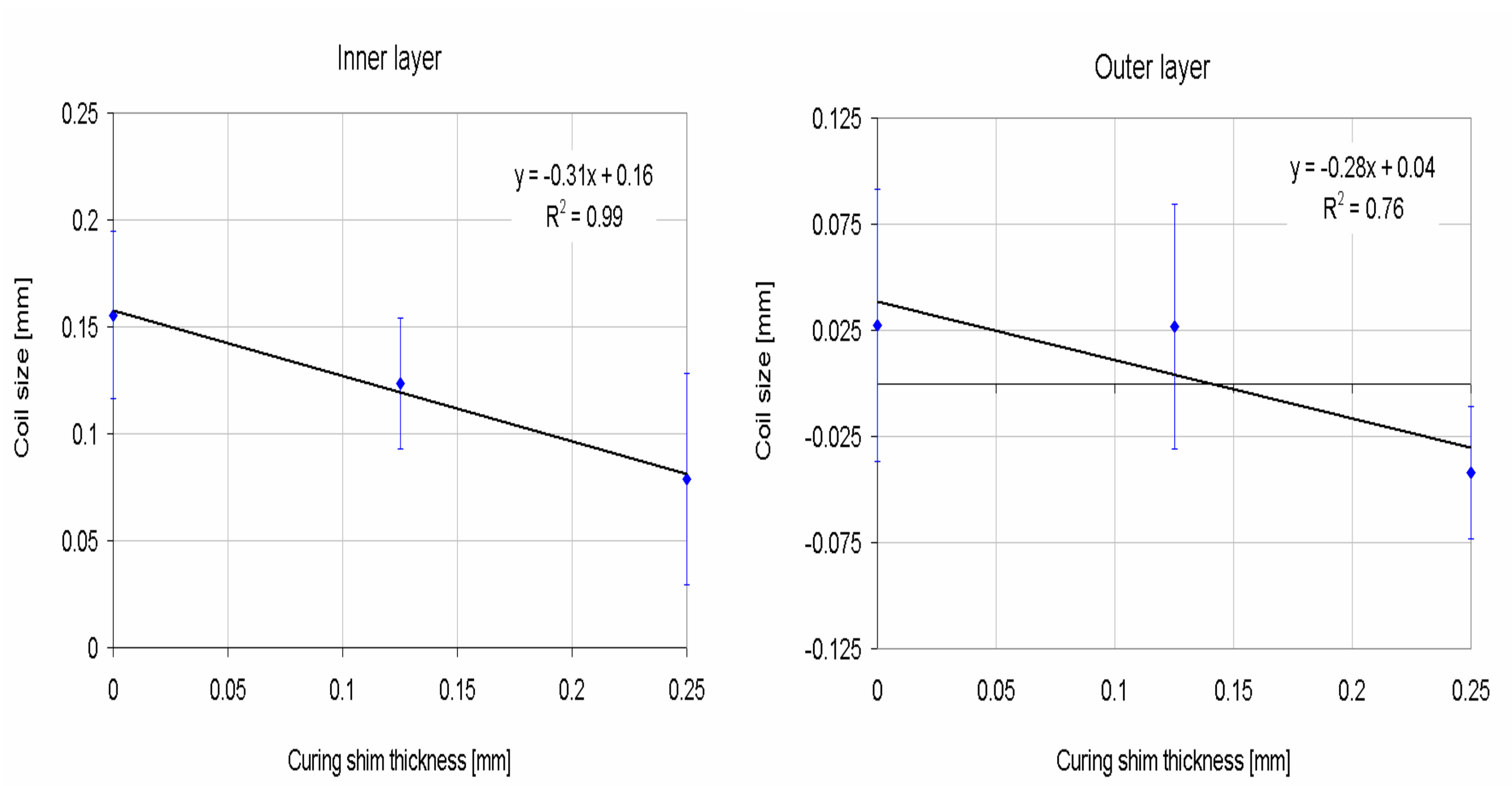


Fig. 1 Firm 1. Average coil size in the straight part of the assembled poles (380 poles).



a) **b)**

Fig. 2 Firm 1. Correlation between curing shim thickness and coil size of the inner (a) and the outer (b) layers evaluated for three batches of coils cured with different shims. The error bars show the standard deviation (one sigma) of coil sizes within the batch of coils.

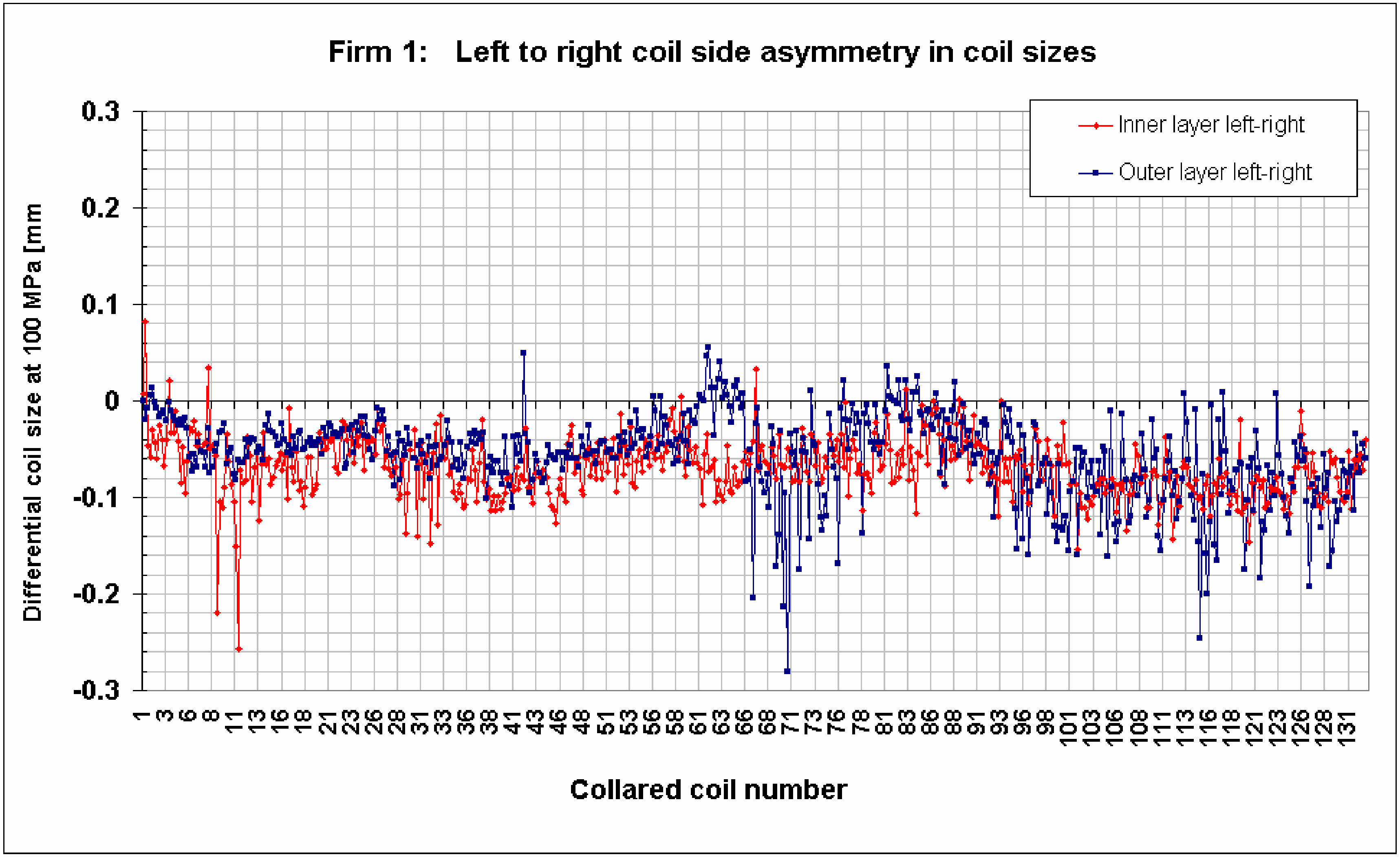


Fig. 3 Firm 1. Difference in the coil size between left and right sides of the coil on both layers.

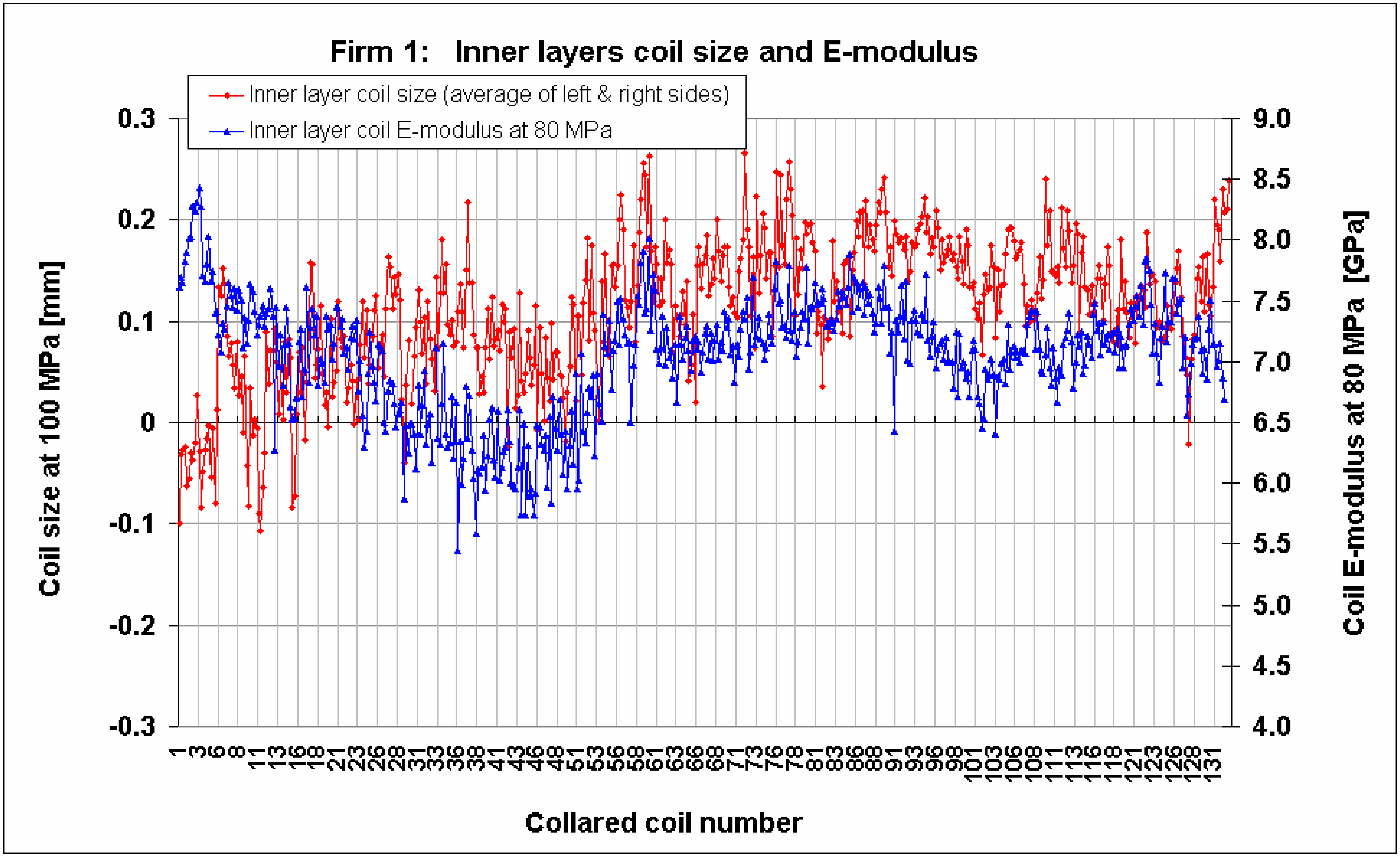


Fig. 4 Firm 1. Inner layer coil size (average) and E-modulus computed at 80 MPa. (Data extracted from pole size measurements).

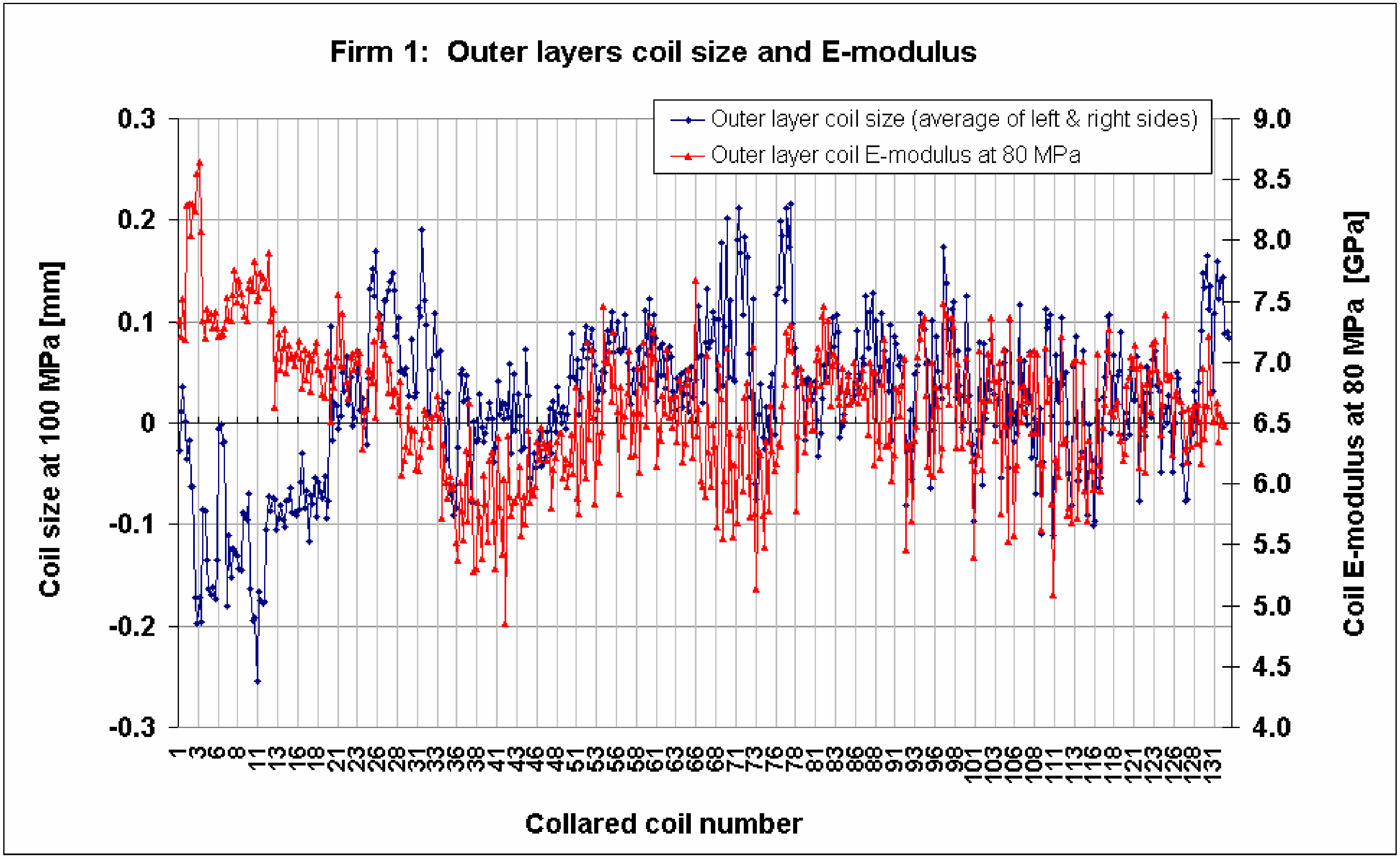


Fig. 5 Firm 1. Outer layer coil size (average) and E-modulus computed at 80 MPa. (Data extracted from pole size measurements).

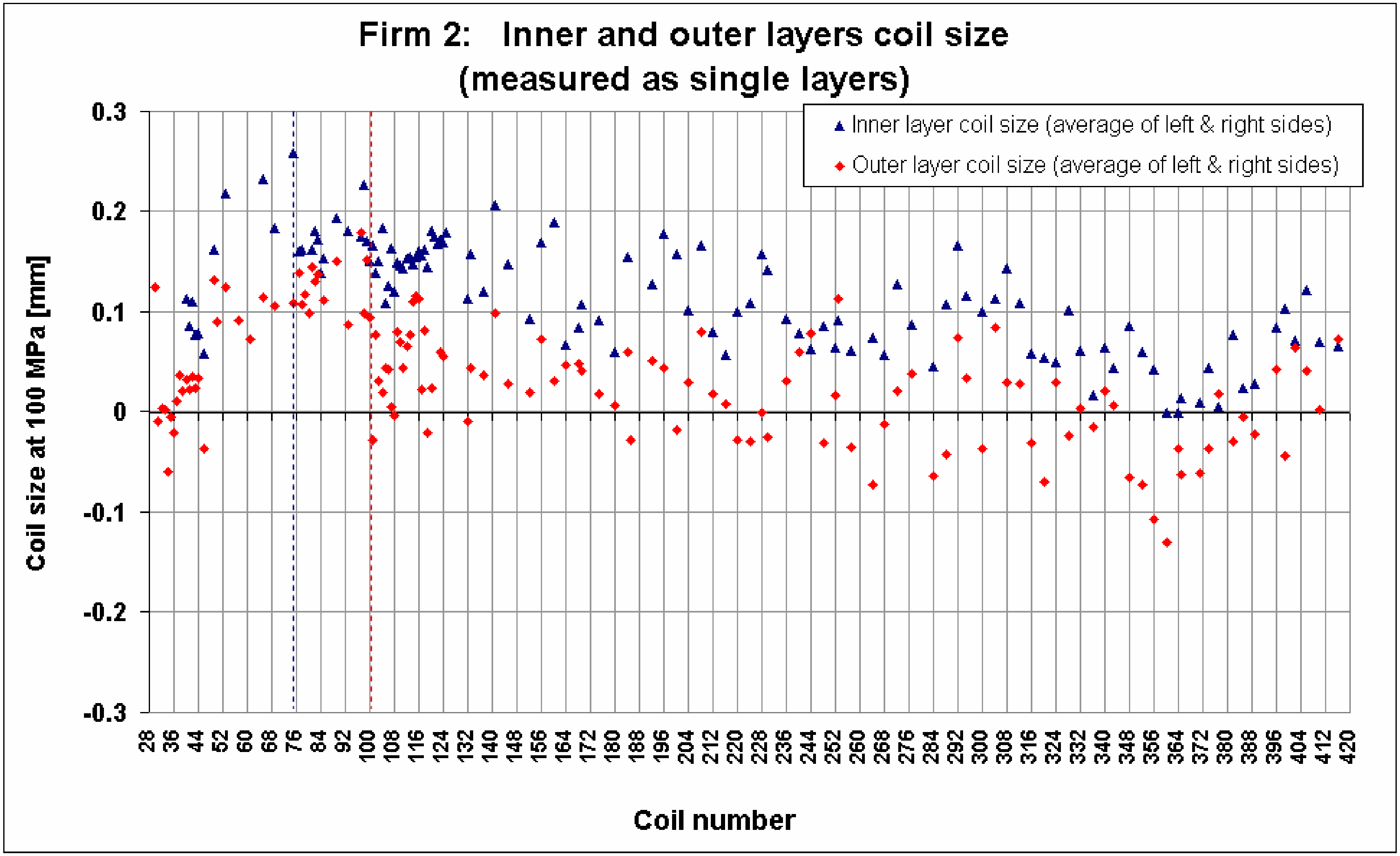
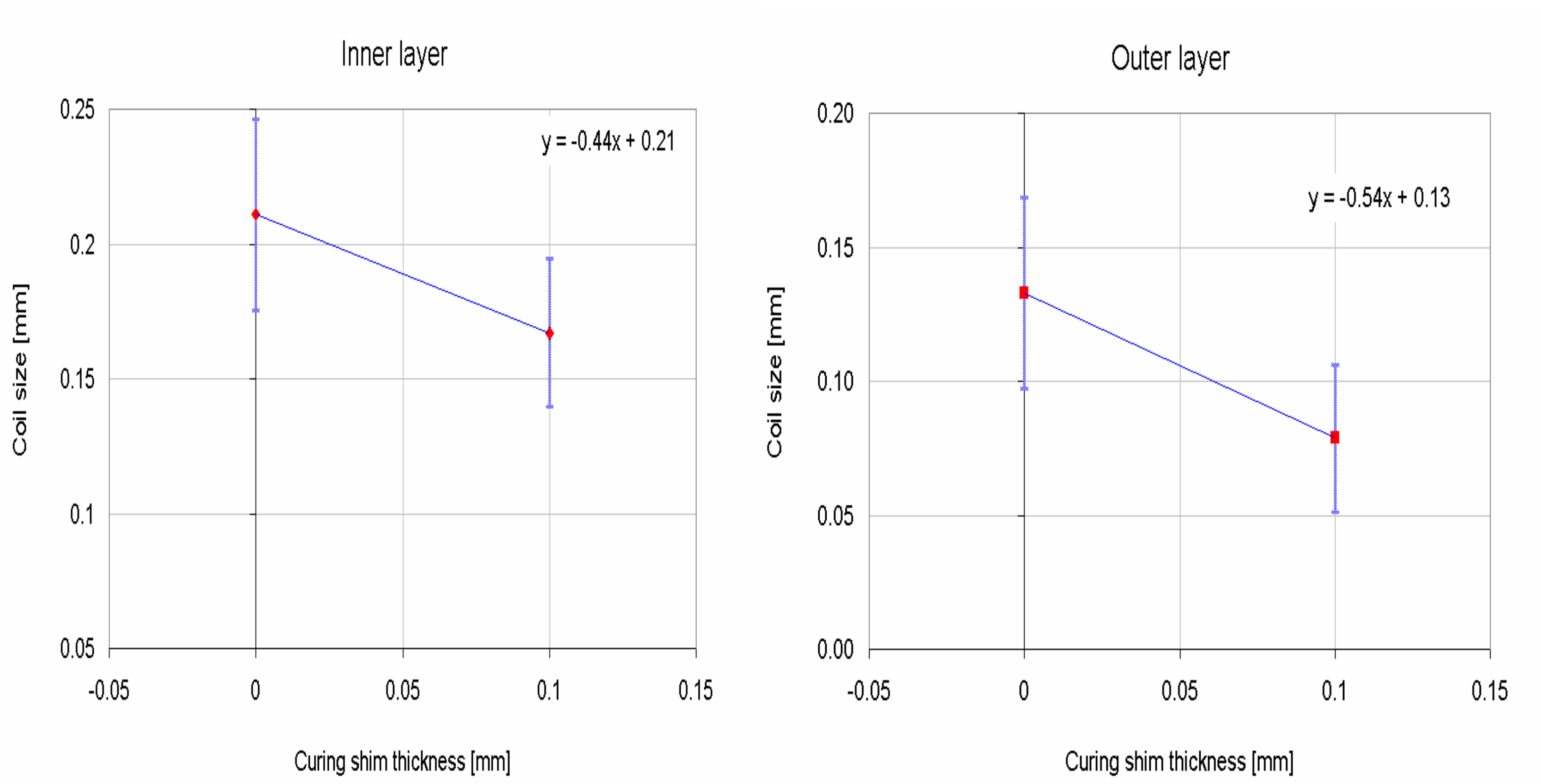


Fig. 6 Firm 2. Average coil size in the straight part of the inner and outer layers.



a) **b)**

Fig. 7 Firm 2. Correlation between curing shim thickness and coil size of the inner (a) and the outer (b) layers evaluated for two batches (one batch include 5 coils) of coils cured with different shims. The error bars show the standard deviation (one sigma) of coil sizes within the batch of coils.

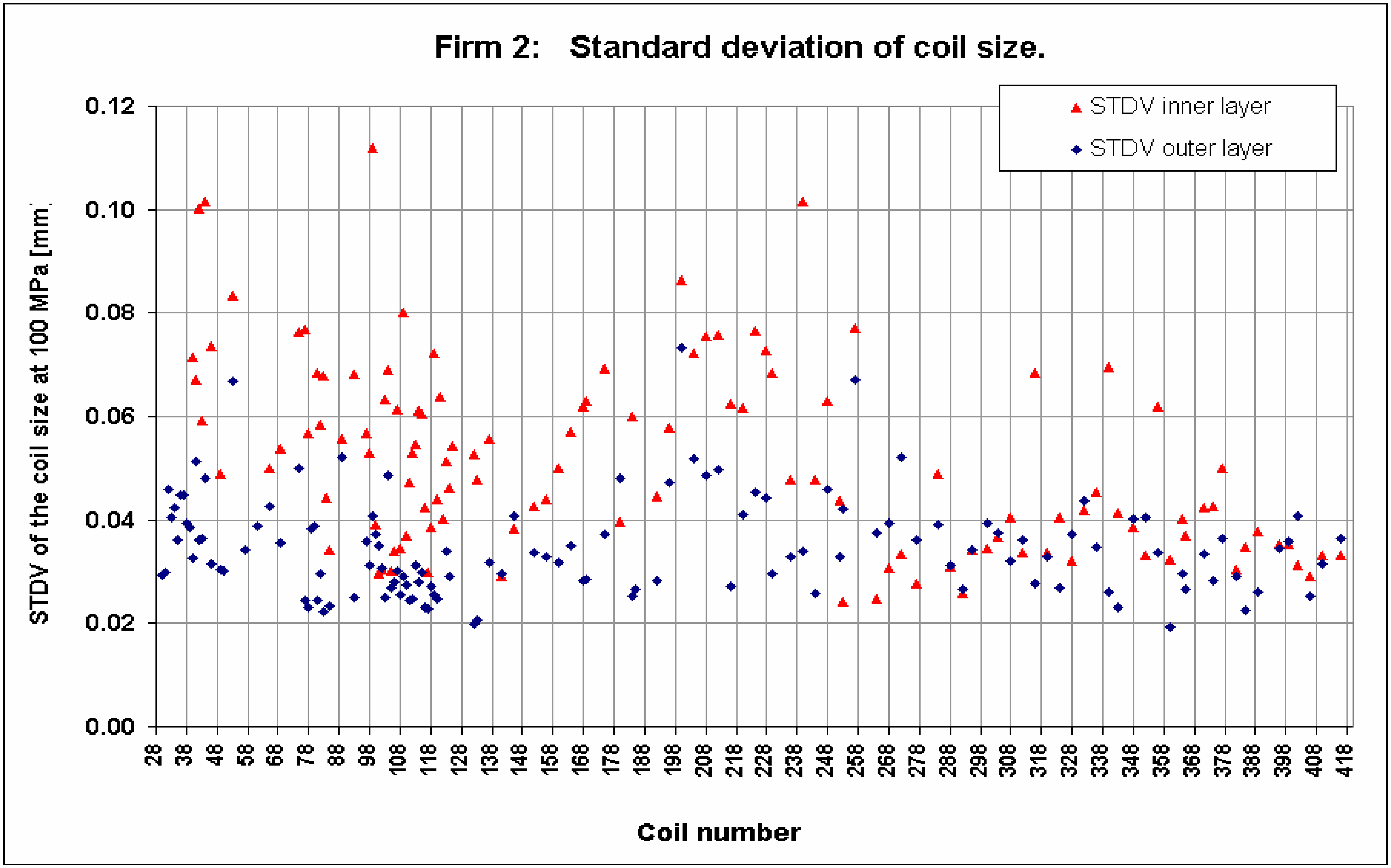


Fig. 8 Firm 2. Standard deviation of coil sizes measured in 15 positions along the coil (left and right coil sides in average).

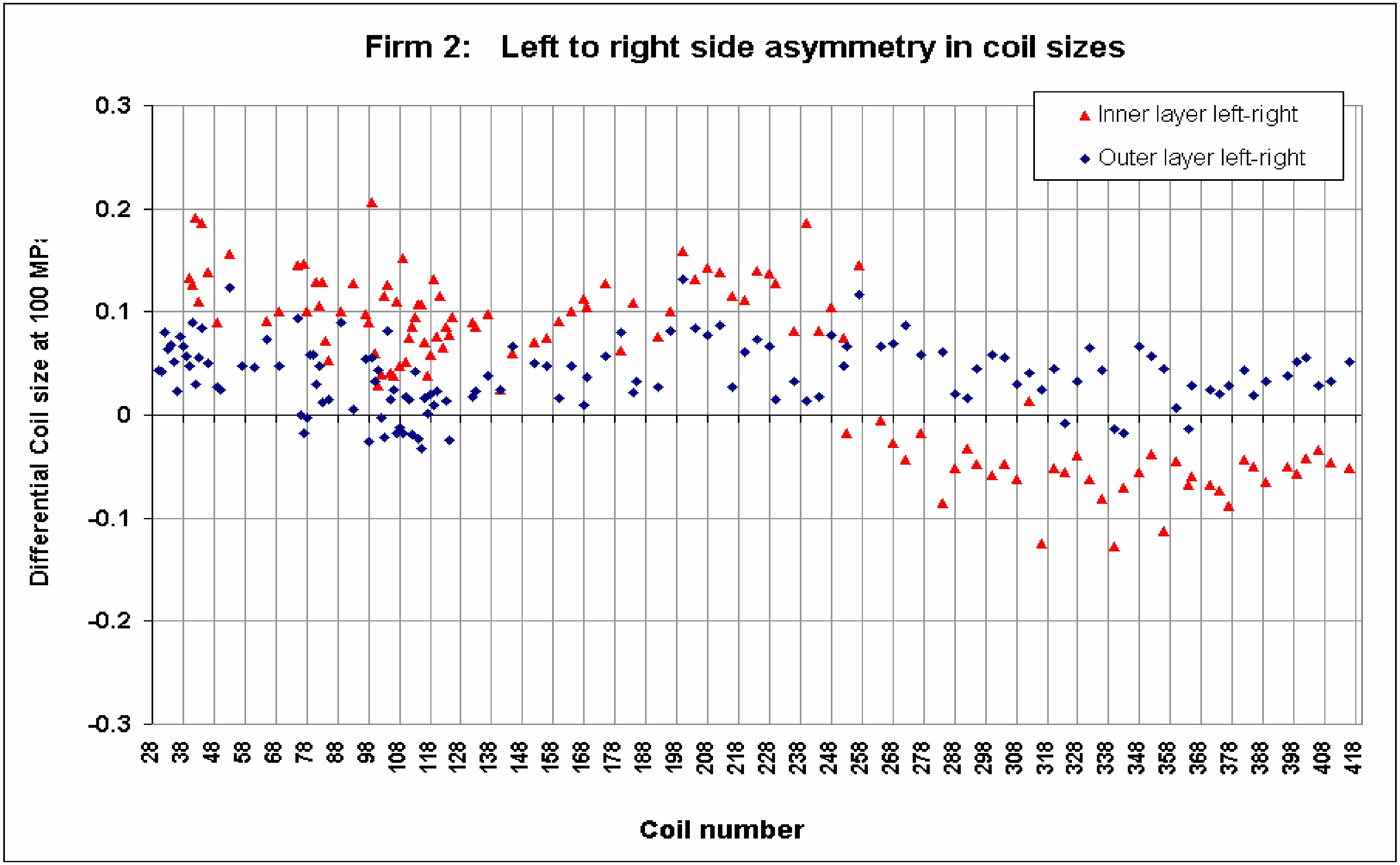


Fig. 9 Firm 2. Difference in the coil size between left and right sides of the coil on both layers.

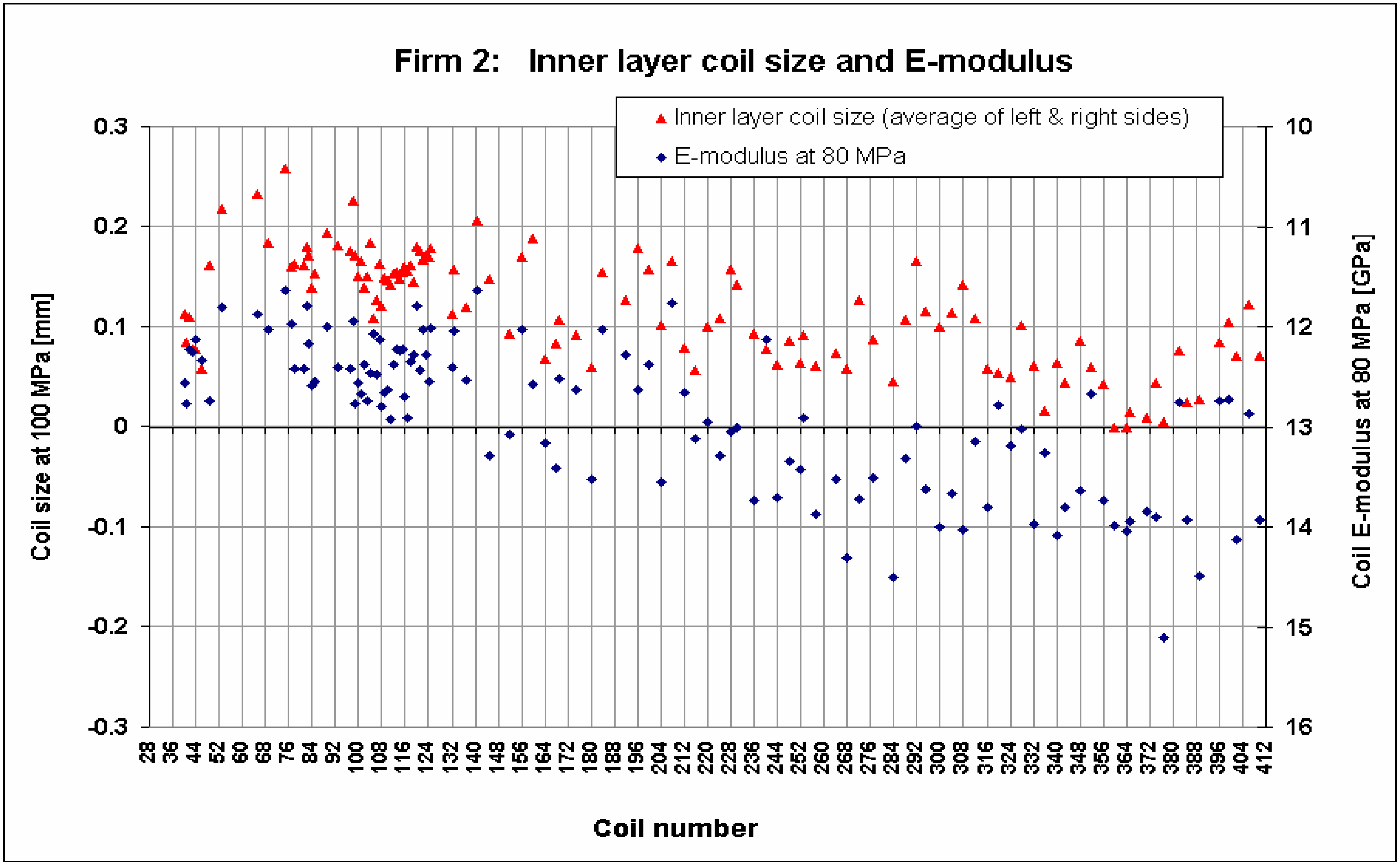


Fig. 10 Firm 2. Inner layer coil size (average) and E-modulus computed at 80 MPa.

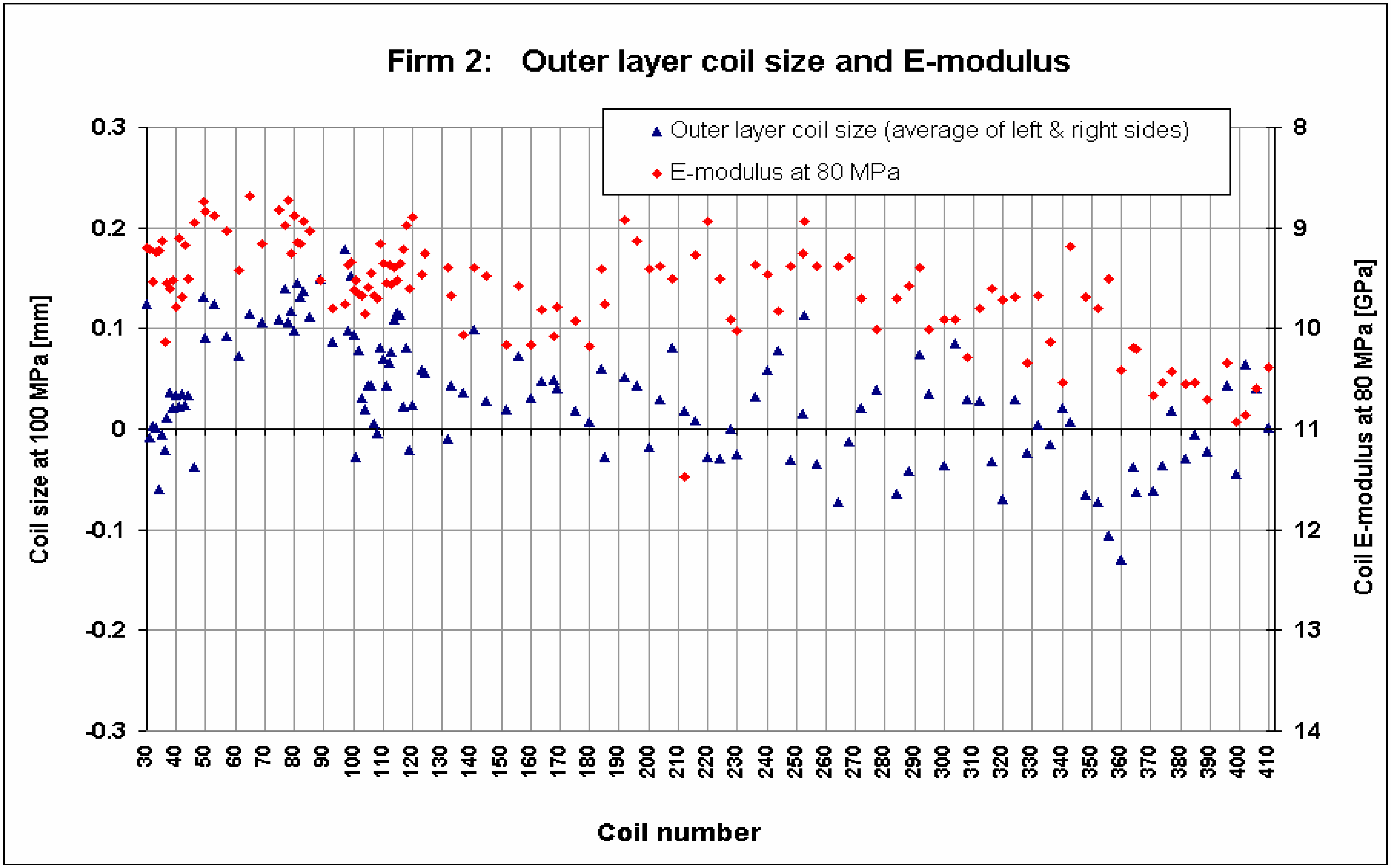


Fig. 11 Firm 2. Outer layer coil size (average) and E-modulus computed at 80 MPa.

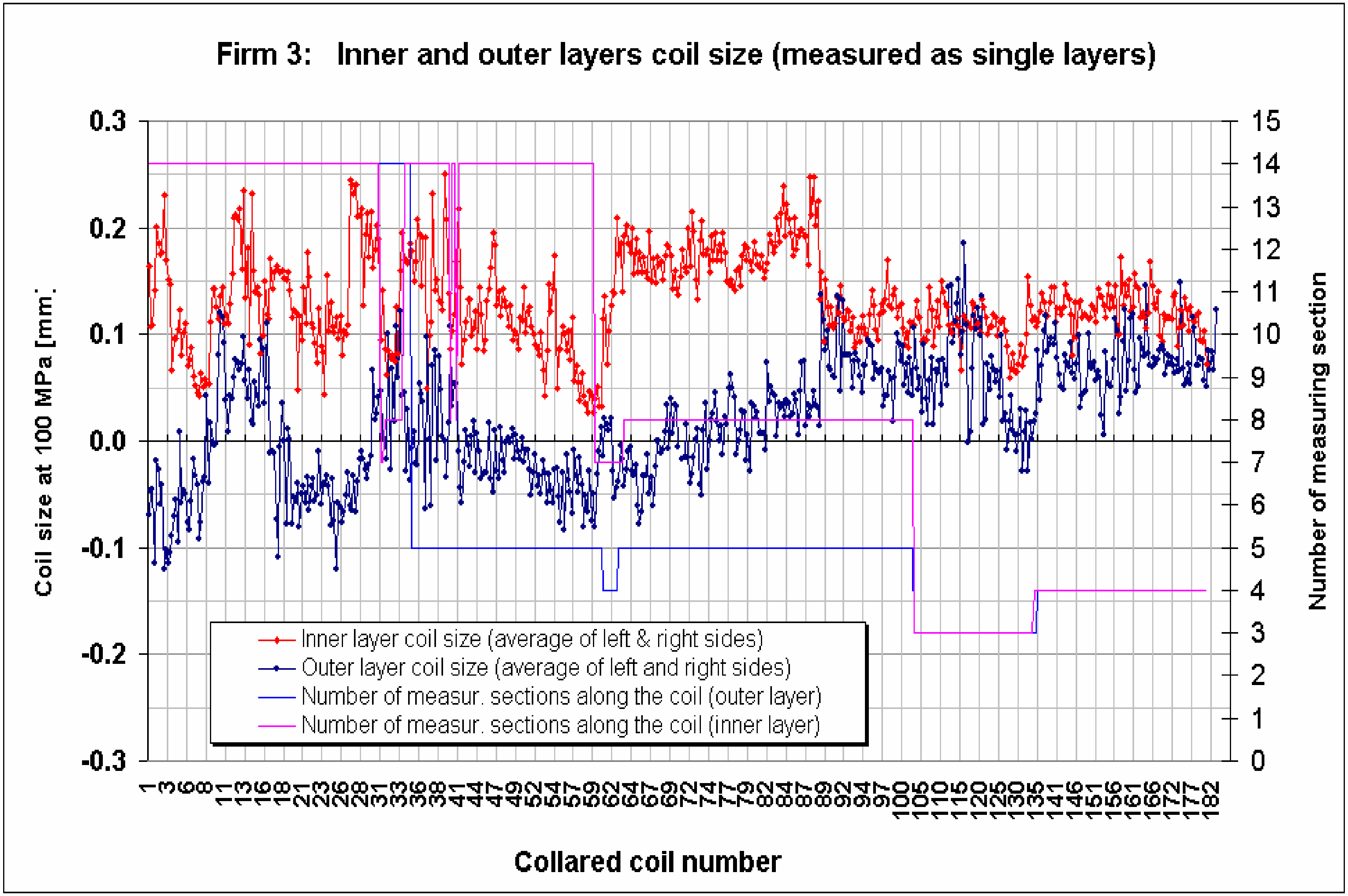


Fig. 12 Firm 3. Average coil size in the straight part of inner and outer layers.

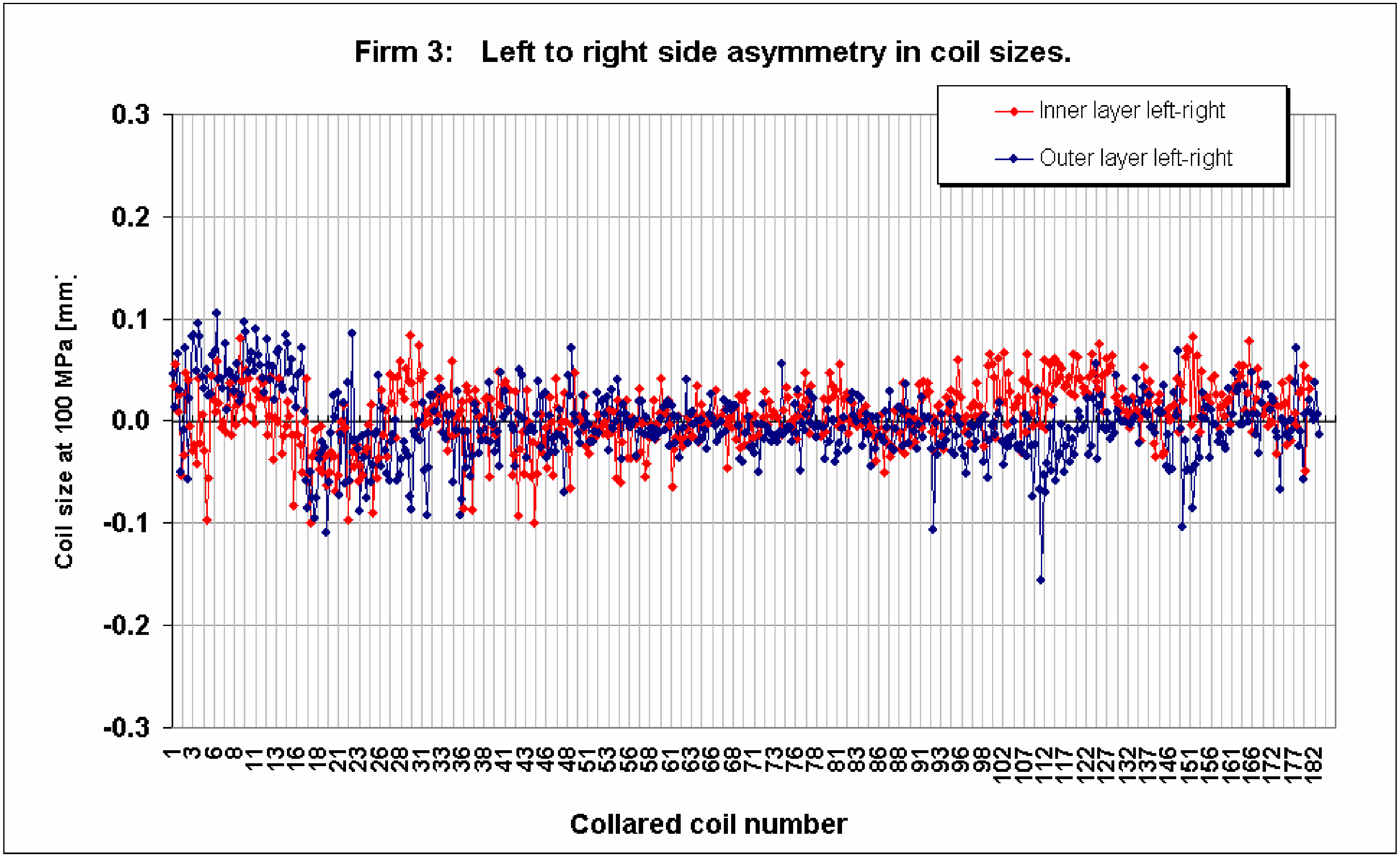


Fig.13 Firm 3. Difference in the coil size between left and right side of the coil on both layers.

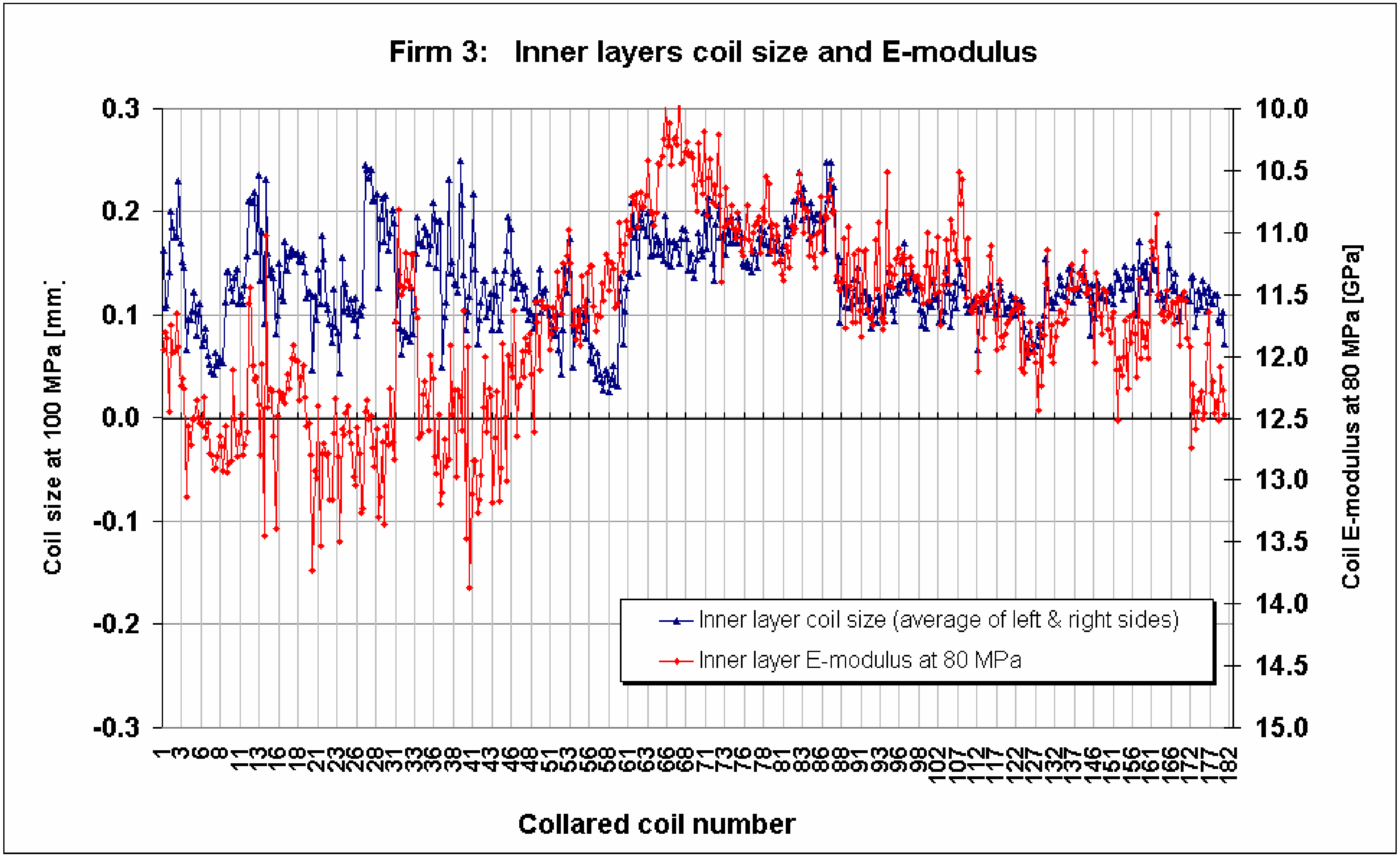


Fig. 14 Firm 3. Inner layer coil size (average) and E-modulus computed at 80 MPa.

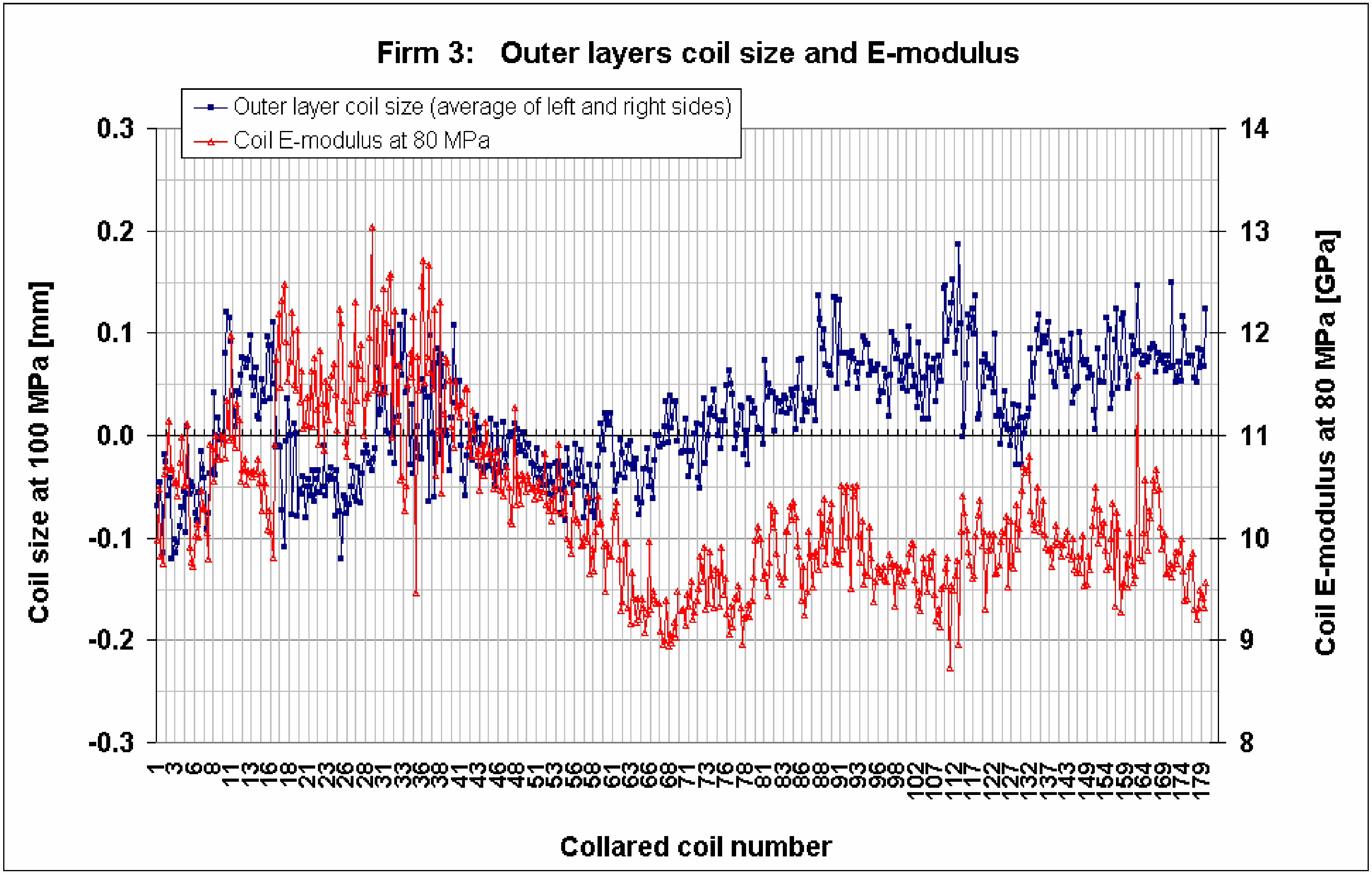


Fig. 15 Firm 3. Outer layer coil size (average) and E-modulus computed at 80 MPa.

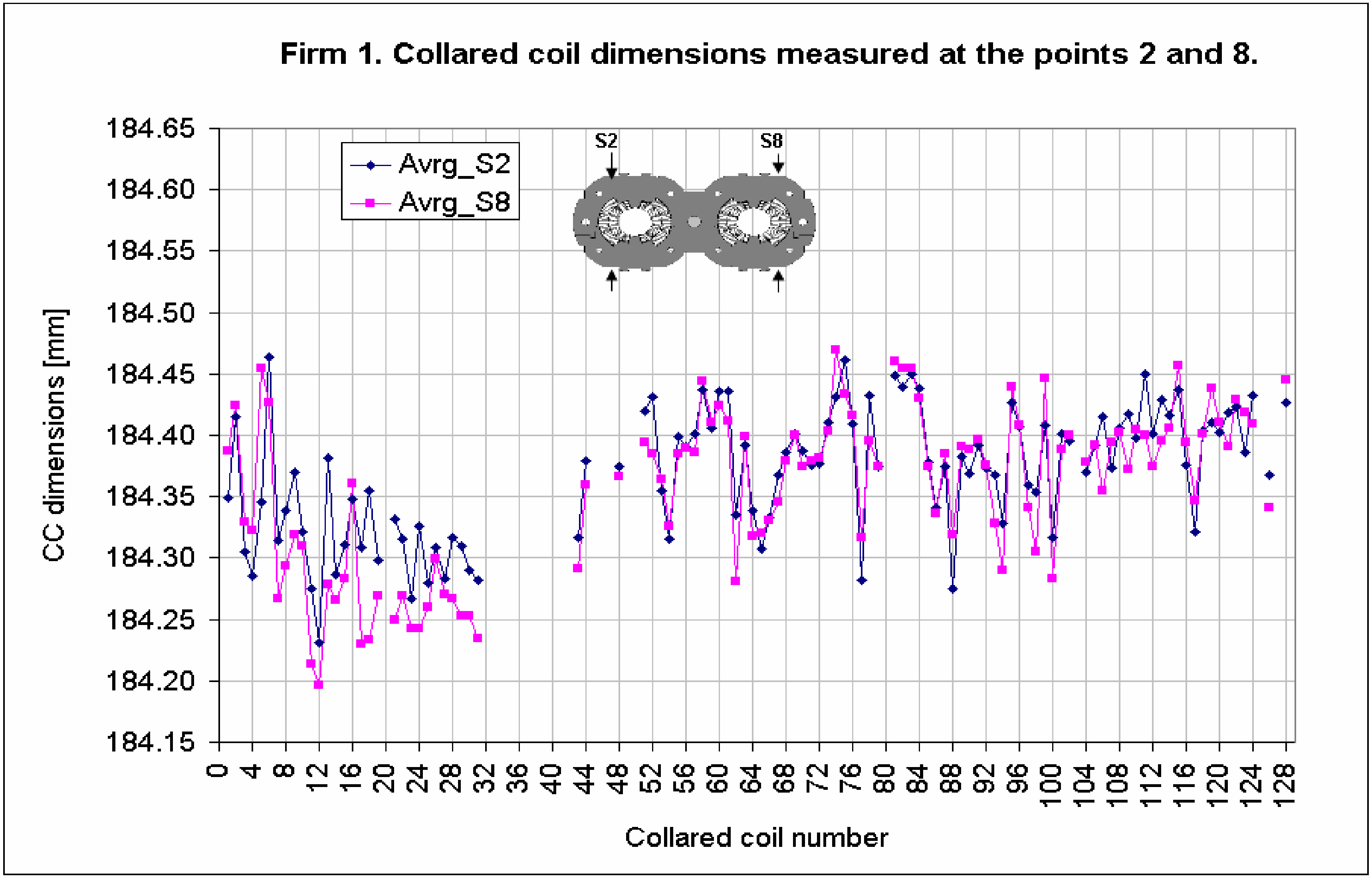


Fig. 16 Firm 1. Collared coil dimensions measured at the points S2 and S8.

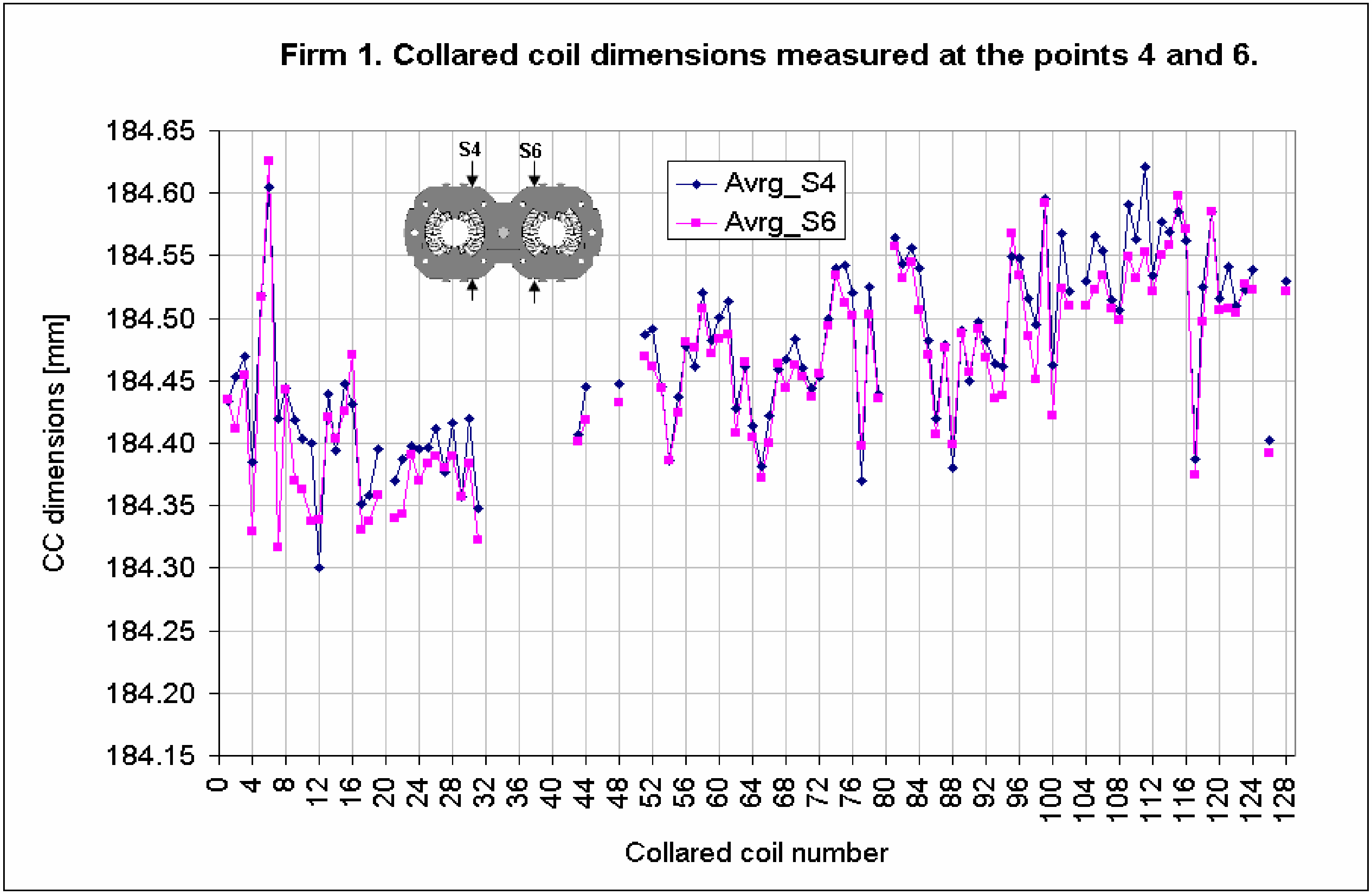


Fig. 17 Firm 1. Collared coil dimensions measured at the points S4 and S6.

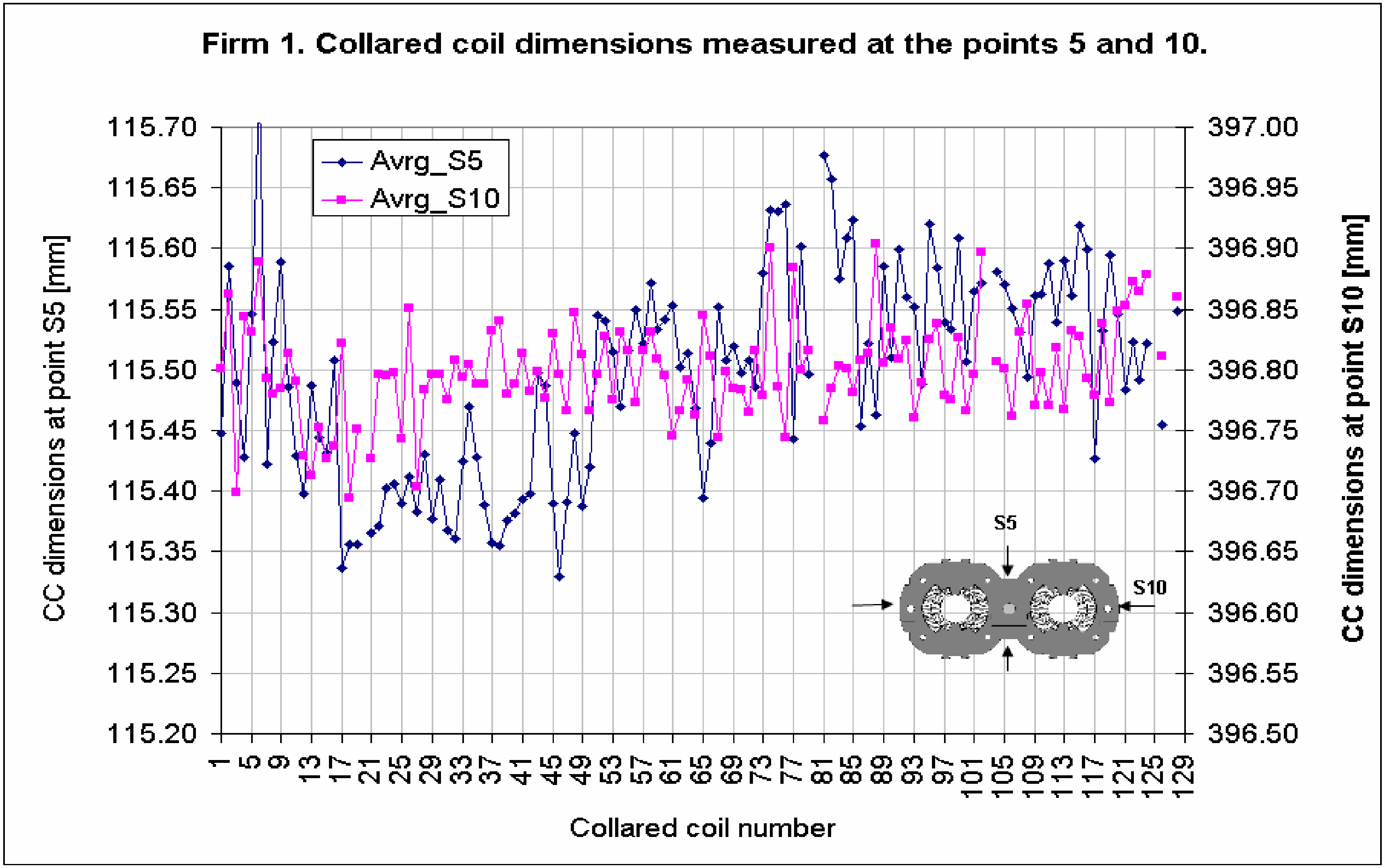


Fig. 18 Firm 1. Collared coil dimensions measured at the points S5 and S10.

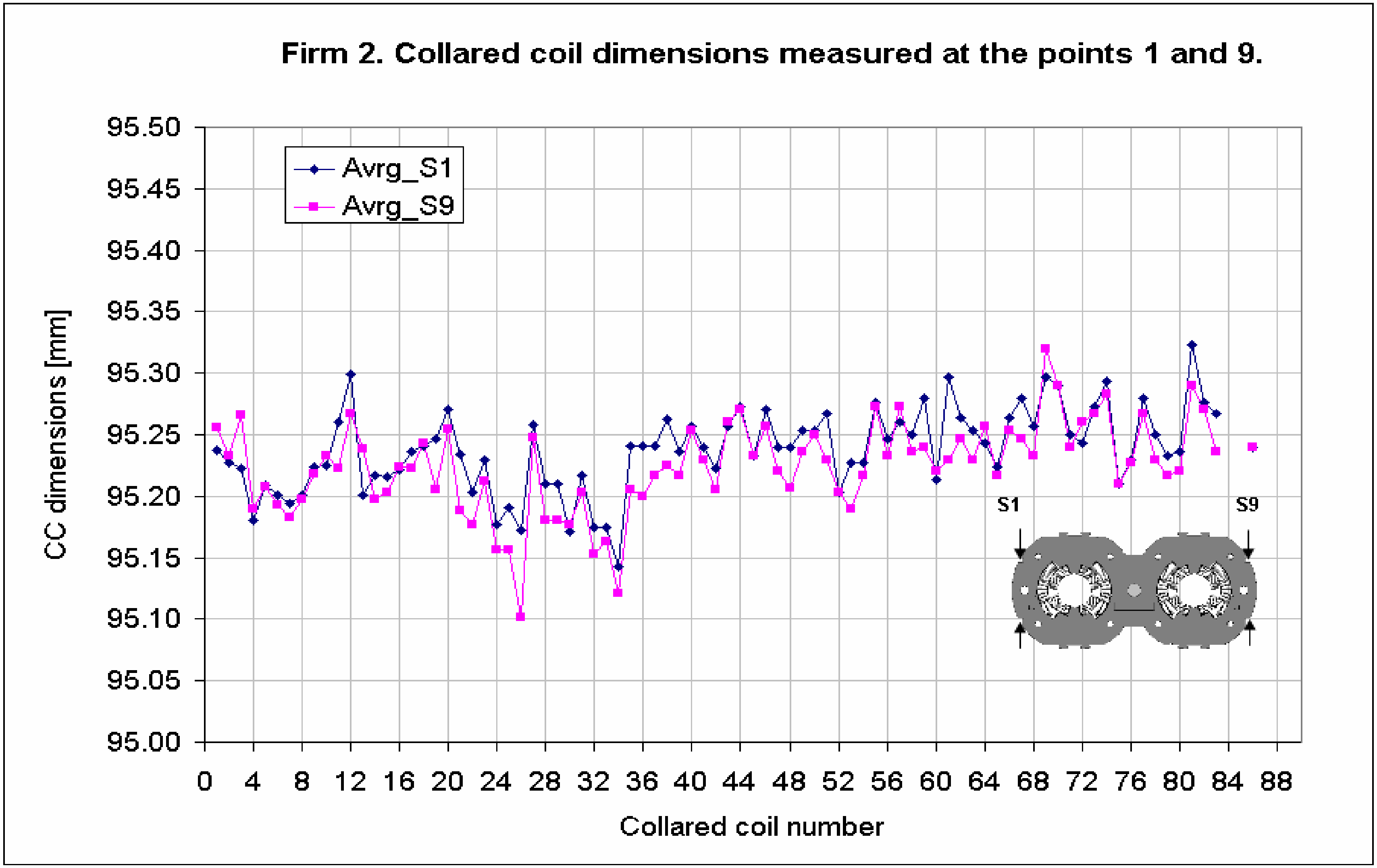


Fig. 19 Firm 2. Collared coil dimensions measured at the points S1 and S9.

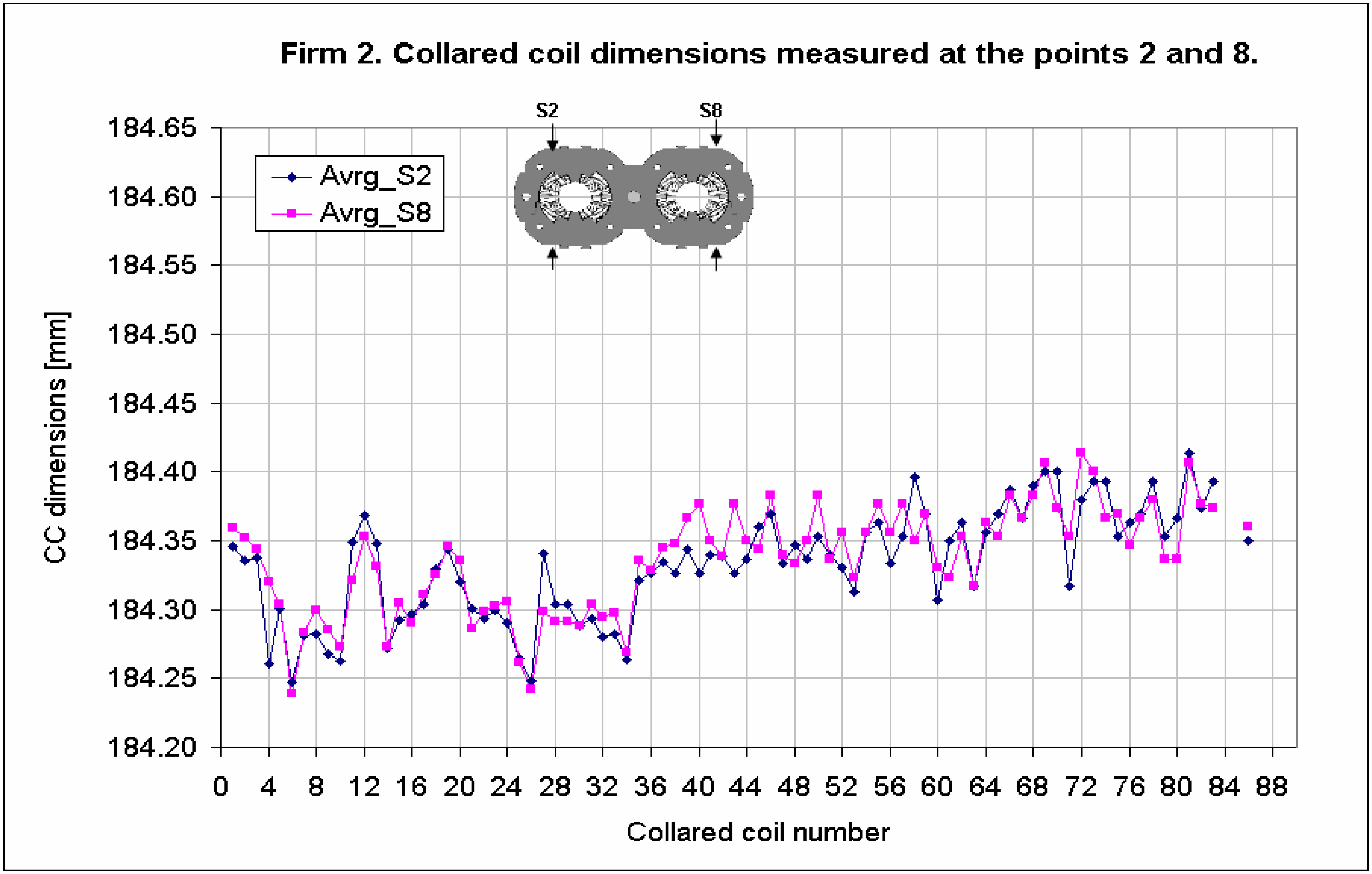


Fig. 20 Firm 2. Collared coil dimensions measured at the points S2 and S8.

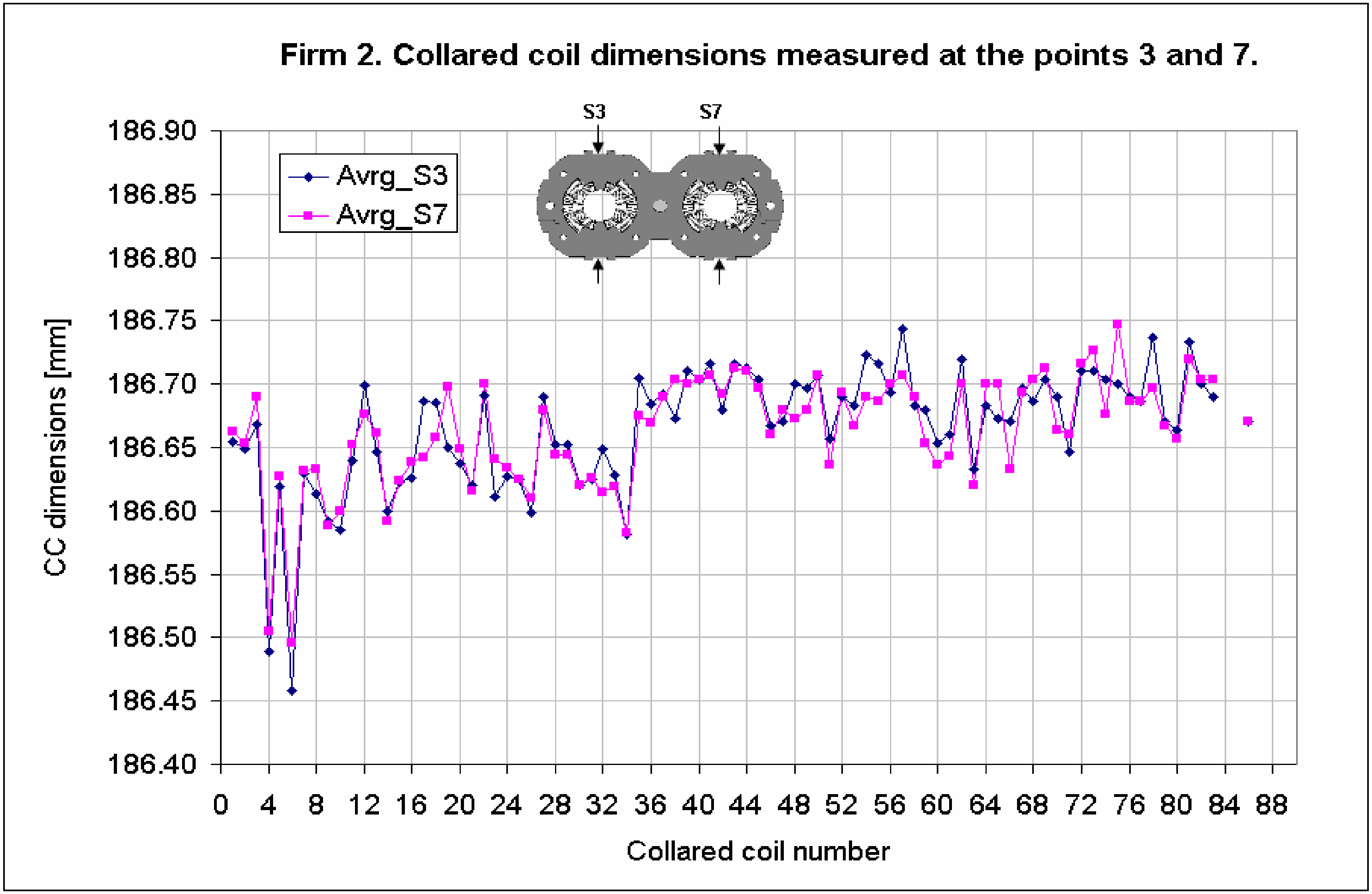


Fig. 21 Firm 2. Collared coil dimensions measured at the points S3 and S7.

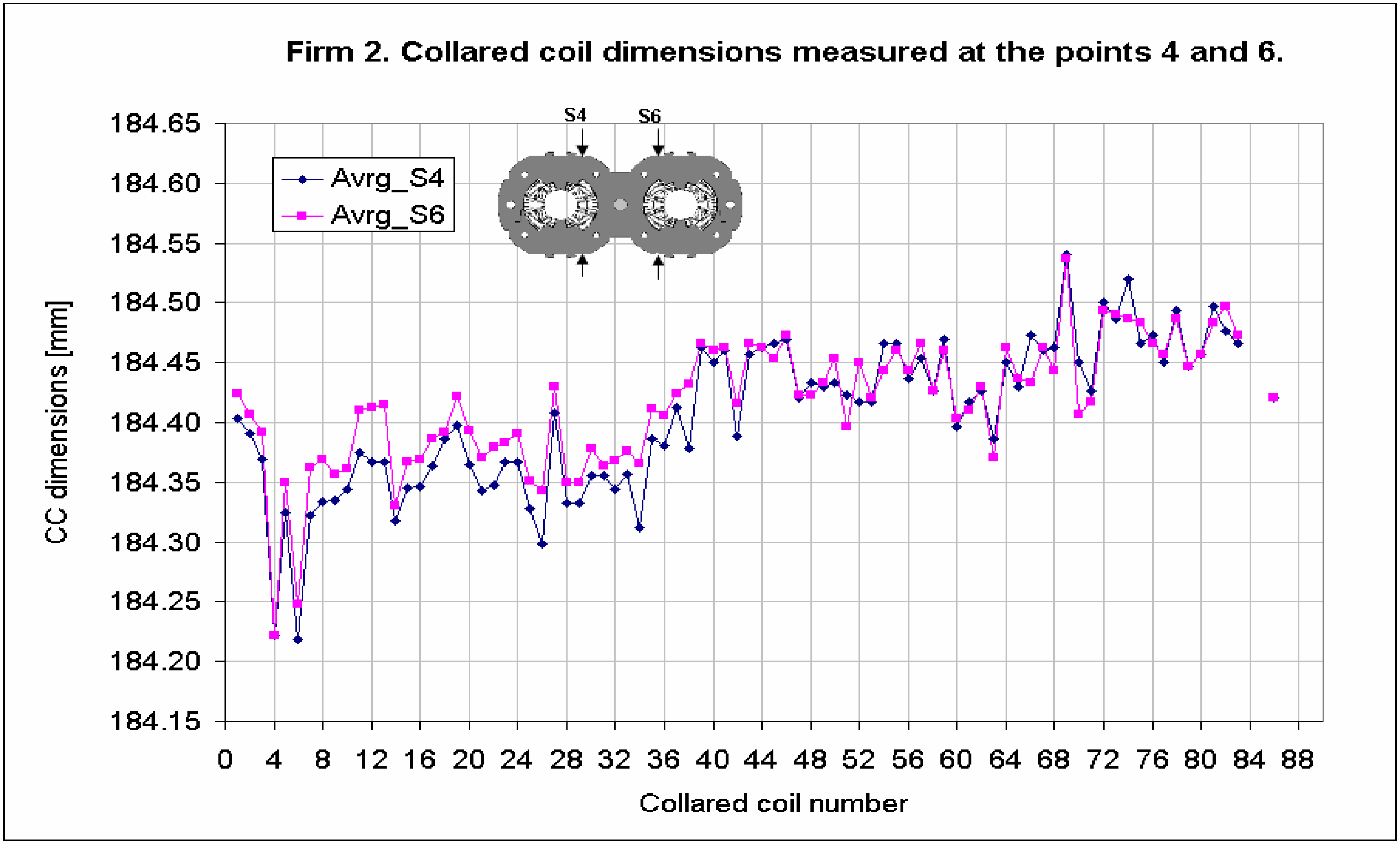


Fig. 22 Firm 2. Collared coil dimensions measured at the points S4 and S6.

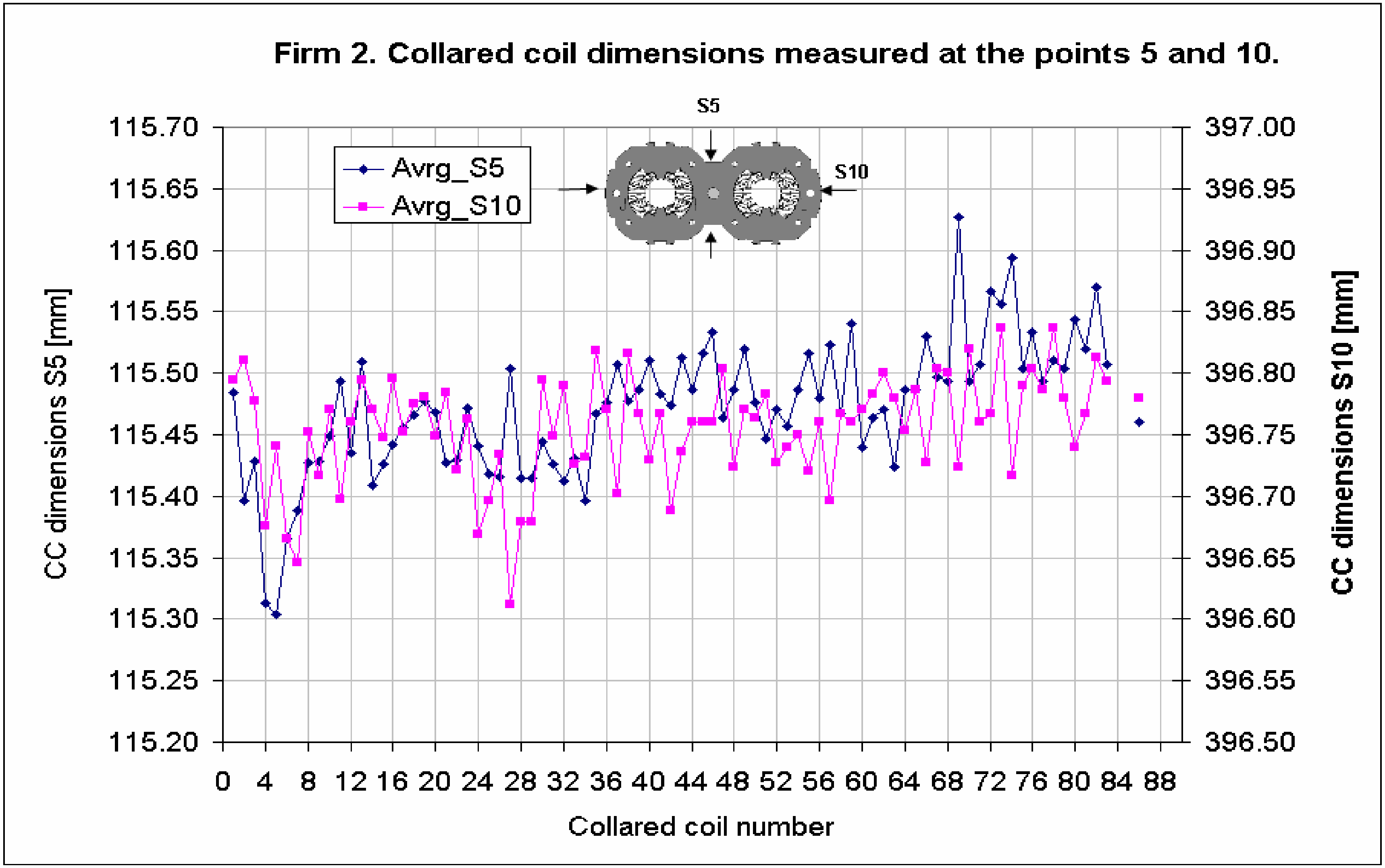


Fig. 23 Firm 2. Collared coil dimensions measured at the points S5 and S10.

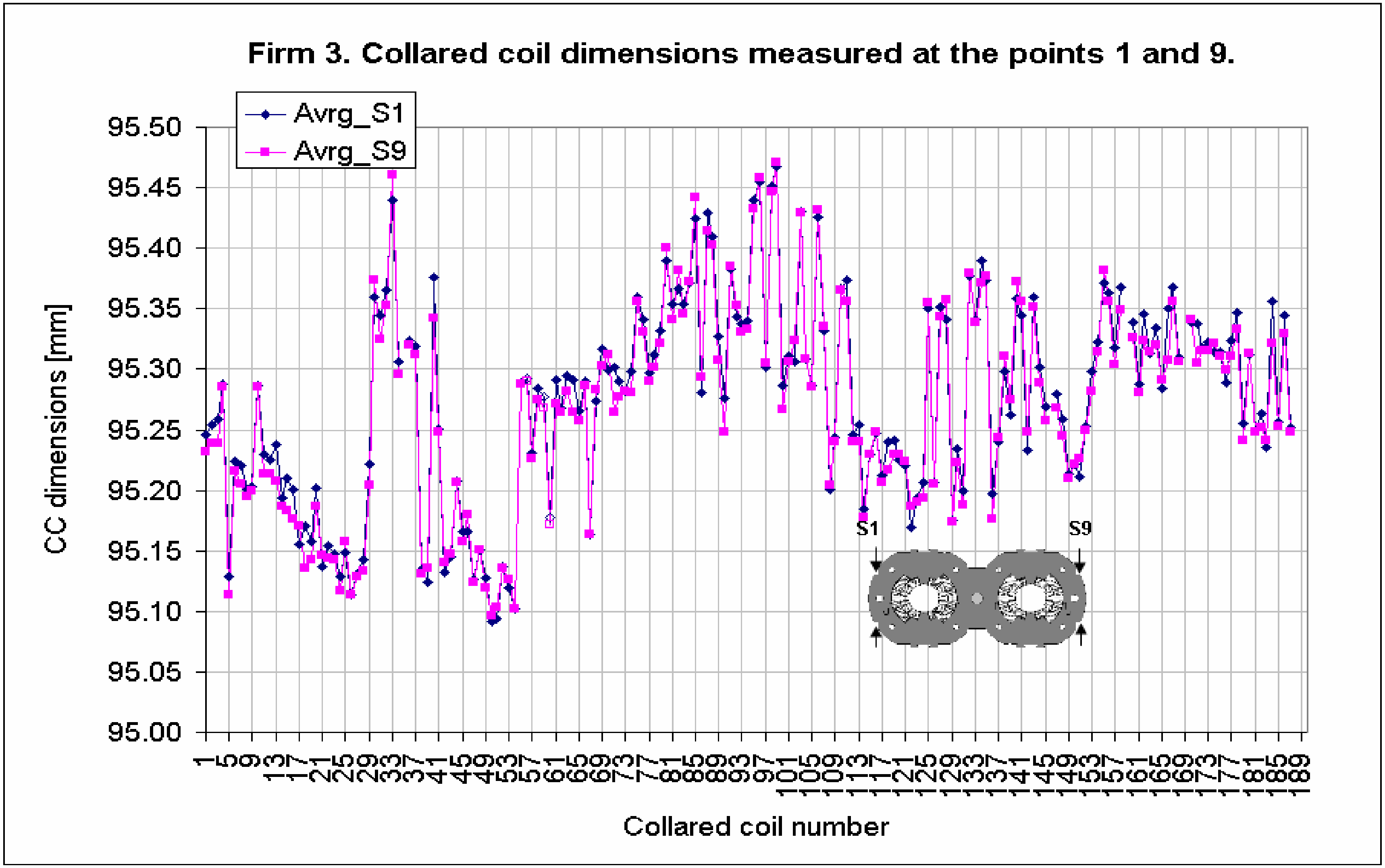


Fig. 24 Firm 3. Collared coil dimensions measured at the points S1 and S9.

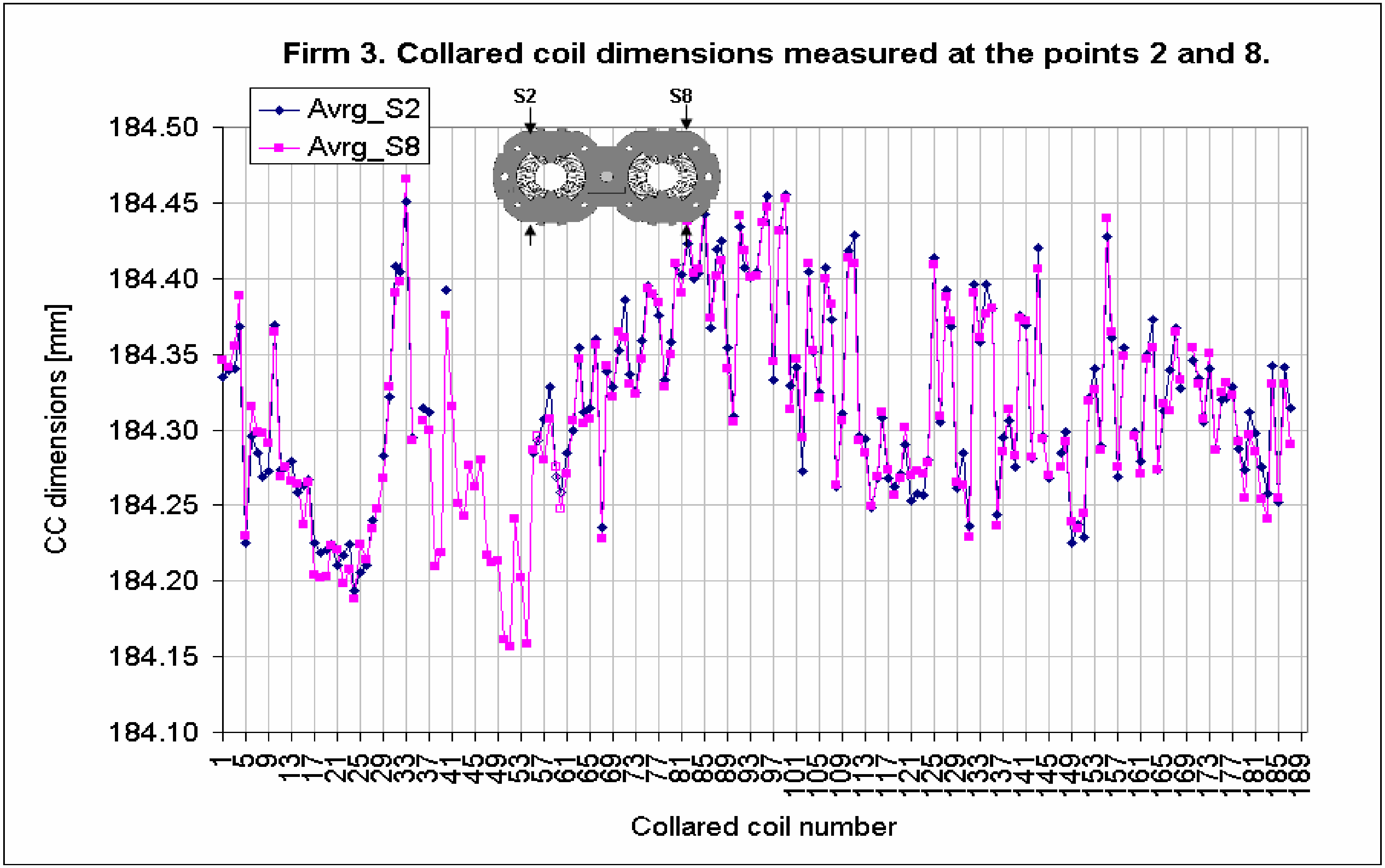


Fig. 25 Firm 3. Collared coil dimensions measured at the points S2 and S8.

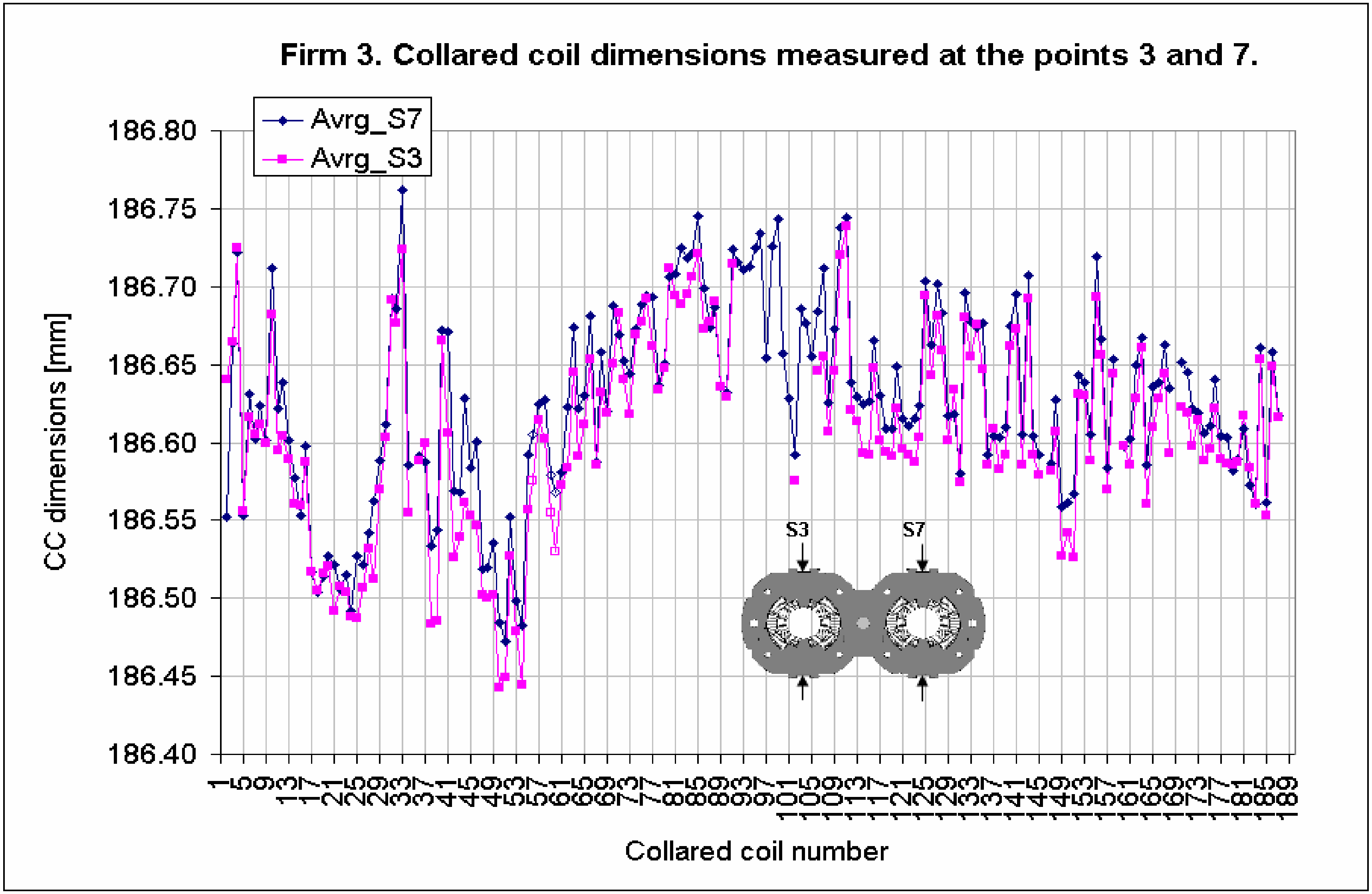


Fig. 26 Firm 3. Collared coil dimensions measured at the points S3 and S7.

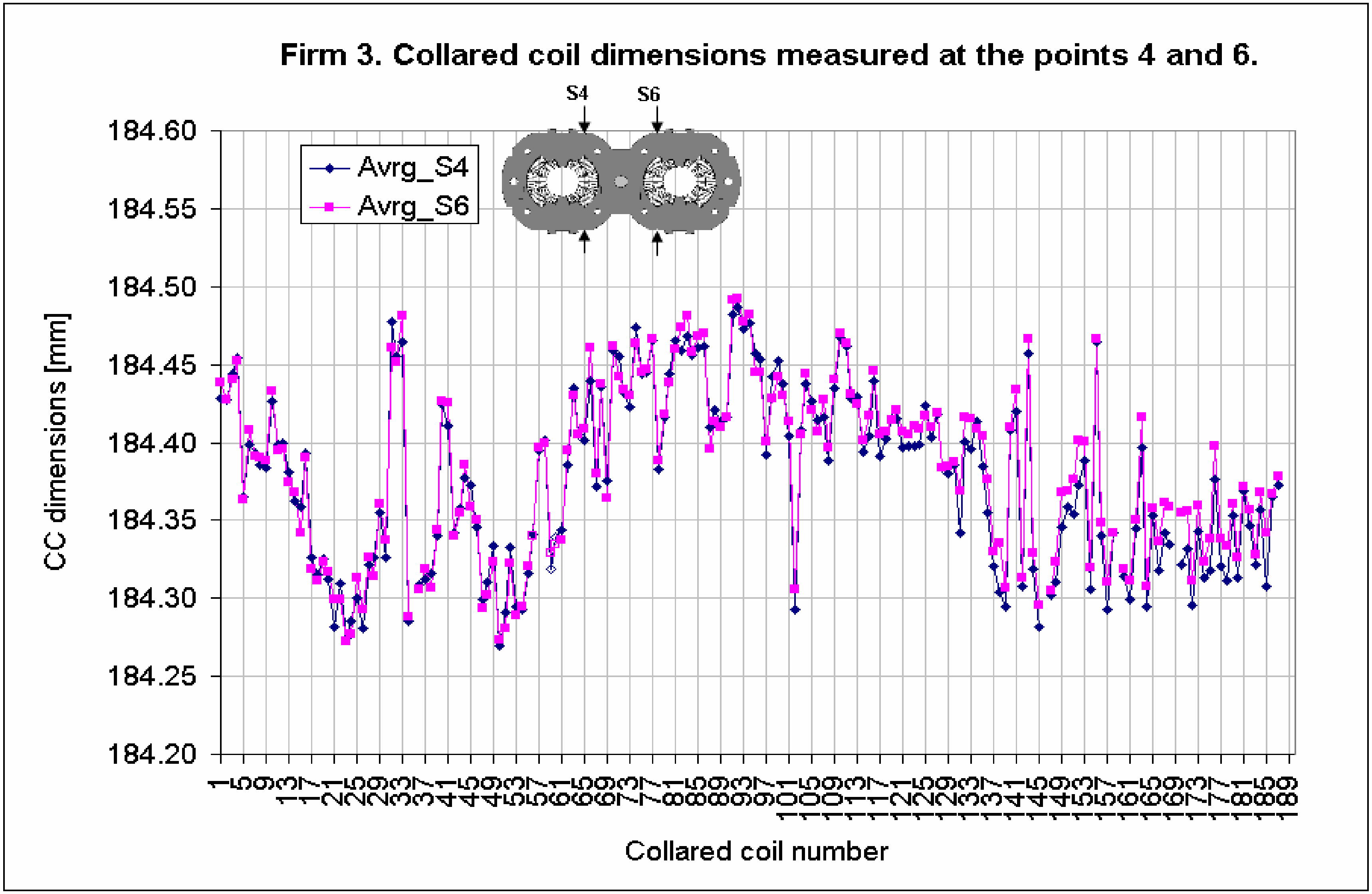


Fig. 27 Firm 3. Collared coil dimensions measured at the points S4 and S6.

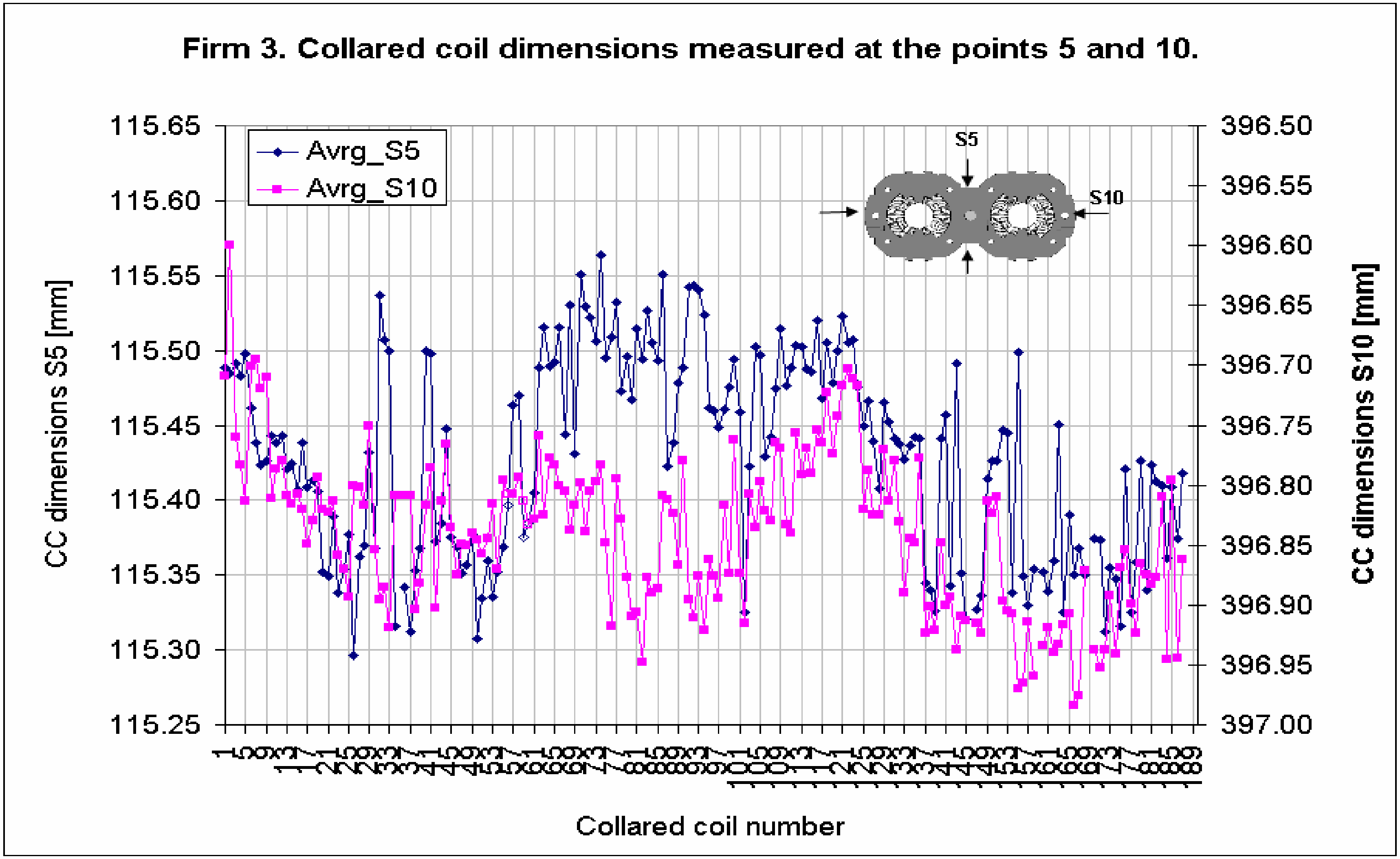


Fig. 28 Firm 3. Collared coil dimensions measured at the points S5 and S10 (notice that the scale for S10 axis is reversed).

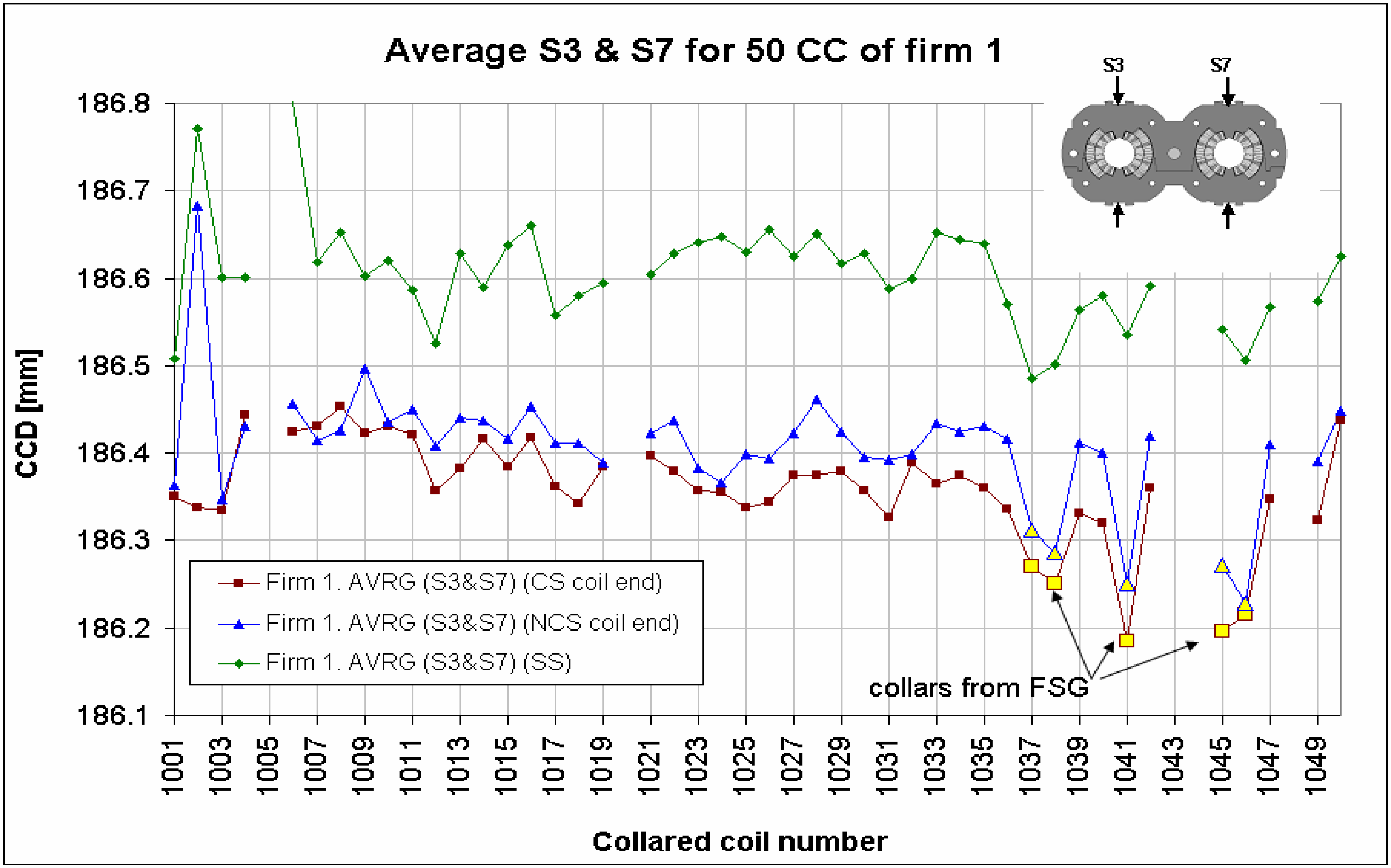


Fig. 29 Firm 1. Average of collared coil dimensions measured over coil ends and coil straight part at the points S3 and S7 (old measuring machine)

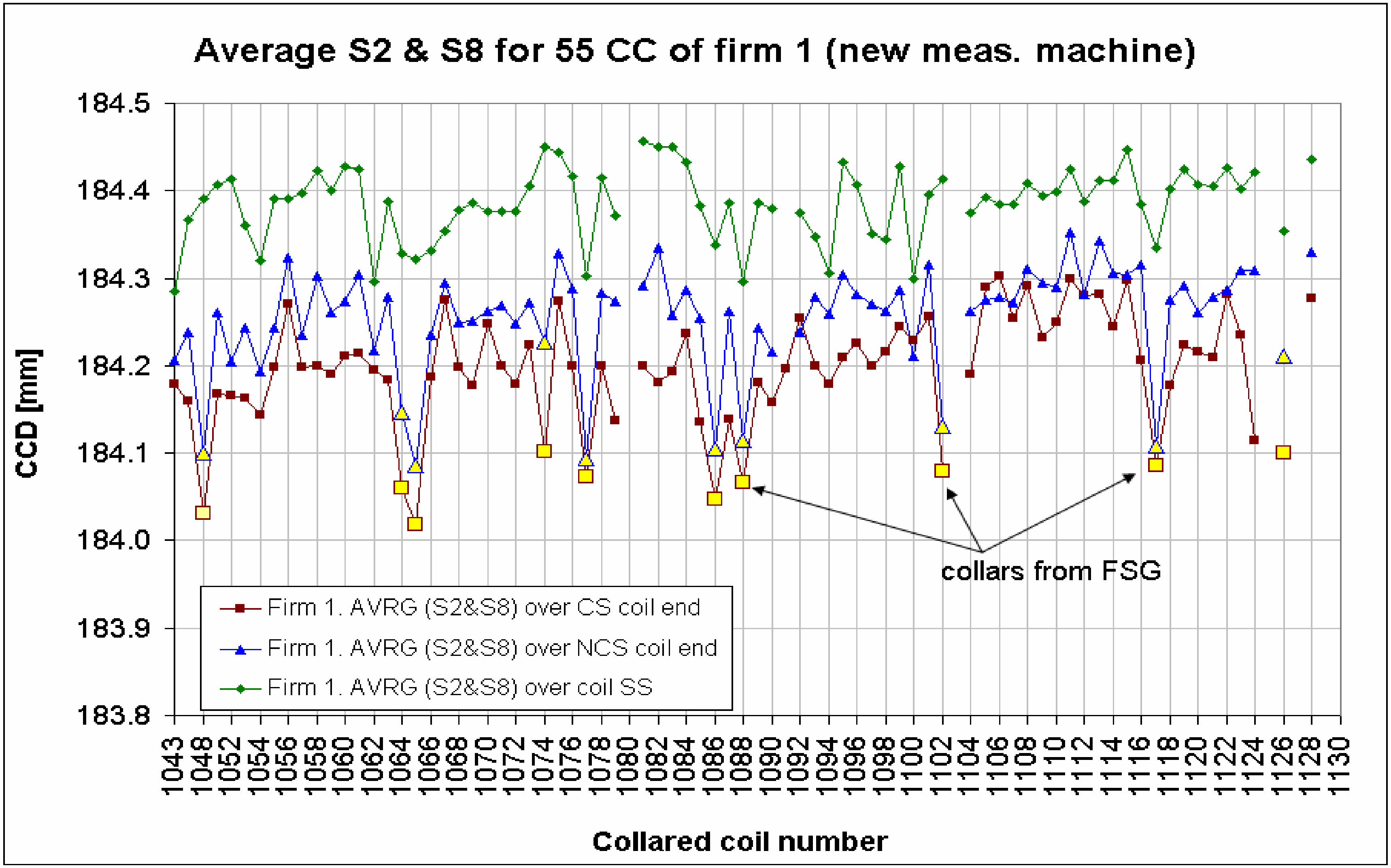


Fig. 30 Firm 1. Average of collared coil dimensions measured over coil ends and coil straight part at the points S2 and S8 (new measuring machine)

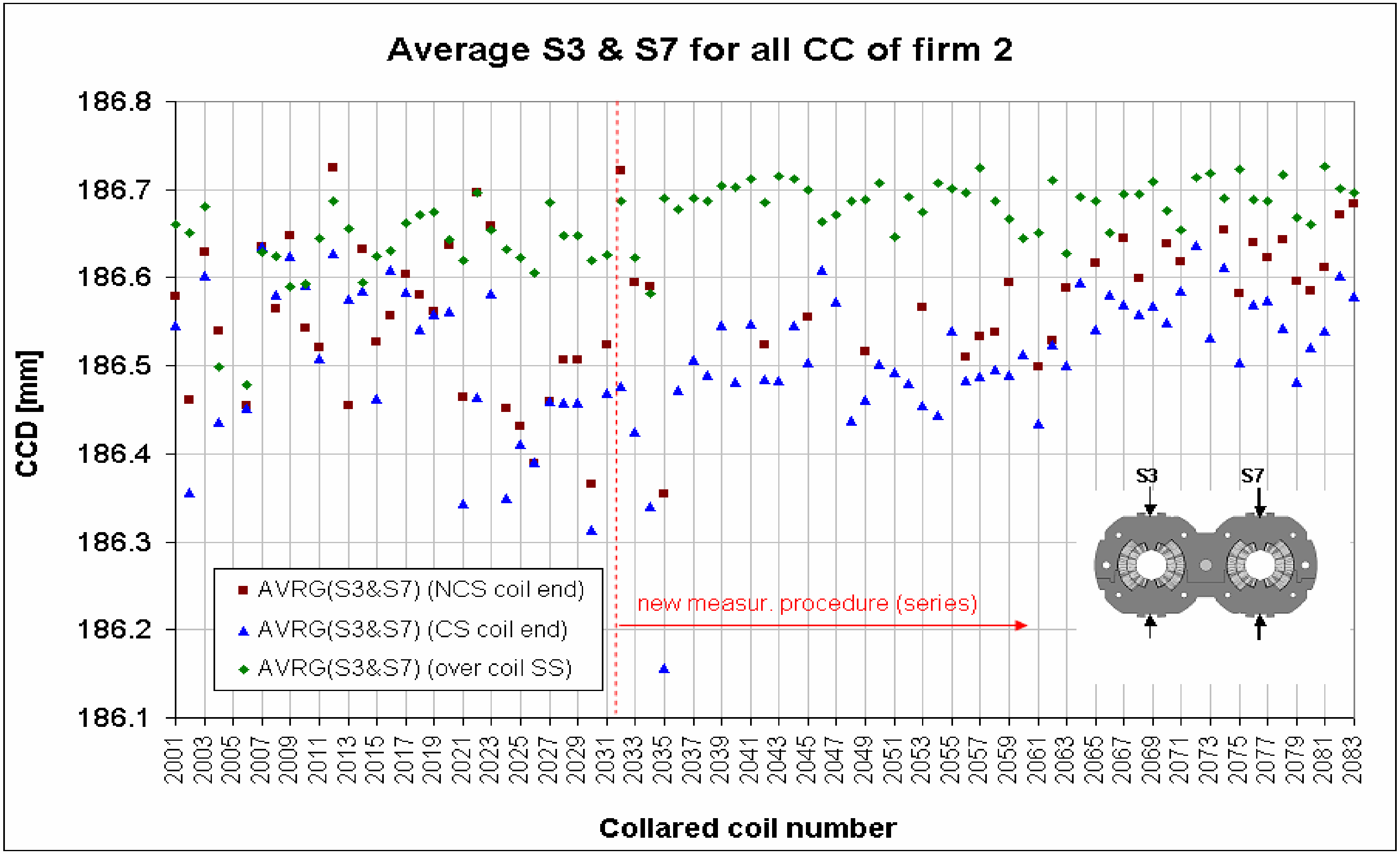


Fig. 31 Firm 2. Average of collared coil dimensions measured over coil ends and coil straight part at the points S2 and S8 (new measuring machine). For some of the magnets the measurements at NCS were done not correctly, therefore the data is not shown.

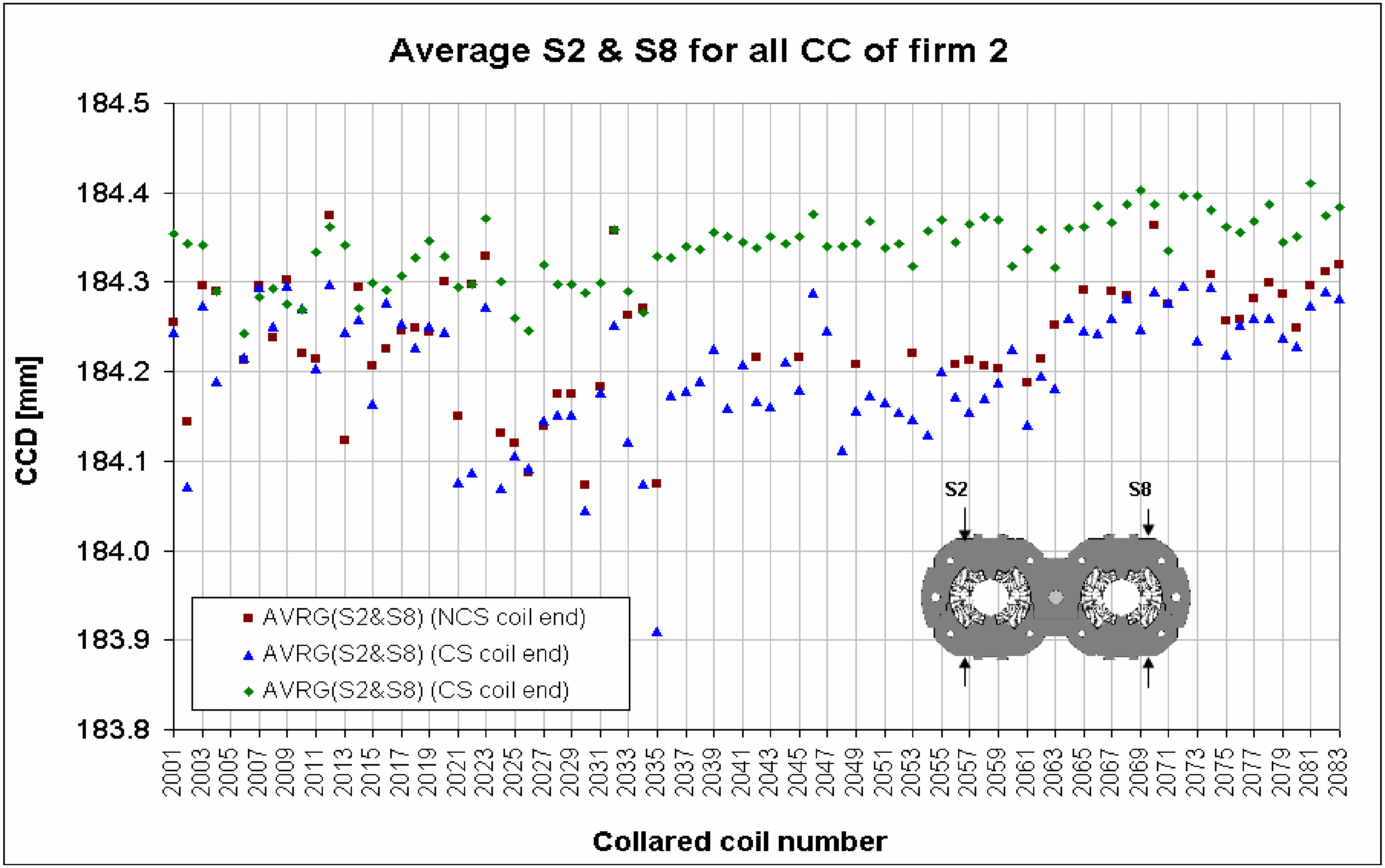


Fig. 32 Firm 2. Average of collared coil dimensions measured over coil ends and coil straight part at the points S2 and S8. For some of the magnets the measurements at NCS were done not correctly, therefore the data is not shown.

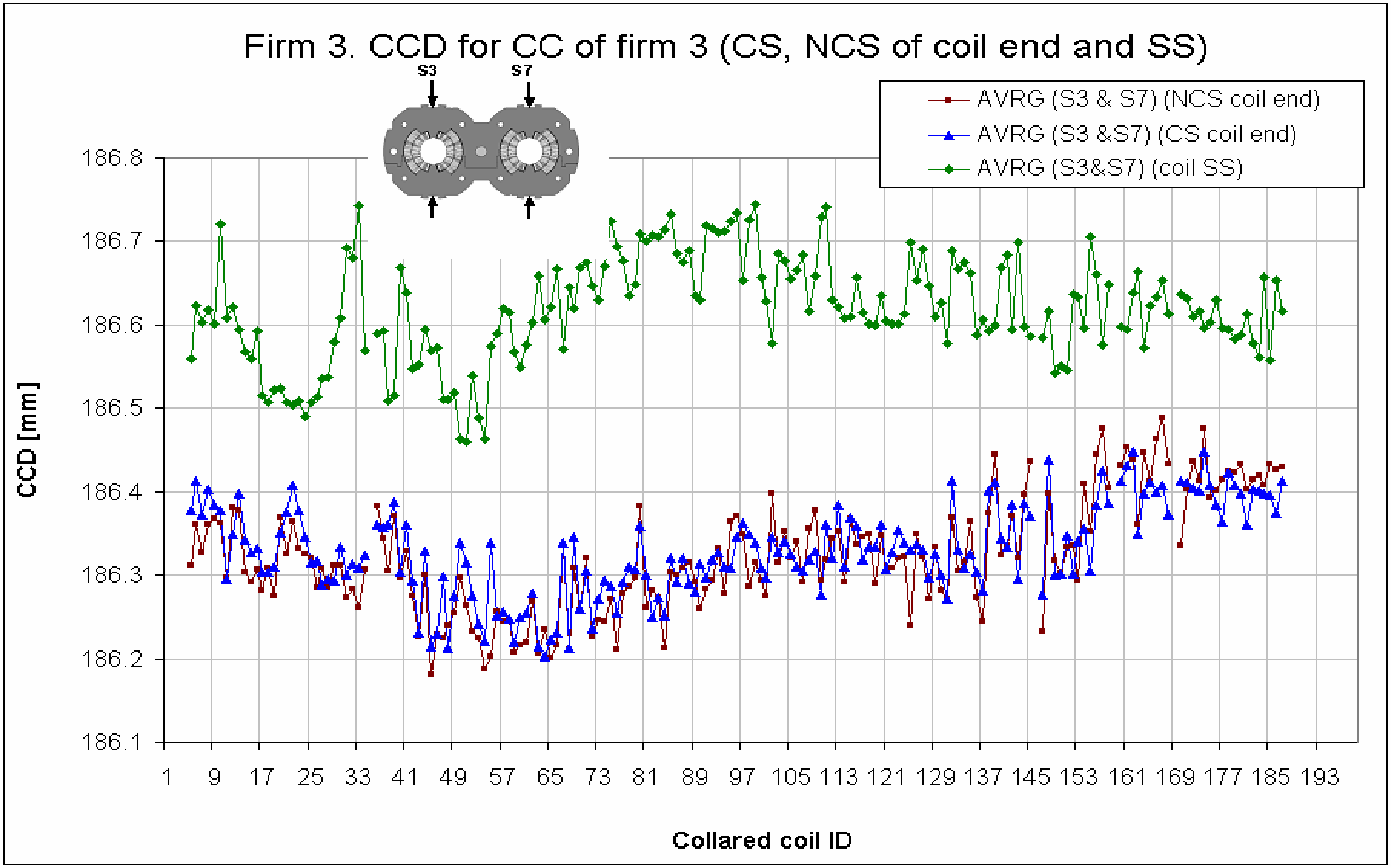


Fig. 33 Firm 3. Average of collared coil dimensions measured over coil ends and coil straight part at the points S3 and S7.

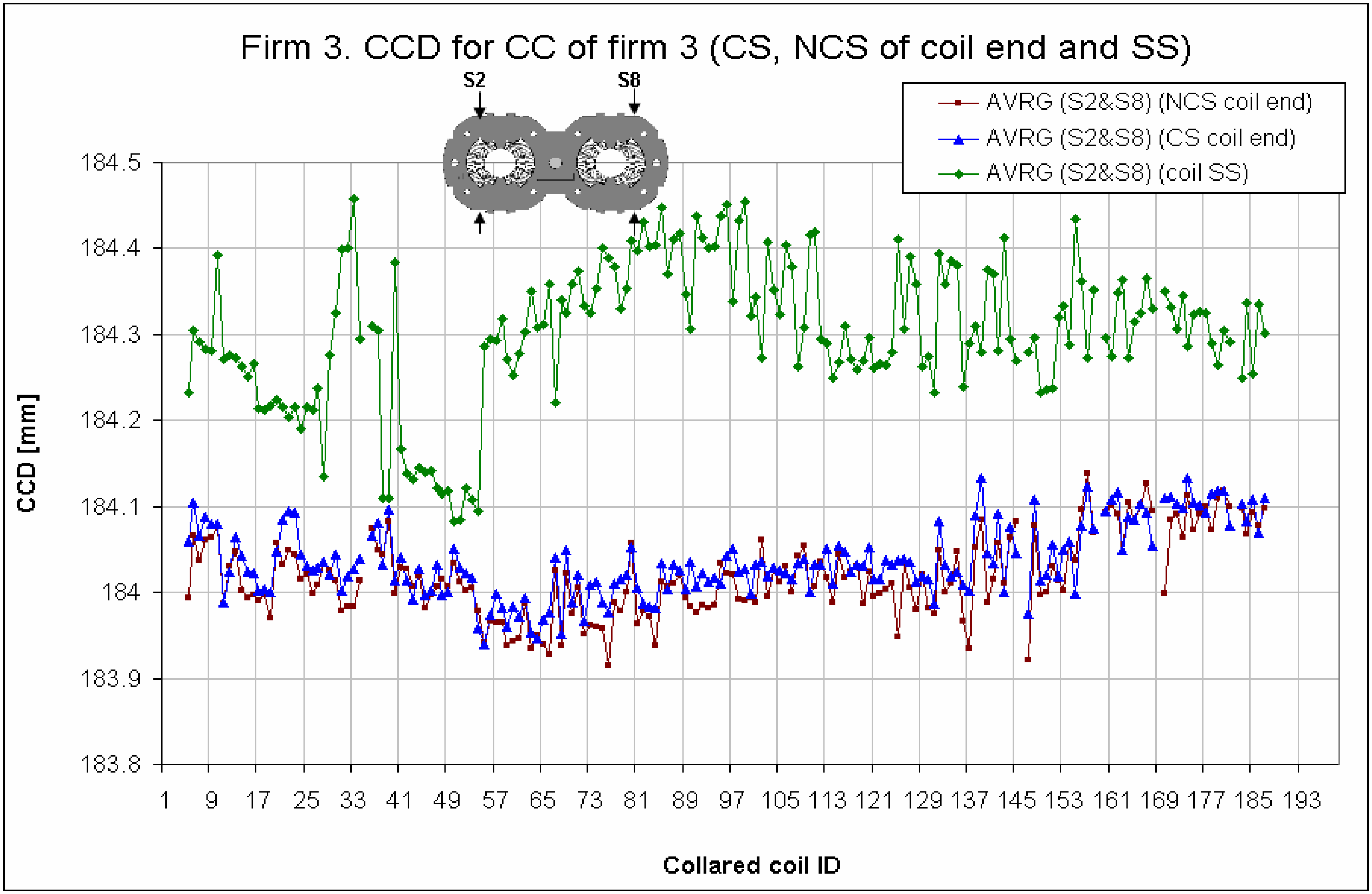


Fig. 34 Firm 3. Average of collared coil dimensions measured over coil ends and coil straight part at the points S2 and S8.

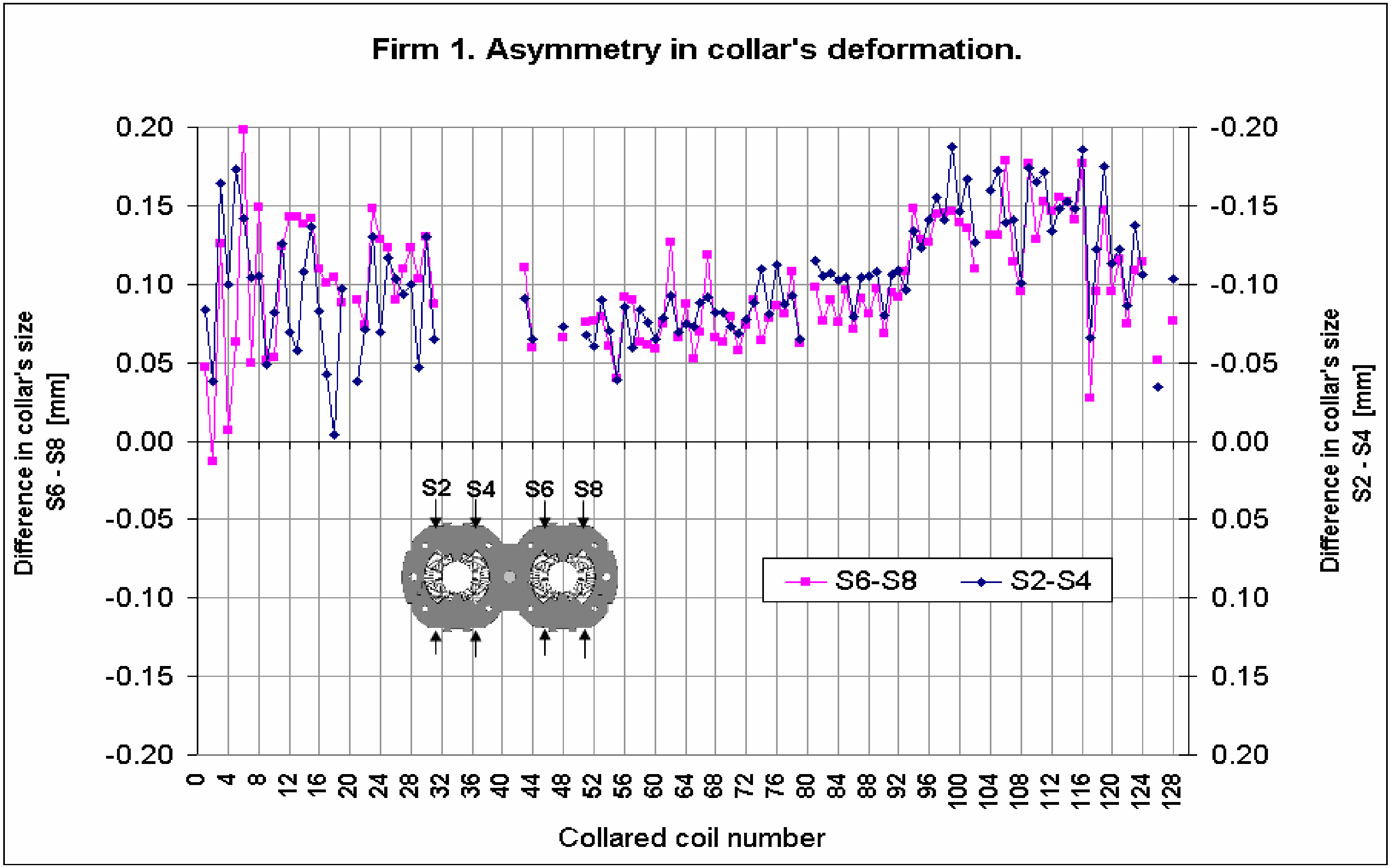


Fig. 35 Firm 1. Measured asymmetry in collared coil dimensions.

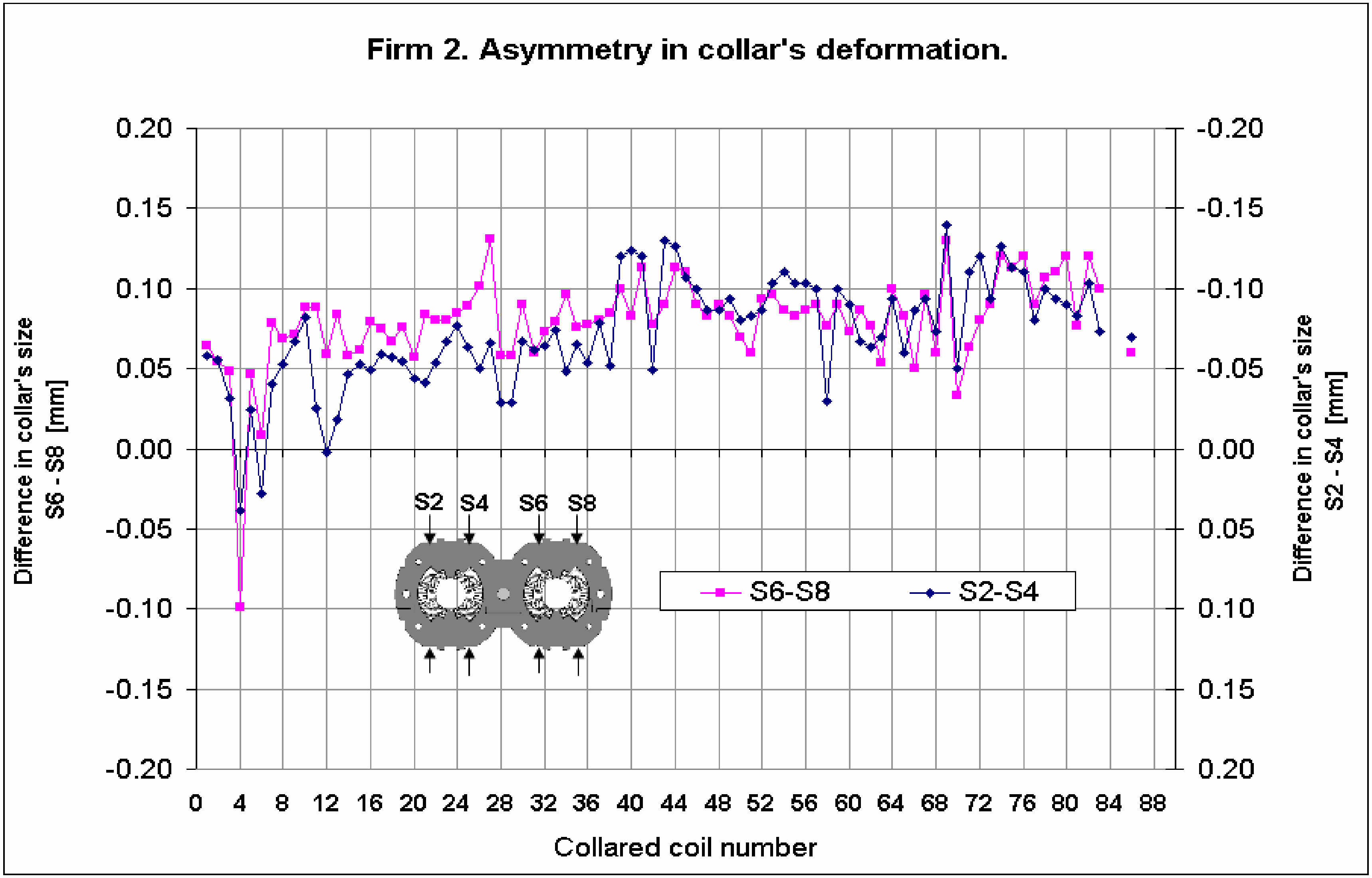


Fig. 36 Firm 2. Measured asymmetry in collared coil dimensions.

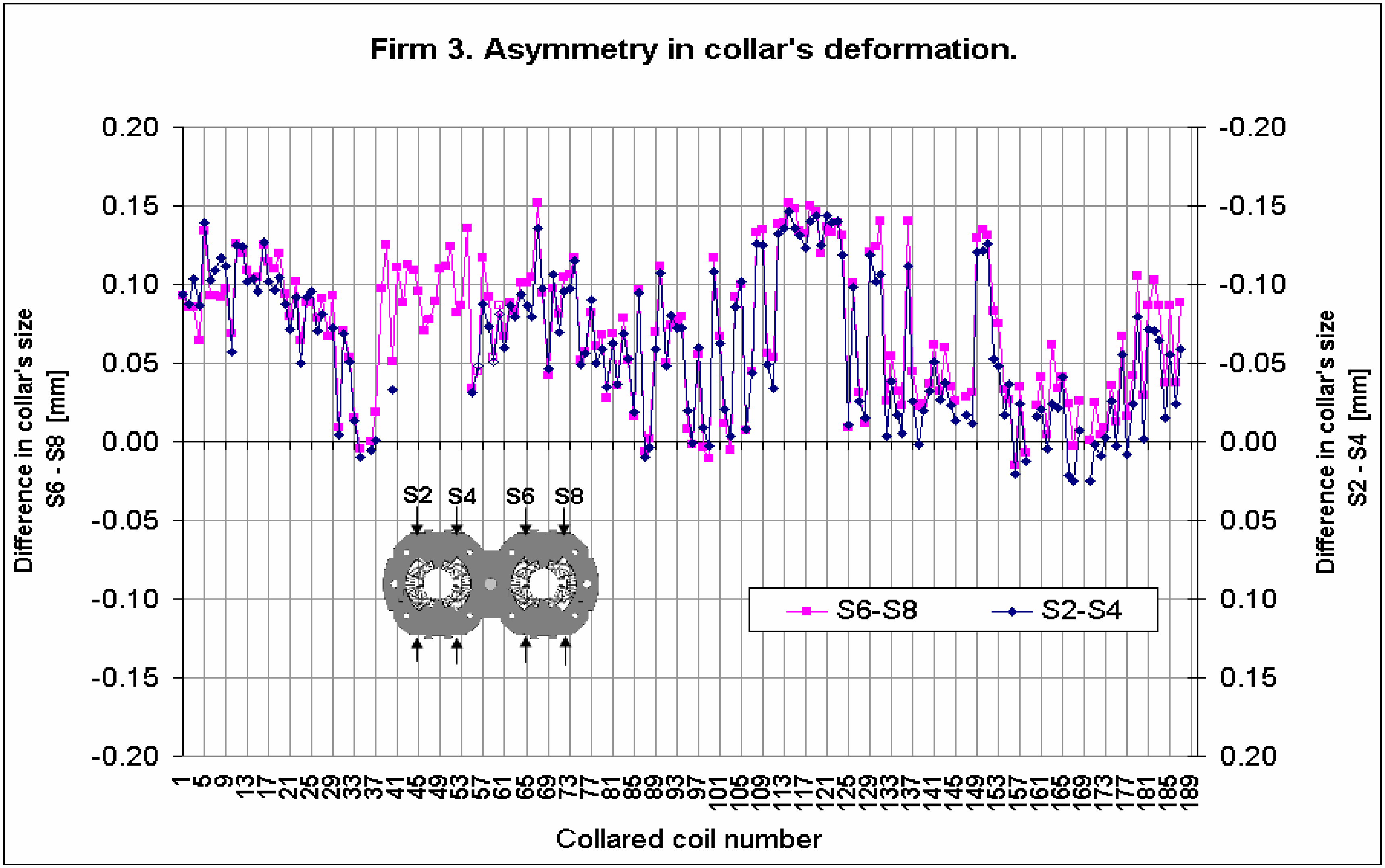


Fig. 37 Firm 3. Measured asymmetry in collared coil dimensions.

Appendix A

Firm 1 coils (poles) curing process parameters (curing temperature and curing shim thickness) for particular pole sets 105 ÷ 132. All previous coils at this firm, apart of few layers, were cured without additional curing shims.

TABLEAU RECAPITULATIF DES MODIFICATIONS DE CYCLE PS 105 à 135

N° Pole set	température palier			shim			stycast	ecobond
	130°	140°	150°	0	0.125	2 x 0.125		
105	■			■			■	
106	■			■			■	
107	■			■			■	
108			■			■	■	
109	■			■			■	
110	■			■			■	
111	■			■			■	
112	■			■			■	
113	■			■			■	
114		■		■			■	
115		■			■		■	
116		■			■		■	
117		■			■		■	
118			■		■		■	
119			■		■		■	
120			■		■		■	
121			■		■		■	
122			■		■		■	
123			■		■		■	
124			■		■		■	
125			■		■		■	
126			■		■		■	
127			■			■	■	
128			■		■		■	
129			■		■		■	
130			■		■		■	
131	■			■				■
132	■			■				■
133		■			■			■
134		■			■			■
135		■			■			■

Appendix B

Recently, at firm 2 a new winding machine was installed (C.S.A. 2), requiring the verification of coil shape quality. The coils at firm 2 are measured in 15 longitudinal positions. After any modifications of coils production tooling or process, the geometry of new coil is compared with so-called "statistical coil profile". The "statistical coil profile" is the coil profile averaged for a number of coils, produced with the same tooling. In figures 1 and 2 the longitudinal coil profile of the I0417 inner layer, wound with the new winding machine and is shown together with the statistical coil profile, evaluated from the data on last 10 measured inner layers. These 10 layers were manufactured with the same winding machine, curing mould and curing press. Comparing the profile of new coil with the statistical coil profile we can be see that their shapes are rather similar. This result was expected, as the shape of the coil is mostly given by the shape of curing mould, and the compared coils were cured with the same curing mould.

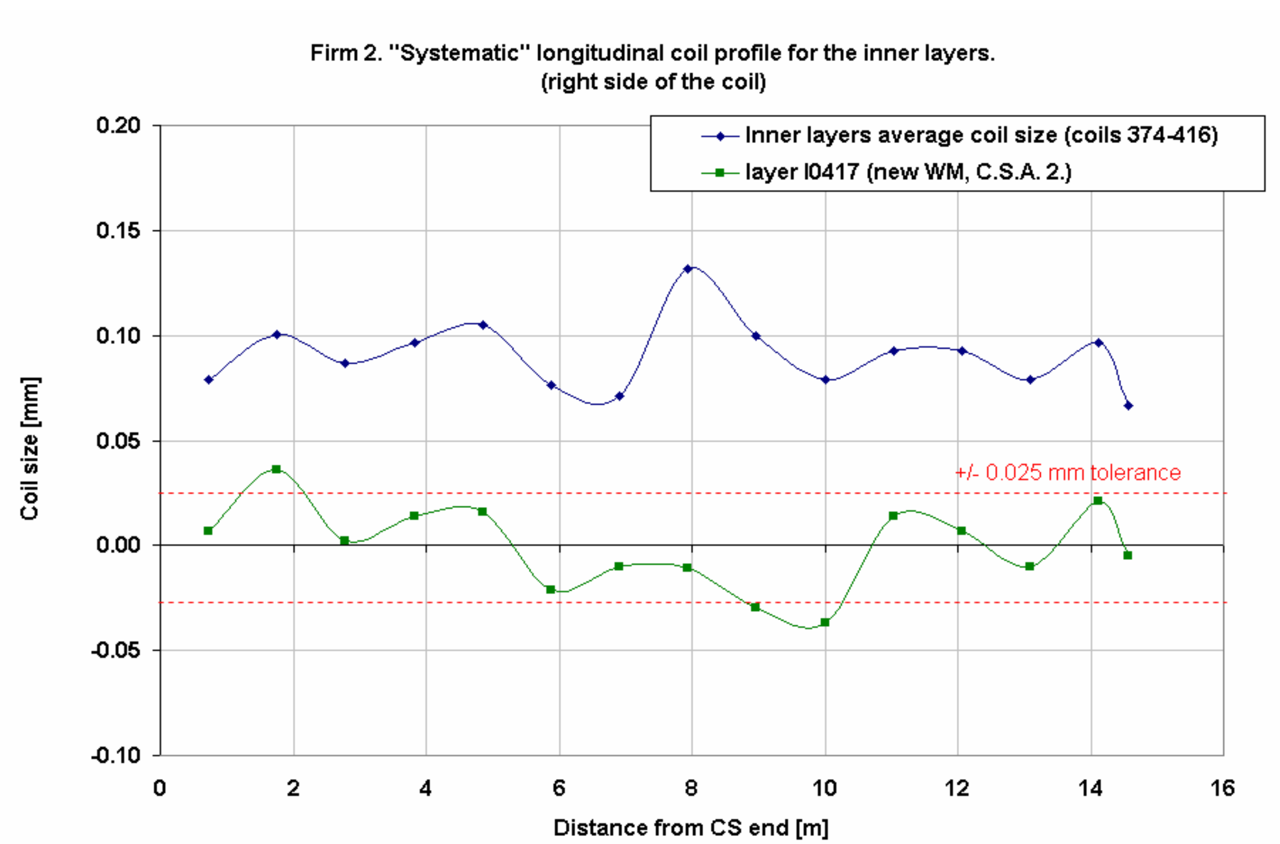
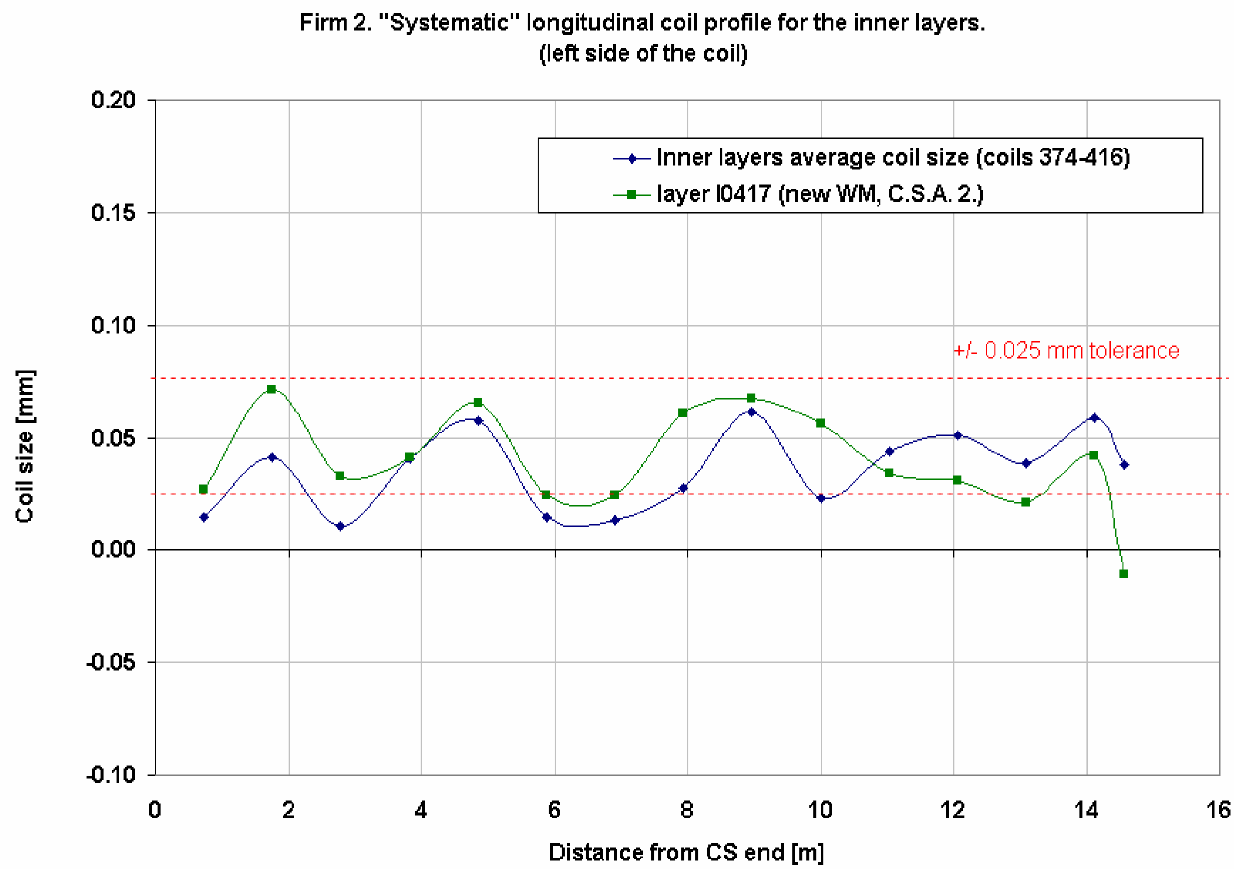


Figure 1.



Firm 2. "Systematic" longitudinal coil profile for the inner layers.
(left side of the coil)
Inner layers average coil size (coils 374-416)
layer I0417 (new WM, C.S.A. 2.)
+/- 0.025 mm tolerance
Coil size [mm]
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
0
2
4
6
8
10
12
14
16
Distance from CS end [m]

Figure 2.