Report on mechanical measurements in the main LHC dipole collared coils: September-October 2004

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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 beginning of November:

- **Firm 1 (ALSTOM-JEUMONT)** – Up to the end of June, in total 763 poles have been produced and 598 have been measured for coil size. During September-October period 100 poles were fabricated at Jeumont and 1/4 of them measured for coil size in coil straight part, while the measurements over coil ends and layer-jump area are being conducted on all poles. The data on layer-jump measurements is regularly sent to CERN for Post-processing. Compared to the July-August period, the average speed of coil production was doubled. In last two months the average production rate was ~ 12 sets of poles per month (6 sets of poles in previous period). All poles are measured with reduced number of measuring sections along the coil (5 instead 15). For coil size measurements Jeumont is still using their old E-modulus machine, the new one is still being commissioned. The Post-processor software for a new press (CTE) was send to Jeumont in the end of September.
- **Firm 2 (ANSALDO)** – Up to the end of October in total, about 528 inner and outer layers have been produced, where 40 layers of each type in the last 2 months. Compared to the July-August and also May-June period, the average coil production speed is remains unchanged: ~ 5 sets of poles per month. The highest production rate at firm 2 was achieved during January – February period of 2004: 8 sets of poles per month. At Ansaldo one inner and one outer layer per magnet are measured.
- **Firm 3 (BNN)** – CERN receives the raw data on mechanical measurements from BNN by batches with 2÷3 weeks interval. All data is post-processed at CERN. Up to date, the data on 780 inner and outer layers for 290 magnets is available at CERN. During September-October period 120 inner and outer layers have been produced (this corresponds to 30 magnets) and half of them were measured for coil sizes. At BNN two inner and two outer layers per magnet are measured, each at 4 longitudinal positions. Compared to the July-August period, the average speed of coil production was slightly reduced to 15 sets of poles per month (in previous period it was 20 sets of poles per month).

What is new:

Trends in coil sizes.

In general, we observe reduction of coil size on both inner and outer layers at firms 1 and 2, while at firm 3 the coil size is stable.
At firm 1 we notice important negative trends on coil sizes of both inner and outer layer. From magnet 132 to 172 the coil size on both layers has been reduced by almost 0.15 mm. With CERN suggestions, an action to recover the optimum coil size by reducing the curing shims was taken at Jeumont starting from the magnet 184. In the last 10 magnets the trends have been saturated, but the coil size still stays at low limits, particularly for the outer layer.
At firm 2 a small negative trend occurred from the beginning of series on the inner layer coil, now has been saturated, while similar positive and negative trends on the outer layer are still present. The amplitude of these trends in the data for last 40 magnets is larger then ±0.1 mm.
The coil size at firm 3 is rather stable on both layers, while the young modulus of coils is varied in rather large range.

Coil waviness. Actually only firm 2 is measuring the coil size in many positions along the coil, allowing monitoring the coil waviness. Therefore the graph on this parameter we show only for this firm.
At firm 3, in order to verify the tooling shape, during the coil size measurements for the last 10 magnets, 1 measuring position among 4 was moved along the coil, and one coil was measured in all 14 longitudinal positions. We present the data on these particular measurements in *Appendix* in comparison with the data on coil waviness for pre-series coils of firm 3.

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 firms.

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 in order to speed up the production, starting from the poles set 114 the number of measuring sections in coil straight part has been reduced to 5 (from 15). In figure 1 the average of all measuring points is used to show the coil size trends. In the past, due to coil oversize, 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, 0.125 mm thick. Despite this action, we do not notice a visible reduction in the amplitude of coil size treads on any coil layer. Moreover, starting from the magnet 137 the coils size has been rapidly increased again and then a long negative trend has brought it down again without any intervention on curing process. In fact, the coils size for magnets 183 and 184 was measured too small and CERN has suggested to firm to remove the additional curing shim in order to try to recover the optimum coil dimensions. As can be seen in figure 1, the coil size of the last few magnets has been measured slightly bigger.

The difference in coil size between the left and right sides of coils is shown in figure 2. As shown by moving average in figure 2, we notice some improvement of left-right coil asymmetry in last 10 magnets. This type of asymmetry can lead to appearance of shift in systematic of a3 multipole. In figures 3 and 4, the inner and outer layers coil sizes are plotted together with their E-modulus.

Firm 2. About 40 inner and outer layers have been produced over last two months, and a quarter of them have been measured for coil sizes. In general, except some magnets, the coil size variation in the inner and outer layers coils of series production stays in the range of ±0.1 mm (fig. 5). A small negative trend present since the beginning of series on the inner layer coil has been saturated in coils of last 15 magnets, while similar positive and negative trends on the outer layer are still present. The amplitude of these trends in the data for last 40 magnets is larger then ±0.1 mm.

At firm 2 the coil size measurements are taken in 15 longitudinal positions along the coil. By measuring the coils at all positions the firm keeps control on the coil production tooling shape. The standard deviation (one sigma) of coil size variation along the coil is shown in figure 6. As we can see from this figure there is very small coil waviness in the last 200 coils (50 magnets).

The difference in coil size between left and right sides of coils is shown in figure 7. As it is shown by moving average in figure 7, the rather stable shift in the systematic of left-right asymmetry in the inner layers coils has been disappeared in the last 10 magnets.

In figures 8 and 9, the inner and outer layers coil sizes are plotted together with their E-modulus (notice that the scale for E-modulus axis is reversed). A significant trend in the coil E-modulus of the inner layer coils, underlined in previous report, have been saturated in the coils of last 20 magnets. The same observations are on the outer layer coils.

Firm 3. Up to date, the data on 780 inner and outer layers for 290 magnets is available at CERN. Starting from the magnet 100, two inner and two outer layers coil per magnet are measured for coil sizes at 4 pre-defined longitudinal positions along coil straight part. Two more measurements are performed on the layer-jump area and the coil ends are measured separately by special machine.

Starting from the magnet 89 (after the last modification of the curing shim), the coil size variation at firm 3 is smallest among three firms. The coil size is varied in the range of ±0.05 mm, which is twice smaller compared to the coils of firm 1 (see figure 10). However, the young modulus in coil of firm 3 is varied as much as at other two firms.

The difference in coil size between left and right sides of coils is shown in figure 11. As it is shown with the moving average in figure 11, we notice some degradation in left-right coil symmetry at firm 3 for the recent magnets. Still this asymmetry is lower then at other two firms.

In figures 12 and 13, the inner and outer layers coil sizes are plotted together with their E-modulus (notice that the scale for E-modulus axis is reversed). Already underlined in previous report, despite rather stable coil size at firm 3, we systematically observe significant trends in the coil E-modulus data on both coil layers. We remind that the field quality of the magnet rely on the final coil geometry which depends not only on the azimuthal coil size, which is reported here at fixed pressure target, but also on coil elasticity, i.e. coil E-modulus, and also on coil radial dimensions. In fact, as we will see later from the collared coil dimensions measurements data, the magnets of firm 3, despite rather homogenous coil size shows significant trends in coil pre-stress, seen as variation of collared coil dimensions.

In order to verify the tooling shape, during the coil size measurements for the last 10 magnets, 1 measuring position among 4 was moved along the coil, and two outer layers coils were measured in all 14 longitudinal positions. We present the data on these particular measurements in *Appendix* in comparison with the data on coil waviness for pre-series coils of firm 3. This statistics shows that the outer layer coils systematically have rather small coil size at the measuring positions 6 and 9, which was not a case in the past. We can’t say much yet about inner layer coils as the data on measuring positions 7÷12 and 14 is missing. We will update this statistics if there are will be more data available in the future.

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 14 ÷ 16 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 no longer measured; therefore the corresponding figures have been removed from this report. For the last 50 magnets we notice a reduction in CCD data variations. However, in CC 182 a rather lower CCD has been measured in straight part and also in coil ends (see figure 27), indicating lower coil pre-stress in that magnet.

Firm 2. In figures 17 ÷ 21 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. We notice a rather low CCD of the magnets 121 and 122 indicating a lower coil pre-stress in these magnets.

Firm 3. In figures 22 ÷ 26 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. 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 and there is no impact of the collaring press on the collar surface during collaring. In figures 27÷30 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÷150, which are measured with the new machine. In this report the data belonged to the first group, already published in the previous reports, has been dropped. In figure 27 the CC dimensions for measurements taken over coil ends are shown together with the data on coil straight part. In this figure, the magnets, collared with collars from FSG, which systematically shows smaller CC dimensions over coil ends due to some particularity of these collars, are marked separately.

For the last 20 magnets we notice a negative trend in CCD data of firm 1, which is in line with the observed trend on coil sizes, mentioned above. Moreover the magnet 182 has the smallest CC dimensions over last 80 magnets, indicating lower pre-stress value not only in coil straight part but also in coil ends.

Firm 2. In figure 28 the CC dimensions for measurements taken over coil ends are shown together with the data on coil straight part. For an easy cross-check with firm 1, in figure 29 the CCD data on the measuring points S2 and S8 is also shown.

For some of the magnets the measurements at NCS were done not correctly, therefore the data is not shown. Some of these magnets were re-measured and their IDs have an extension “R”.

In general for magnets of series the average on CCD data is rather stable in firm 2, but in the last 15 magnets we observe a positive trend and in few recent magnets the average collared coil dimensions taken over coil ends are even measured larger then in the straight part (see CC 127 and 135 in figure 29). We also observe a systematically bigger CCD taken over layer-jump area of the magnet compared to the straight part of the coil.

Firm 3. In figures 30 the CC dimensions for measurements taken over coil ends are shown together with the data on coil straight part. For collared coils 240÷260 the data on S3 and S7 are not shown due to the problem with the sensors of the measuring machine. 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 31 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.

There is a systematic difference in the CCD data for two collars producers. This difference is in the order of 0.1÷0.2 mm (see figures 27 and 31).

Similarly to the magnets of firm 2 we observe a small positive trend in CCD data taken over coil ends, indicating increase of coil pre-stress in the magnets of firm 3 (see figure 31).

Asymmetry in collar's deformation

The left-to-right side asymmetry with respect to the aperture axes in collars deformation produces the non-allowed multipole b2. In figures 32÷34 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).
For the firm 3 CC we observe the largest variation for the asymmetry in collar's deformation between the lateral and central part of the collars: ±0.15 mm while at other two firms it stays within ±0.05÷0.1 mm

Acknowledgments

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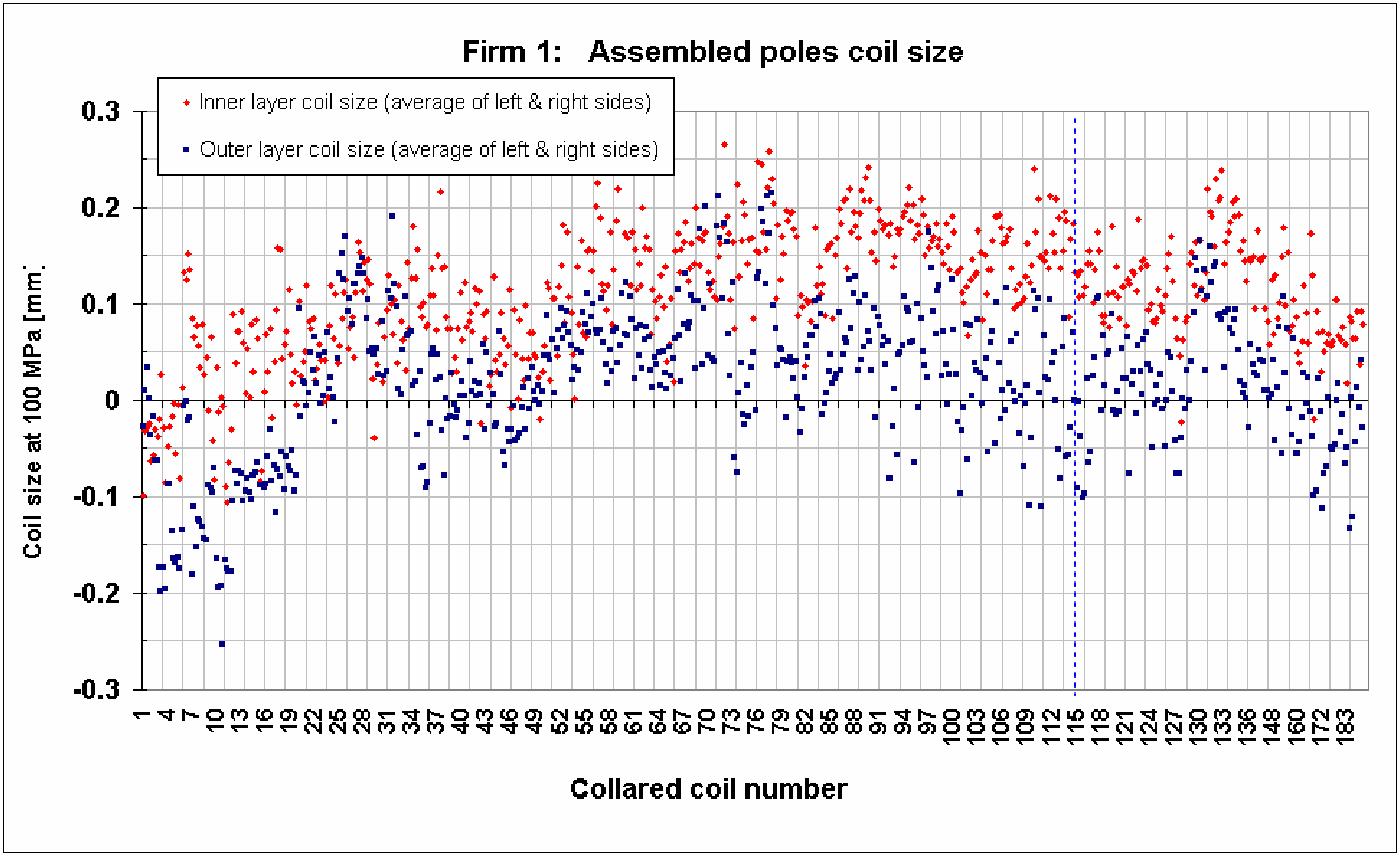

Fig. 1 Firm 1. Average coil size in the straight part of the assembled poles (642 poles).

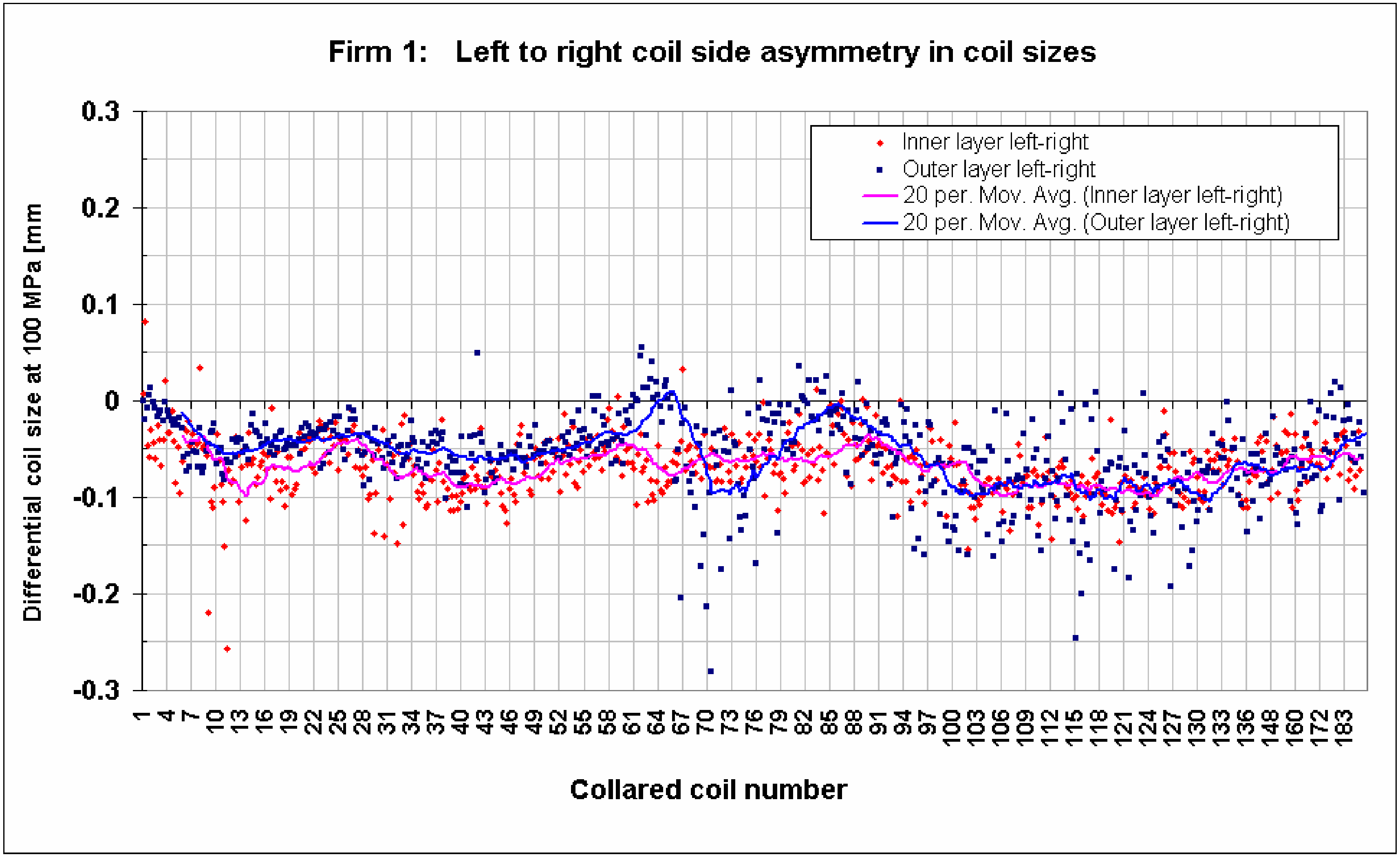

Fig. 2 Firm 1. Difference in the coil size between left and right sides of the coil on both layers.

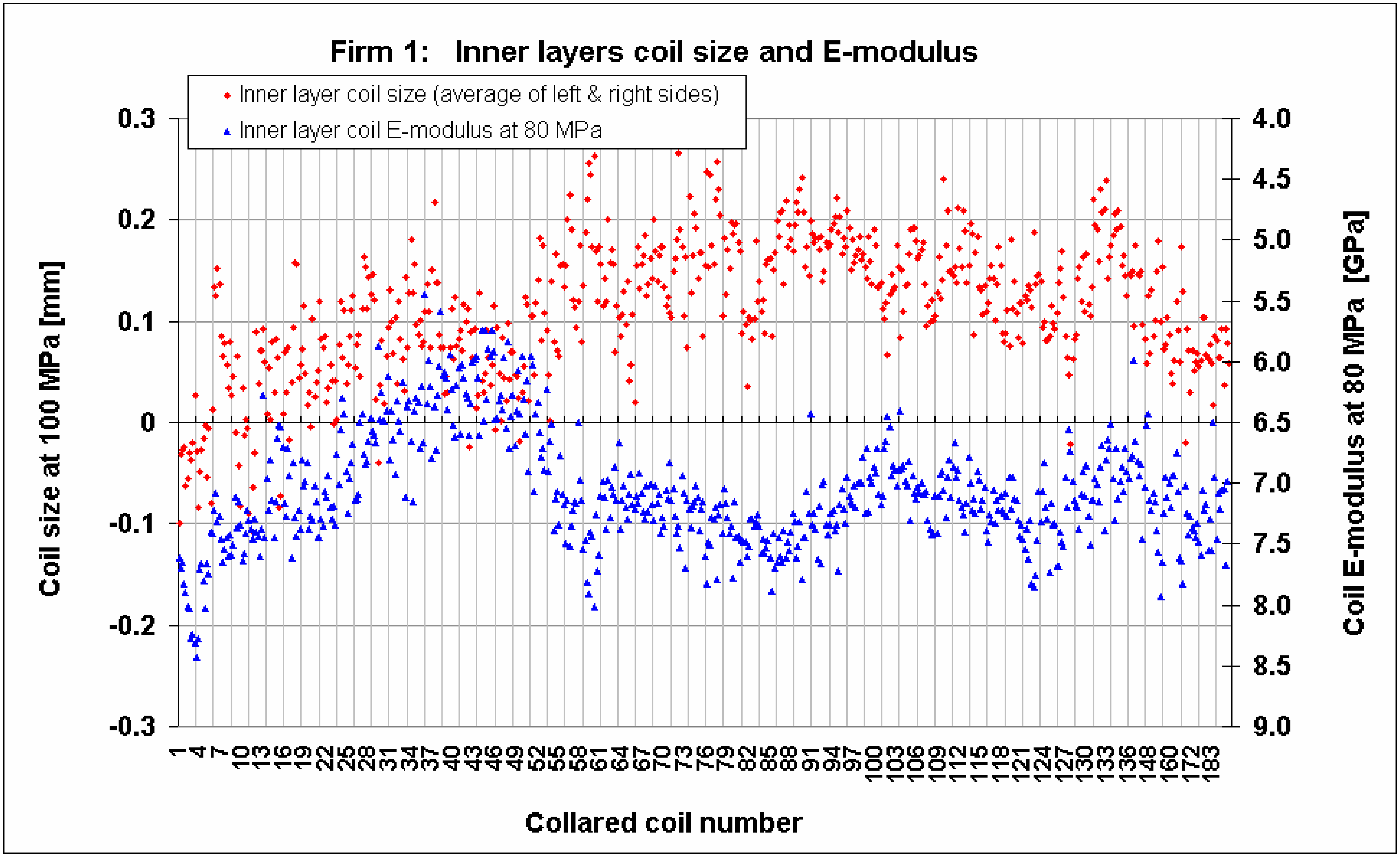

Fig. 3 Firm 1. Inner layer coil size (average) and E-modulus computed at 80 MPa.
(Data extracted from pole size measurements).

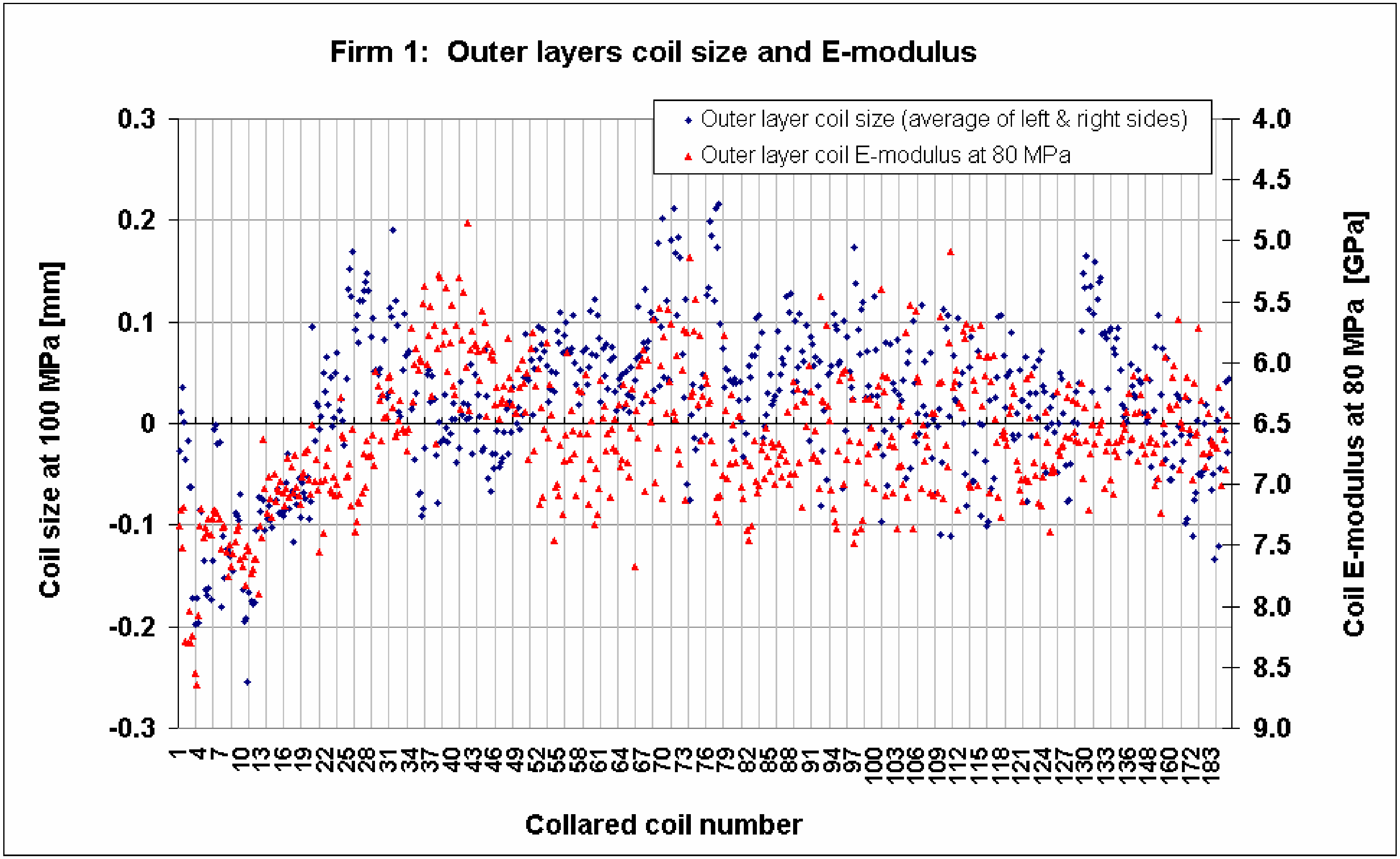

Fig. 4 Firm 1. Outer layer coil size (average) and E-modulus computed at 80 MPa. (Data extracted from pole size measurements).

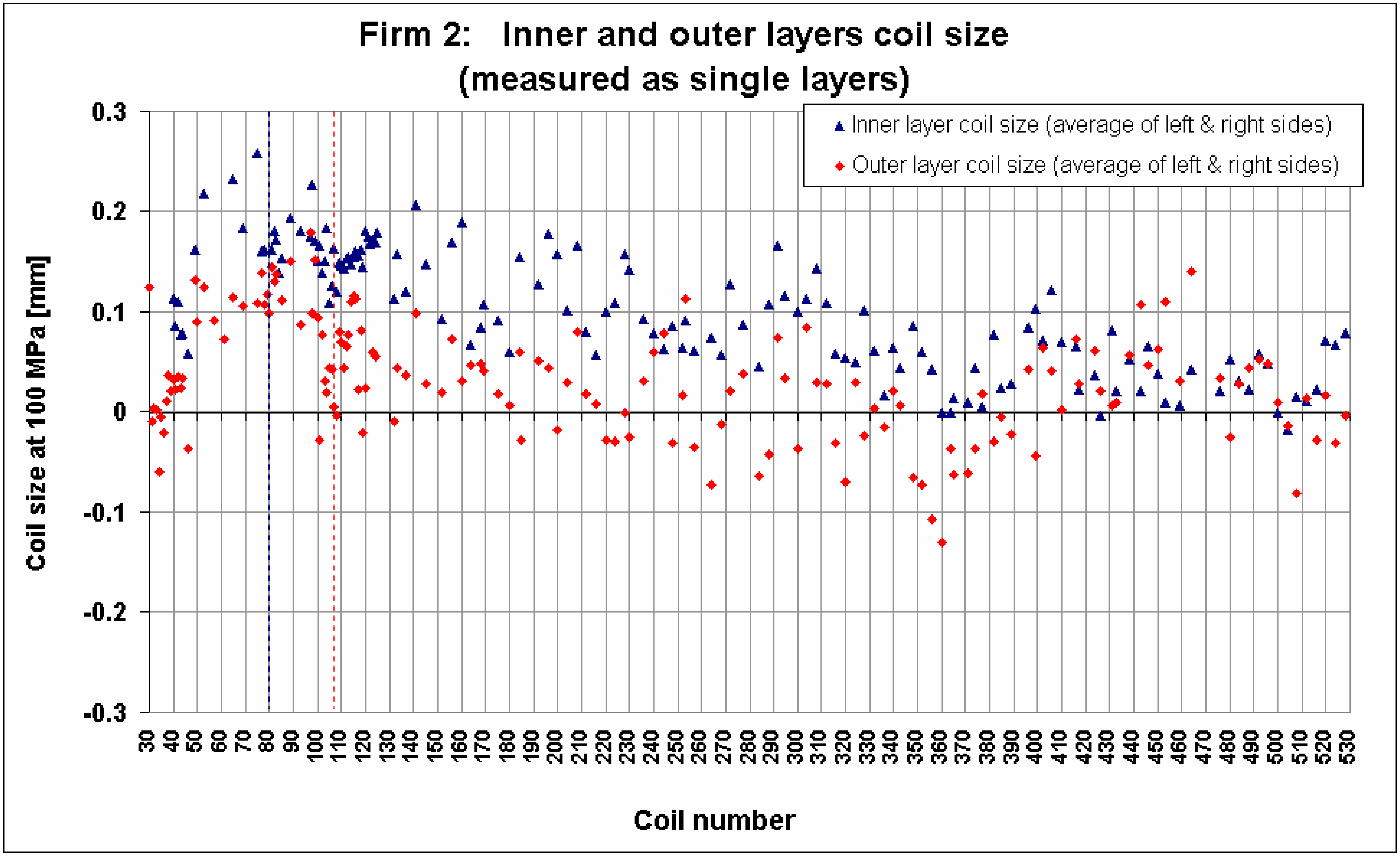

Fig. 5 Firm 2. Average coil size in the straight part of the inner and outer layers.

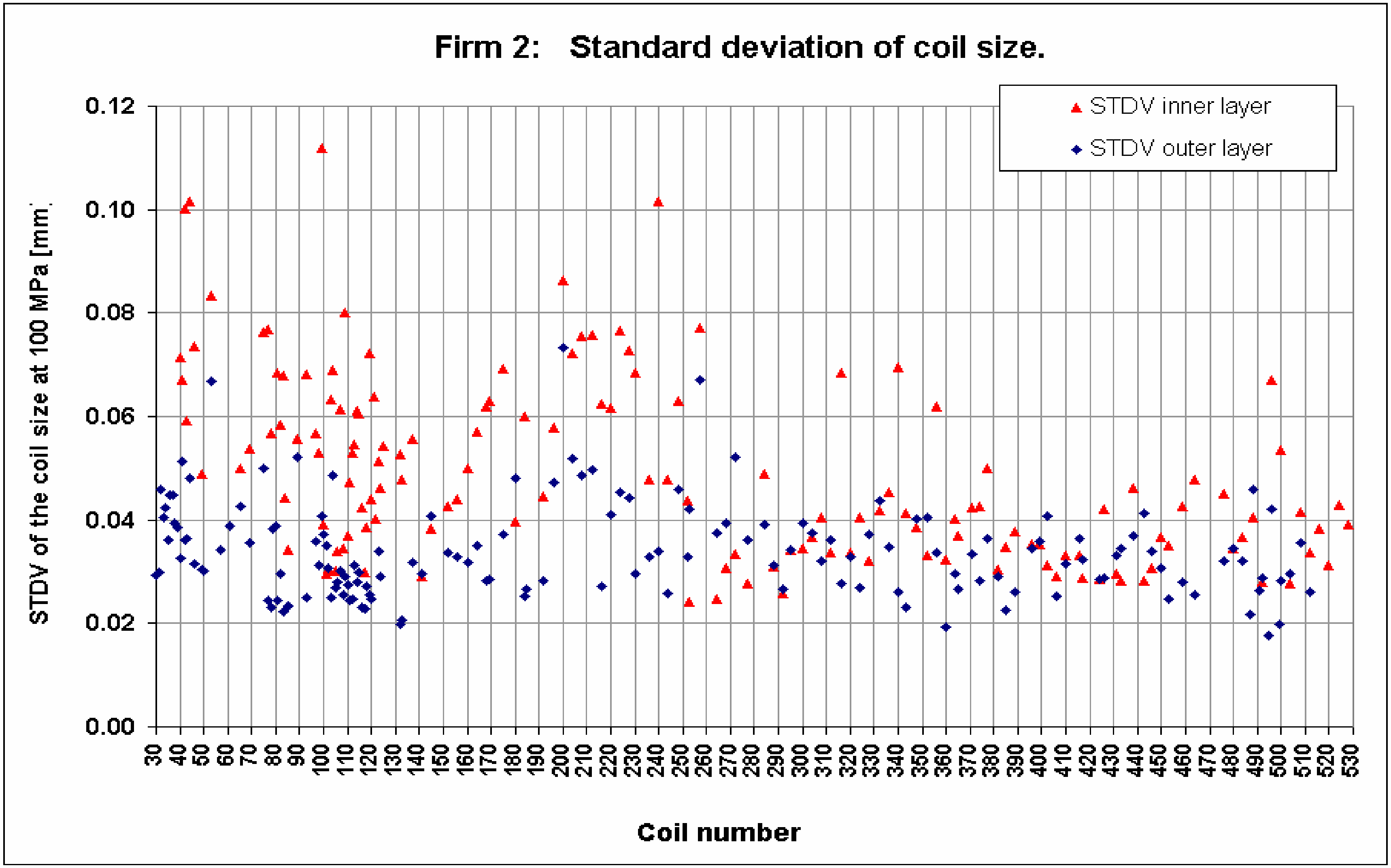

Fig. 6 Firm 2. Standard deviation of coil sizes measured in 15 positions along the coil (left and right coil sides in average).

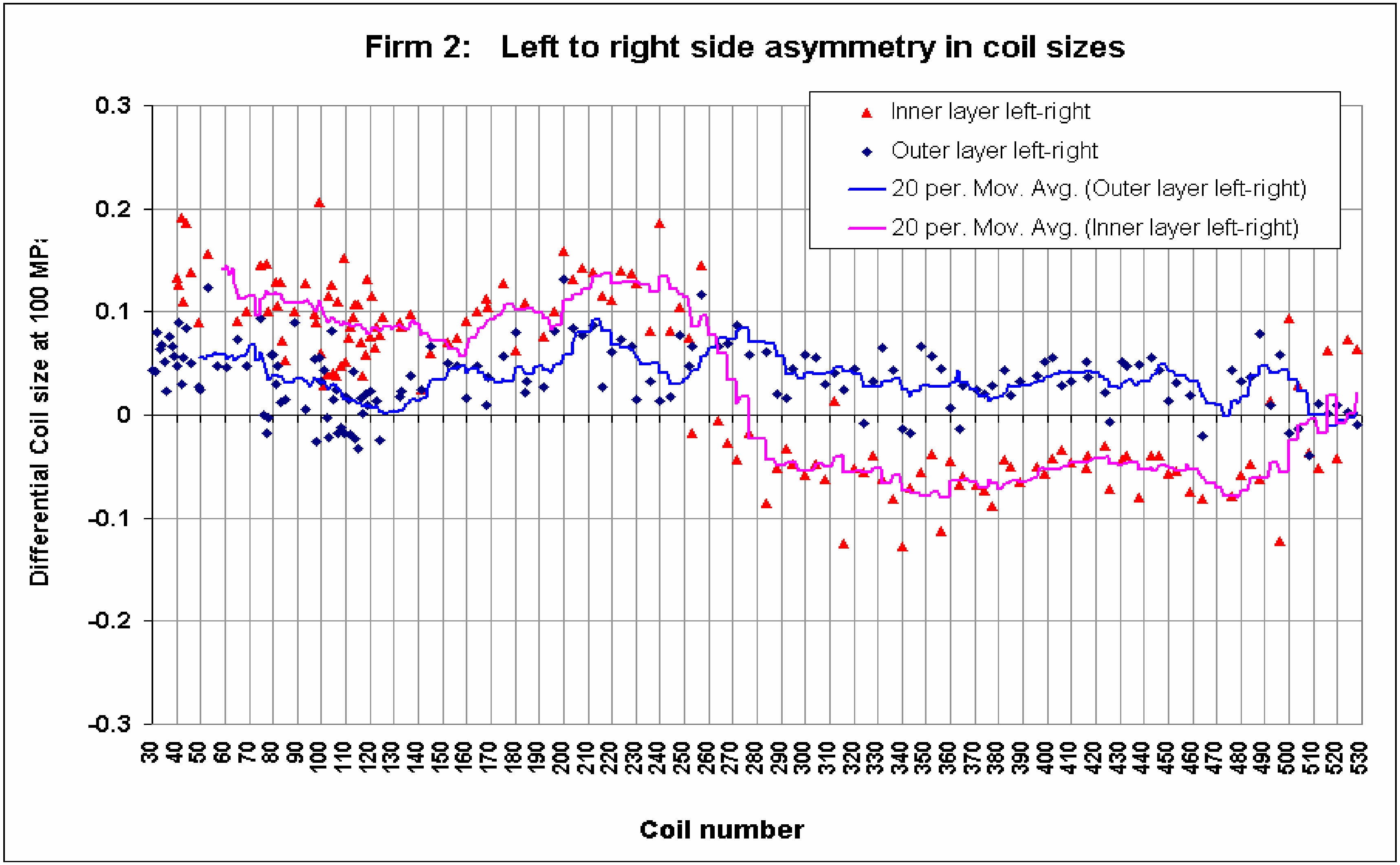

Fig. 7 Firm 2. Difference in the coil size between left and right sides of the coil on both layers.

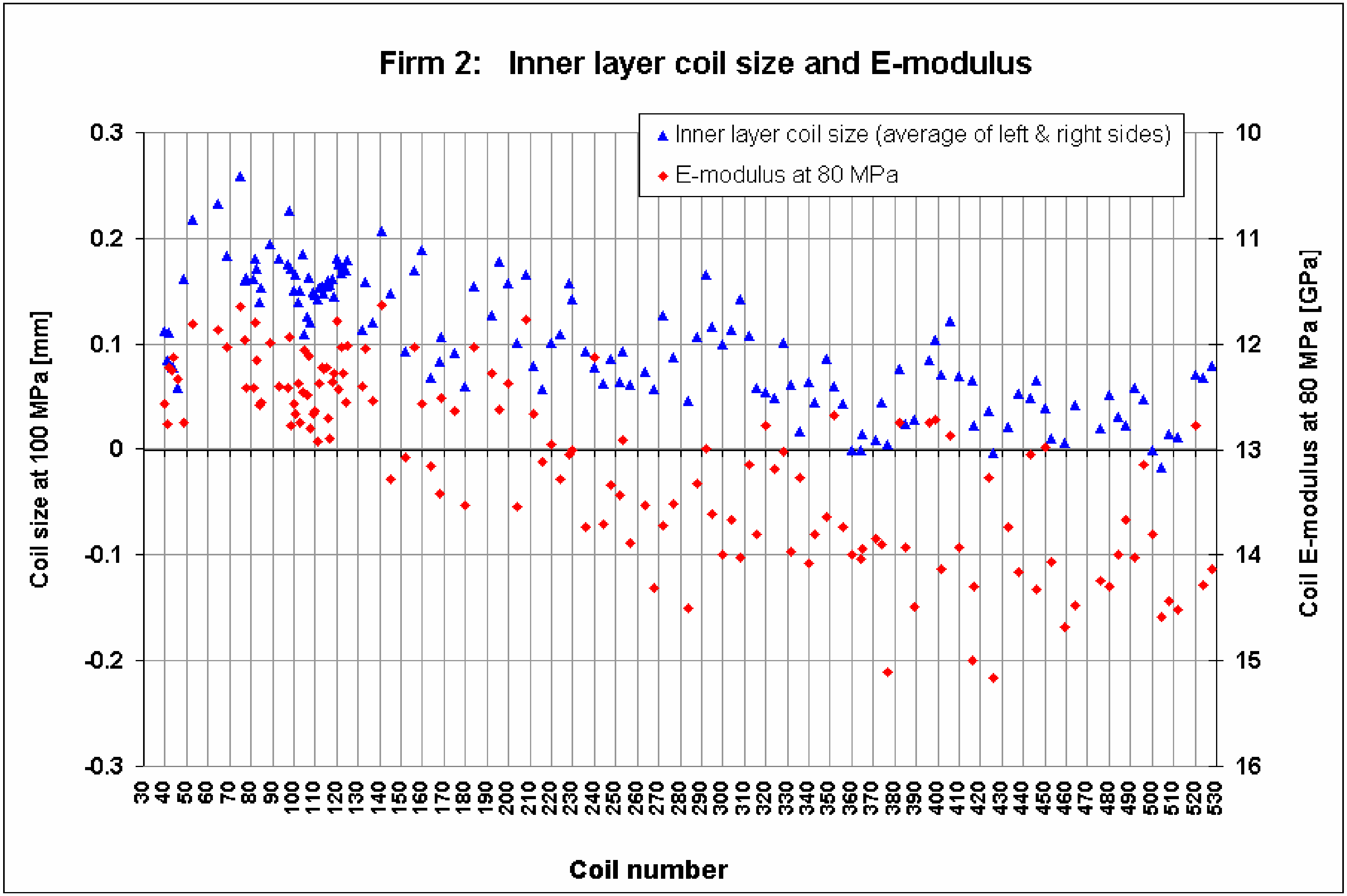

Fig. 8 Firm 2. Inner layer coil size (average) and E-modulus computed at 80 MPa.

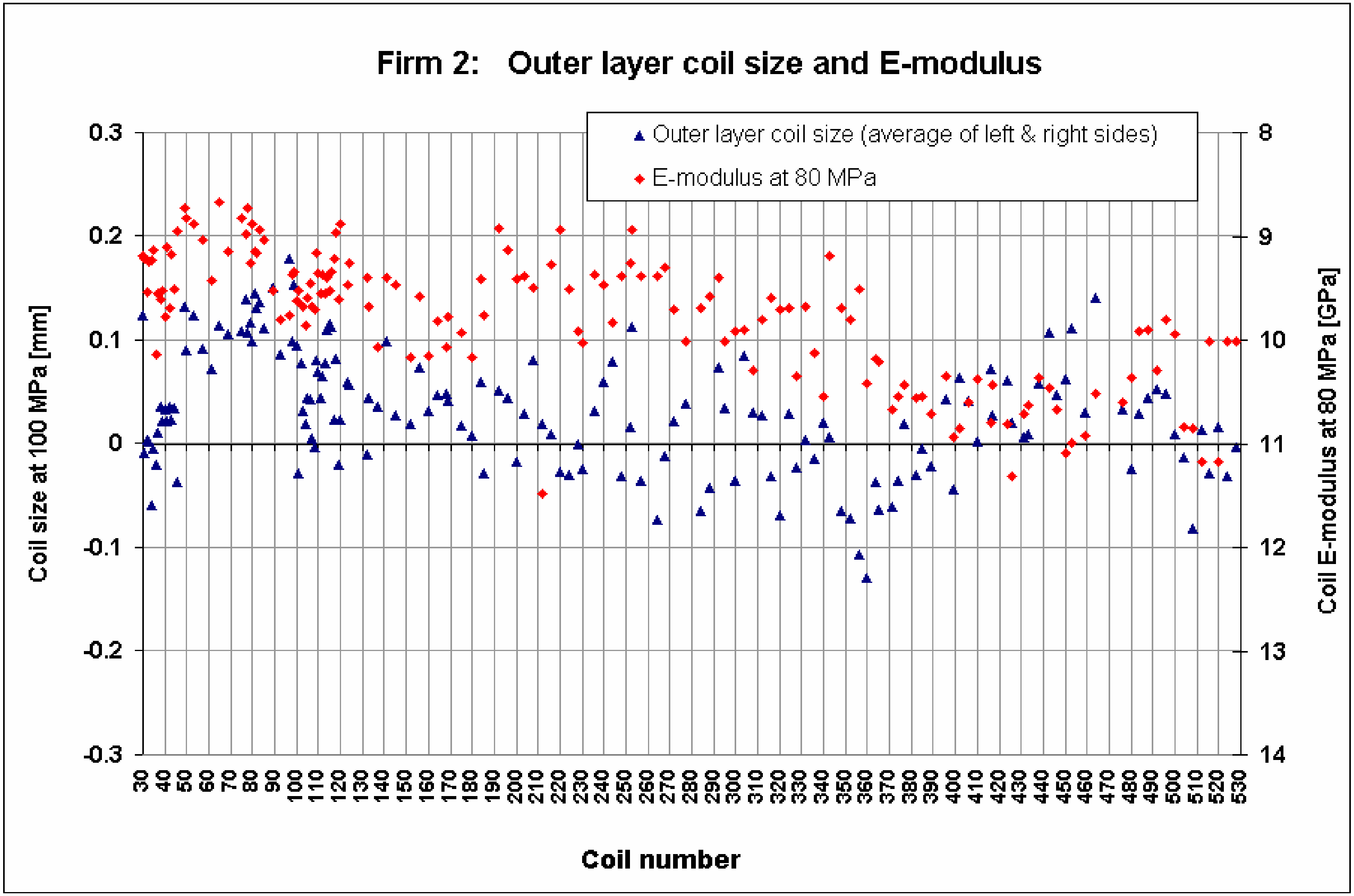

Fig. 9 Firm 2. Outer layer coil size (average) and E-modulus computed at 80 MPa.

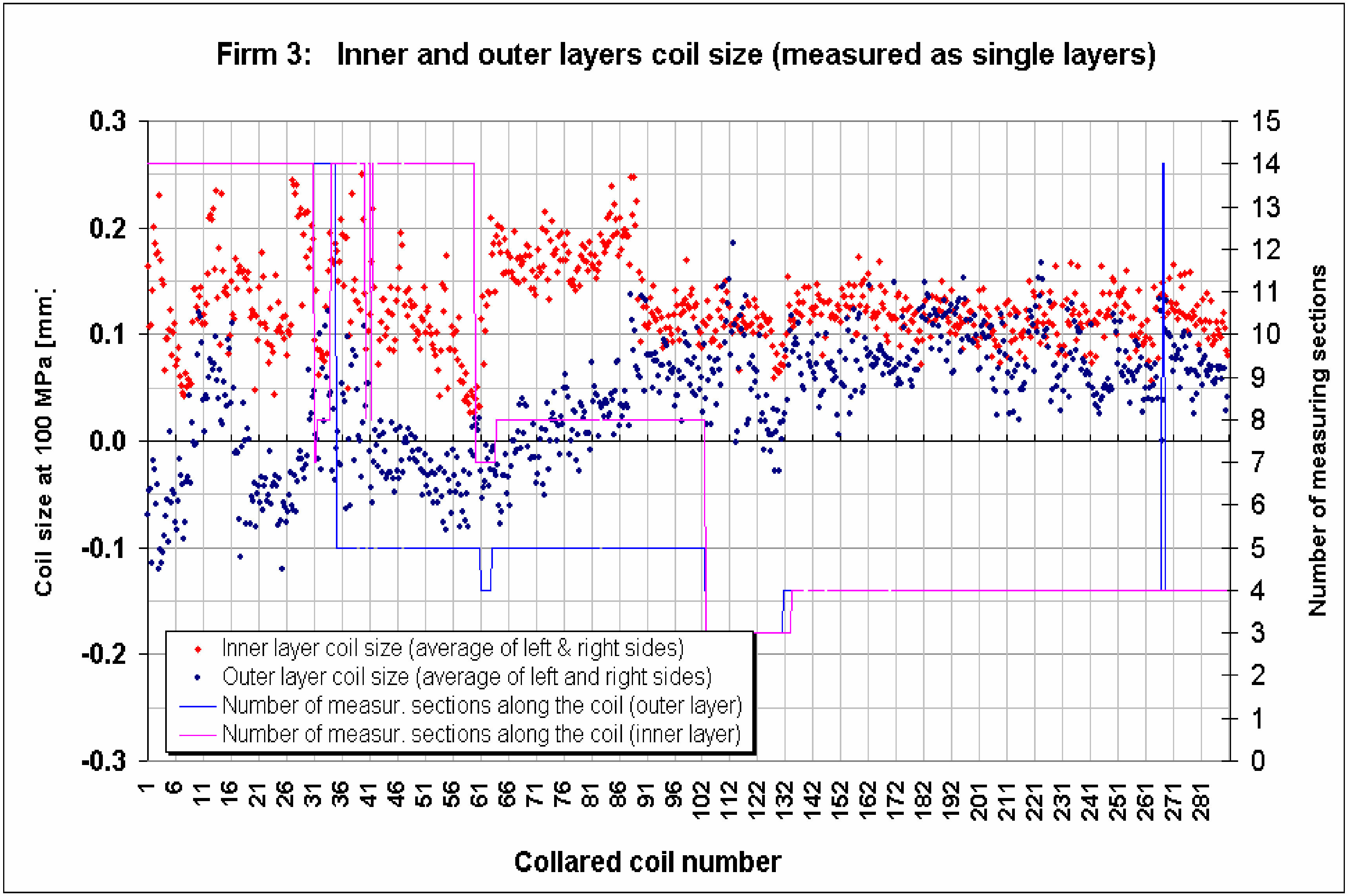

Fig. 10 Firm 3. Average coil size in the straight part of inner and outer layers.

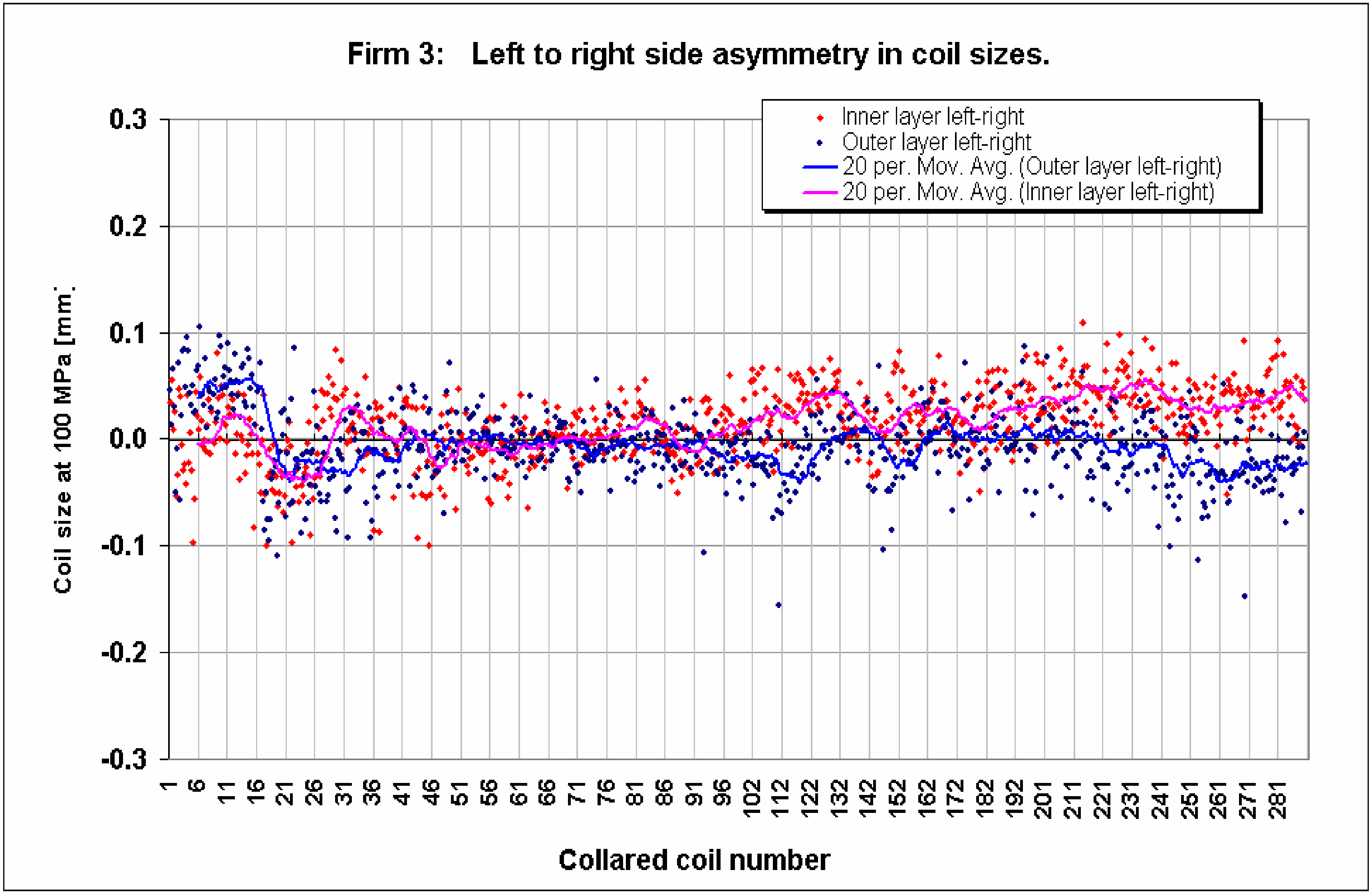

Fig.11 Firm 3. Difference in the coil size between left and right side of the coil on both layers.

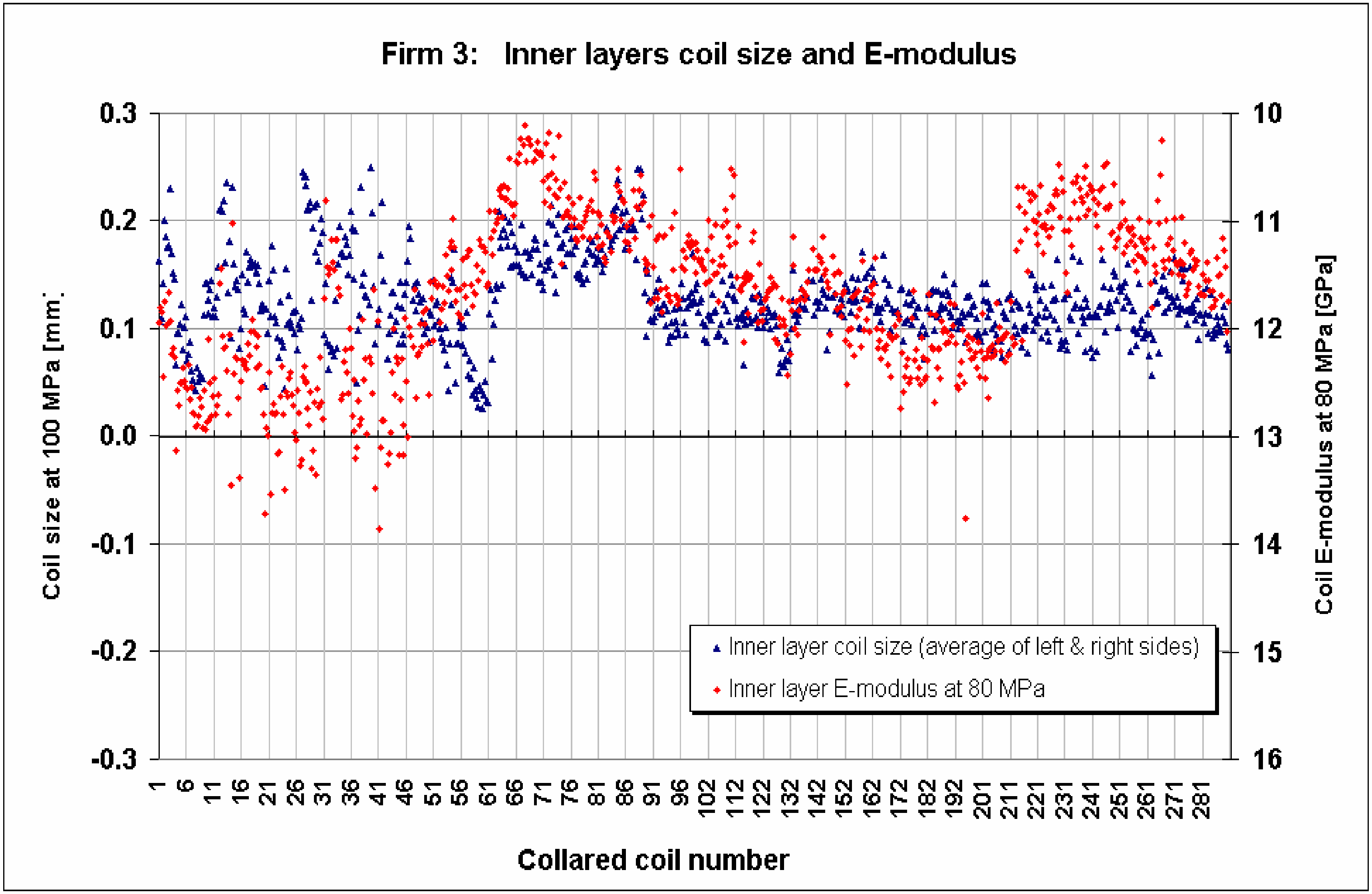

Fig. 12 Firm 3. Inner layer coil size (average) and E-modulus computed at 80 MPa.

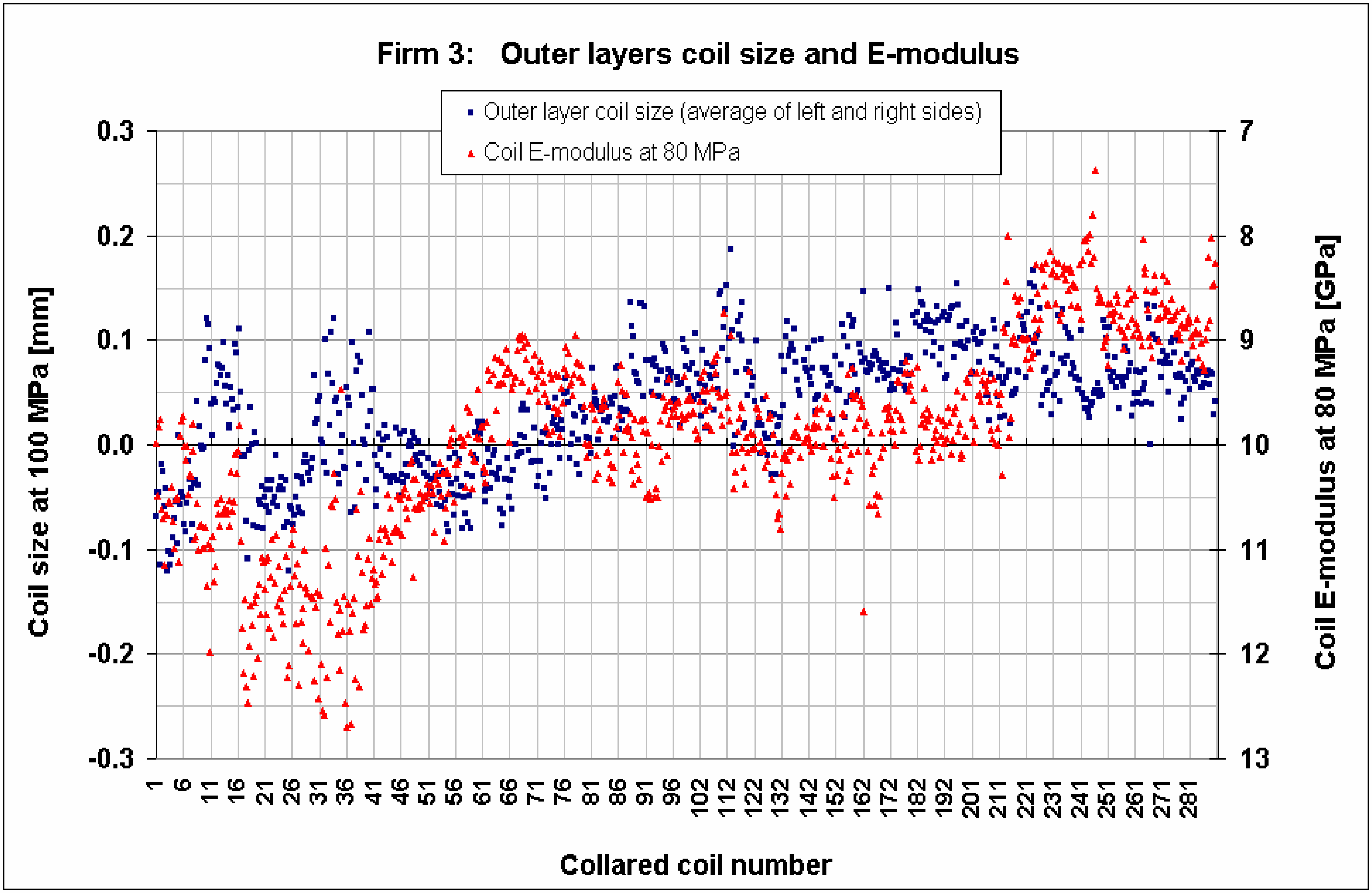

Fig. 13 Firm 3. Outer layer coil size (average) and E-modulus computed at 80 MPa.

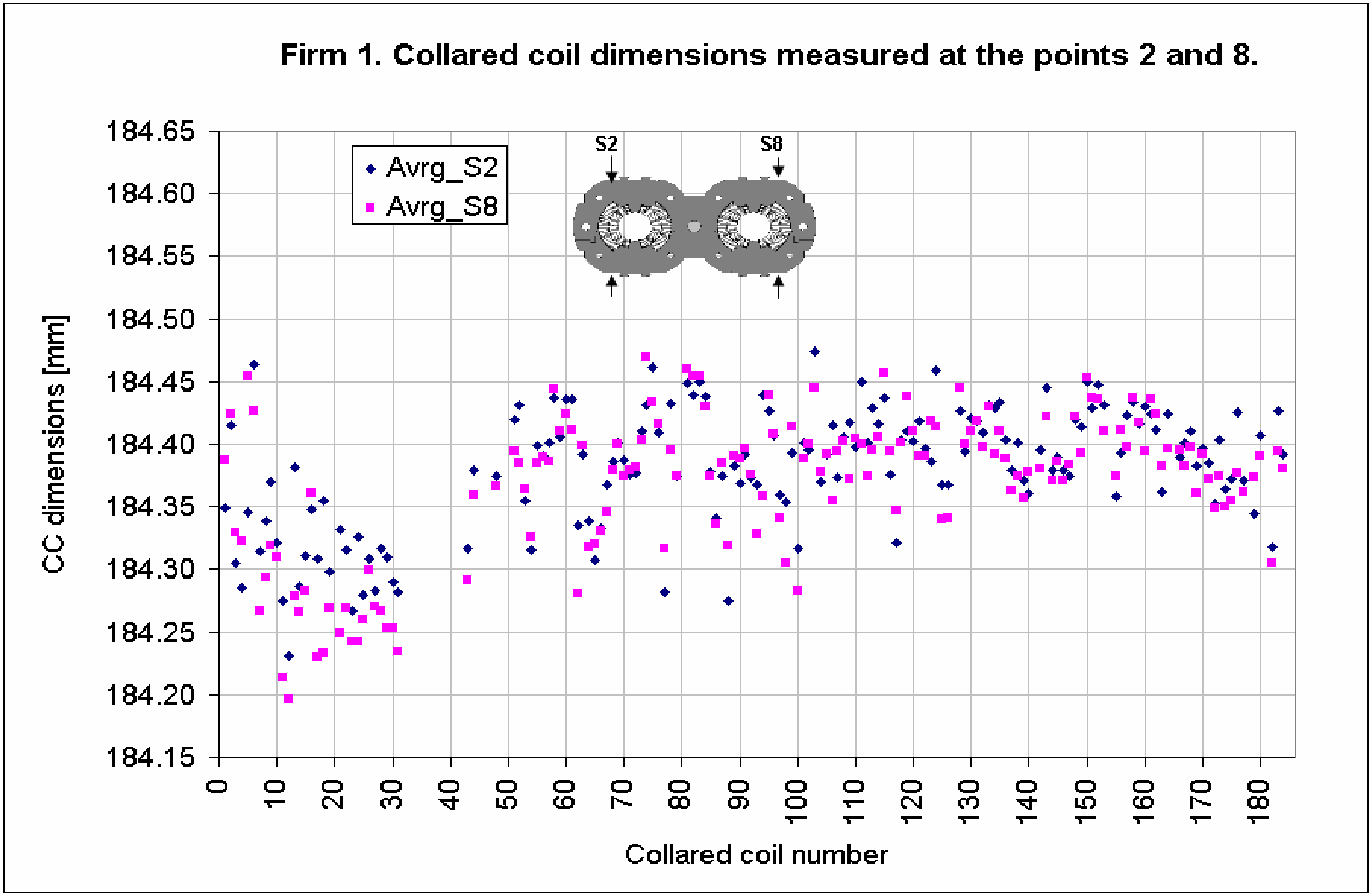

Fig. 14 Firm 1. Collared coil dimensions measured at the points S2 and S8.

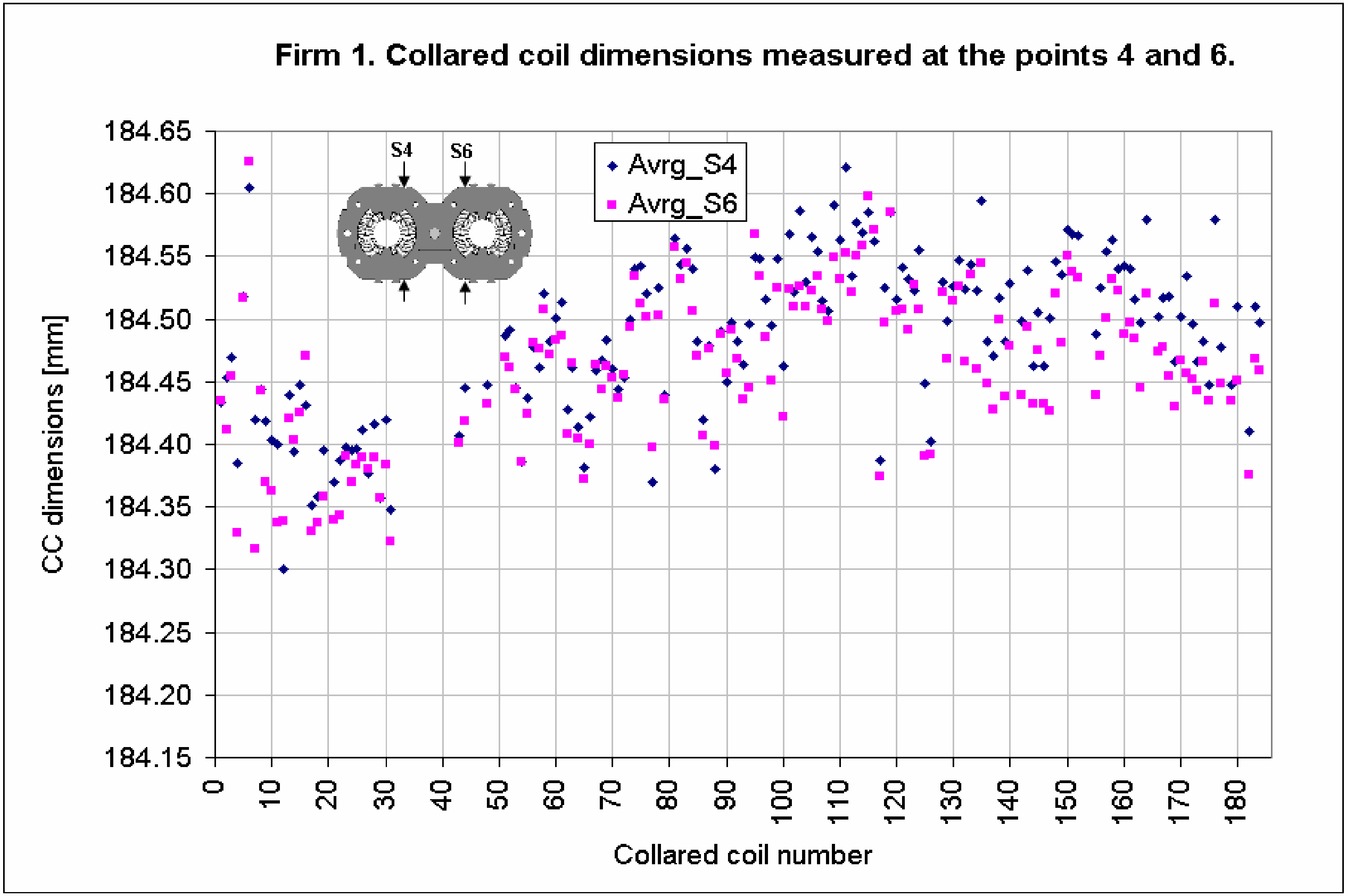

Fig. 15 Firm 1. Collared coil dimensions measured at the points S4 and S6.

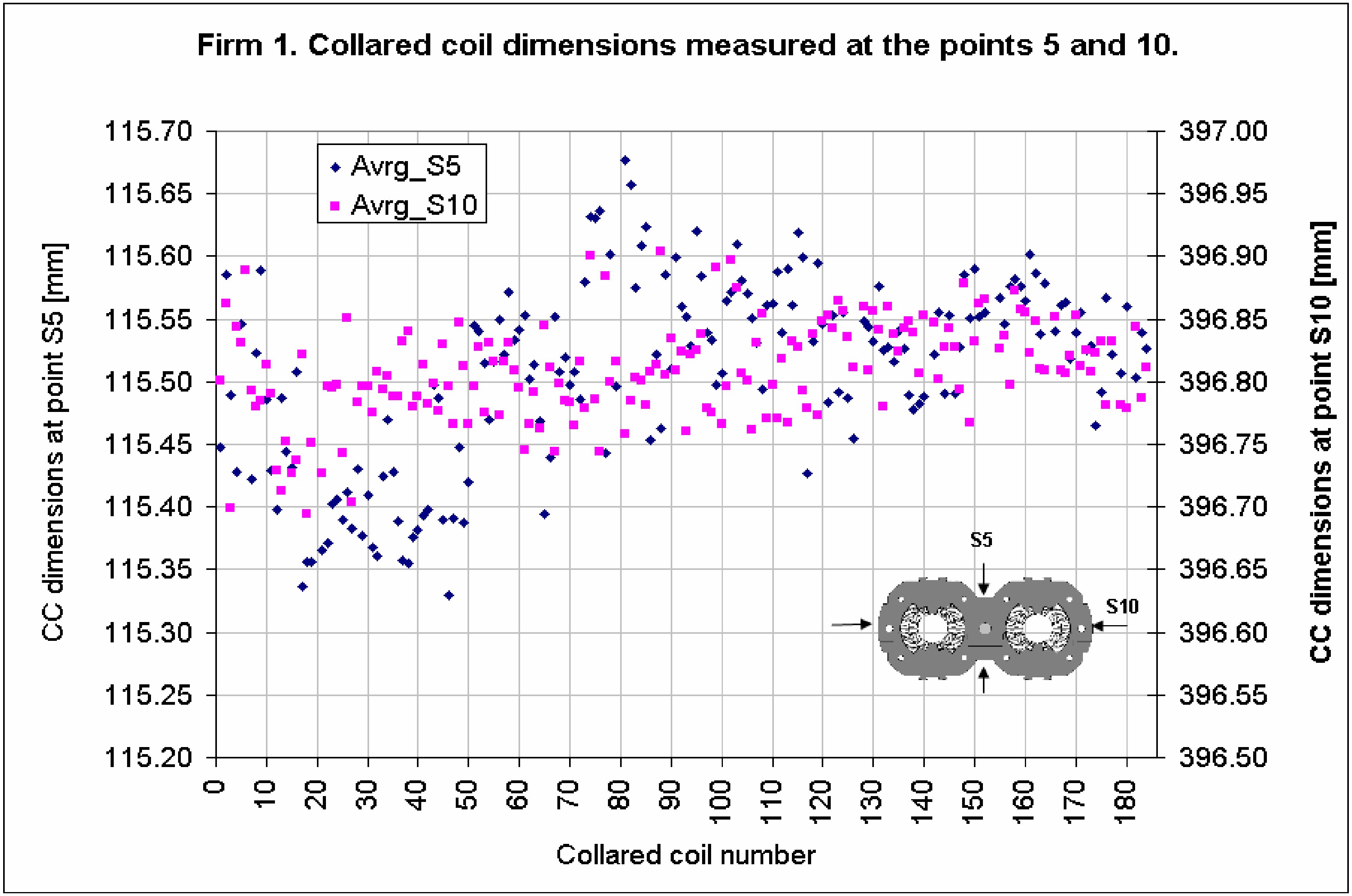

Fig. 16 Firm 1. Collared coil dimensions measured at the points S5 and S10.

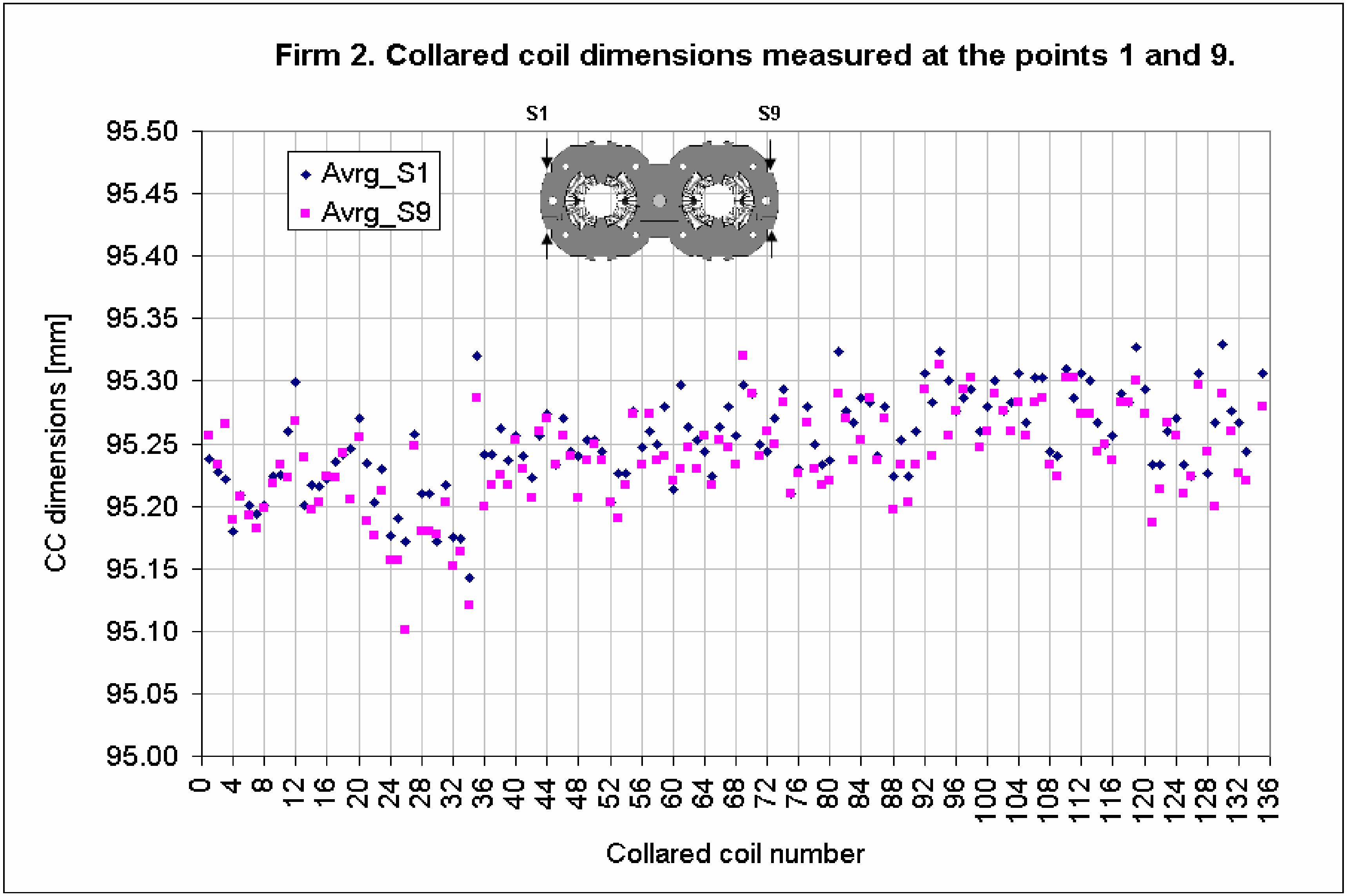

Fig. 17 Firm 2. Collared coil dimensions measured at the points S1 and S9.

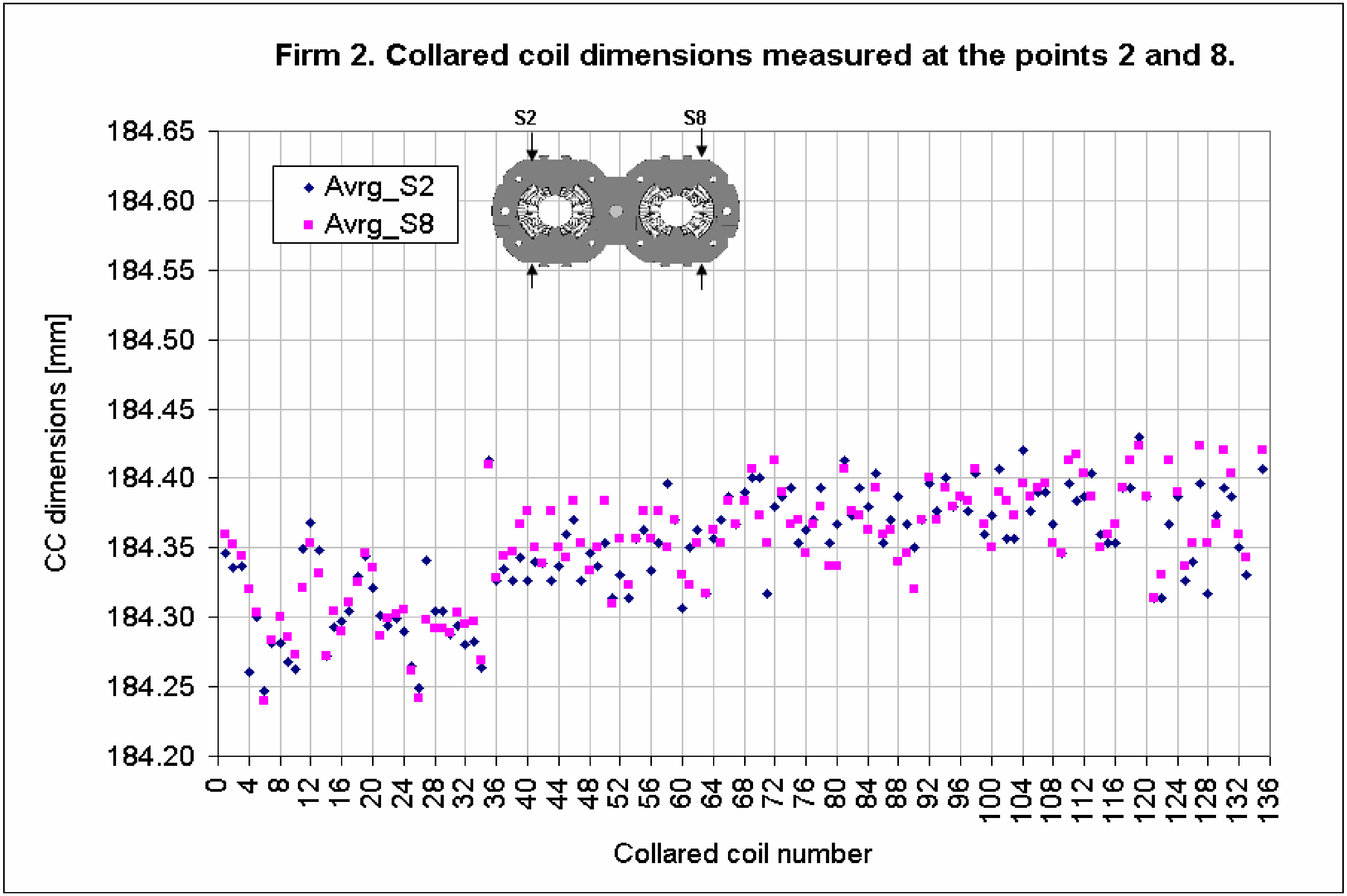

Fig. 18 Firm 2. Collared coil dimensions measured at the points S2 and S8.

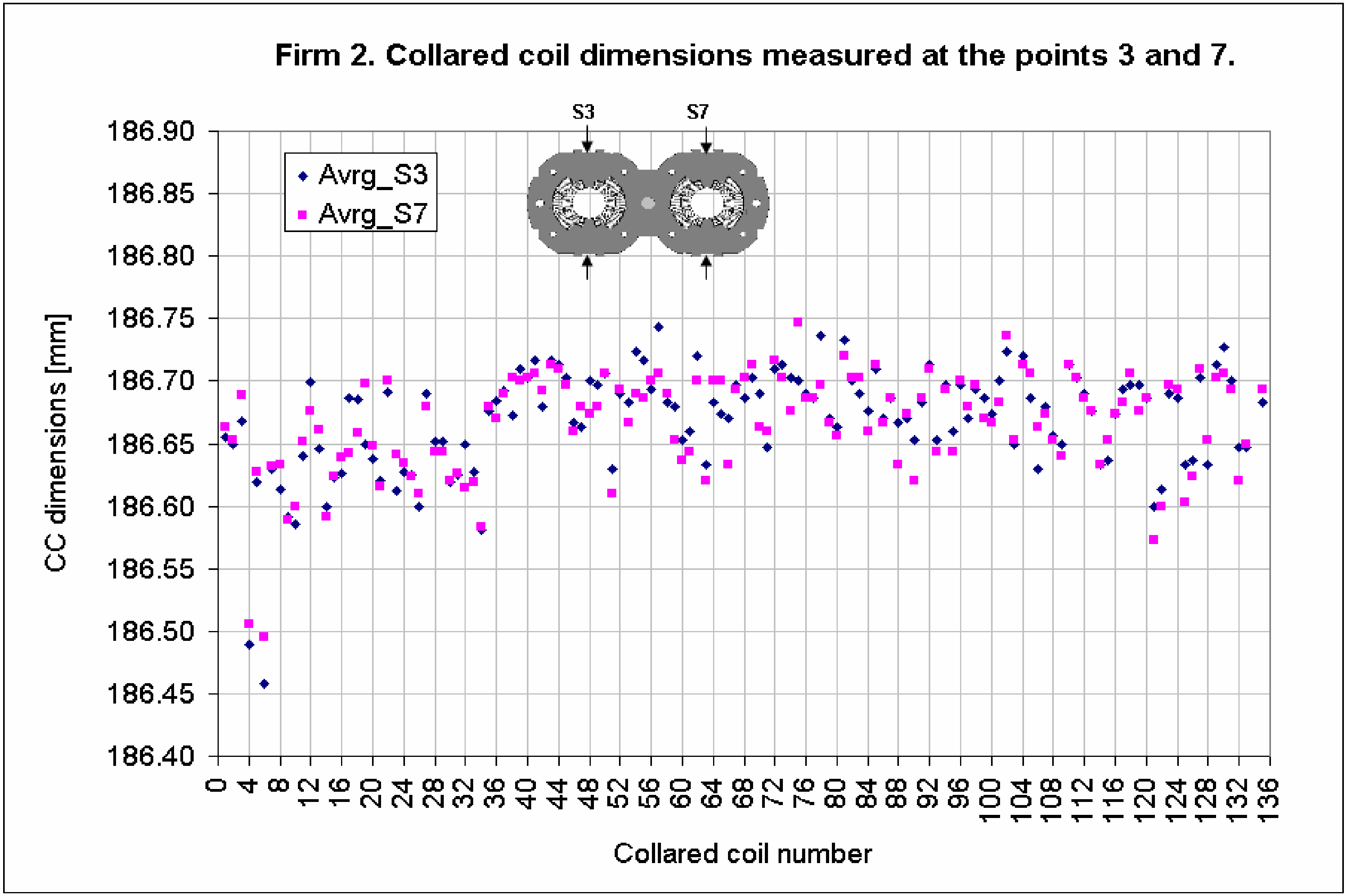

Fig. 19 Firm 2. Collared coil dimensions measured at the points S3 and S7.

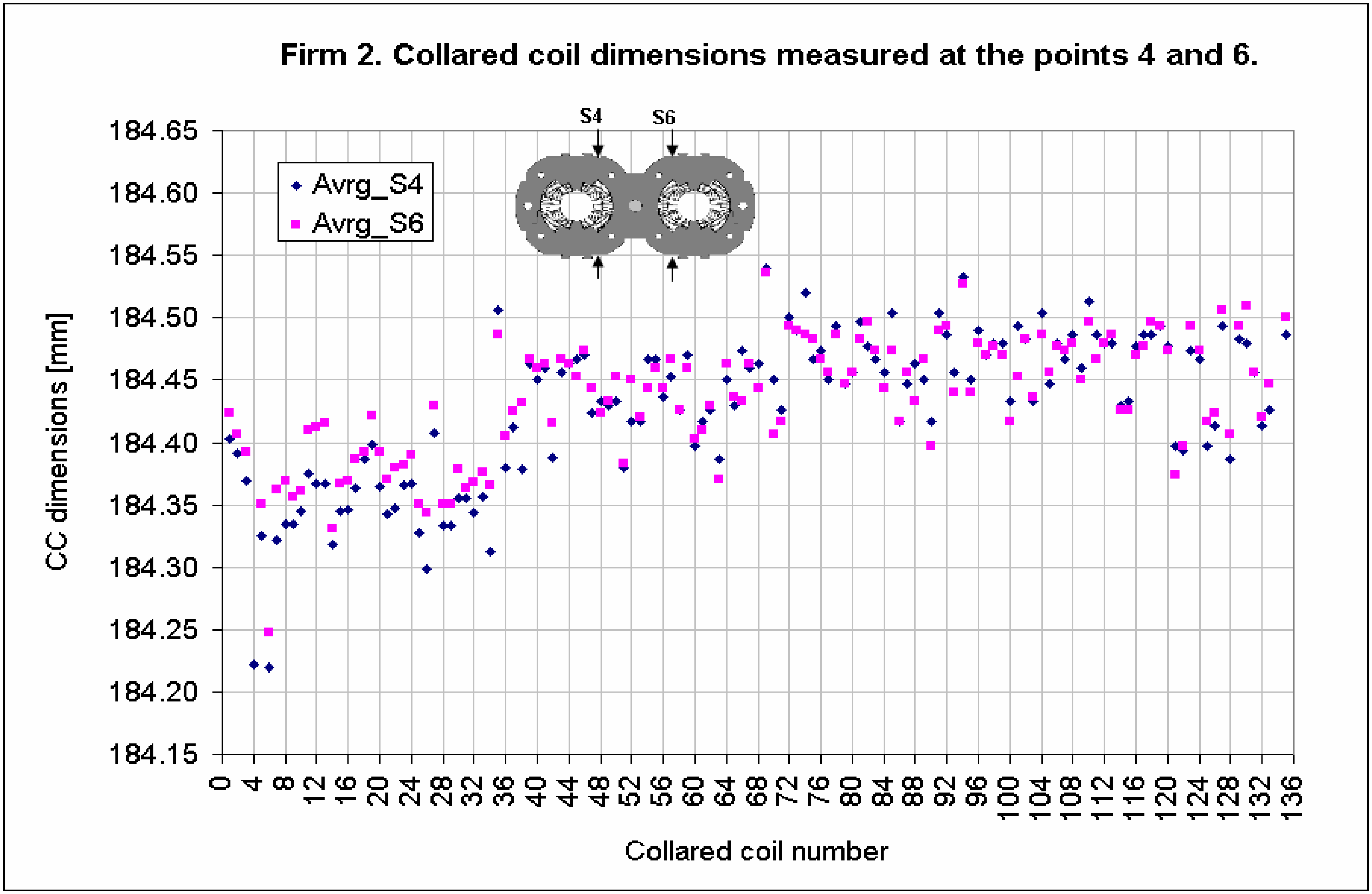

Fig. 20 Firm 2. Collared coil dimensions measured at the points S4 and S6.

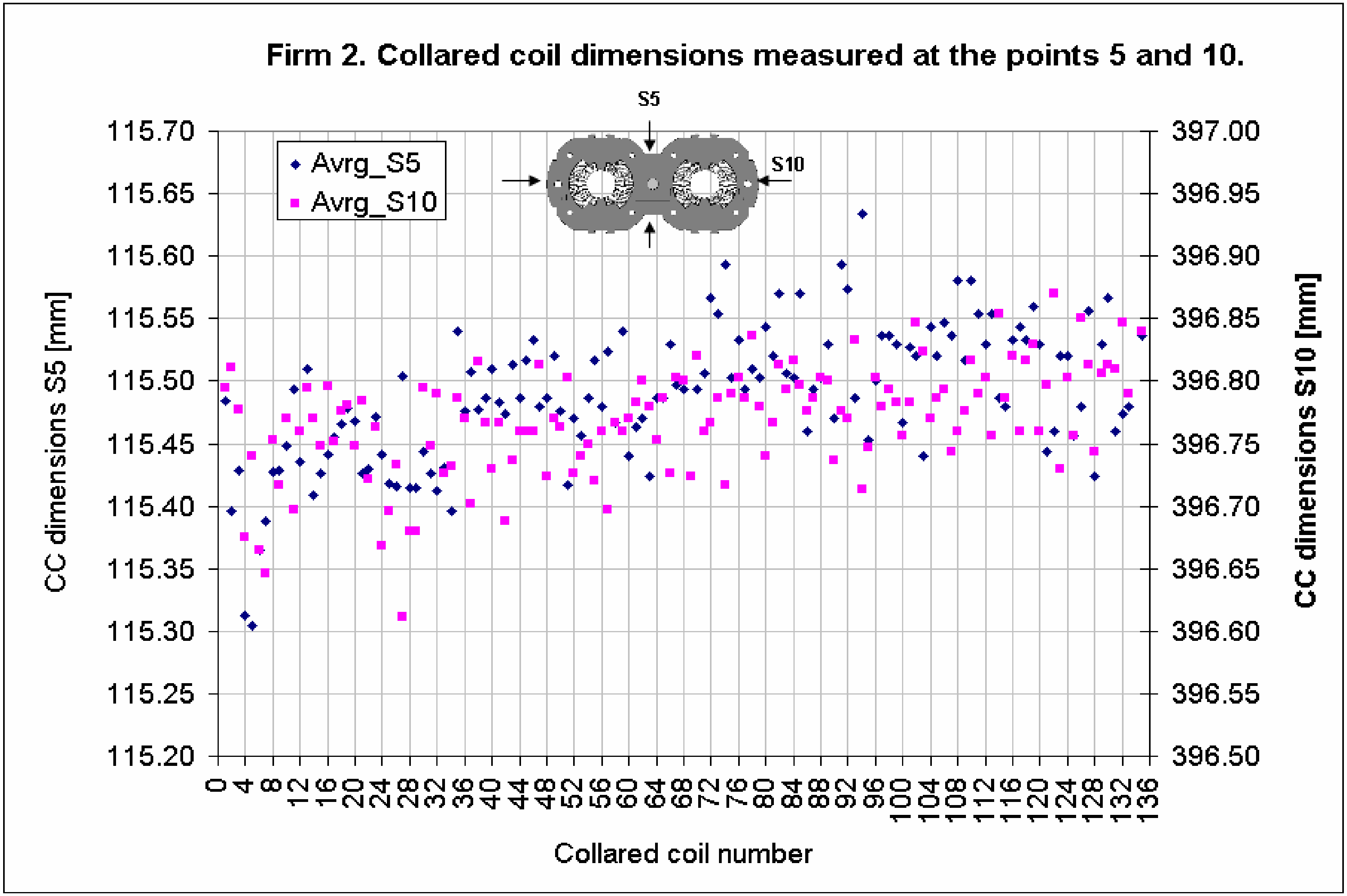

Fig. 21 Firm 2. Collared coil dimensions measured at the points S5 and S10.

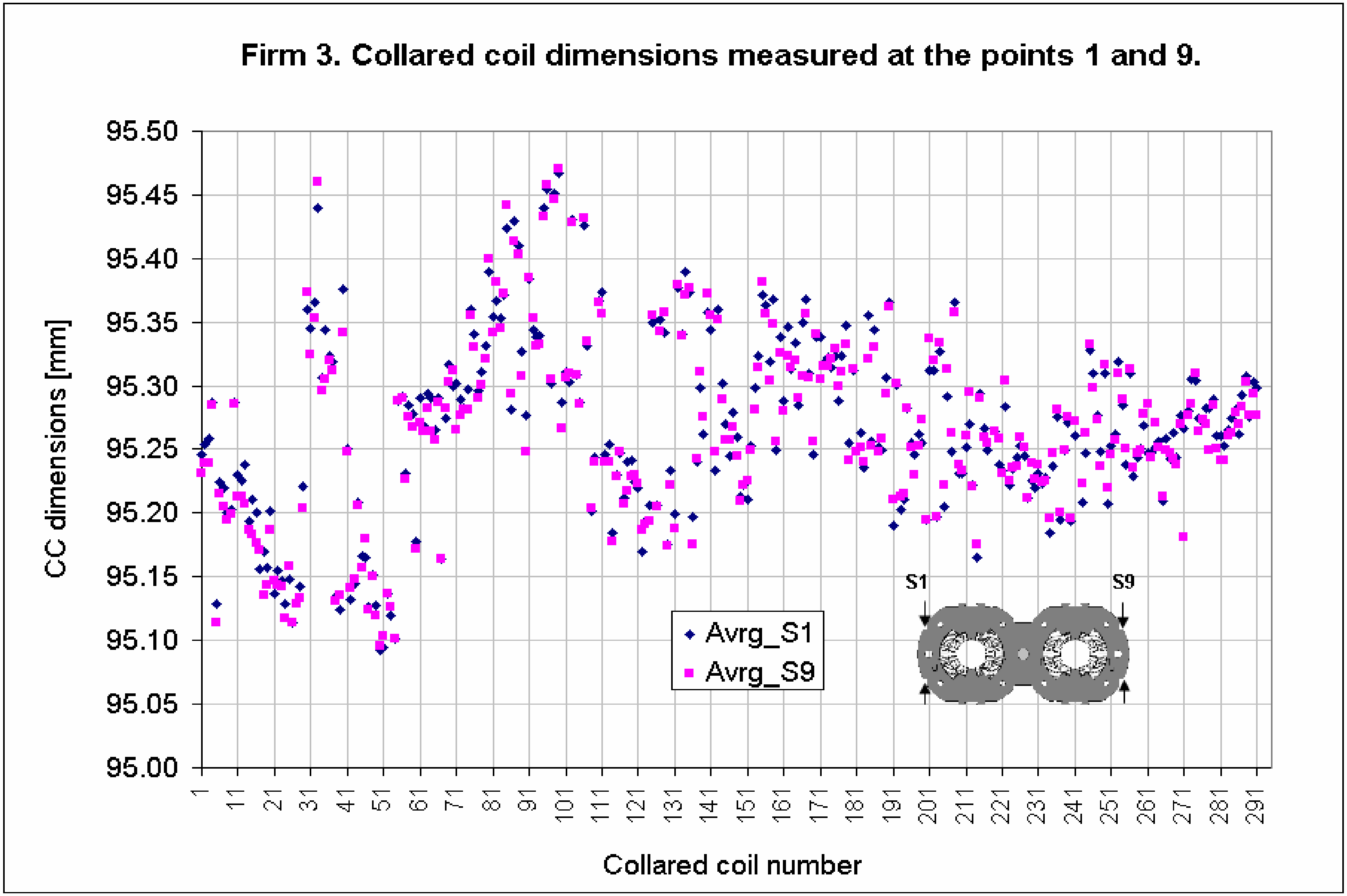

Fig. 22 Firm 3. Collared coil dimensions measured at the points S1 and S9.

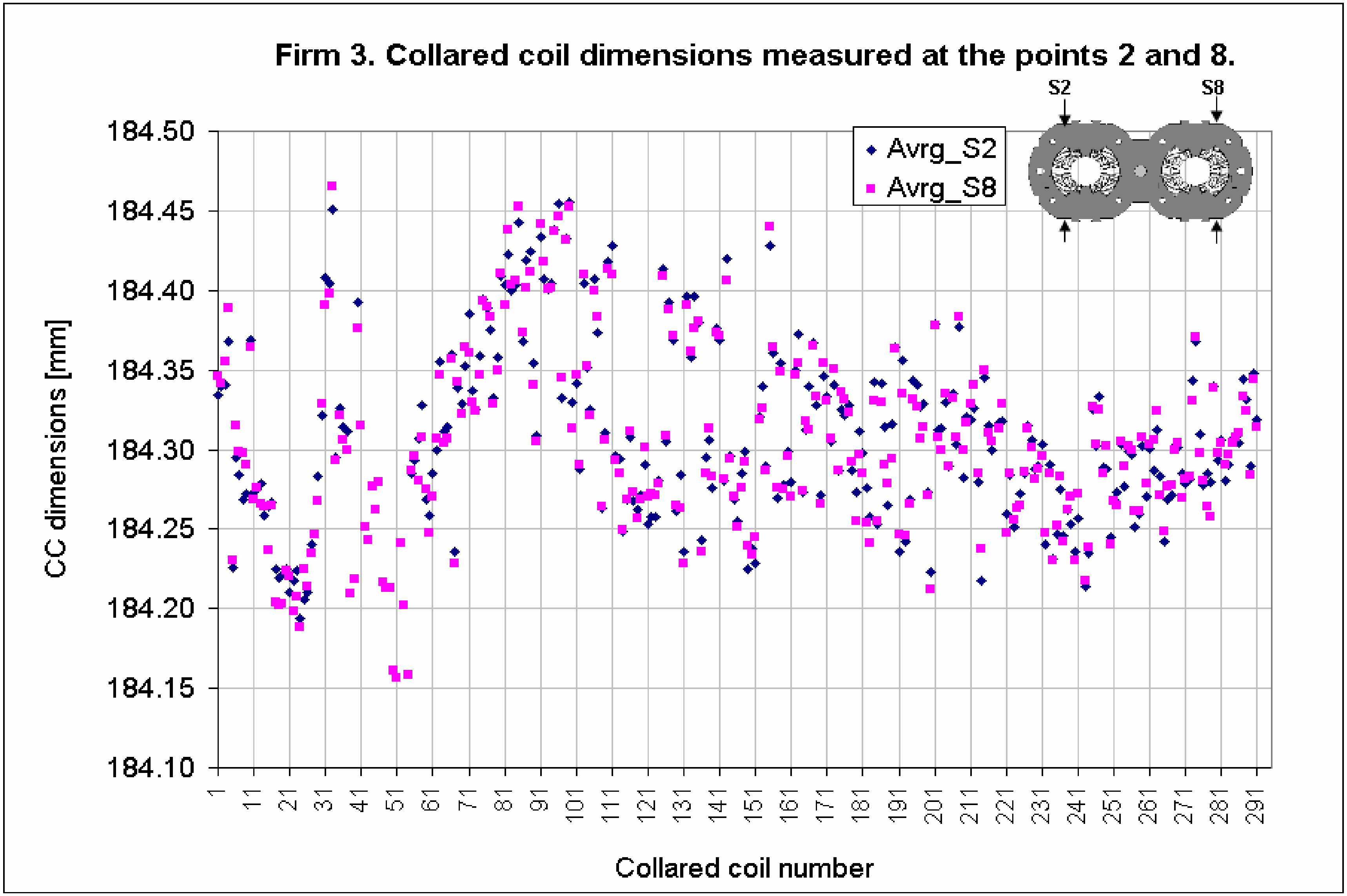

Fig. 23 Firm 3. Collared coil dimensions measured at the points S2 and S8.

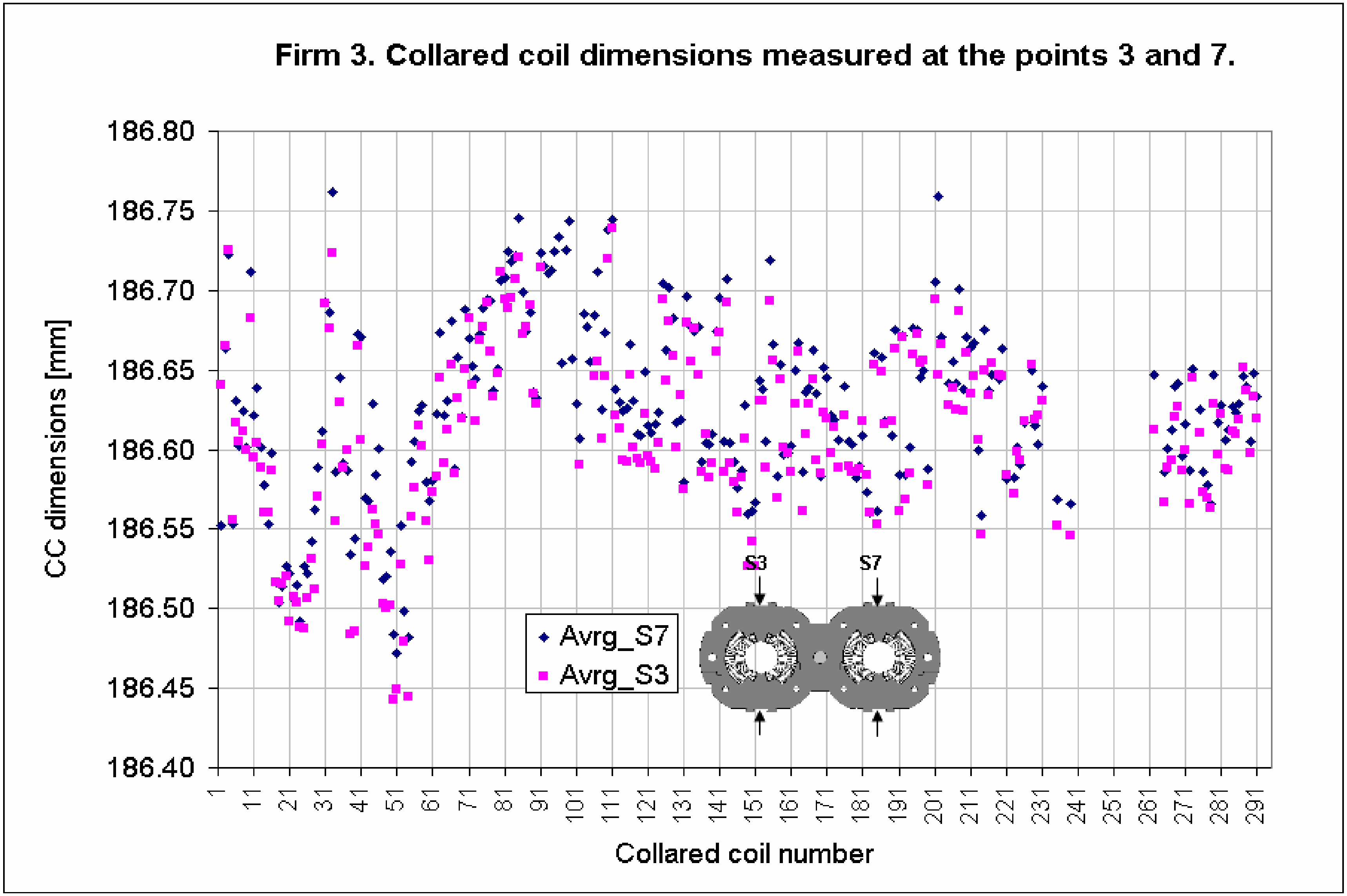

Fig. 24 Firm 3. Collared coil dimensions measured at the points S3 and S7.

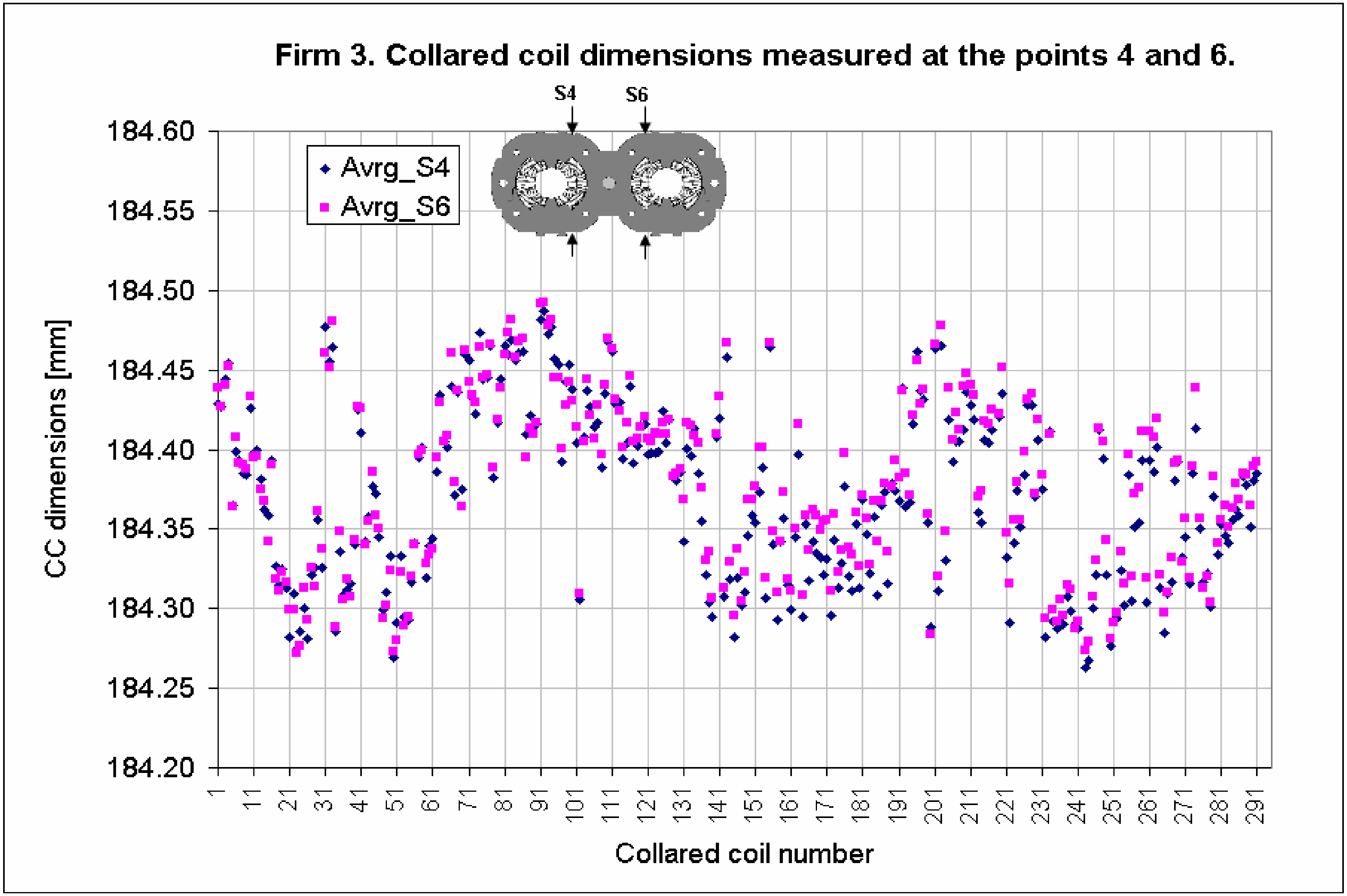

Fig. 25 Firm 3. Collared coil dimensions measured at the points S4 and S6.

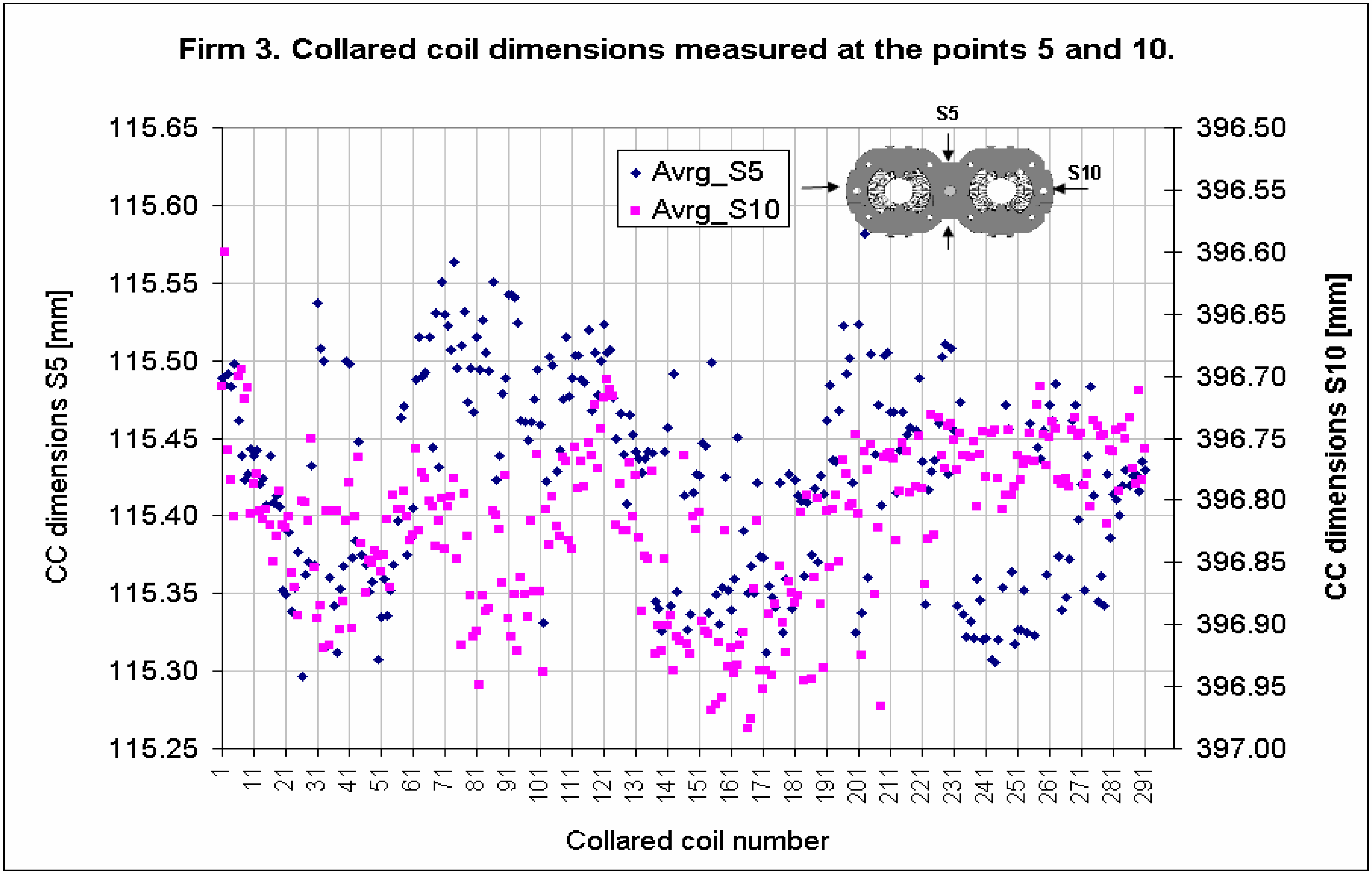

Fig. 26 Firm 3. Collared coil dimensions measured at the points S5 and S10 (notice that the scale for S10 axis is reversed).

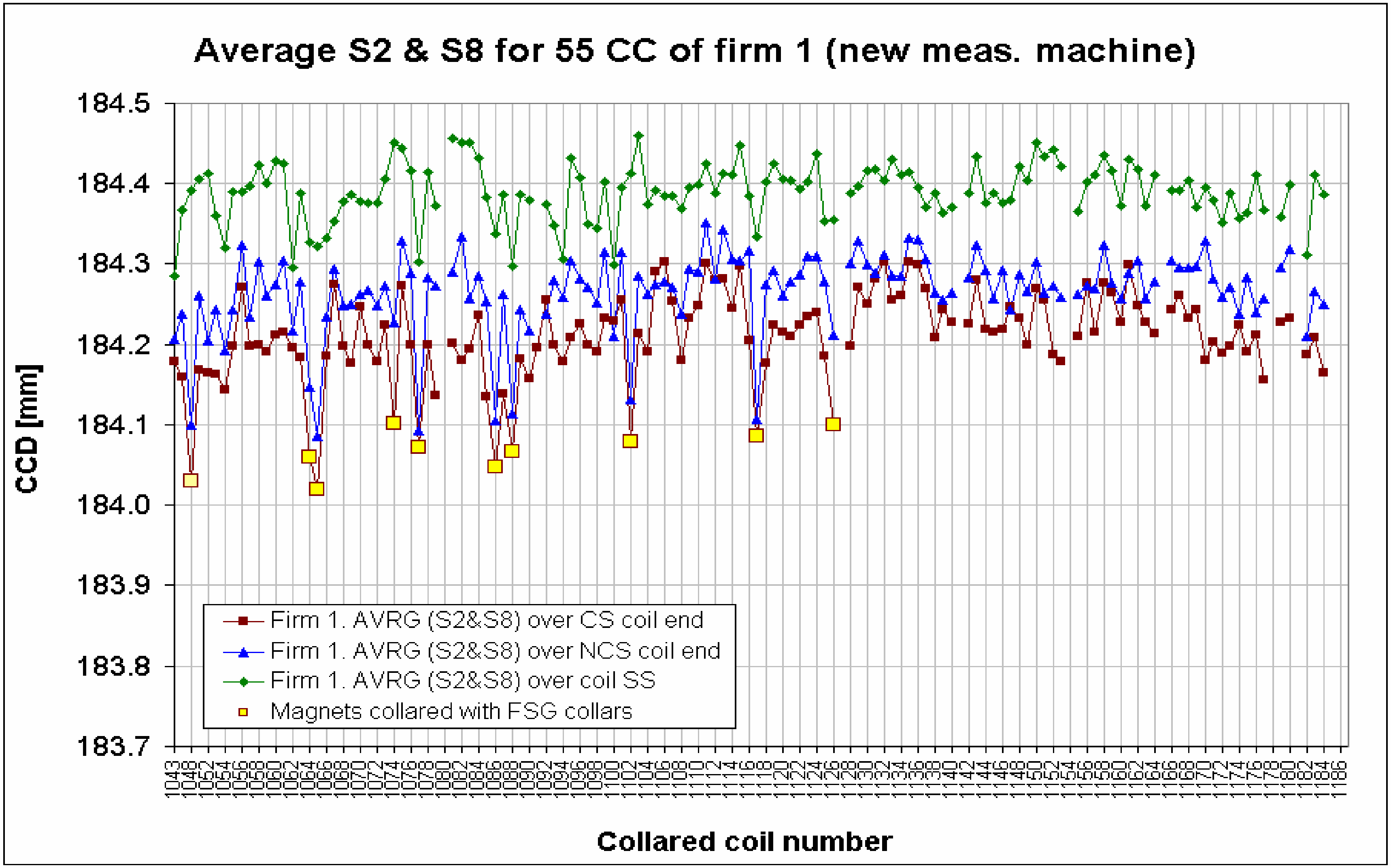

Fig. 27 Firm 1. Average of collared coil dimensions measured over coil ends and coil straight part at the points S2 and S8 (new measuring machine)

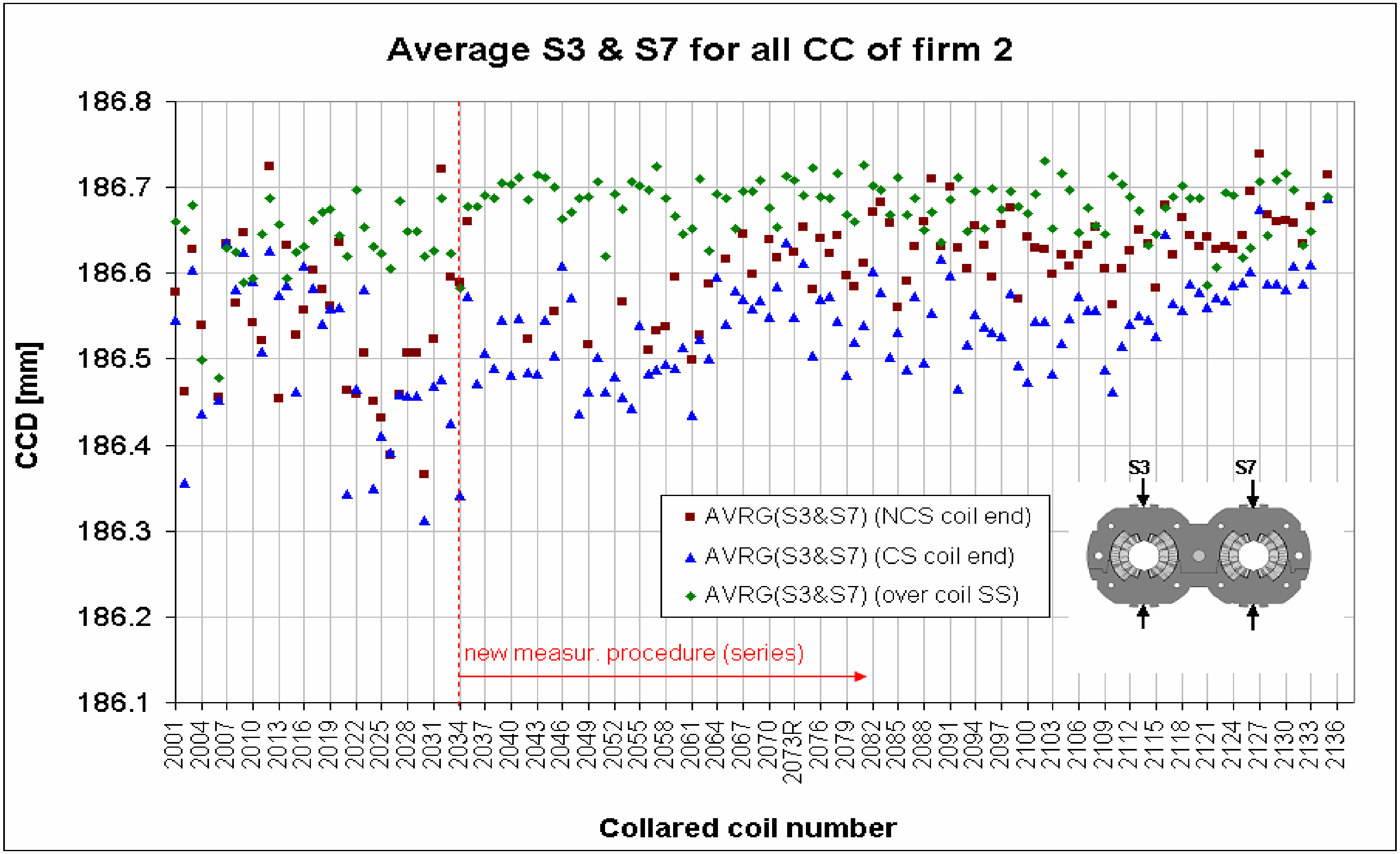

Fig. 28 Firm 2. Average of collared coil dimensions measured over coil ends and coil straight part at the points S2 and S8 (new measuring machine). For some of the magnets the measurements at NCS were done not correctly, therefore the data is not shown. Some of these magnets were re-measured and their IDs have an extension "R".

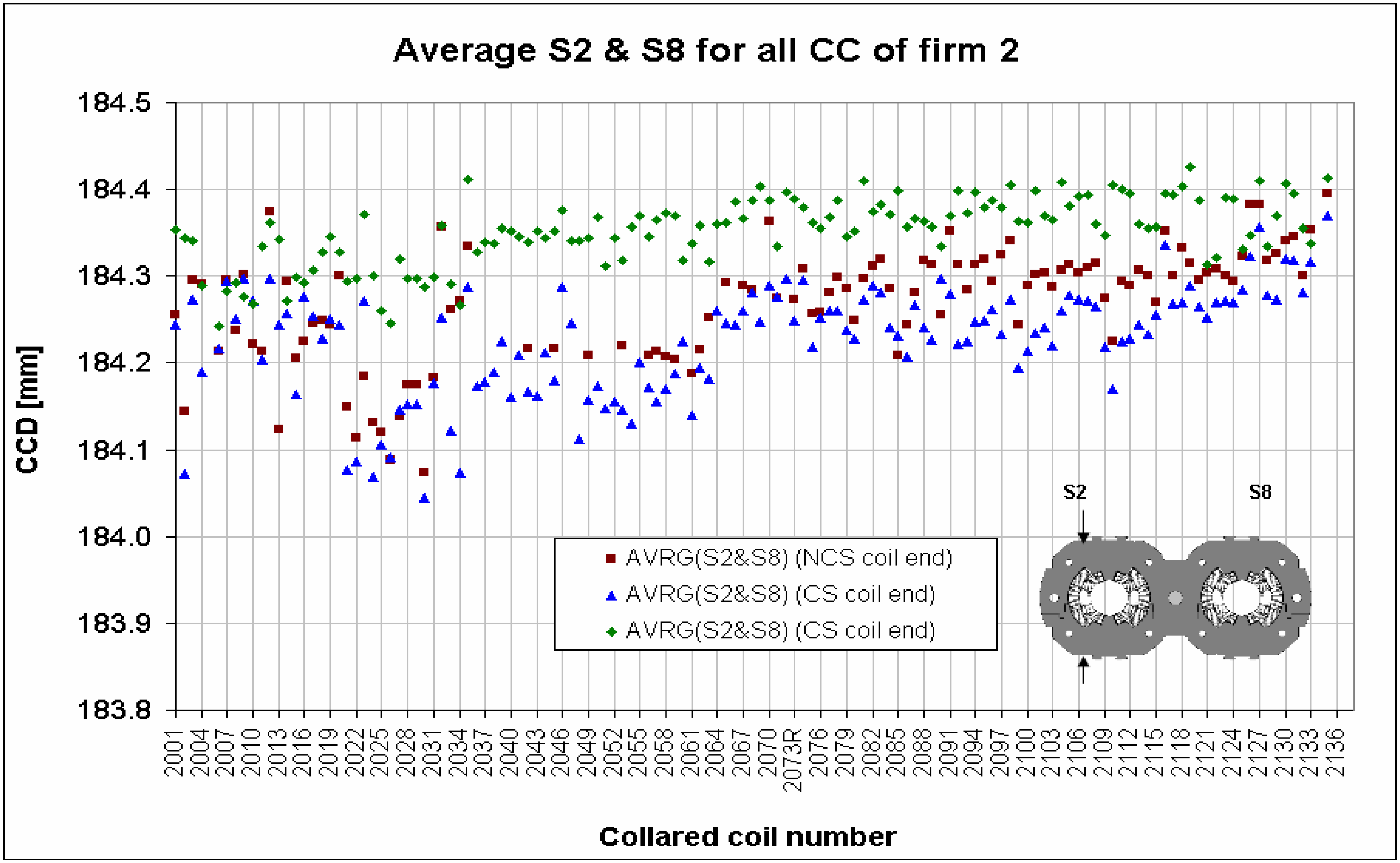

Fig. 29 Firm 2. Average of collared coil dimensions measured over coil ends and coil straight part at the points S2 and S8. For some of the magnets the measurements at NCS were done not correctly, therefore the data is not shown.

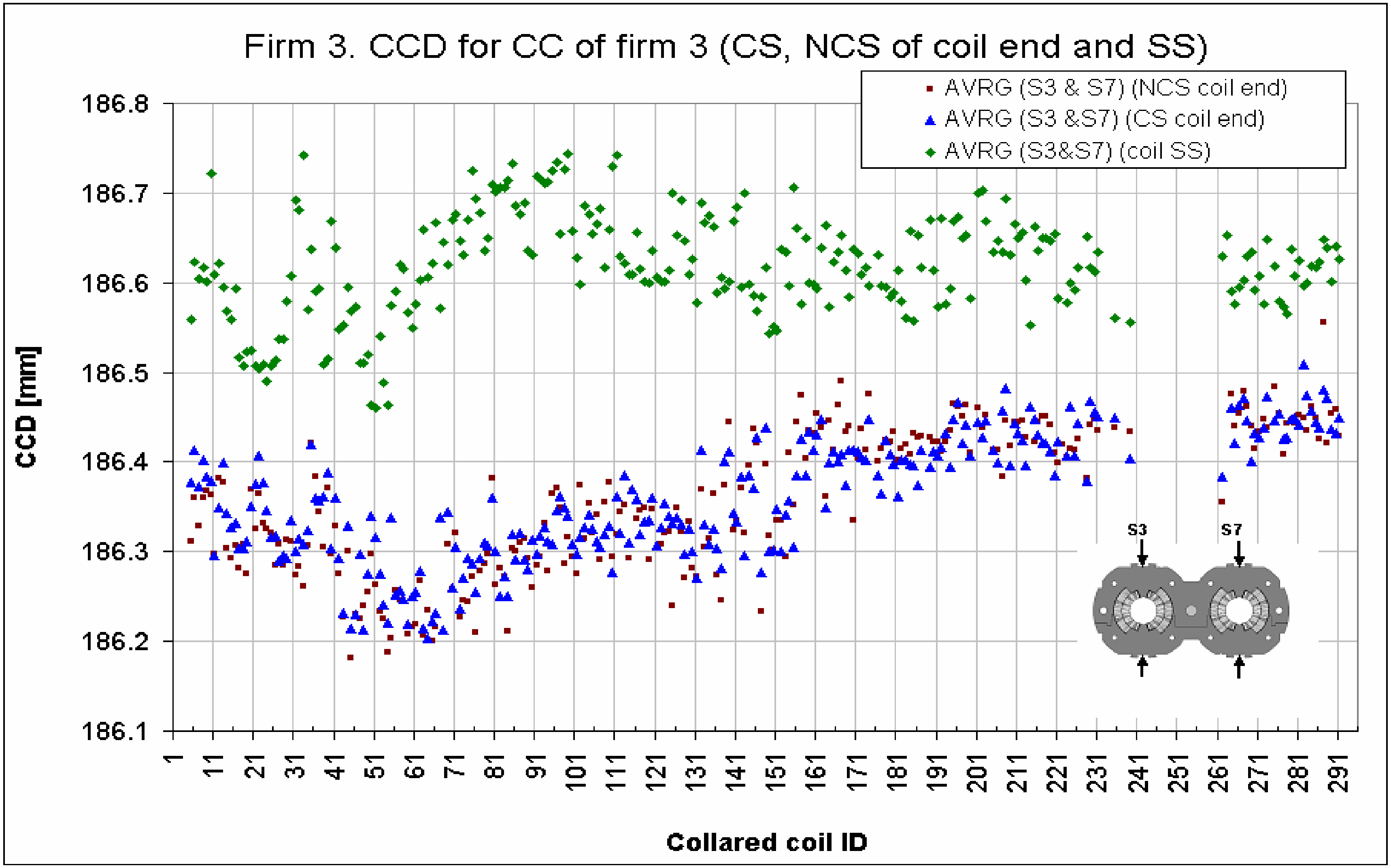

Fig. 30 Firm 3. Average of collared coil dimensions measured over coil ends and coil straight part at the points S3 and S7.

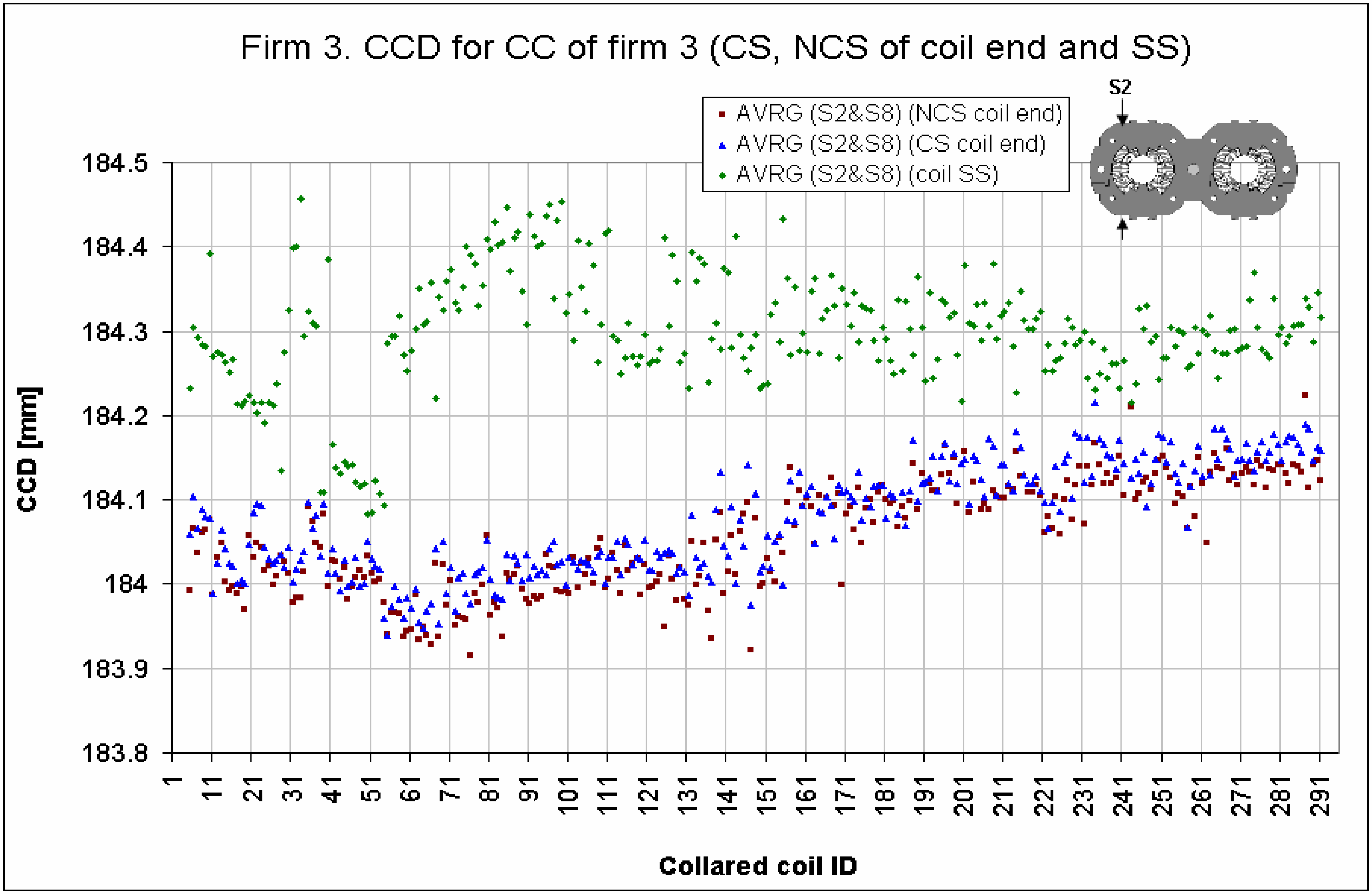

Fig. 31 Firm 3. Average of collared coil dimensions measured over coil ends and coil straight part at the points S2 and S8.

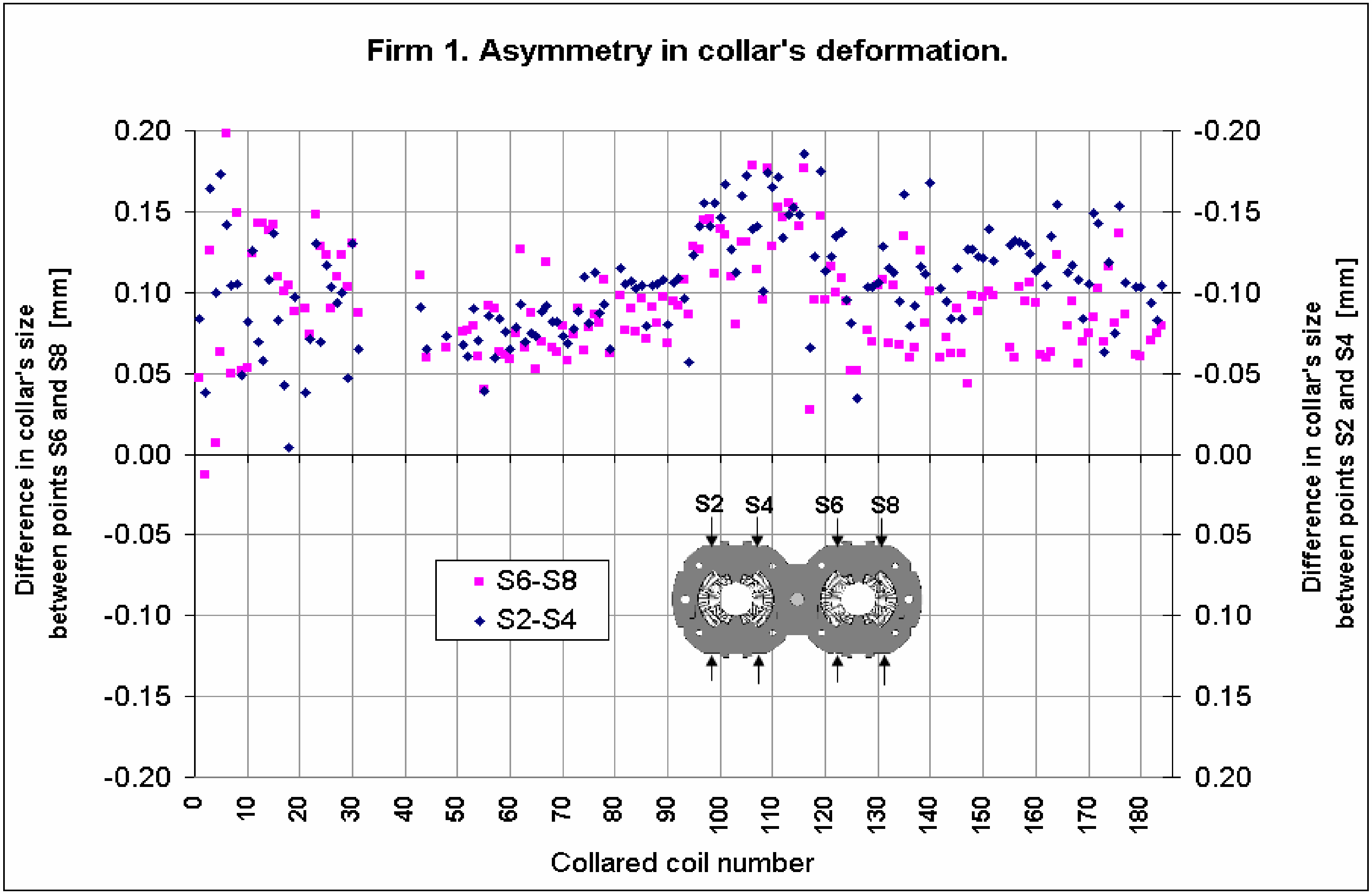

Fig. 32 Firm 1. Measured asymmetry in collared coil dimensions.

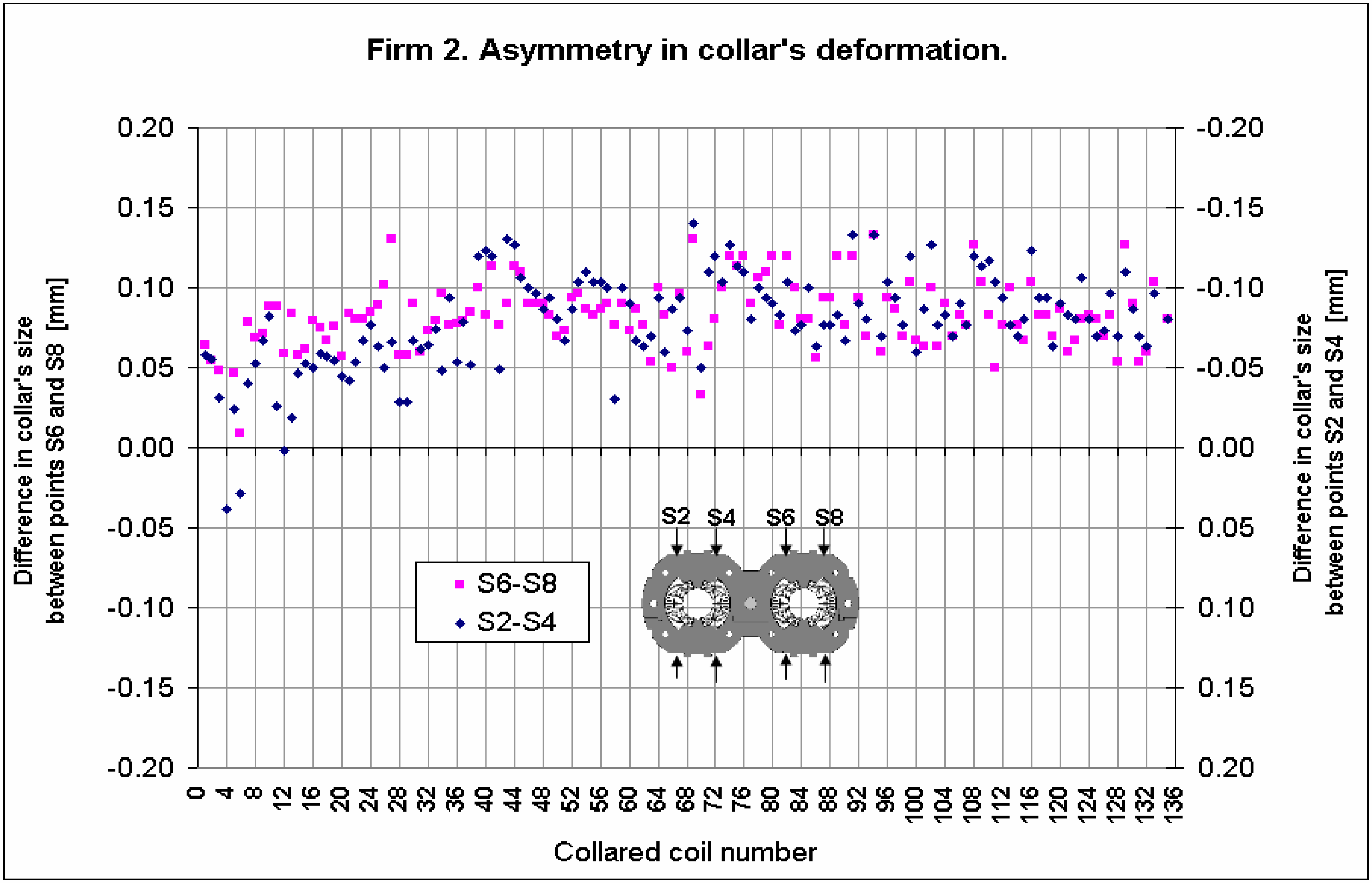

Fig. 33 Firm 2. Measured asymmetry in collared coil dimensions.

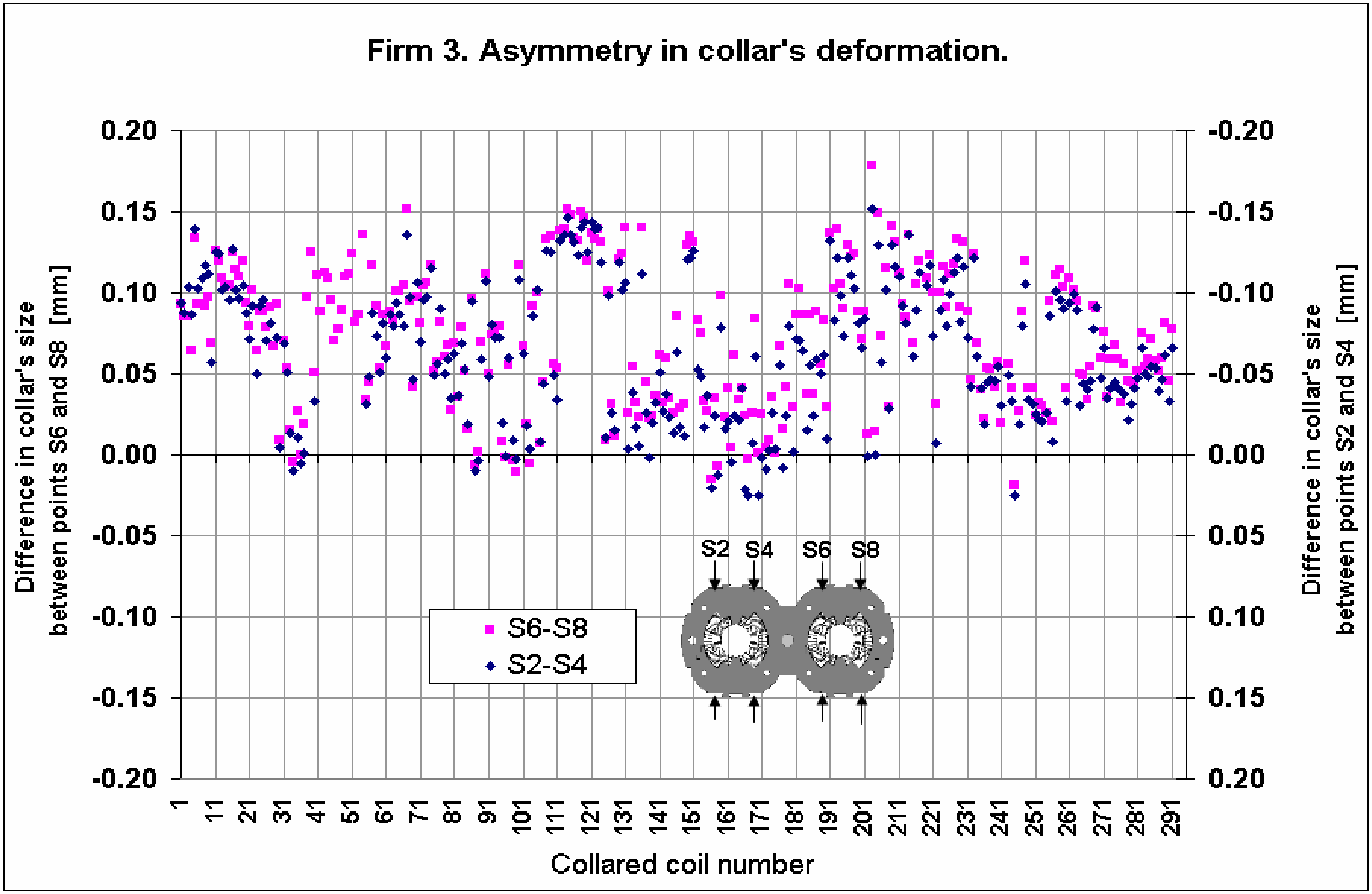

Fig. 34 Firm 3. Measured asymmetry in collared coil dimensions.

Appendix. Actually the coils at firm 3 are measured in 4 fixed positions along the coil. In order to verify the shape of coil production tooling, the coils 4026-4040 have been measured with 3 fixed and 1 moving measuring positions along the coil. Early, two outer layers 3946, 3948 were measured in all 14 positions along the coil. The average value for each measuring position was computed to obtain so-called "Systematic" longitudinal coil profile for inner and outer layers. In figures 1, 2 the comparisons are given for the "Systematic" longitudinal coil profiles obtained during pre-series and for the recently produced coils 4026-4040.

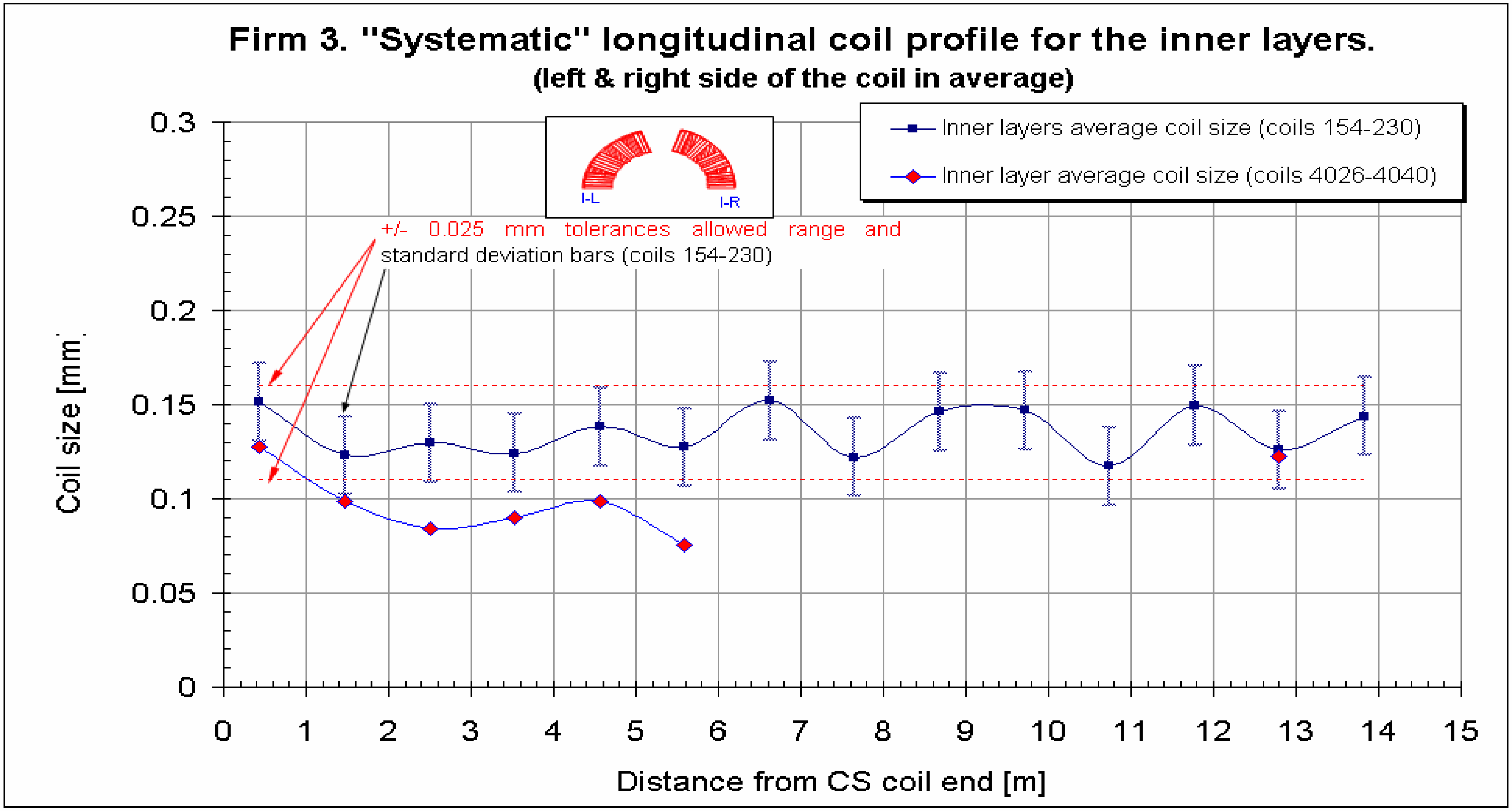

Figure 1

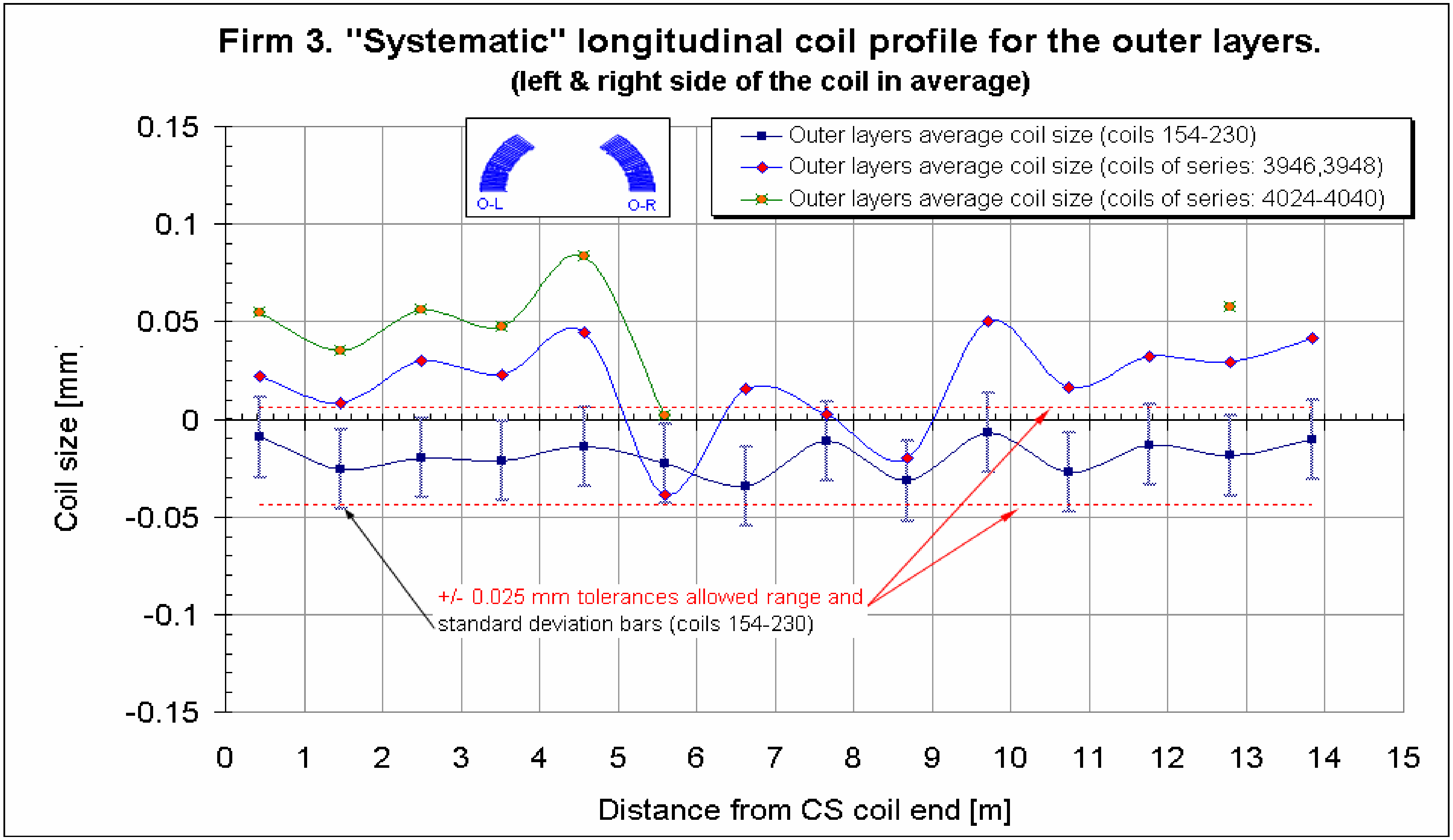

Figure 2

This statistics shows that the outer layer coils systematically have rather small relative coil size at the measuring positions 6 and 9, which was not a case in the past. We can't say much yet about the inner layer coils as the data on measuring positions 7÷12 and 14 is missing at the moment. We will update this statistics if there are will be more data available in the future.