Report on mechanical measurements in the main LHC dipole collared coils: November-December 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.

1. The dashboard

The available data on coils size measurements by the end of year 2004 is given in table 1 together with the statistics on production rate during last 4 months.

Firm	Number of poles produces in 2 months		% of poles / pairs of layers measured in straight part	Number of measuring sections	Total number of measured poles / pairs of layers
	Sep-Oct 2004	Nov-Dec 2004			
Firm 1	100	80	25% / 0	5	618 / 0
Firm 2	40	76	0 / 25%	15	80 / 180
Firm 3	120	100	0 / 50%	4	0 / 850

Table 1. Statistics on coil production rate and coil size measurements for firms 1÷3.

- **Firm 1 (ALSTOM-JEUMONT)** – as can be seen in table 1, compared to the September-October period, the average speed of coil production was slightly reduced. In last two months the average production rate was ~ 10 sets of poles per month compare to 12 sets of poles in previous period. The poles are measured with reduced number of measuring sections along the coil (5 instead 15).
- **Firm 2 (ANSALDO)** – Compared to September-October period, the average coil production speed was doubled: ~ 10 sets of poles per month. Actually it is the highest production rate achieved at firm 2 since the beginning of mass production. At this firm the coil size measurements usually performed on one inner and one outer layer per magnet. The coils are measured in 15 sections along the coil.
- **Firm 3 (BNN)** – Compared to the September-October period, the average of coil production rate is slightly reduced: 12 sets of poles per month instead of 15. At this firm, the highest rate was registered during June-July period of 2004 year: ~20 sets of poles per month. With some exceptions, the coils are measured in 4 sections along the coil straight part.

2. Summary

Trends in coil sizes

Firm 1. The negative trend in coil dimensions (reduction of coil size) observed before in the data on both inner and outer layers at firm 1 has been saturated. Moreover, data on the outer layer coils shows some recovery in coil sizes in the last 20 pole sets (before, the coil size of outer layers was approaching the lower limit). However, two magnets 197 and 198 were assembled with relatively smaller coil size on both layers. All magnets are being collared with nominal polar shims.

Firm 2. The coil size on the inner layer is rather stable for the coils of last 50 magnets; it is varied in the range of ± 0.05 mm. The coil size on outer layers experience twice larger variation, exceeding for some coils the recommended range ± 0.1 mm. A new small negative trend is seen in the coil size data of outer layers for the last 20 magnets.

Firm 3. At firm 3 the coil size on both inner and outer layer is very stable for coils of series. Generally, for inner layer coils the coil size is varied in the range of ± 0.05 mm. Similarly to other firms, the coil size variation of on the outer layer coils is larger than on the inner layer, but it stays within the recommended range ± 0.1 mm. However, in the data of last 30 magnets a small negative trend in coil size of inner layers is noticed.

Coil waviness

Actually only firm 2 is regularly measuring the coil size in many positions along the coil, allowing monitoring the coil waviness parameter. Other two firms conducting the coil size measurements with reduced number of measuring sections along the coil straight part. However, at firm 3 during last tree months, in order to verify the status of coil production tooling, a number of coils have been measured more extensively. In the next paragraph we give the results of analysis performed on these particular measurements. As a remark, we notice a small increase of coil waviness on both inner and outer layers at firm 3.

Collared coils dimensional data

There is no important trend observed in data on collared coil dimensional (CCD) measurements taken over magnets straight part at any firm. Opposite, CCD data on the measurements taken over coil ends shows a significant difference in the CC dimensions between different magnets and firms.
At firm 2 an important positive trend in CCD over magnets ends is being observed in the last 30 magnets. Even this trend is affecting the very far ends of the coil, where

no SC cable is present (mostly the last end-spacers) a warning message was transmitted to PE and to responsible person at firm. As an action, to verify and localize the source of this trend, extra measurements were requested by CERN and followed by firm on a number of collared coils. In next paragraph we reporting about results of our investigations conducted on that matter.
No important remarks on the CCD data from firms 1 and 3, except few magnets where rather low value in CCD data over coil ends is observed (1177, 1184, 3257, 3262 and 3303).

We recall that for monitoring the coil size and collared coil dimensions measurements in the production the most important graphs from this report are daily updated and available on the **web site** at http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/obs_coil.html. You would need your 'Nice' password to retrieve the information from this web site.

3. Analysis and discussions

3.1 Coil size trends

Firm 1. The coil size at firm 1 is measured on assembled poles. 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 and red dashed lines in figure 1) the coils are cured with additional curing shim, made of polyimide tape, 0.125 mm thick. Later, due to too small coils size in the magnets 183 and 184, particularly on the outer layer, CERN suggested to remove the additional curing shim in order to recover the optimum coil dimensions. The extra curing shim for outer layer coils was removed starting from the magnet 187 (green dashed line in figure 1) and we notice a small positive trend in coil sizes of outer layers of the last 20 magnets. However, it is too early to say if this is related to the removal of curing shim or if it is just a natural trend. Two collared coils 197 and 198 were assembled with relatively smaller coil size on both layers. Actually, at firm 1 all magnets are being collared with the nominal polar shims on both coil layers.
In figure 2 the coil sizes of the inner and the outer layers are plotted together with their E-modulus. According to the specification the poles assembled in a twin aperture dipole shall have a similar modulus of elasticity with maximum permissible difference ± 15% with respect to the average computed over the layers belonging to the same twin aperture dipole. For simplicity, in our plot the recommended range for E-modulus value is referred to the average on all the poles.

Firm 2. The coil size is rather stable in data of inner layer coils for last 50 magnets (see figure 3); its variation is not exceeding ± 0.05mm range. Opposite, the coil size on outer layers is showing twice larger variation and for some of the coils it is going

out of the recommended range ± 0.1 mm. A new small negative trend is seen in the coil size data of outer layers for the last 20 magnets.
In figure 4 the coil sizes on the inner and outer layers are plotted together with their E-modulus. For some of recently produced inner and outer coils we observe significant sudden jumps in their E-modulus value. The amplitude of these jumps is rather big: up to 3 GPa! This is more than 20% of the average E-modulus value and outside of recommended range. From another hand, we don't see visible changes in coil sizes. Generally the trends in coil dimensions are produced by the tolerances in coil components, which usually affecting both parameters: the coil size and coil E-modulus. This is indicating that the curing process at this firm now is well optimized. Nevertheless, in general the situation with coil sizes is good at this firm.

Firm 3. At firm 3 the coil size on both inner and outer layer is rather stable for coils of series. Generally, for inner layer coils the coil size is varied in the range of ±0.05 mm (see figure 5). Similarly to other firms, the coil size variation of on the outer layer coils is larger than on the inner layer, but it stays within the recommended range of ± 0.1 mm. However, in the data of last 20 magnets a small negative trend in the inner layer coil size is noticed.
In figure 6 the inner and outer layers coil sizes are plotted together with their E-modulus. Already underlined in previous reports, despite significant trends in the coil E-modulus data on both coil layers, the coil size at firm 3 is rather stable. This is indicating that the curing process at this firm is very well optimized. The situation with the coil sizes at this firm is so far the best among all three firms.

3.2 Coil left-right sides asymmetry

The left-right asymmetry graphs are withdrawn from this report as the tolerances window estimated from the tolerances on a3 multipole, the mostly effected by this coil parameter is 3 times lager then the real variation in coil size asymmetry observed up to now at any firm.

3.3 Coil waviness

Actually only firm 2 is regularly measuring the coil dimensions at many positions along the coil. By measuring the coils in 15 longitudinal positions this firm keeps control on coil waviness and on the status of coil production tooling. The standard deviation (one sigma) of coil size variation along the coil is shown in figure 7. As we can see from this figure, generally in all coils of series, except few magnets, the coil waviness is rather small compared to recommended range.
At firm 3 during last four months some extra measurements were performed in order to verify the tooling shape. At this firm the coils are typically measured in 4

positions along the coil, while for the last 30 magnets a number of coils have been measured more extensively: at 5 longitudinal positions instead of 4, where the location of 5th position was moved along the coil from one measured coil to another, covering all 14 measuring positions used for pre-series production control. In such a way it was possible to collect statistical data on the longitudinal coil shape with comparably low extra effort. Moreover, some coils have been measured completely in all 14 longitudinal positions, fully following the procedure of pre-series.

We profited the availability of this extra data on coil size measurements to update the status on so-called "Systematic" longitudinal coil profiles which were already published in this report in the past for the data on pre-series magnet coils. We recall that the average value for each measuring position is computed to obtain the "Systematic" longitudinal coil profile, which represents the shape of tooling involved into coil production chain. In figures 8 and 9 the "Systematic" longitudinal coil profiles for recently produced coils are shown in comparisons with the coil profiles obtained from the data on pre-series magnets. As we can see on these figures, for both coil layers the shape of profiles generally stay the same, but there is some degradation in the shape of the inner layer coils: the coil size is systematically relatively smaller at the measuring positions 2÷5 and 7, which was not a case in the past. The "Systematic" longitudinal coil profiles on the outer layer coils also shows relatively smaller coil size at the measuring positions 6 and 9. The standard deviation is not shown for new coil profiles, as the number of measurements per measuring section is too small to evaluate it correctly.

4. Measurement data of the collared coil dimensions

4.1 Trend graphs (coil straight part and coil ends)

The available data on collared coil dimensions (CCD) measurements by the end of year 2004 is given in table 1 together with the statistics on production rate during last 4 months. For the details on the procedure of collared coil dimensions measurements at each dipole manufacturer see previous reports.

Firm	Number of collared coils measured in 2 months		Number of measuring sections over coil SS /LJ/ coil ends	Total number of measured collared coils
	Sep-Oct 2004	Nov-Dec 2004		
Firm 1	24	18	6/2/3	200
Firm 2	28	17	3/2/3	150
Firm 3	47	29	8/2/3	318

Table 2. Statistics on collared coil dimensions measurements for firms 1÷3.

As can be seen in figures 10÷12, the data on collared coil dimensional (CCD) measurements taken over magnets straight part is rather stable at all firms and generally consistent with the coil size variation except the data from firm 3.

Firm 1. In this report the data belonged to the first 50 magnets, measured with different machine and already published in the previous reports, has been dropped. In figure 10 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, are marked separately. There is some difference in nominal dimensions of these collars compared to collars from another producer and this explains systematically smaller CC dimensions over coil ends. Compare to the data on straight part, the CCD over coil ends are varies in a bit wider range, but without important trends. For the last 50 magnets, except few, the variations in CCD data are not exceeding the ±0.08 mm range.

Firm 2. At firm 2, for the collared coils of the series, the variations in CCD data over coil straight part is even smaller than at firm 1 and generally not exceeding the ±0.05 mm range (see figure 11). Already underlined in previous report, a strong positive trend observed in CCD data over coil ends since the CC 1112, is being saturated in the last 12 magnets, but the collared coil dimensions still stay above the average value for this firm. The investigations are going on to understand the source of this trend.

Firm 3. At firm 3, despite smallest coil size variation compared to firms 1 and 2, the CCD taken over coil straight part varies in a larger range compared to other firms, which is probably due to particularity of FSG collars, mainly used by this firm. 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 for both types of collars: collars for magnet straight section and collars for magnet ends. However for the last 20 magnets at this firm we notice a significant reduction in CCD data variation.

4.2 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 13÷15 the asymmetry in collar's deformation between the lateral and central part of the collars are shown separately for each firm.
Firm 1. There is a small shift between moving averages on collar's asymmetry corresponding to the first and the second apertures. This shift is particularly visible in the data on last 60 magnets. This is consistent with the magnetic measurements data on $b2$ multipole where a small difference in the average values of the last 60

magnets between two apertures is seen as well.[1] (see E. Todecso bimonthly report on field quality).

Firm 2. Compared to firm 1 the collar's asymmetry is a bit smaller at firm 2 and no visible differences between two apertures. The variation in collars asymmetry from one collared coil to another is also smaller than at firm 1. However this is not confirmed by magnetic measurements data, which shows that there is also a systematic offset in *b2* multipole mean values between two apertures for collared coils at firm 2.

Firm 3. Usually for firm 3 CC we observe the largest variation for the asymmetry in collar's deformation between lateral and central part of the collars, but in the last 30 magnets this asymmetry is considerably reduced: from ±0.15 mm to ±0.05 mm or even smaller. The same observation can be seen in magnetic measurements data on *b2* multipole. The largest difference in collars asymmetry of firm 3 compared to other firms is due to particularity of FSG collars. The detailed report concerning the investigations of the source of large tolerances in FSG type collars is under publications.

Acknowledgments

We wish to acknowledge M. Bajko, M. Cornelis, P. Fessia, A. Musso and J.P. Koutchouk for comments, discussions and valuable help.

[1] For CC 1140÷1200 the difference in the average of b2 multipole between two apertures is ~0.12 units. Nevertheless, this difference is too small to be considered.

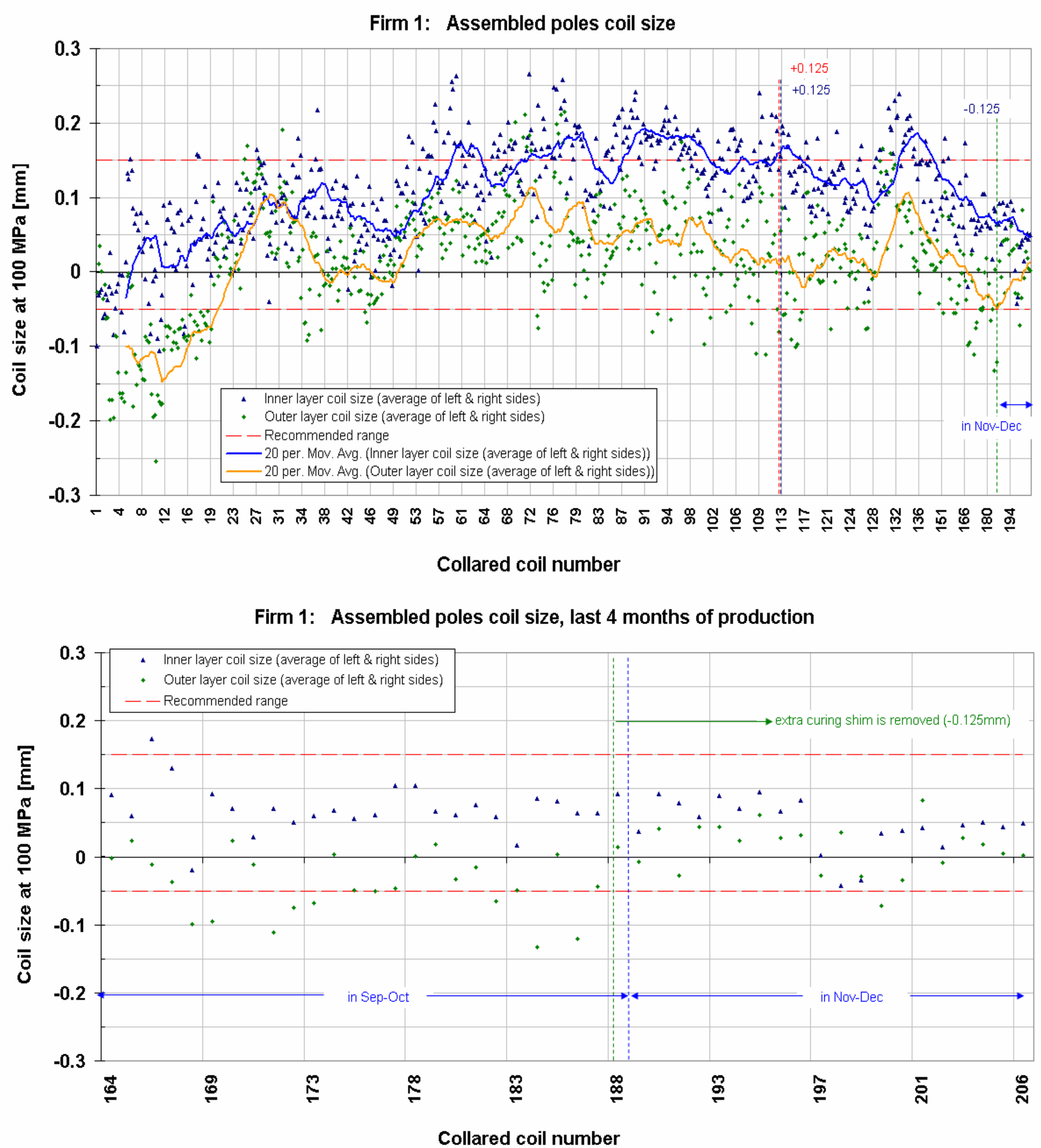


Fig. 1 Average coil size in the straight part of the assembled poles at Firm 1. Upper plot all data up to date, lower plot: last 4 month of production.

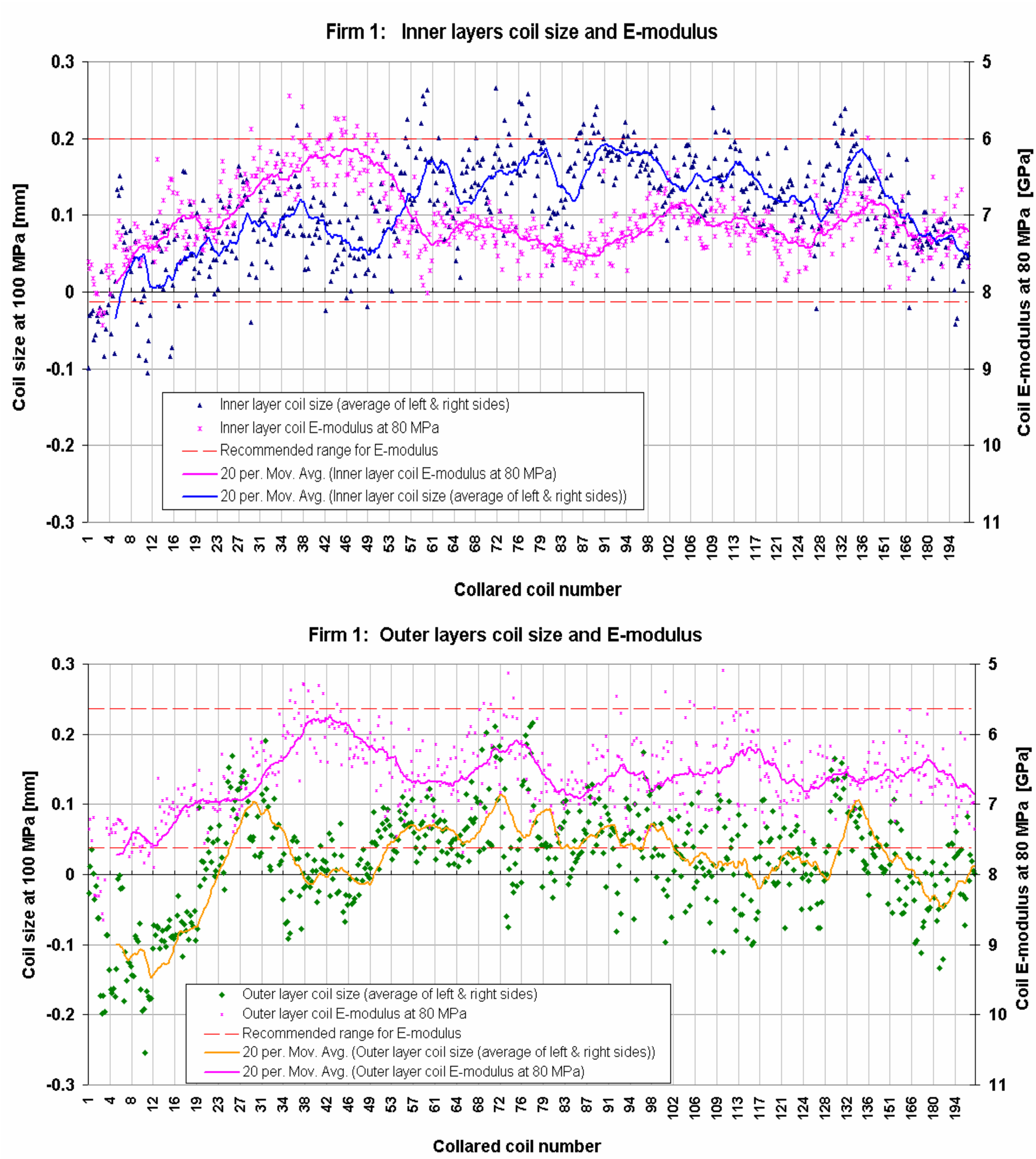
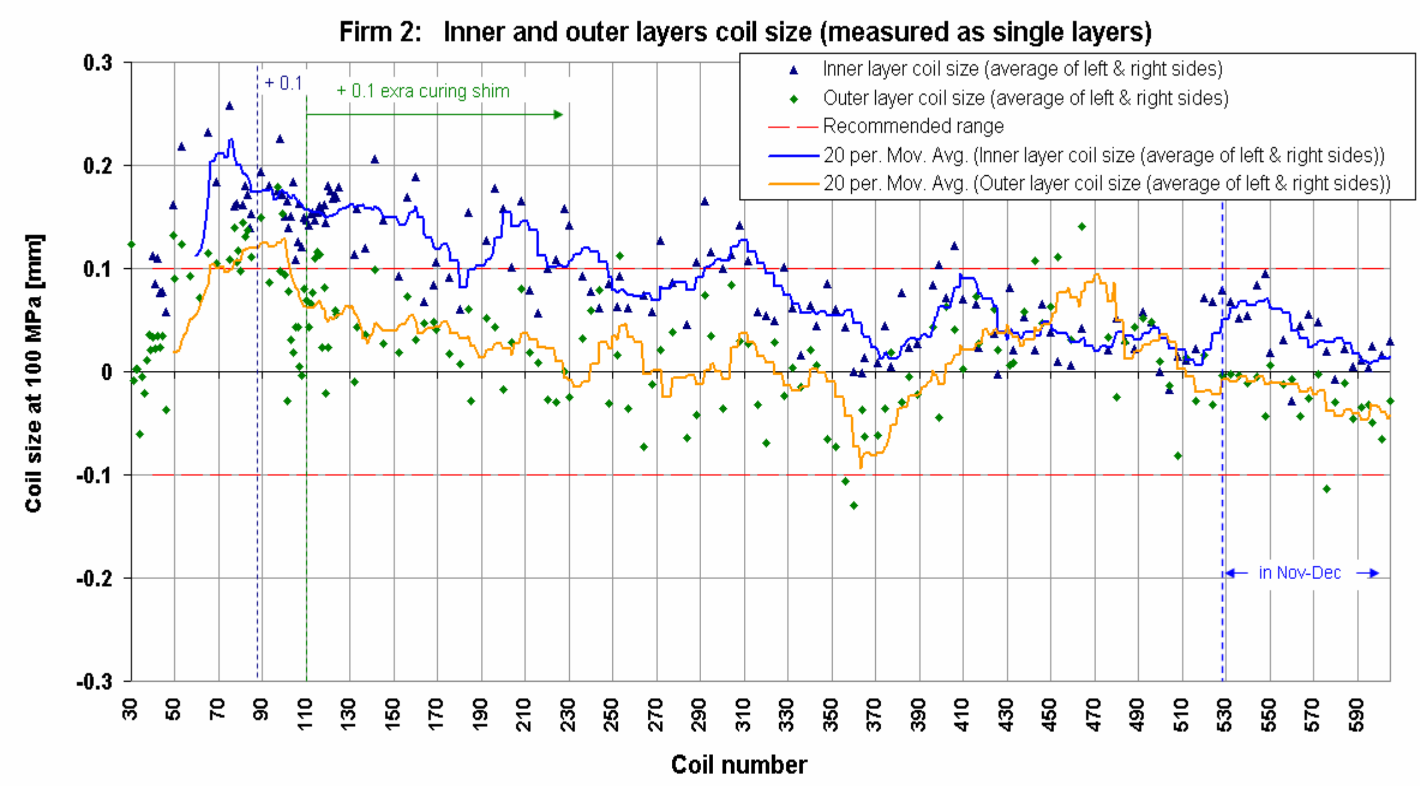


Fig. 2 Average coil size and coil E-modulus computed at 80 MPa compressive stresses (data from the measurements on assembled poles at Firm 1).



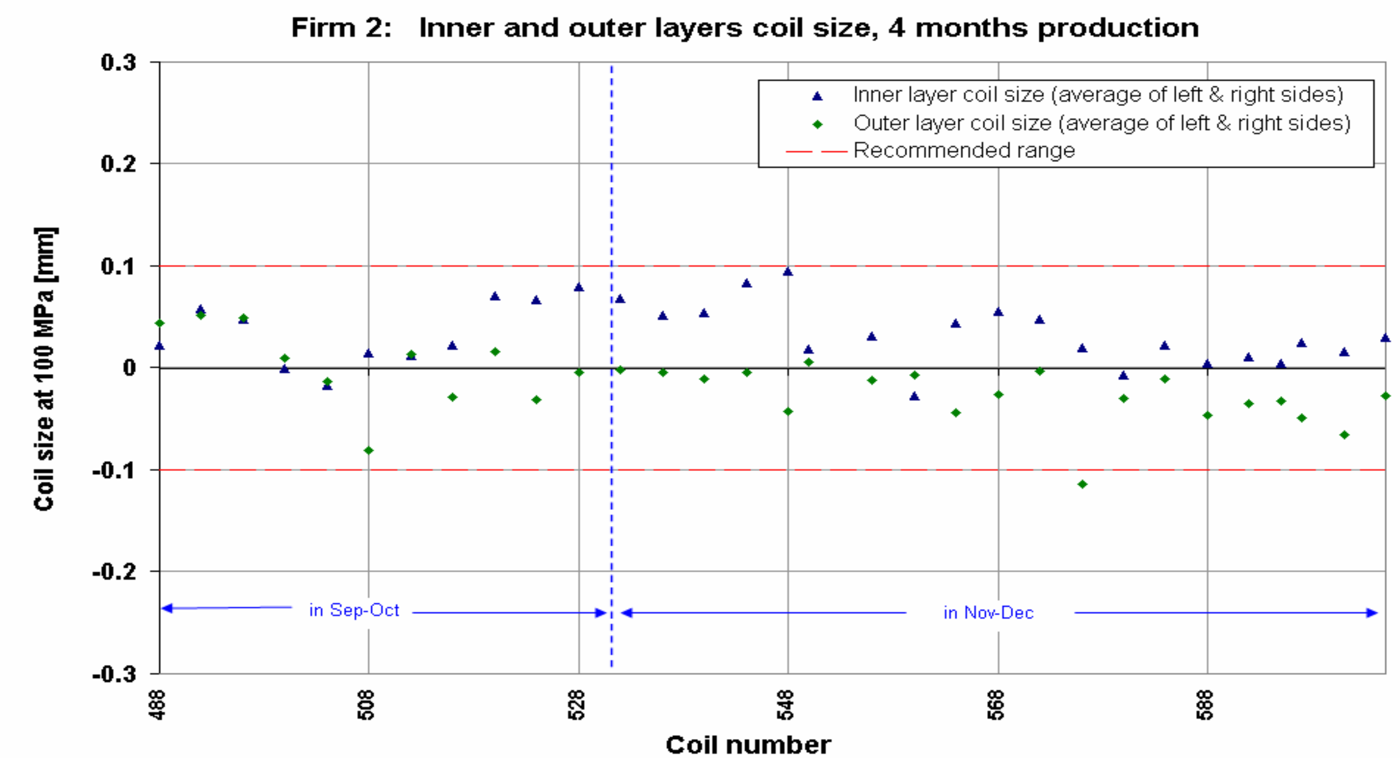
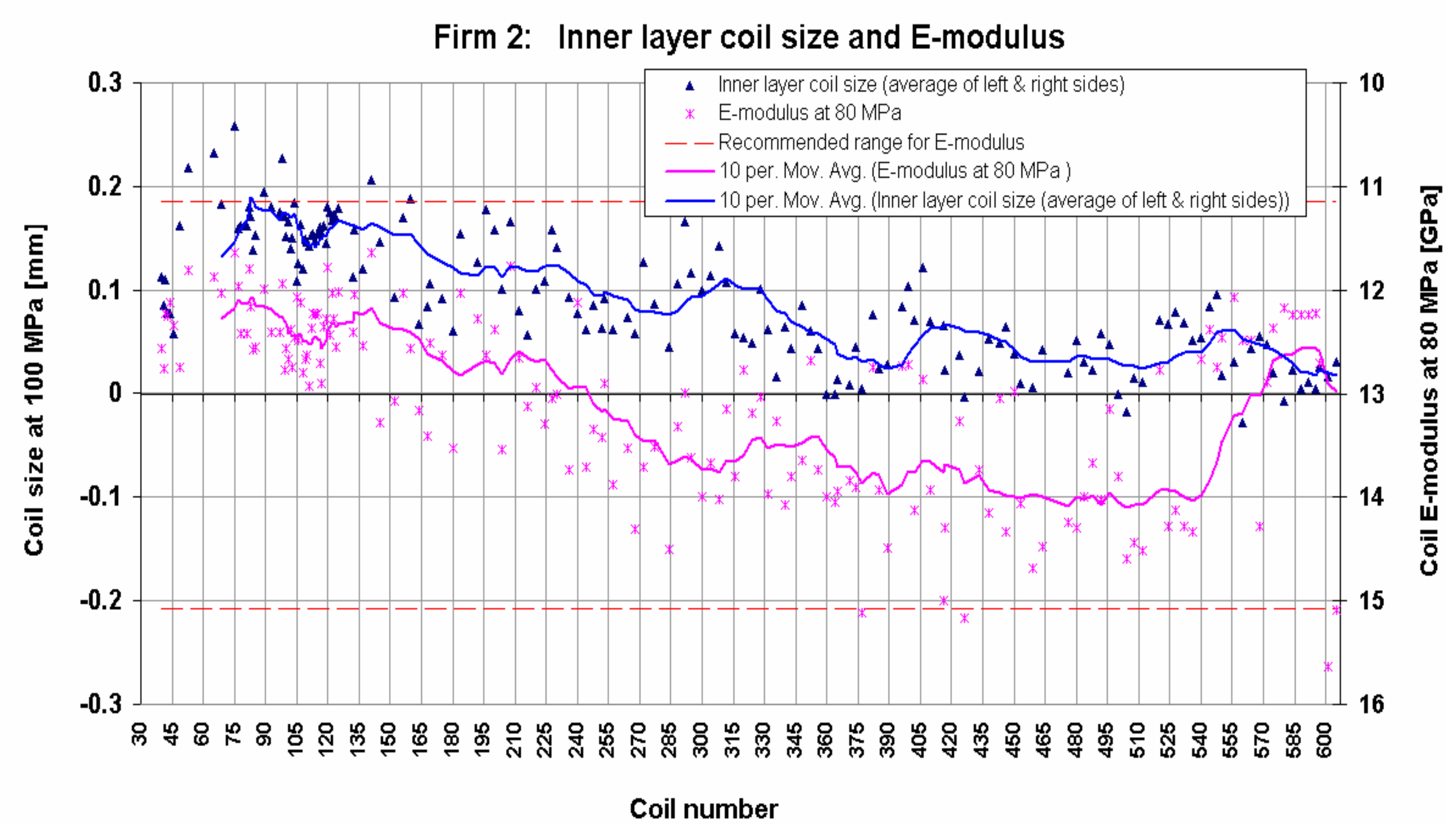


Fig. 3 Average coil size in the straight part of the single layers at Firm 2. Upper plot all data up to date, lower plot: 4 month production.



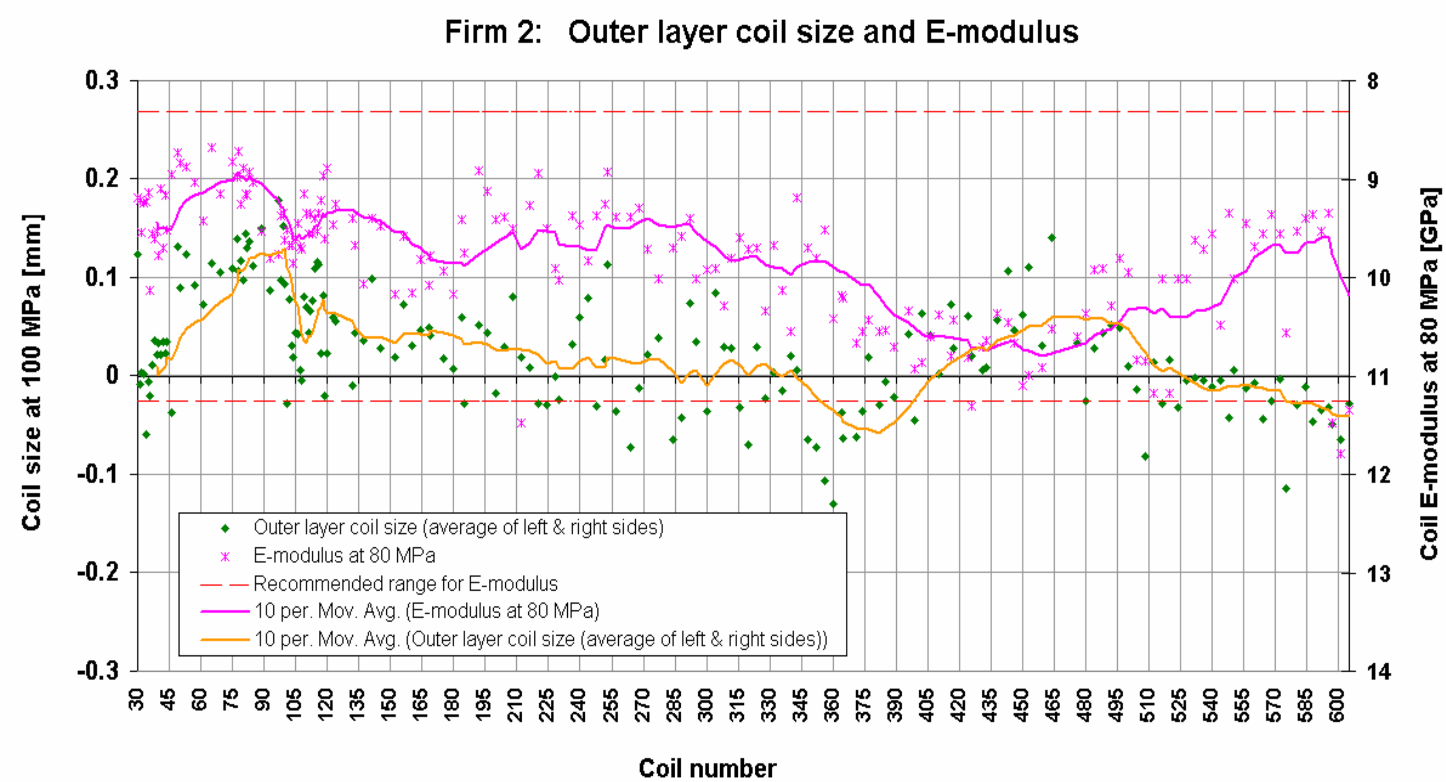


Fig. 4 Average coil size and coil E-modulus computed at 80 MPa compressive stresses (data from the measurements on single layers at Firm 2).

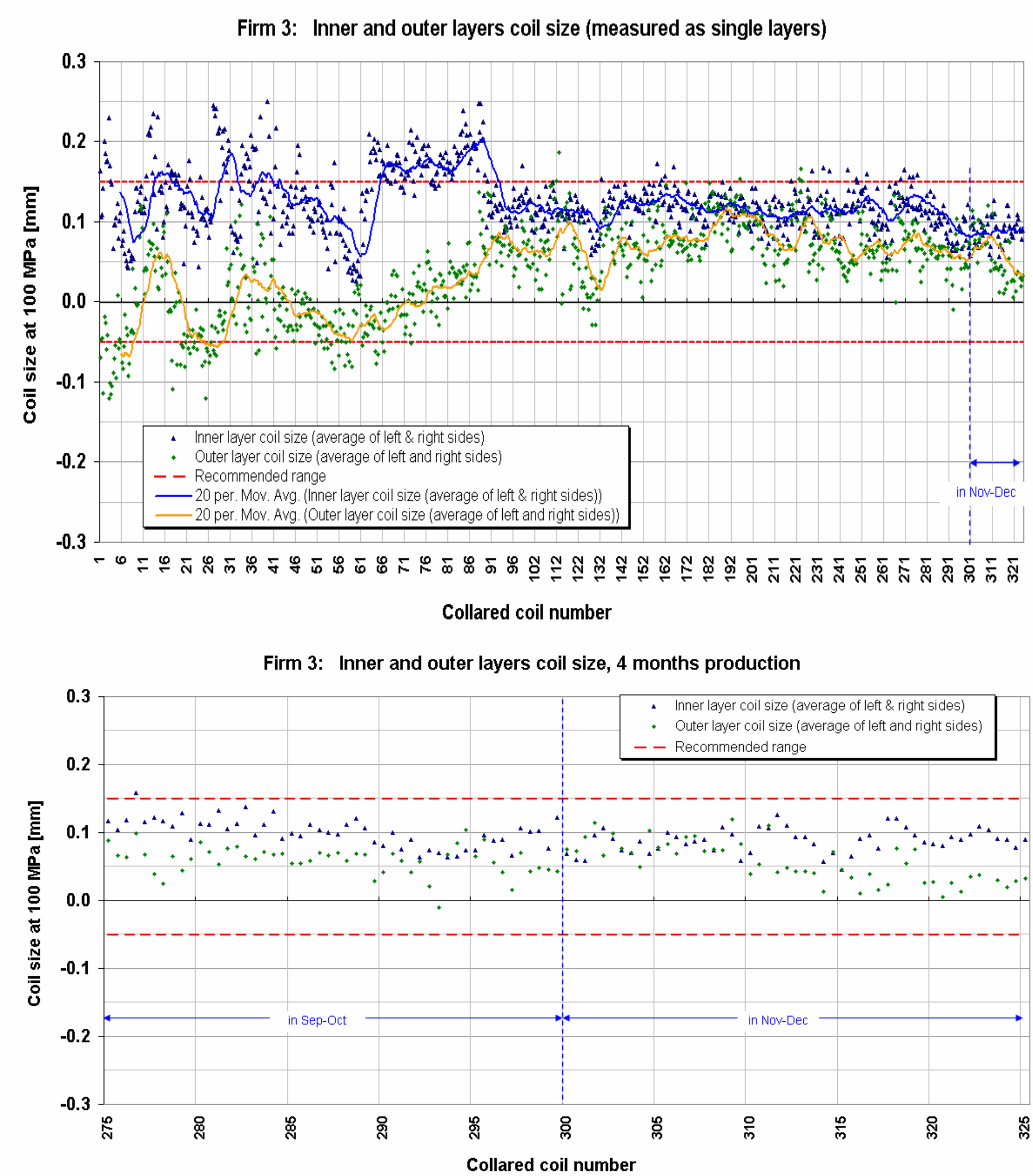


Fig. 5 Average coil size in the straight part of the single layers at Firm 3. Upper plot all data up to date, lower plot: 4 month production.

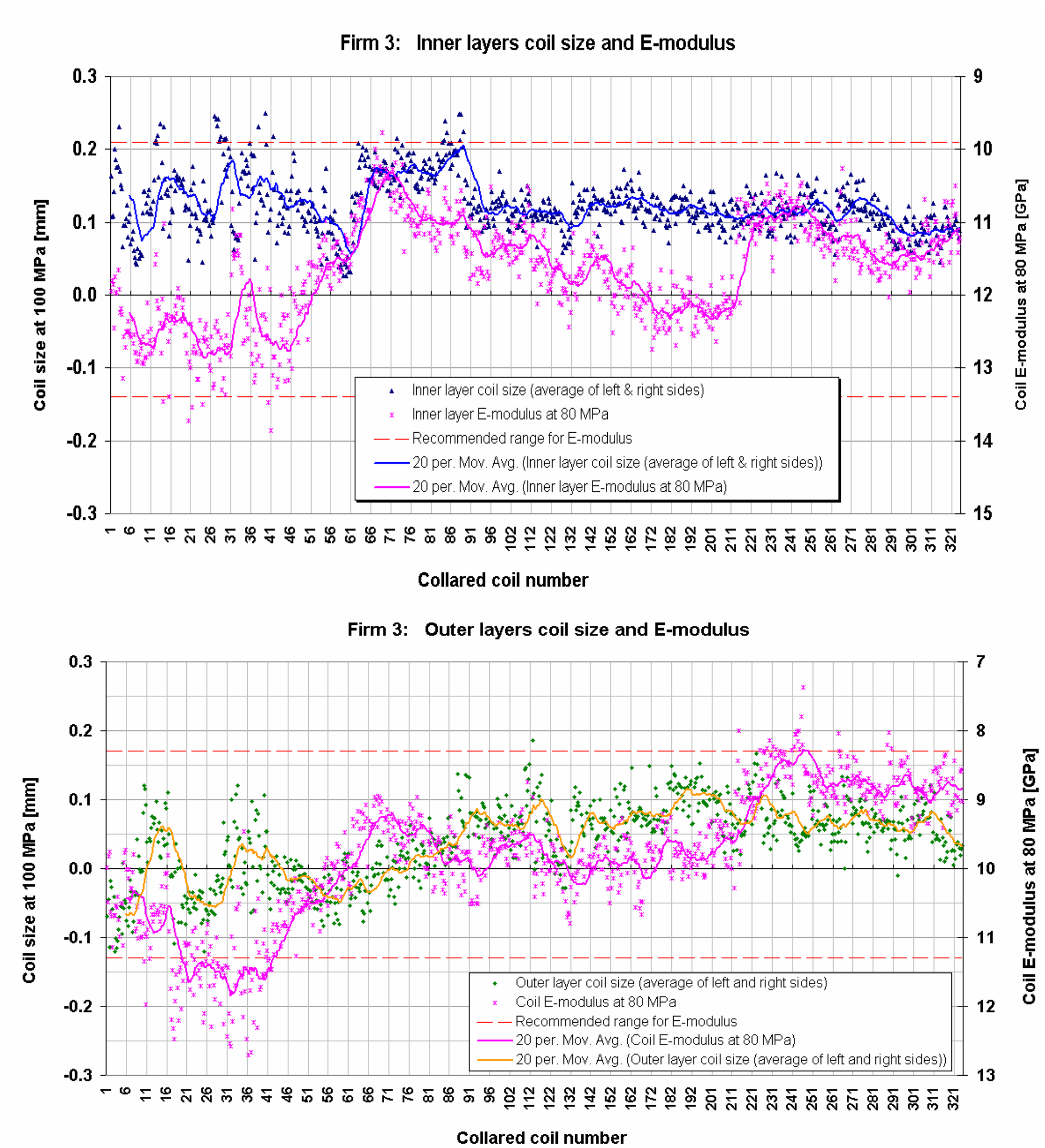


Fig. 6 Average coil size and coil E-modulus computed at 80 MPa compressive stresses (data from the measurements on single layers at Firm 2).

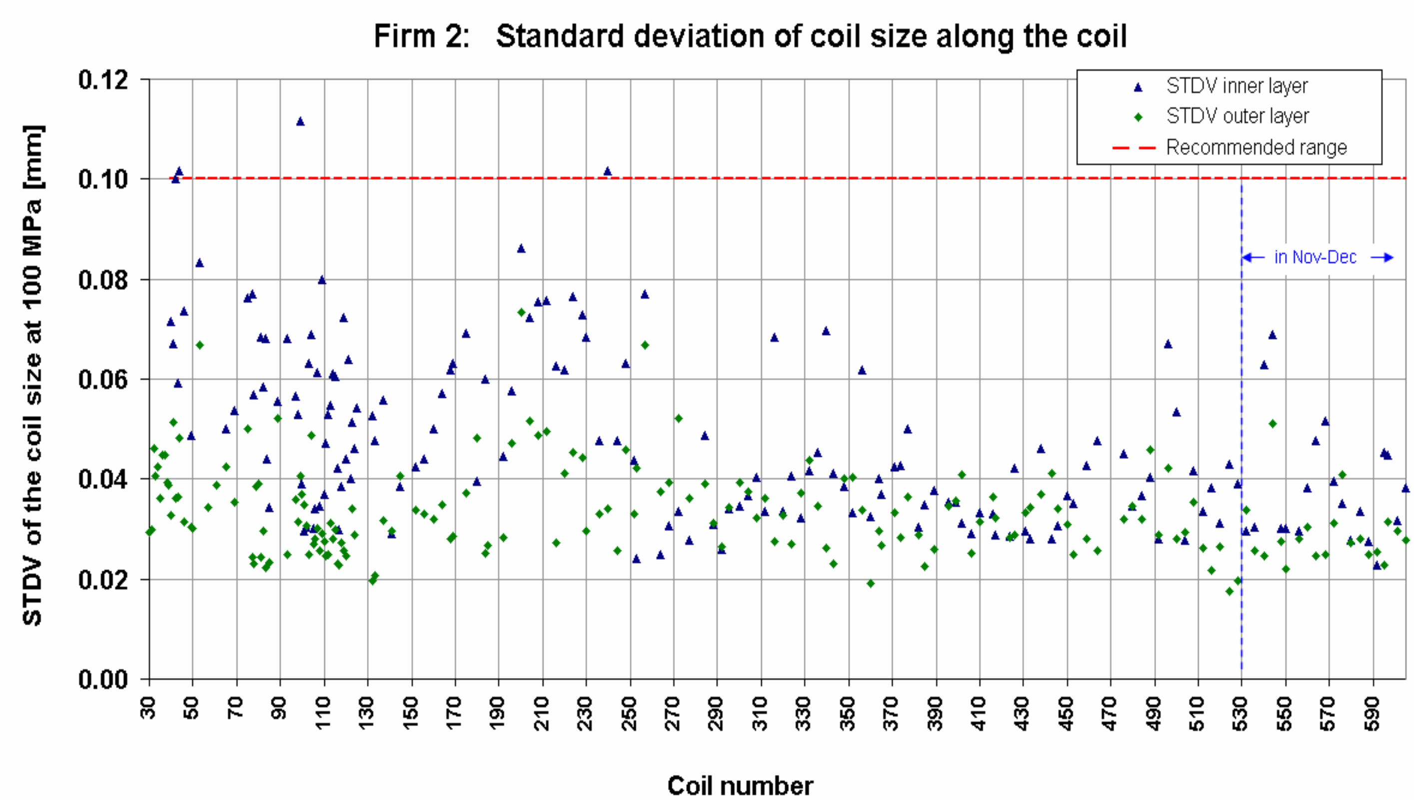


Fig. 7 Firm 2. Standard deviation of coil sizes measured in 15 positions along the coil (left and right coil sides in average).

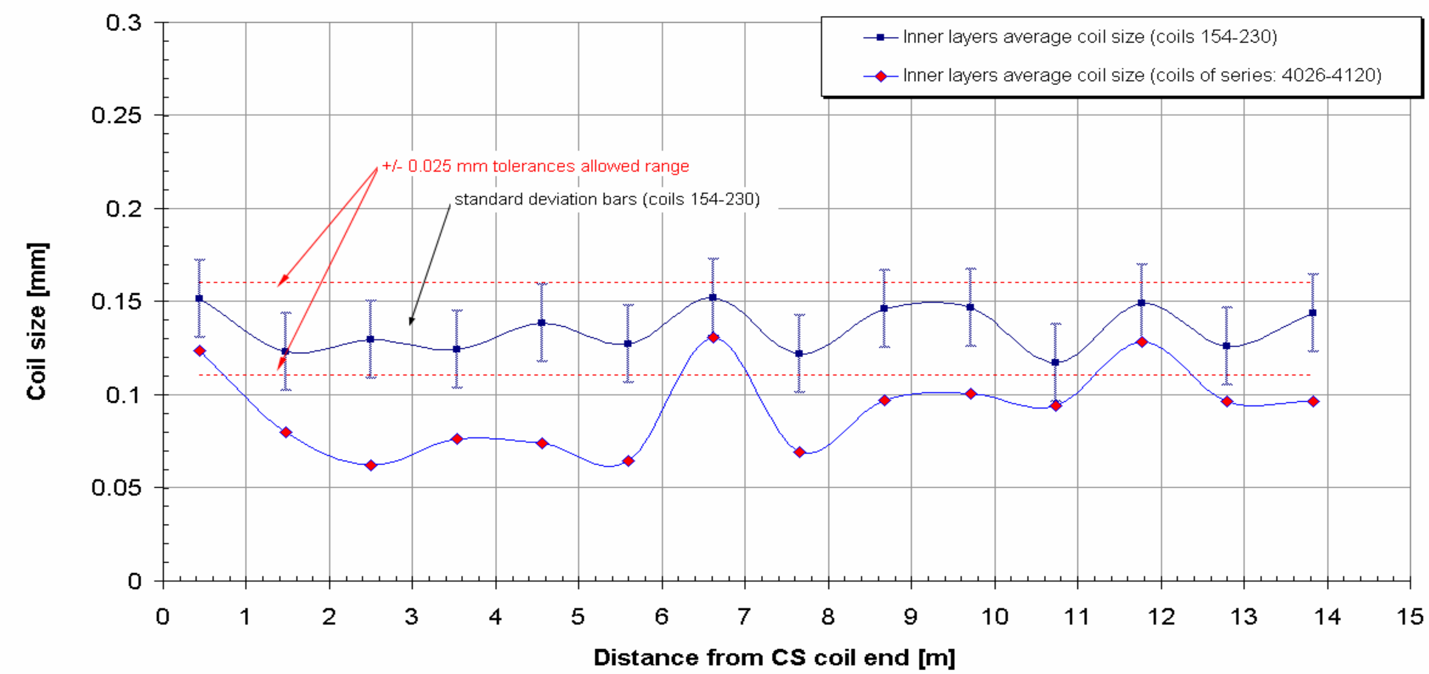


Fig. 8 "Systematic" longitudinal coil profile for the inner layer coils at firm 3. (left & right coil side in average)

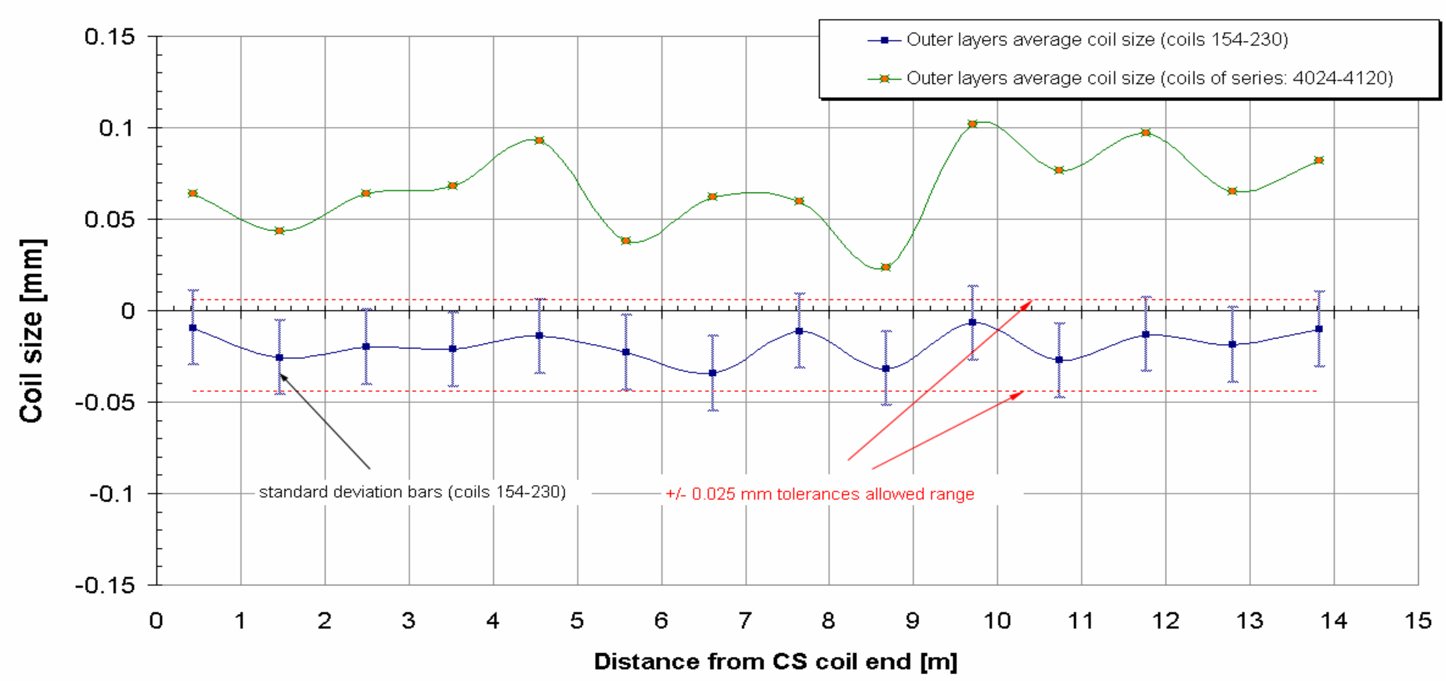


Fig. 9 "Systematic" longitudinal coil profile for the outer layer coils at firm 3. (left & right coil side in average)

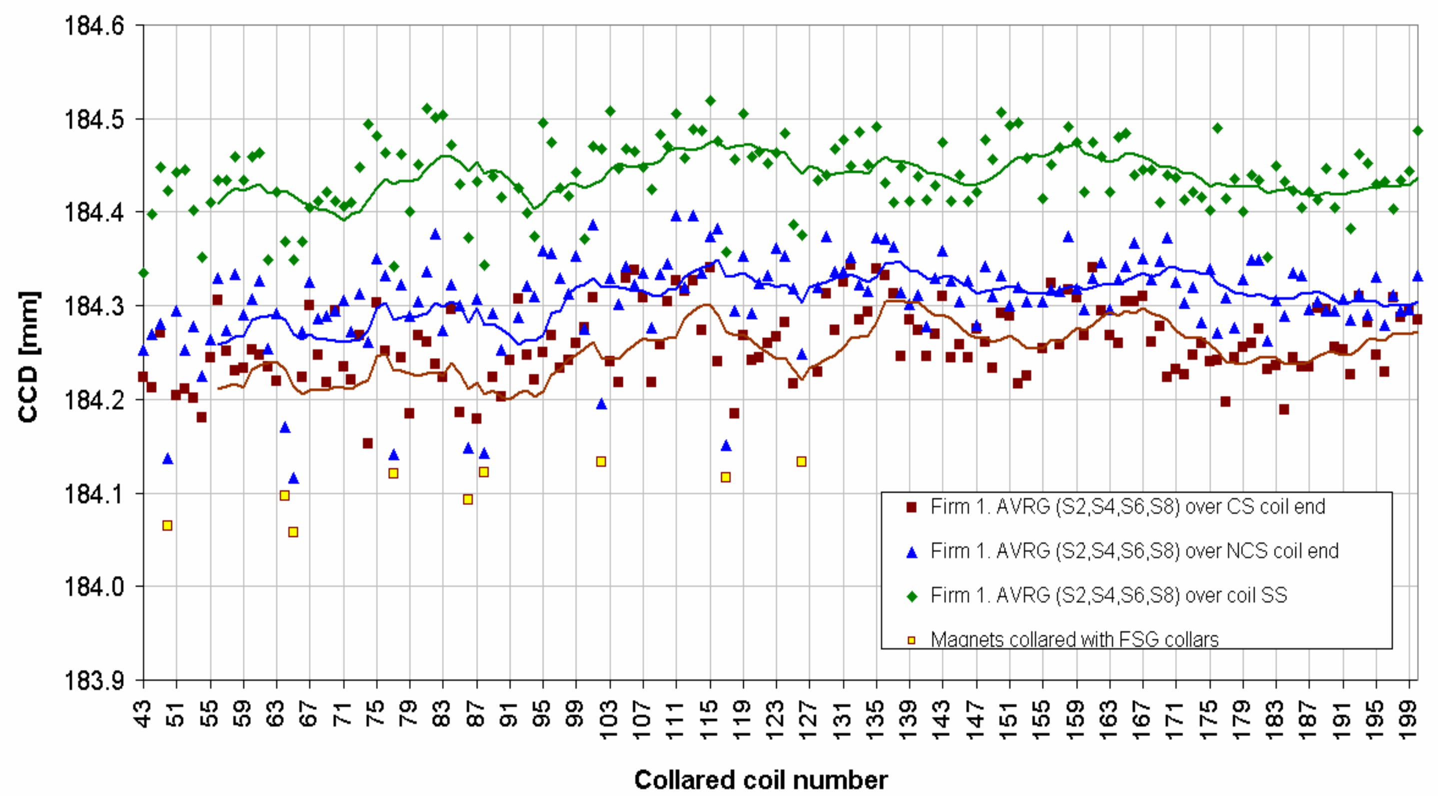


Fig. 10 CCD data for collared coils of firm 1 in averages for coil straight section (SS), connection side (CS) and non-connection side (NCS) ends.

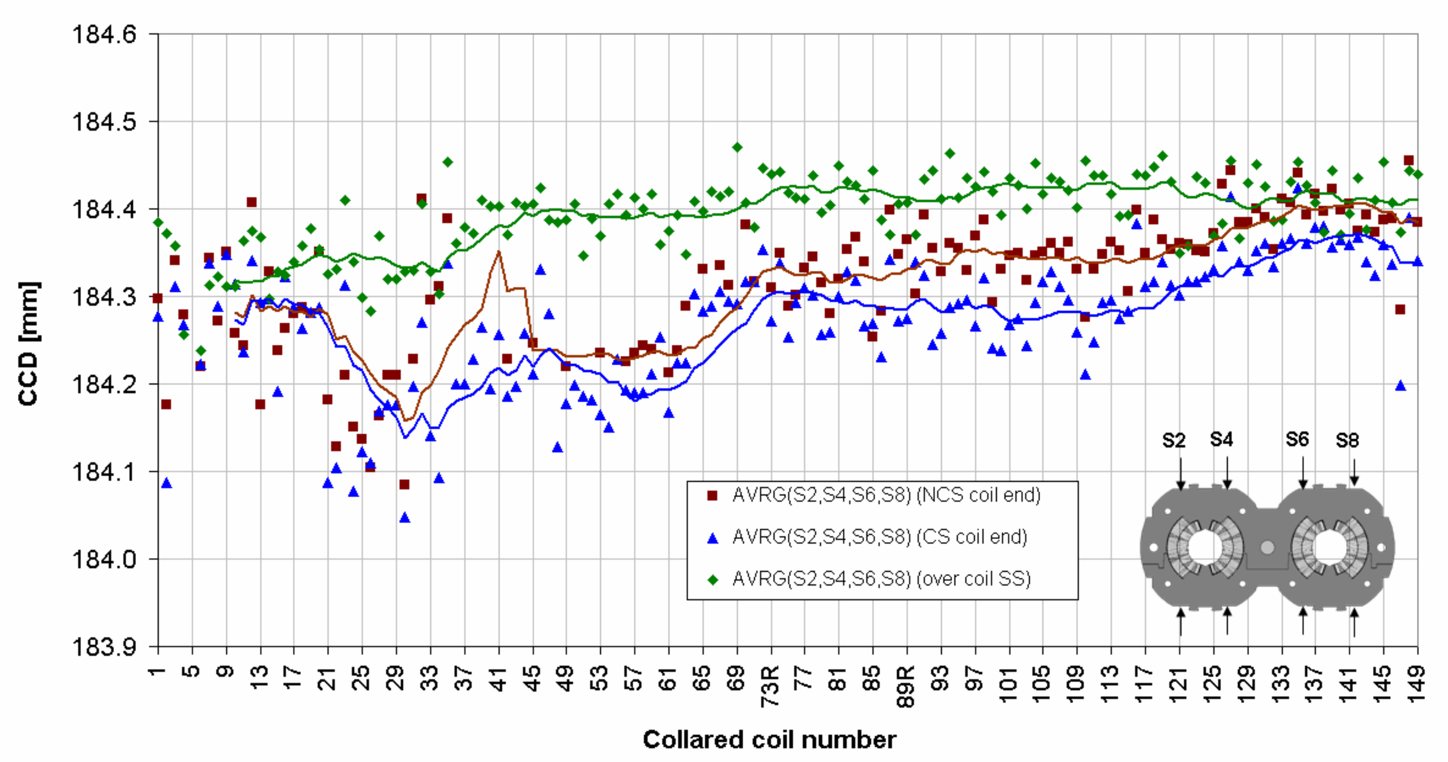


Fig. 11 CCD data for collared coils of firm 2 in averages for coil straight section (SS), connection side (CS) and non-connection side (NCS) ends.

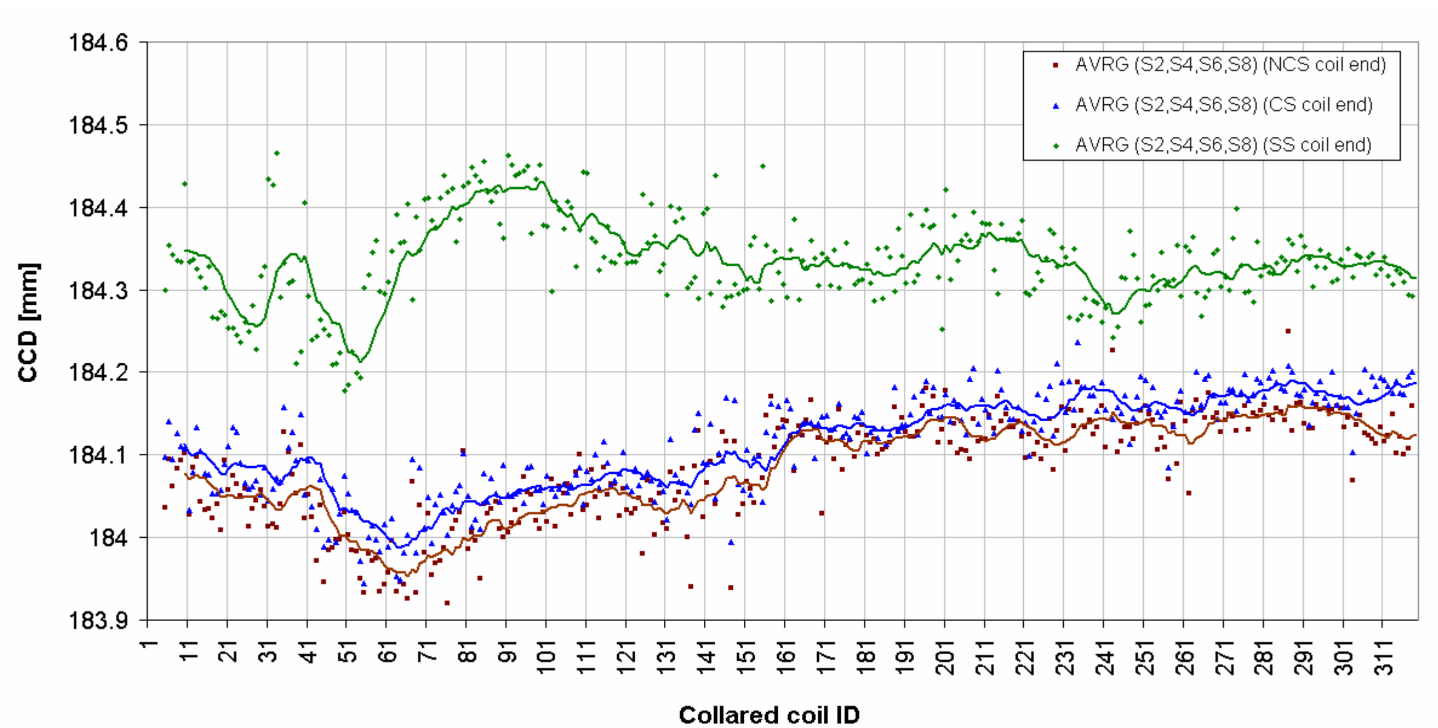


Fig. 12 CCD data for collared coils of firm 3 in averages for coil straight section (SS), connection side (CS) and non-connection side (NCS) ends.

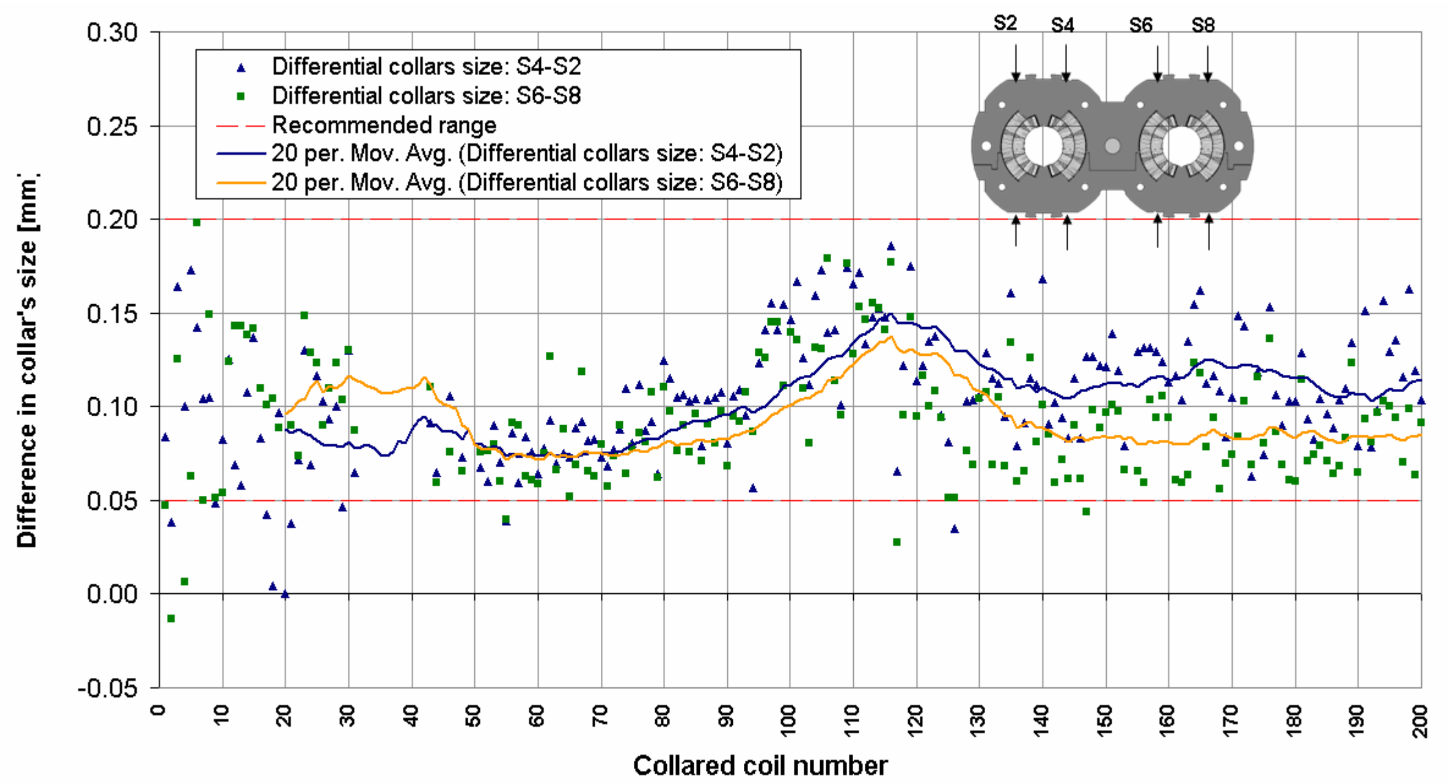


Fig. 13 Firm 1. Asymmetry in collar's vertical dimensions.

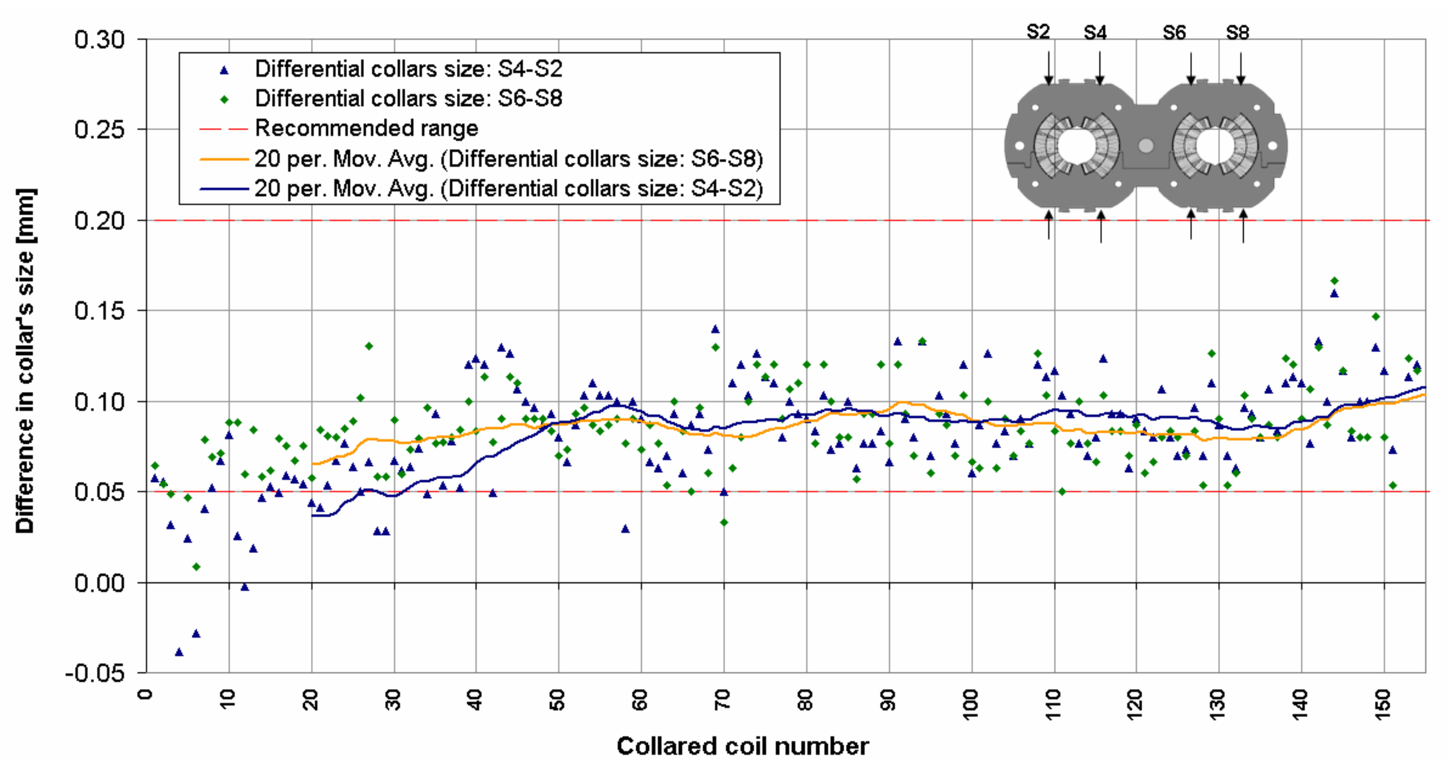


Fig. 14 Firm 2. Asymmetry in collar's vertical dimensions.

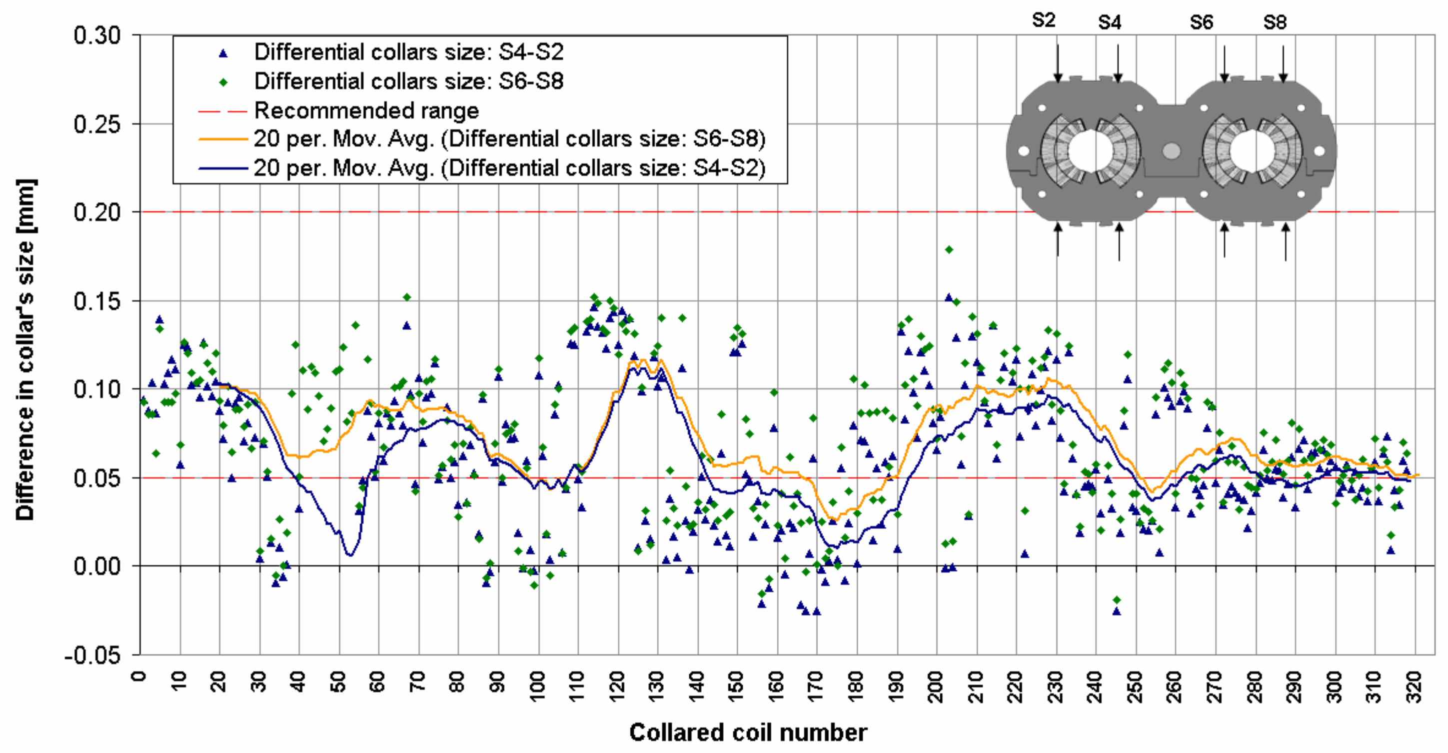


Fig. 15 Firm 3. Asymmetry in collar's vertical dimensions.