Report on mechanical measurements in the main LHC dipole collared coils: December 2002-March 2003

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

The dashboard

- **Firm 1 (ALSTOM-JEUMONT)** – up to date, 200 assembled poles are measured with the old press and following JEUMONT measuring procedure, the post-processing of raw data is done at CERN. The Collared Coil Database software package, developed at CERN, was installed at JEUMONT. This software allows to introduce a simplified measuring procedure, proposed by CERN, will be used for coil size measurements on the magnets of series.
- **Firm 2 (ANSALDO)** – 50 assembled poles, starting from the pole P30 are measured with the new press (IMMG), then the press was not working for ~ 3 months. The press was repaired on 12.03.03. Ansaldo is producing now the coils for magnets of series and a new schema for these measurements is under discussion with CERN. Up to date, 52 inner and 65 outer layers have been measured. For latest magnets typically only one inner and one outer layer per magnet are measured.
- **Firm 3 (NOELL)** – No measurements on assembled poles so far, due to continues problems with IMMG press. All coil for magnets of pre-series (120 inner and 120 outer layers) were measured with the old NOELL press. For the magnets of series a new procedure will be applied for the measurements of coil sizes.

What is new

Trends in coil sizes. Some improvements in the coils size trends at firm1; actions are taken at firms 2 and 3 to reduce coil size variations (coil curing shims have been modified).

Coil pre-stress in the collared coil. We present our estimates on the coil pre-stress variation in the magnets.

Coil waviness. Firm1 is still producing coils with a rather big coil size variation along its length, this means no visible progress for the last 40 coils. In this report, statistical profile of the coil waviness for each firm is shown, together with the recommended longitudinal positions, where the coil size should be measured in the case that only a limited number of measurements is taken.

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

1.1 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. The data on the coil size shows a significant non-systematic variation (fig. 1). The coil size varies from –0.3 up to +0.2 of mm in a random way. For the latest poles, some reduction in the coil size variation is noticed. From this data we calculated the estimated coil pre-stress variation (figure 2). As can be seen from this graph, despite a rather big variation of the coil size, for most of the magnets the coil pre-stress stays in the specified range (+/- 15 MPa). Nevertheless, such a variation in coil sizes disturbs the field quality of the magnets. The impact of the asymmetries of the upper/lower poles coil size on the skew quadrupole (*a2)* is presented later in this report. The main reasons for coil size trends are the tolerances in coil components (cable, insulation and copper wedges). Coil components can be split into two groups: "soft components"- cable insulation, bond and "hard components" – bare cable and copper wedges. In figure 3, the outer layers coil size is plotted together with their E-modulus (notice that the scale for E-modulus axis is reversed). From this graph we could see that in most of the cases the increase in coil sizes is followed by the decrease of coil E-modulus and opposite. This coil properties variation is due to tolerances on "soft components", which dominate (see first report at http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/Obs_coil.html. There it was shown that the change of the cable insulation type, accompanied by the small increase in thickness of cable insulation tape (~ 2 microns) results in a coil size rise by ~60 microns and E-modulus decrease by ~1 GPa). In figure 3 we can see, that there are also cases when both, the coil size and its E-modulus rise their values (coils 3-10). This is an example where the tolerances on the "hard components" are dominating.

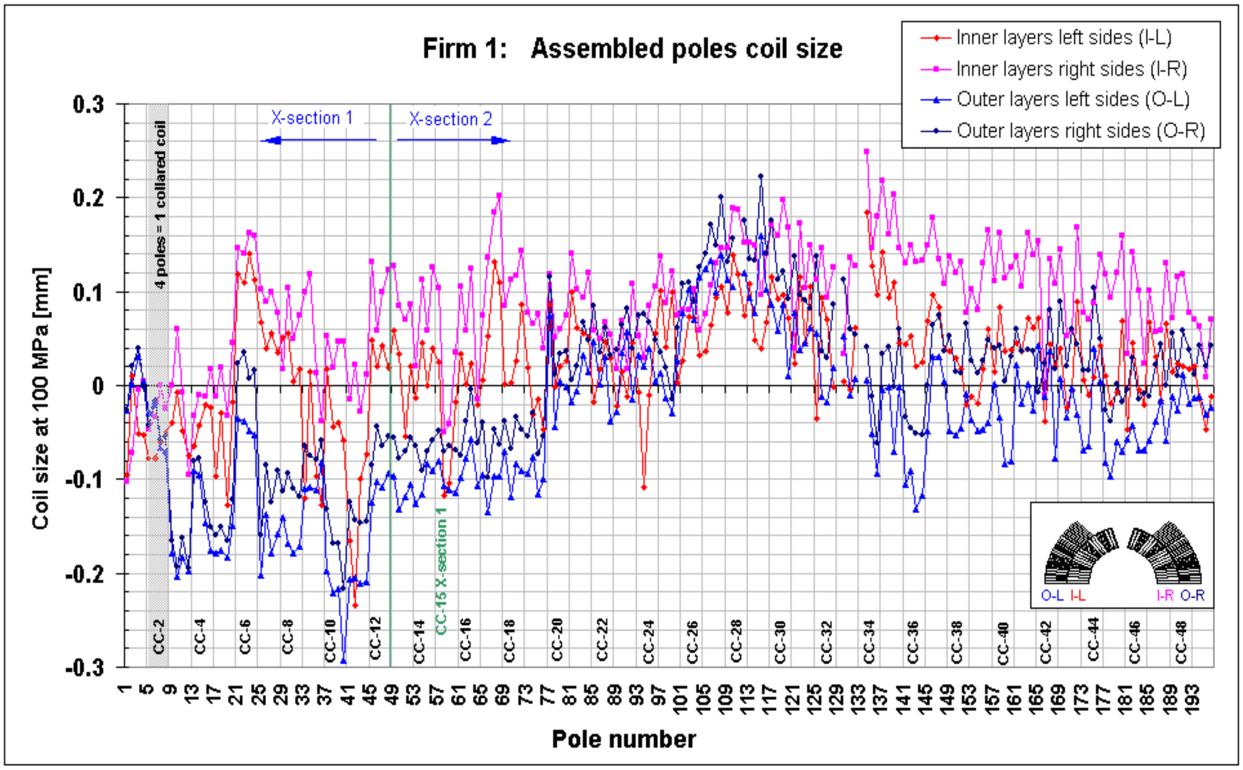

Fig.1 Firm 1. Average coil size in the straight part of the assembled poles (196 poles).

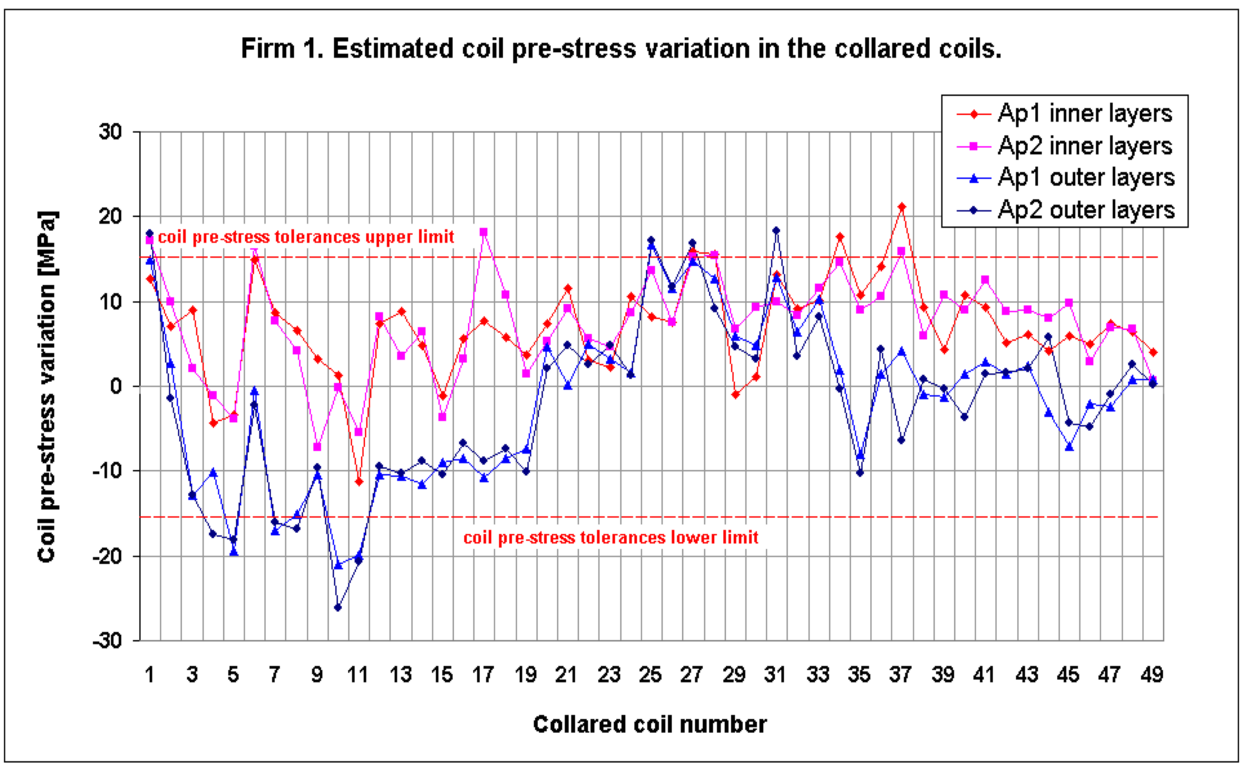

Fig.2 Firm 1. Estimated coil pre-stress variation in the collared coils.

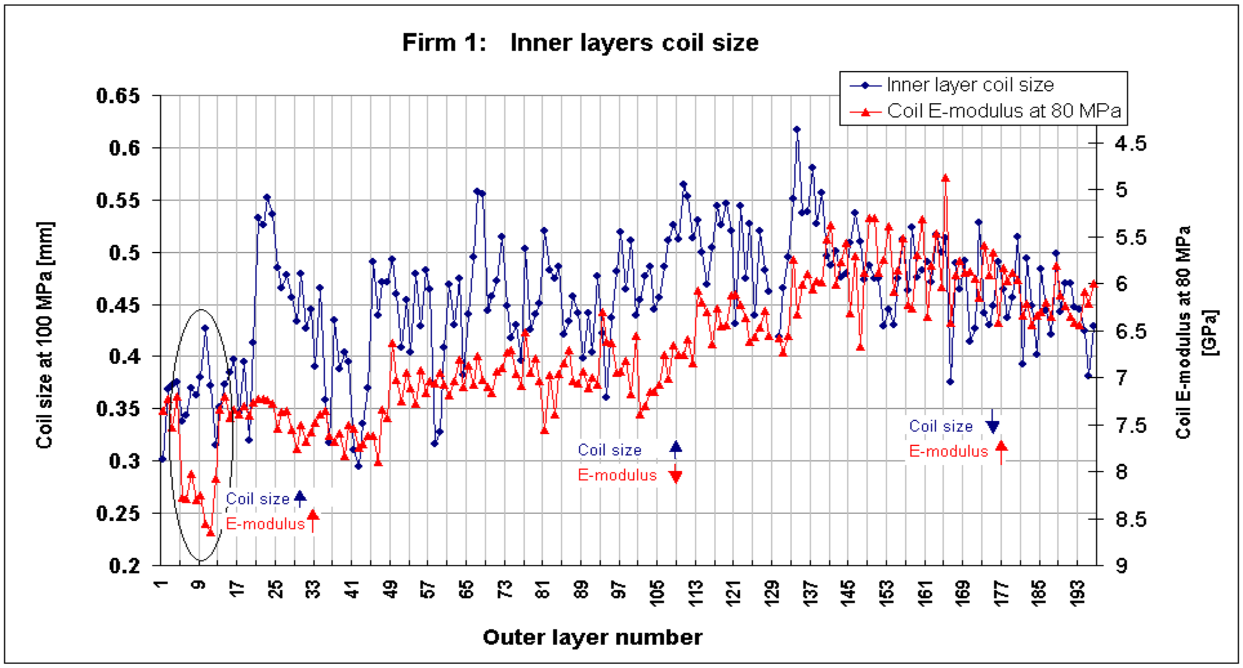

Fig.3 Firm 1. Influence of the tolerances of "soft" and "hard" coil components on the coil size and E-modulus trends.

The analysis on coil sizes at JEUMONT is carried out by the company itself; according to them, the biggest coil size variation is linked to the change of the delivery batch of the copper wedges. Independent investigations were done by B. Bellesia at CERN to check if the tolerances on copper wedges could explain the observed coil size variation. The results have shown that it is not a case (see figures 4 and 5).

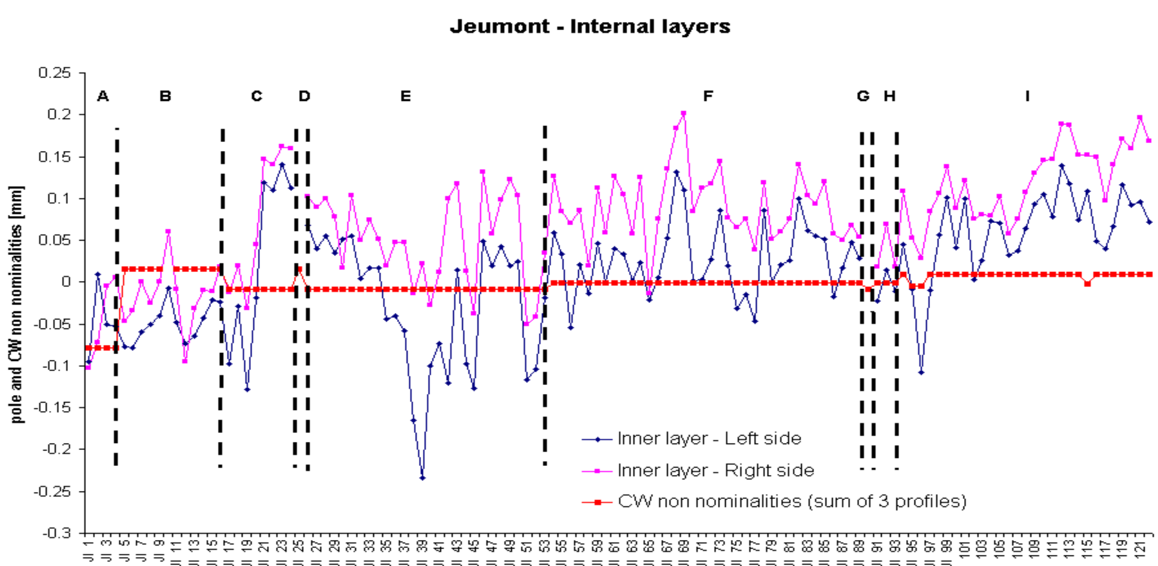

Fig. 4 Firm 1. Inner layers coil size and the copper wedges mid-thickness tolerances (by B. Belessia MAS/MA)

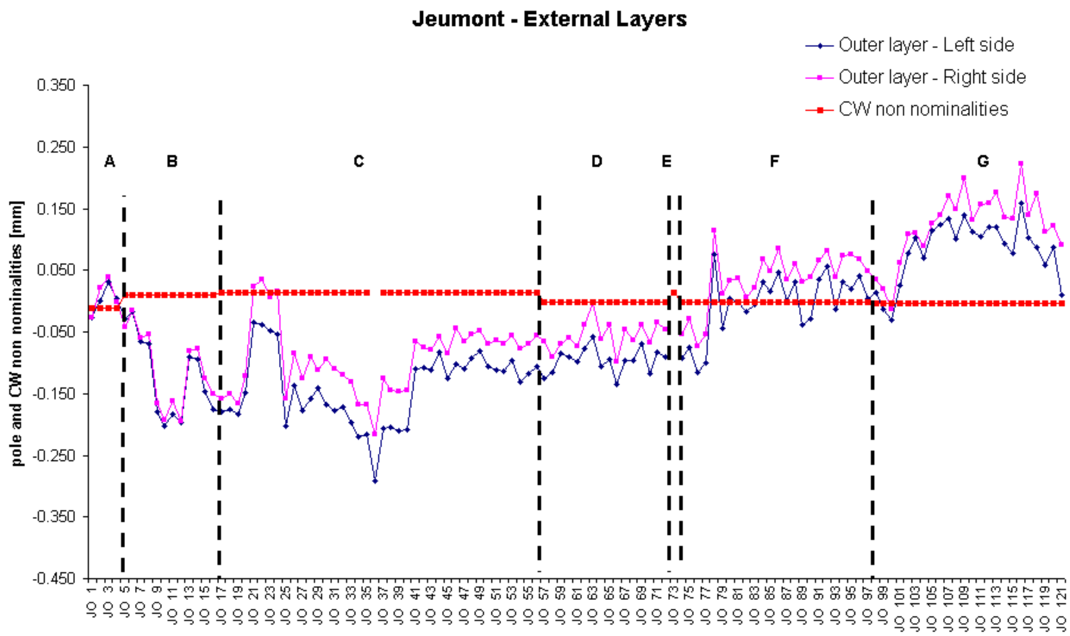

Fig. 5 Firm 1. Outer layers coil size and the copper wedges mid-thickness tolerances (by B. Bellesia MAS/MA)

Firm 2. Only a few more layers have been measured in last 3 months. The IMMG press was not working from December last year till mid of March this year, then it was repaired, but no new measurements on the poles are made up to now. In fact, for pre-series magnets not all the layers (see fig. 6 and 7) were measured at firm 2 and they are suspended at the moment for the coils of series (these measurements are not covered by contract). The discussions between CERN and firms about a new procedure for these measurements for the magnets of series are under way.

The variation in the coil size is smaller by almost a factor of two compared to the coils that are made by firm 1. However, trends were observed in the coils size on both inner and outer layers, and as a corrective action, starting from the inner layer № 75 (fig. 6), the coils were cured with an extra shim of 0.1 mm in the curing mould. Later, similar action was taken also for the outer layers coils, starting from the outer layer № 98 (fig. 7).

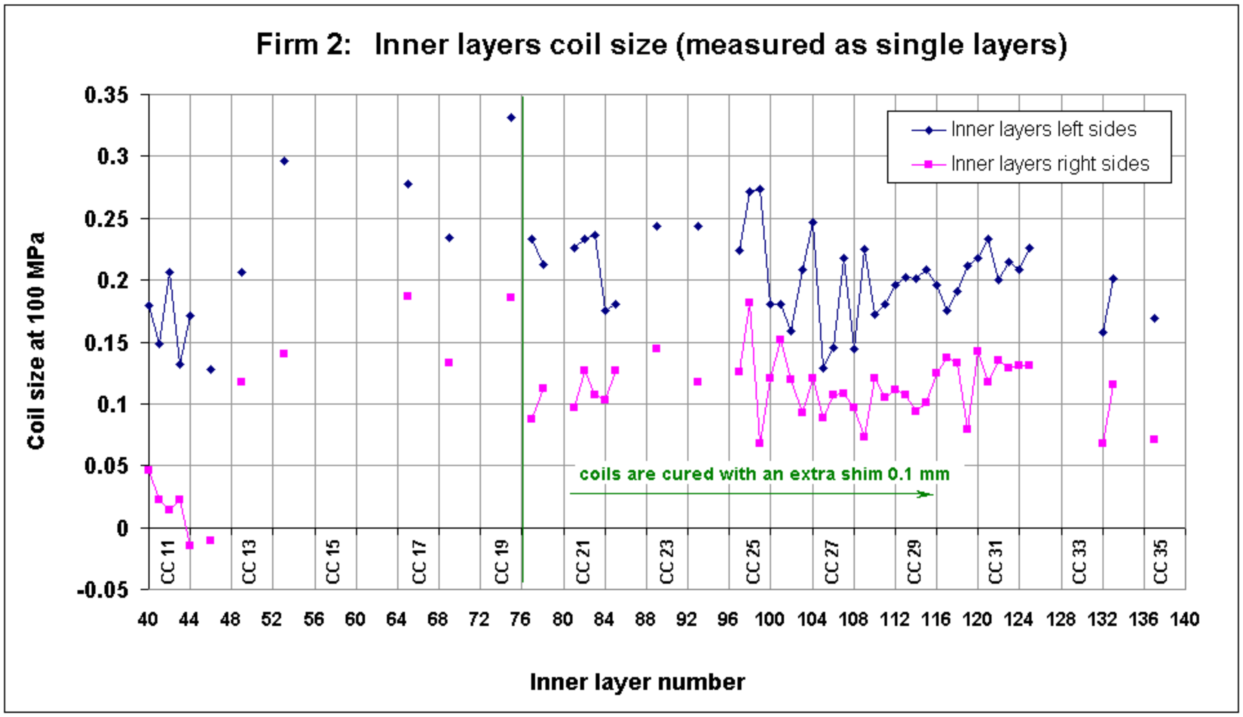

Fig.6 Firm 2. Average coil size in the straight part of the inner layers

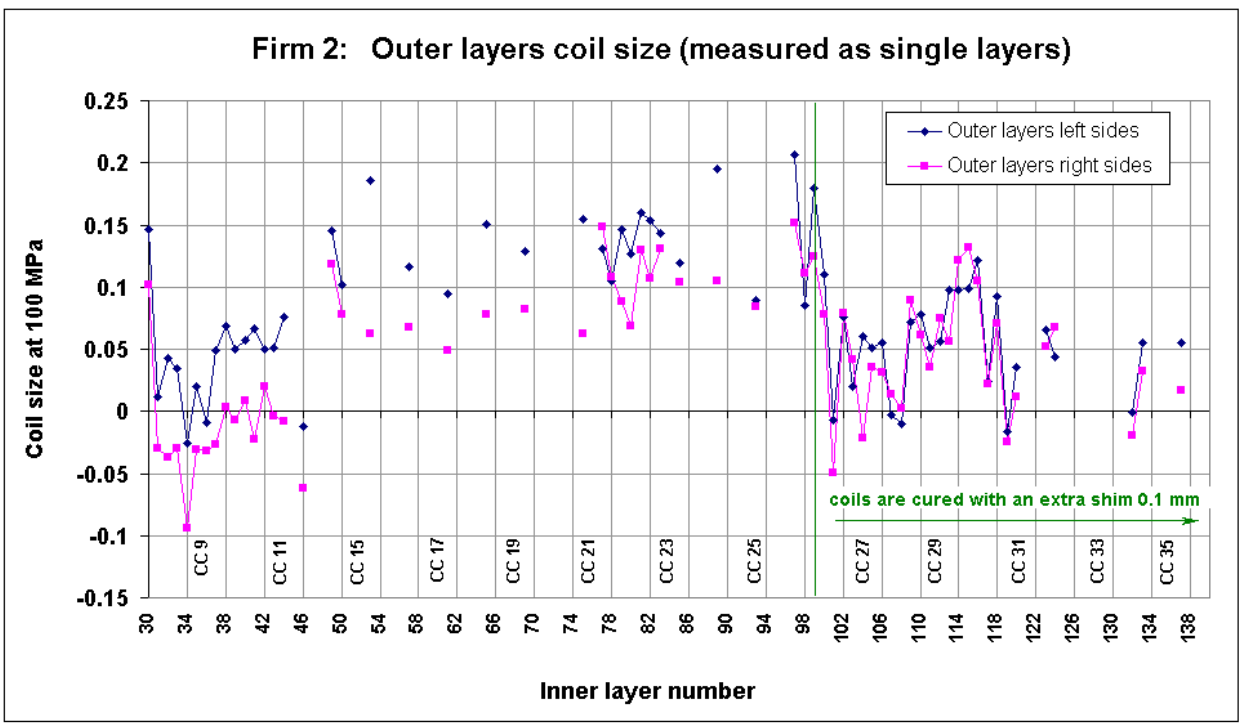

Fig.7 Firm 2. Average coil size in the straight part of the outer layers.

Firm 3. All the coils for the magnets of the pre-series (120 inner and 120 outer layers) were measured with the old NOELL press. So far, among the three contractors, firm 3 is producing the coils with the smallest variation in the average coil size (fig. 8 and 9).

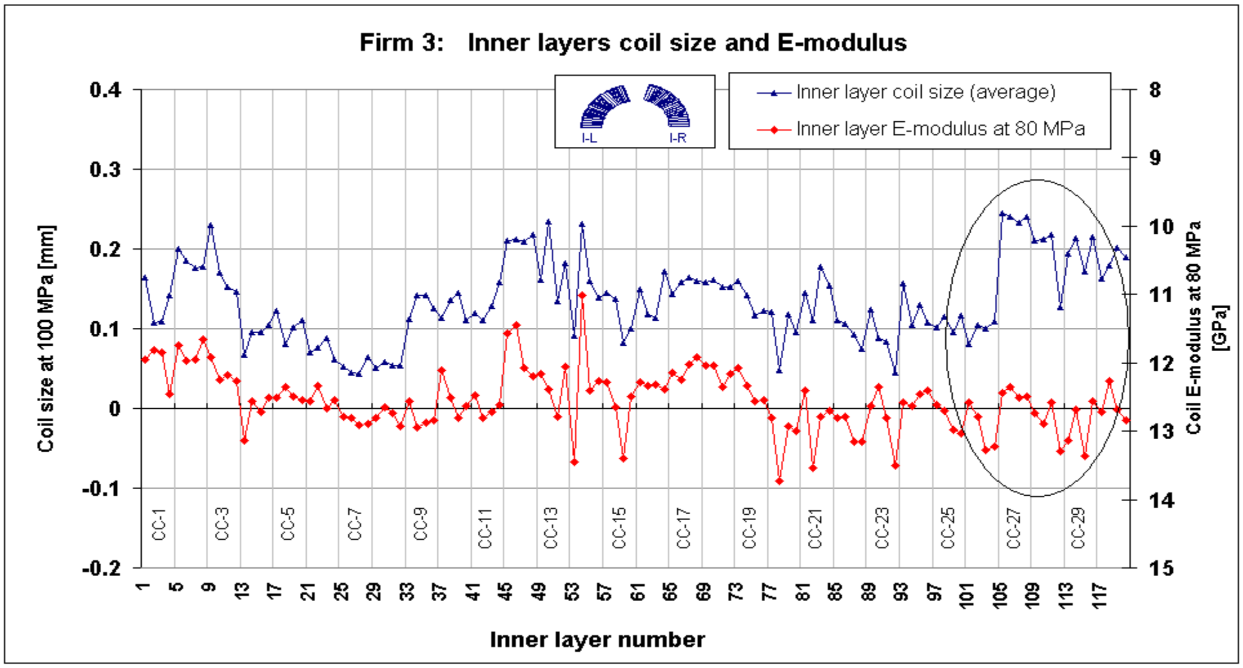

Fig.8 Firm 3. Average coil size in the straight part of the inner layers.

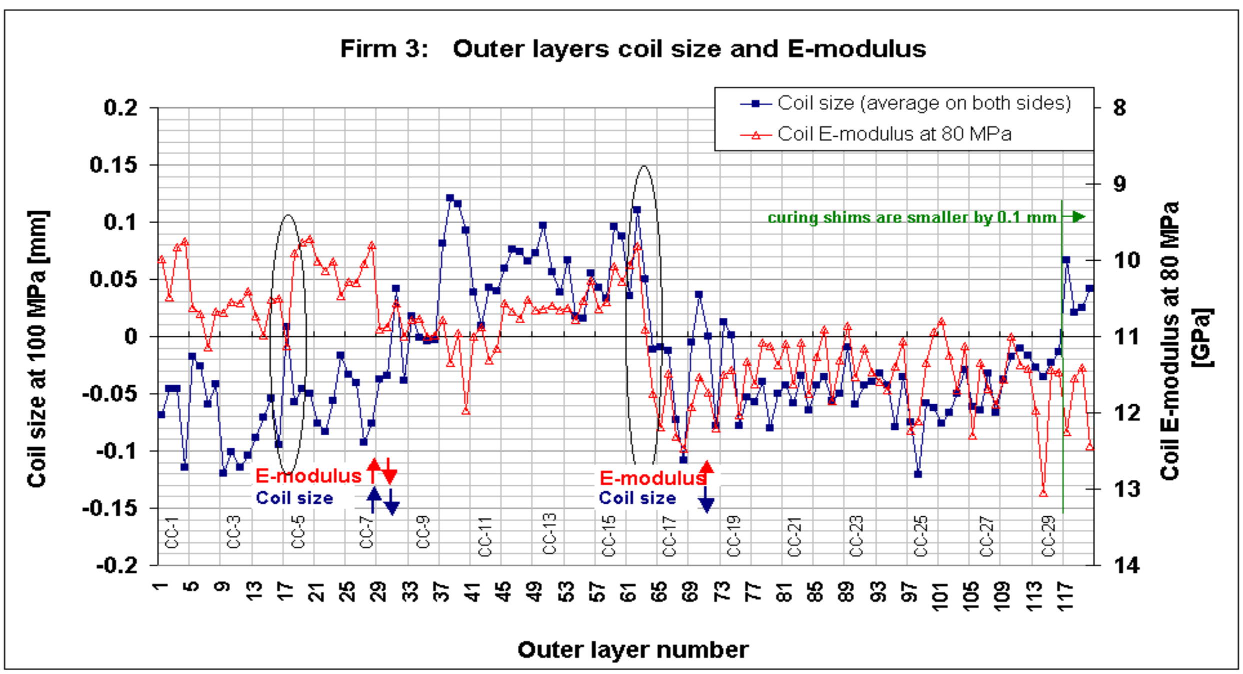

Fig.9 Firm 3. Average coil size in the straight part of the outer layers.

However, the coil size of the outer layers dropped by ~ 0.1 mm starting from the layer 65 (fig. 9) and as a corrective action, starting from the inner layer 118, the coils were cured with the curing shim smaller by 0.1 mm. This way, the coil size was partially recovered. In figures 7 and 8 together with the coil size, the E-modulus is plotted in order to show, that the similarly to the firms 1 and 2 in the coil size variation is mostly due to the tolerances on the cable insulation thickness (see paragraph 1.1.1).
For the magnets of series, a new procedure with a limited number of points will be applied for measuring coil sizes.

1.2 Size tolerances of the coil cross-section along the coil

The size of the coil cross-section of single layers or assembled poles is typically measured in 14-20 longitudinal positions along the coil. The "systematic" longitudinal coil profile, which is calculated as an average longitudinal coil profile for the batches of 30-50 coils, shows that despite the rather big variation of the coil size during mass production (trends), the longitudinal shape of coils made with the same tooling is rather stable. This "systematic" longitudinal coil profile is unique for each manufacturer and comes from the tooling tolerances (winding mandrels, curing press and curing moulds). In the first report it was shown that the coil mandrels and curing press have minor influence and the coils are carrying a"signature" of the curing mould. It is known, that the biggest impact on the magnet filed quality comes from the inner layer coil geometry imperfection. In figure 10, we could see that the coil waviness is well seen on the b5 multipole systematic.

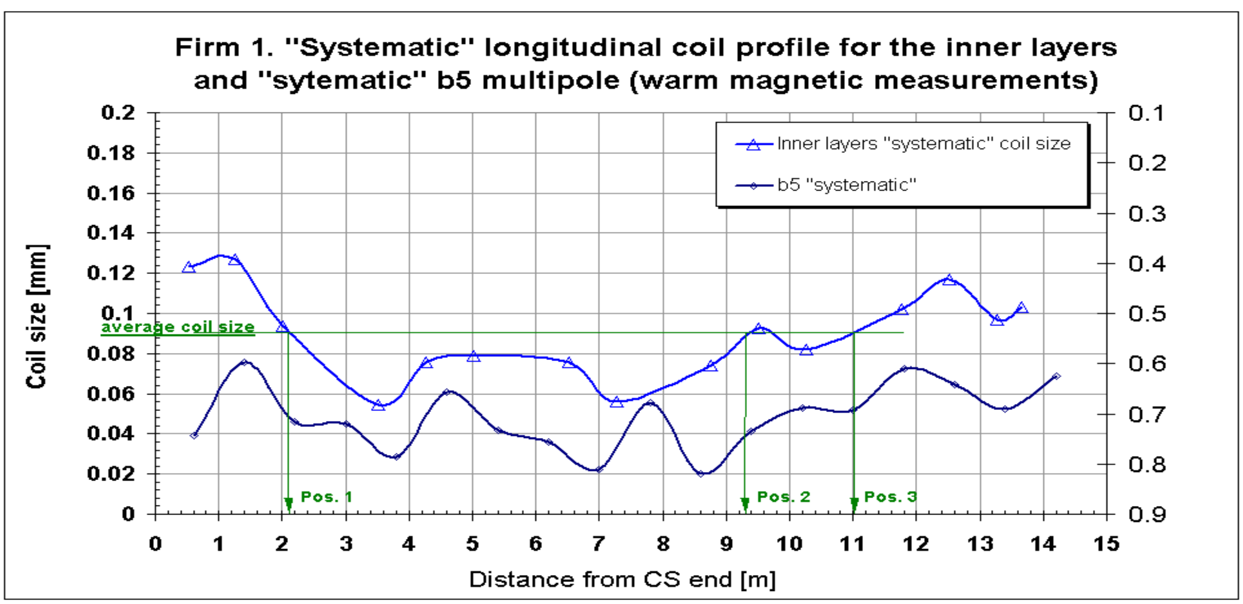

Fig.10 Firm 1. "Systematic" longitudinal coil profile for the inner layer and systematic on b5 multipole. In case of reduced number of measurements along the coil, we proposeto use the Pos. 1 to Pos.3 for the minimum impact on coil size trends statistics.

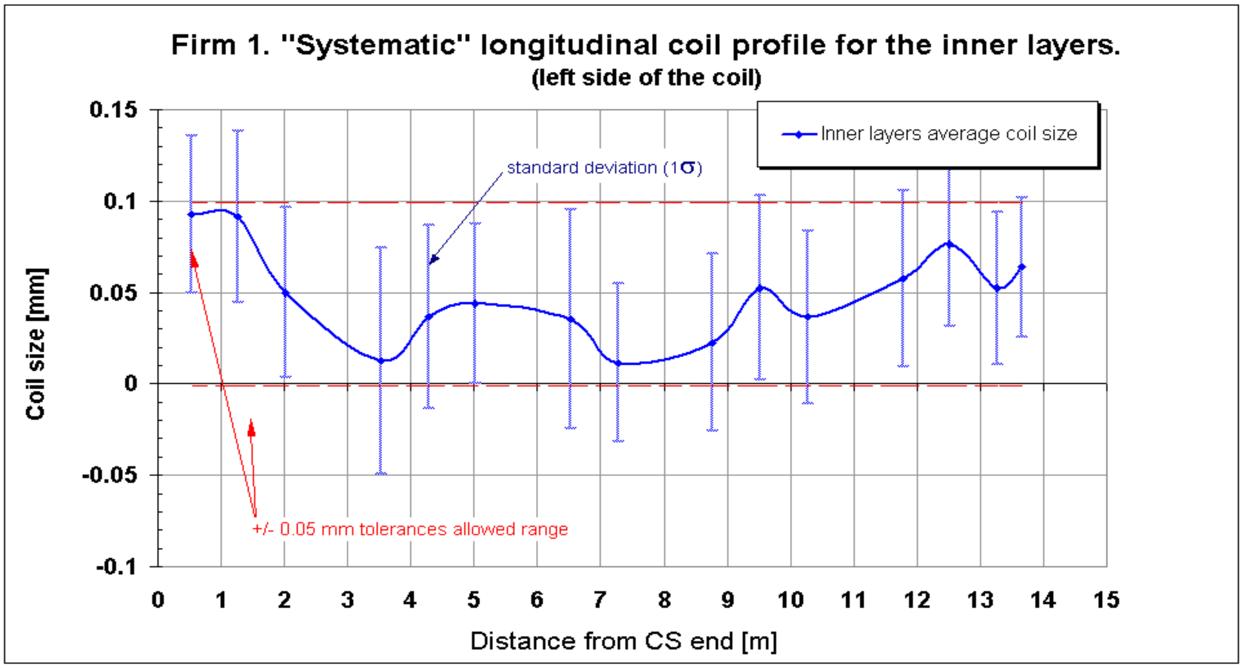

Fig.11 Firm 1. “Systematic” longitudinal coil profile for the inner layers left side (Curing mould 1).

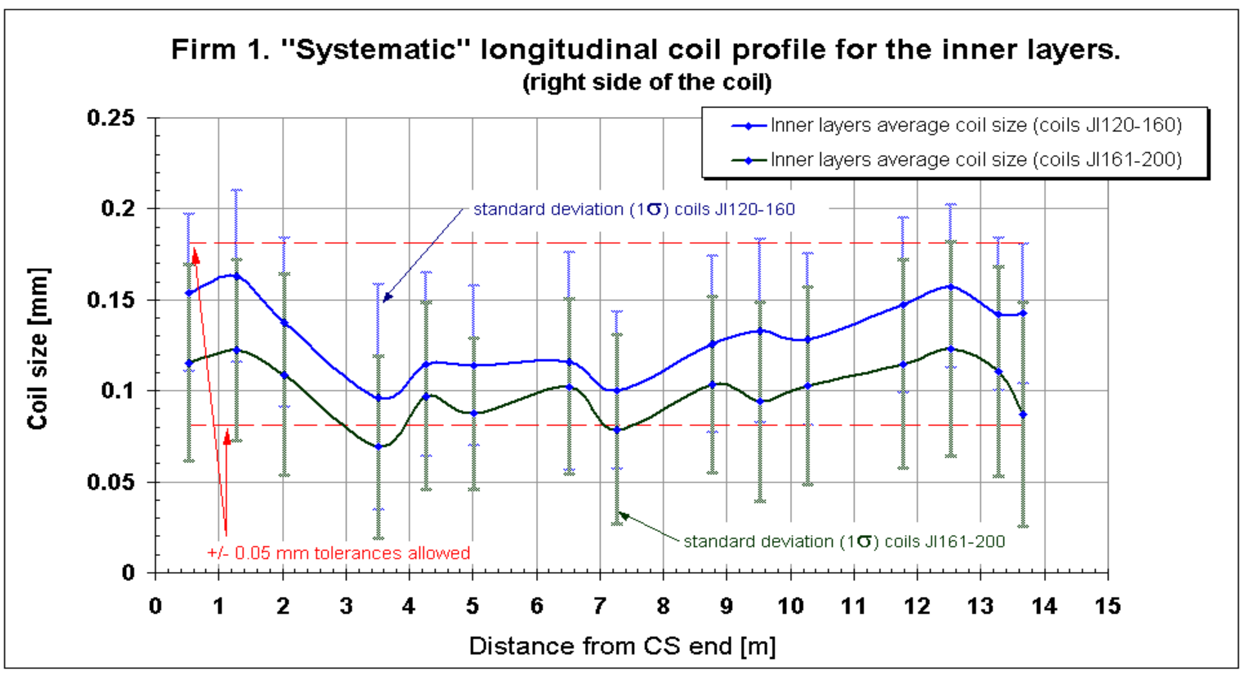

Fig. 12 Firm 1. “Systematic” longitudinal coil profile for the inner layers right side (Curing mould 1).

The “signature” of the tooling is different on the left and right hand sides of the coils as well as on both layers.

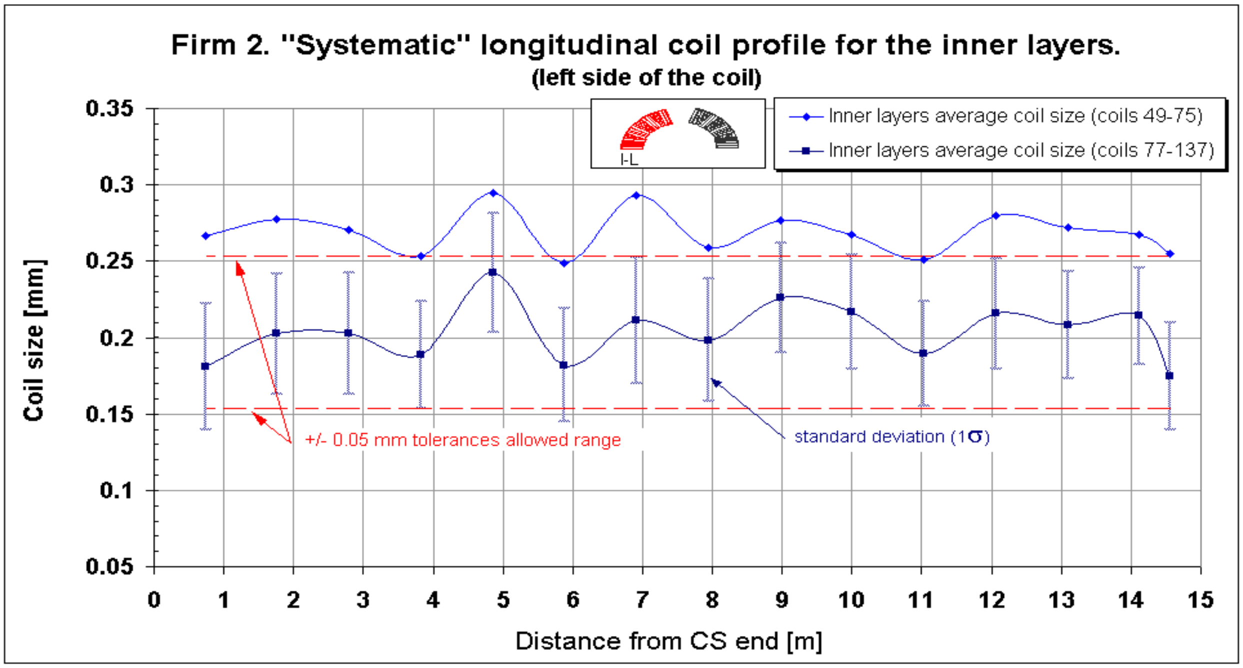

Fig. 13 Firm 2. “Systematic” longitudinal coil profile for the inner layers left side (Curing mould 1).

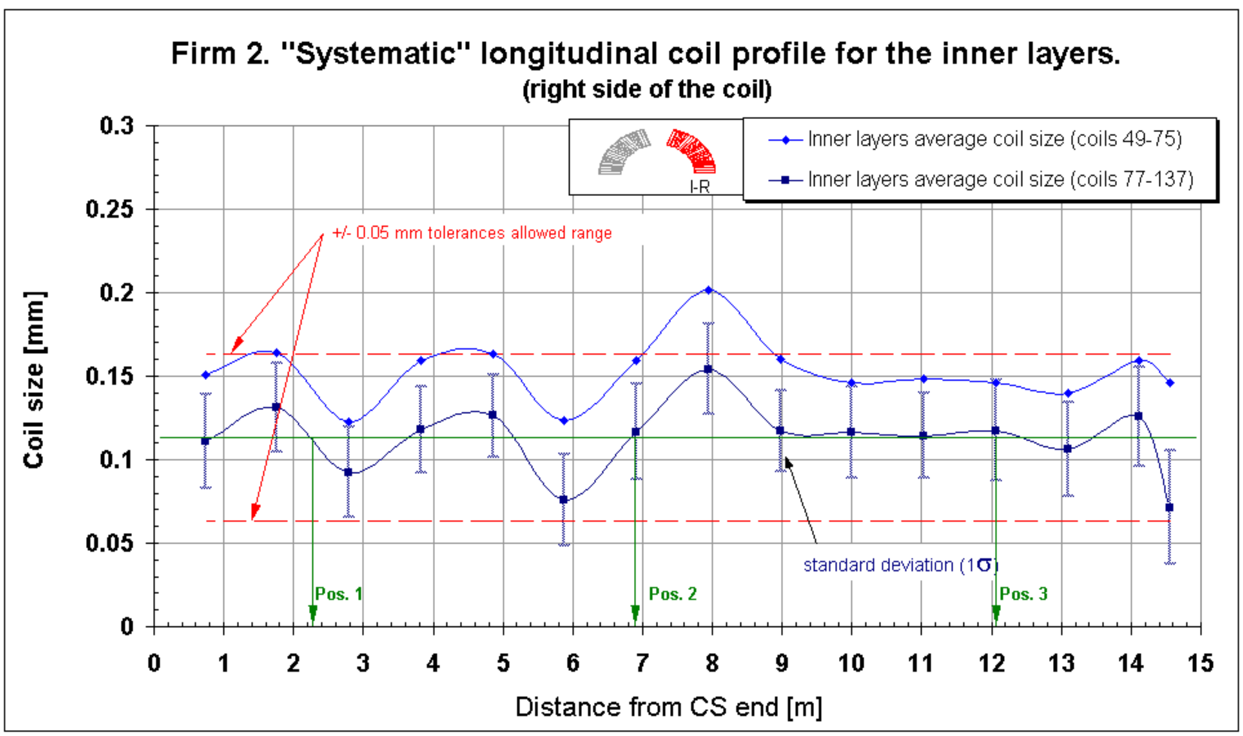

Fig. 14 Firm 2. “Systematic” longitudinal coil profile for the inner layers right side (Curing mould 1).

As it can be seen from the figures 12-14, among the three contractors, the firm 2 is producing the coils with the smoothest coil size tolerances (smallest sigma). The last 40 coils produced in firm 1 have the same waviness as the coils of pre-series (see fig. 12)

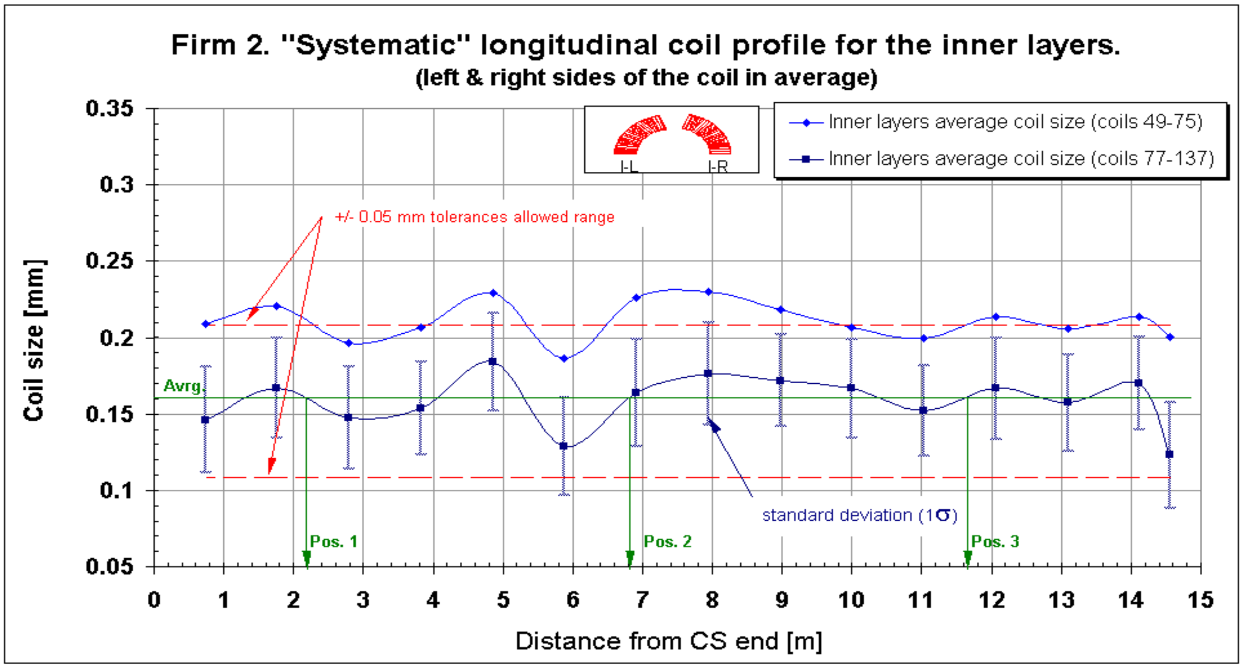

Fig. 15 Firm 2. "Systematic" longitudinal coil profile for the inner layers (Curing mould 1). In case of reduced number of measurements along the coil, we proposing to use the Pos. 1 to Pos.3 for the minimum impact on coil size trends statistics.

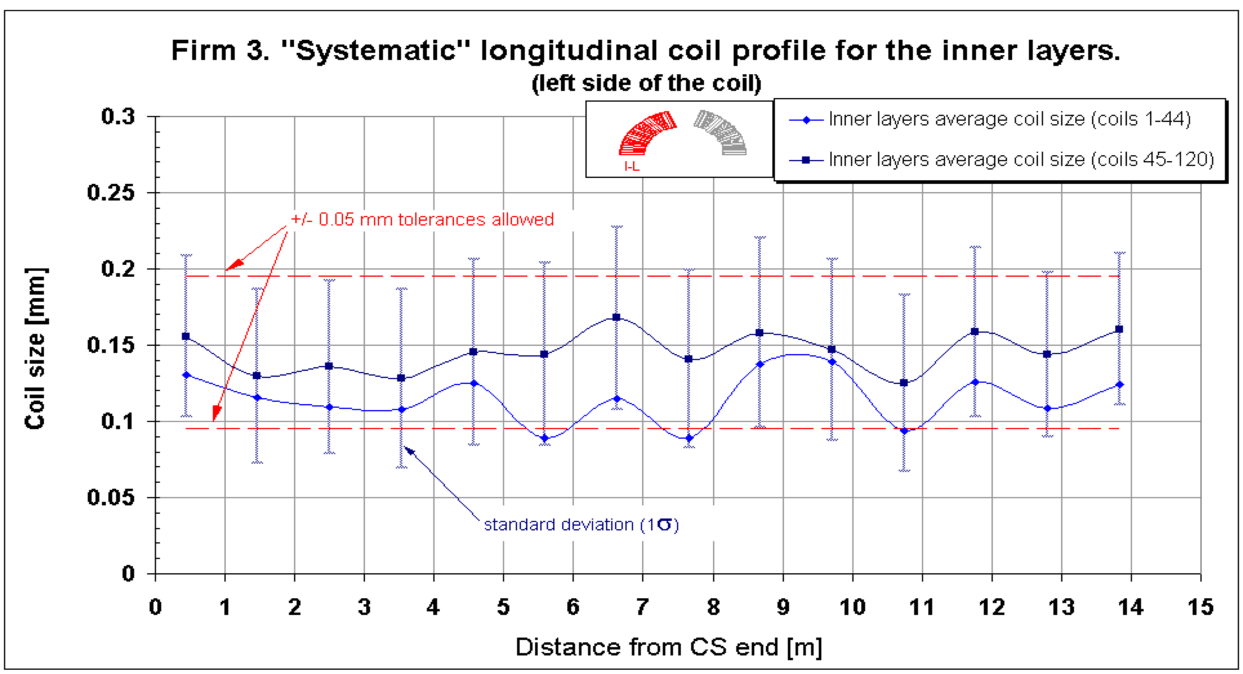

Fig. 16 Firm 3. "Systematic" longitudinal coil profile for the inner layers left side.

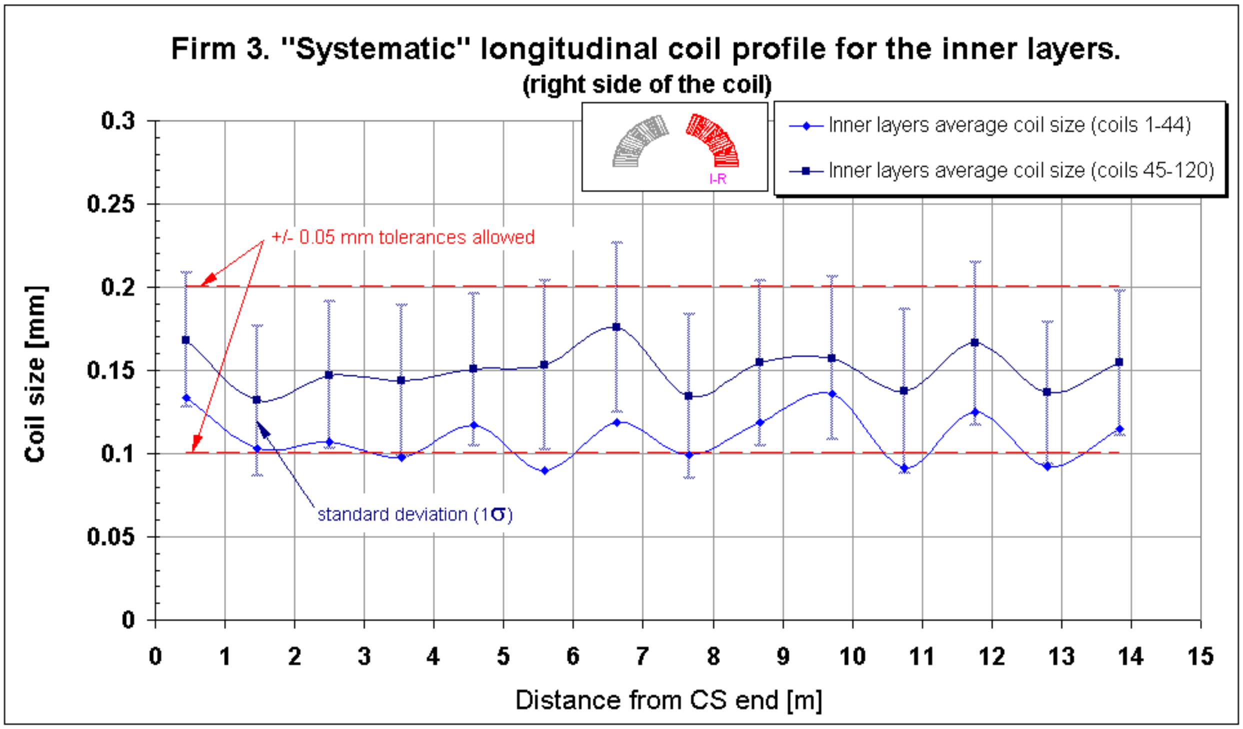

Fig. 17 Firm 3. “Systematic” longitudinal coil profile for the inner layers right side.

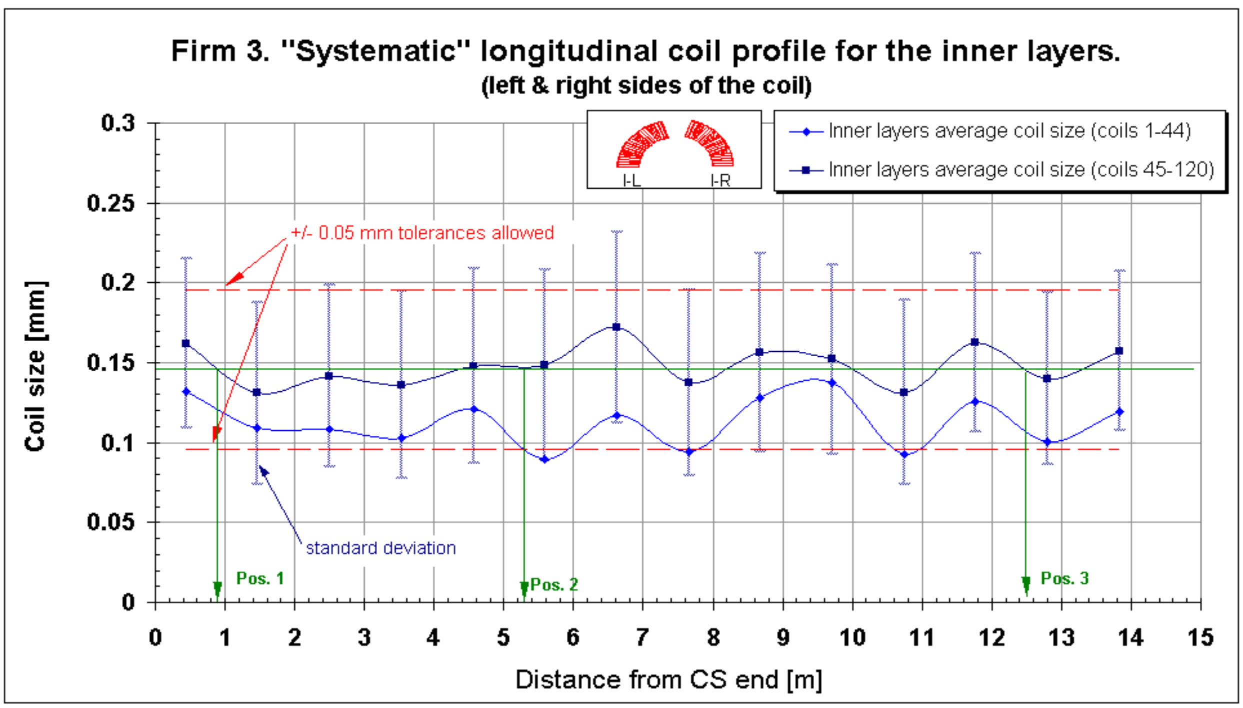

Fig. 18 Firm 3. Systematic” longitudinal coil profile for the inner layers. In case of reduced number of measurements along the coil, we proposing to use the Pos. 1 to Pos.3 for the minimum impact on coil size trends statistics.

1.3 Left/ right and up/down coil asymmetries in the collared coils

The left/right asymmetries in coil sizes were analyzed in the first report. It was shown that their impact on field quality, especially on the *a3* multipole is rather small; therefore we will not present this data.
The difference in the average coil sizes between two poles assembled into one aperture of the magnet produces an up/down asymmetry and results in a shift of the magnet midplane. In magnetic measurements this shift is seen as a non-zero value of the skew quadrupole (*a2*). Due to the fact, that the allowed range for *a2* multipole is smaller then for *a3*, the up/down coil asymmetry in the magnets is more crucial compared to the one of the left/right sides. We should say that for this analysis, the coil size data taken from the measurements on the assembled poles is more accurate compared to the data from the measurements on the single layers.
At the moment only firm 1 is measuring coil sizes in pole configuration. There is no new data on such measurements for the firm 2 and firm 3. Therefore only the data concerning the firm 1 is presented in this chapter.

Firm 1. Considering the data on coils sizes, a rather big up/down asymmetry of up to 0.15 mm is expected. This asymmetry arises from two sources: the big random coil size variation, shown in fig. 2 and from the fact, that for the magnets of pre-series the poles which are going into the magnet assembly were not sorted for an optimum coil geometry. In the first report, we recommended sorting of poles and at firm 1 this procedure is now implemented into the magnet production process. Nevertheless, due to the rather big coil size variation and restrictions coming from constrains on the mix of cables, often the up/down asymmetry still is rather big in firm 1 magnets. In figures 19 and 20 the expected up/down mid-plane shift from coil size measurements and the computed value of *a2* multipole from this asymmetry are shown together with the measured values of skew quadrupole. As we can see there is a rather good agreement between the mechanical and the magnetic measurements. On this graphs, for clarity only the coil size asymmetry in inner layers is shown as the inner layers contributes almost 70% of the total value of *a2* (according to the sensitivity tables given by E. Todesco), while for the computed *a2* the data from both coil layers was used.

Firm 2. No new measurements on the poles since last year.

Firm 3. No new measurements on the poles since last year.

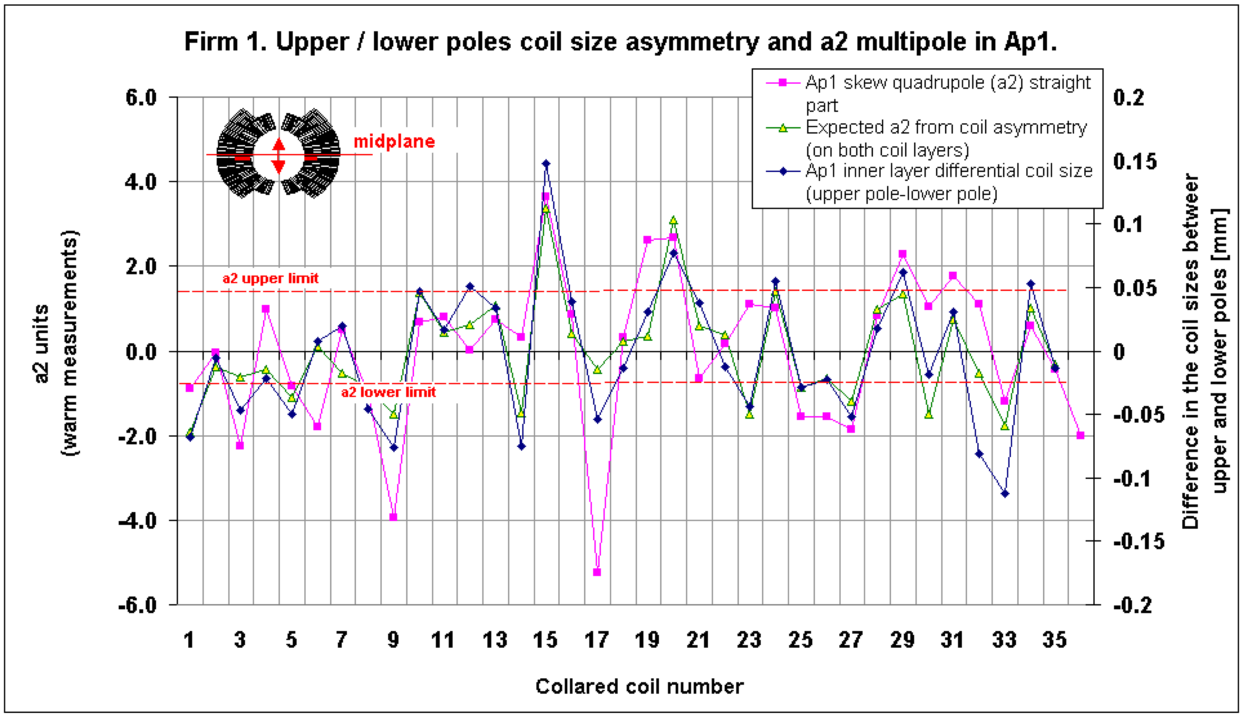

Fig. 19 Firm 1. Expected up/down coil size asymmetry in the collared coil (Aperture 1), computed and measured a2 multipole (warm magnetic measurements).

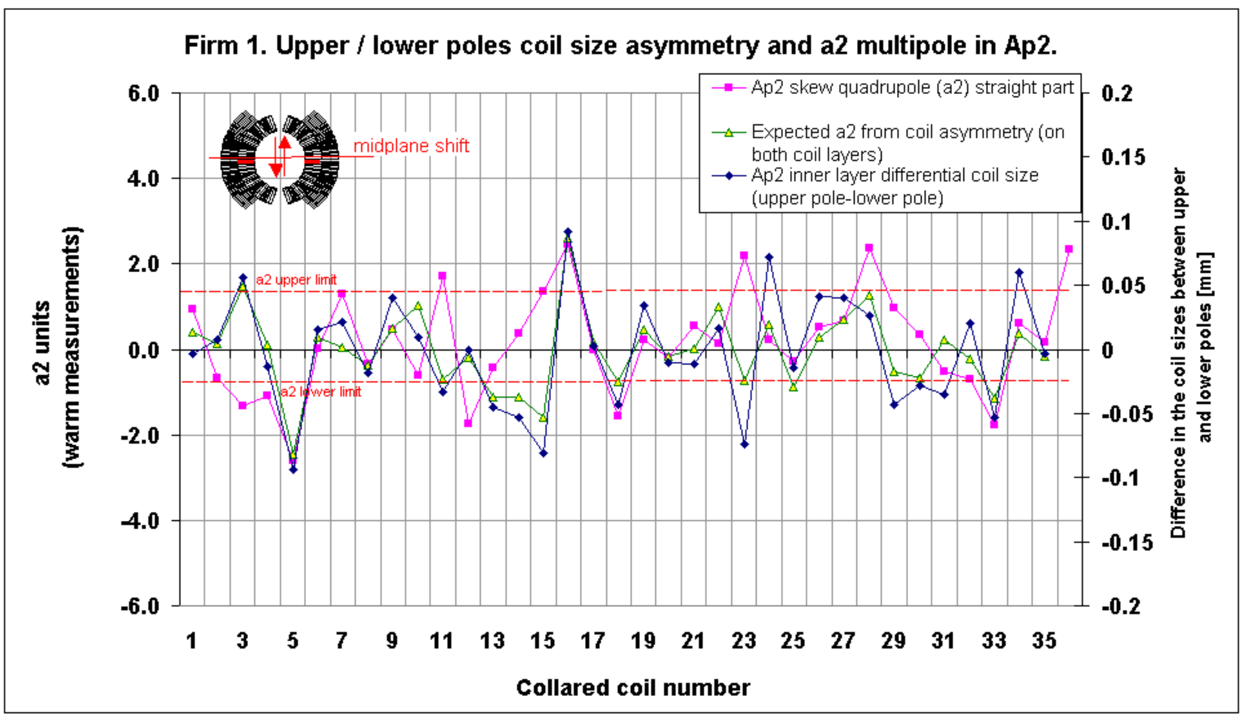

Fig. 20 Firm 1. Expected up/down coil size asymmetry in the collared coil (Aperture 2), computed and measured a2 multipole (warm magnetic measurements).

2. Measurement data of the collared coil dimensions

2.1 Trend graphs (straight part of the coil)

The measured dimensions of the collared coils after collaring are functions of the coil pre-stress. Due to coil pre-stress the collars expand. The collared coils dimensions (later CC dimensions) are measured at 10 points (see Fig. 21) in 50-80 positions in the longitudinal direction. In all figures, the CC dimensions are given not in absolute values, but relative to their nominal value. In fact, the collars itself have production tolerances, which are not taken into account here (the analysis of the influence of collars dimensions and other components tolerances on the magnet field quality is under way in the MMS/MA section and will be given in a separate paper).

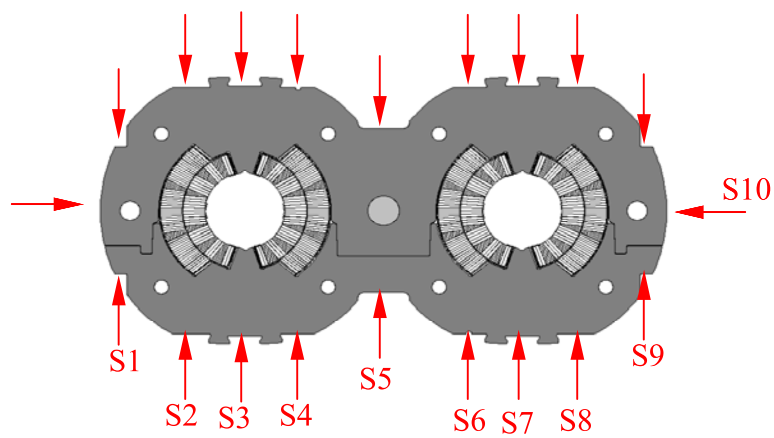

Fig. 21 Measurement points of the collared coil dimensions

Firm 1. For the magnets of pre-series, the CC dimensions were measured in 40 pre-defined positions along the coil, where 25 positions are taken in the straight part of the coil (each 0.5 m). Should be noticed that up to now, all the measurements are taken manually, this could explain rather pour correlation of this measurements data with the magnetic measurements data. Starting from the collaring coil 27, the new measuring procedure was implemented. This procedure follows the Spec for series production and has reduced number of measured points and sections: the measurements are taken for the points 3, 5, 7 and 10 and at three longitudinal positions in the coil straight part. Therefore the data from the last measured collared coil become almost useless for our analysis. This is why our analysis on CC dimensions is made only for the magnets of pre-series. The new measuring system is actually under construction. It will be equipped with electronic sensors, which should improve the quality of this measurement. It was agreed to extend this measurements up to 6 measuring points (the measurements will be taken on the points 2, 4, 6, 8 and 10). The average on CC dimensions for measuring points S2 & S4 (aperture 1) and S6 & S8 (aperture 2) are shown in figures 22 and 23 together with the estimated variation of the coil pre-stress from the coil size data the in collared coils.

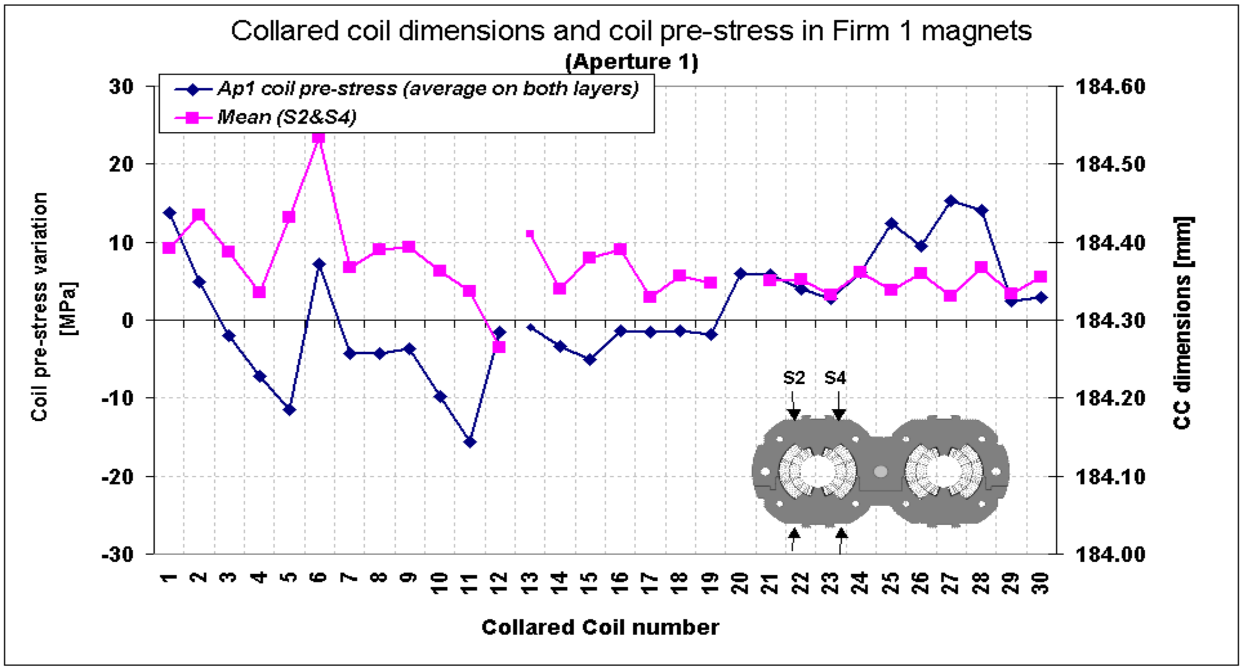

Fig. 22 Firm 1. Collared coil dimensions and estimated from the coil size measurements data coil pre-stress variation in the collared coils (aperture 1).

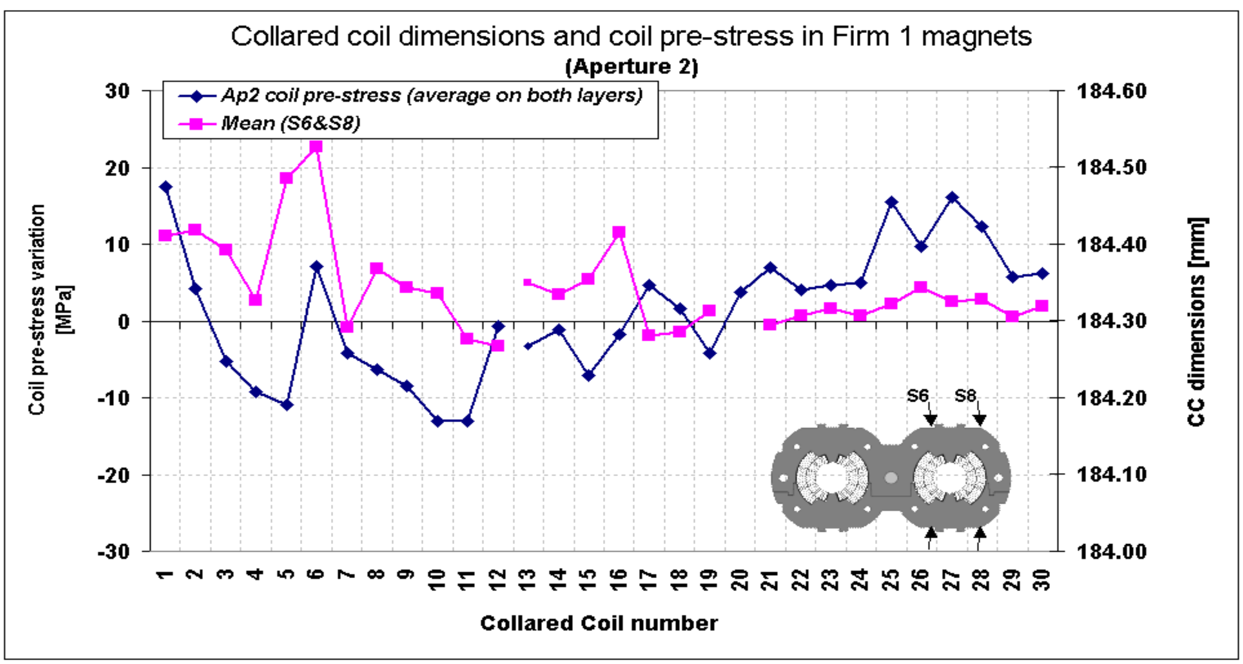

Fig. 23 Firm 1. Collared coil dimensions and estimated from the coil size measurements data coil pre-stress variation in the collared coils (aperture 2).

Firm 2. The CC dimensions are measured in 78 pre-defined positions along the coil, where 54 positions are taken in the straight part of the coil (each 0.25 m). For the first 7 collared coils the measurements were done manually, whereas starting from the CC-8, the automated measuring machine is in use. The average on CC dimensions for measuring points S2 & S4 (aperture 1) and S6 & S8 (aperture 2) are shown in figure 24 together with the estimated the variation of the coil pre-stress from the coil size data in collared coils.

The data on the coils size is taken from the measurements done on assembled poles, which are available only from the magnet 8 till magnet 19. The thickness of the polar shims is taken into account.

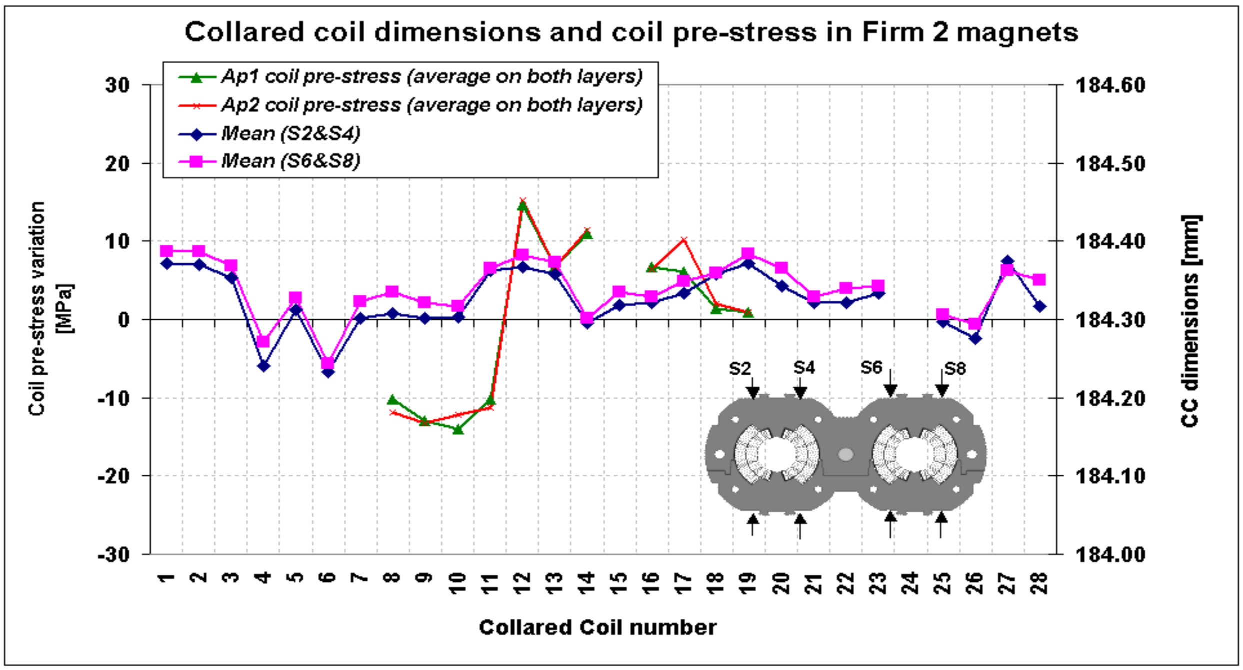

Fig. 24 Firm 2. Collared coil dimensions and estimated from the coil size measurements data coil pre-stress variation in the collared coils.

Firm 3. The CC dimensions are measured in 44 pre-defined positions along the coil, where 28 positions are taken in the straight part of the coil (each 0.5 m). All collared coils are measured with the automated measuring machine. For post-processing and transfer of data to CERN the firm is using the Collared Coil Database software package, which was developed by CERN. The average on CC dimensions for measuring points S2 & S4 (aperture 1) and S6 & S8 (aperture 2) are shown in figures 25 and 26 together with the estimated the variation of the coil pre-stress from the coil size data in collared coils.

The data on the coils size is taken from the measurements, which are done on individual layers, as there is no data available yet on assembled poles. The thickness of the polar shims is taken into account.

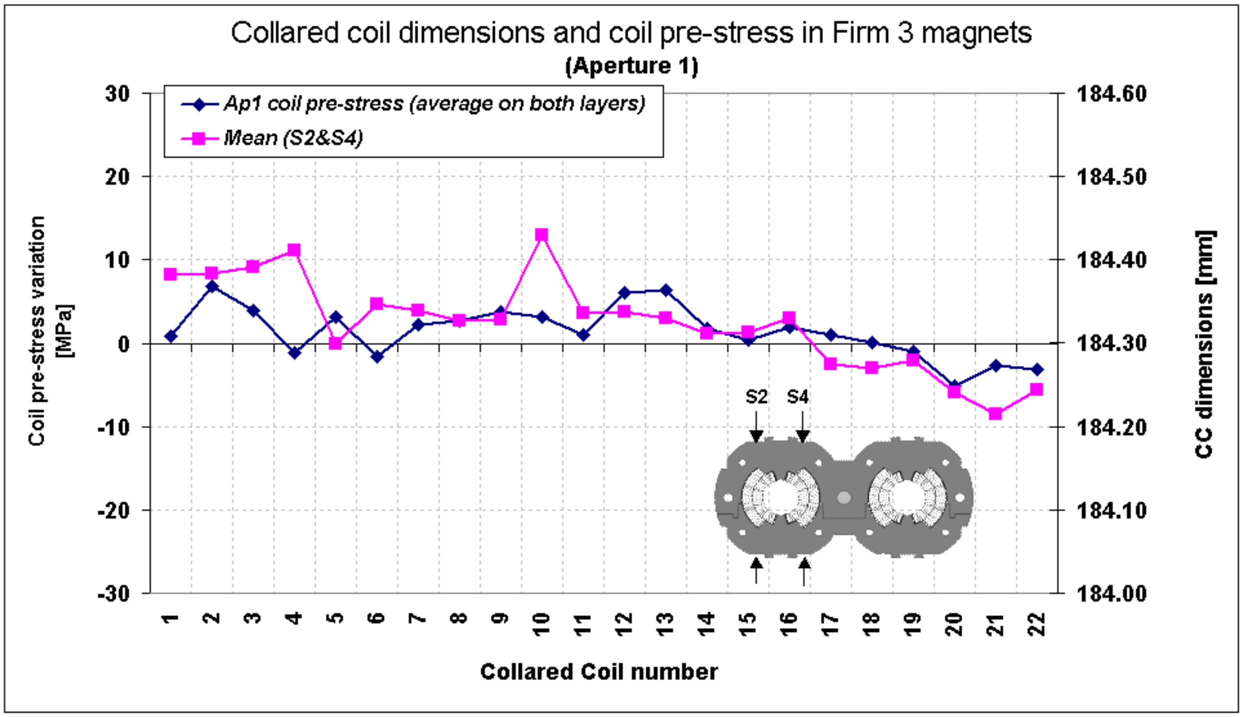

Fig. 25 Firm 3. Collared coil dimensions and estimated from the coil size measurements data coil pre-stress variation in the collared coils (aperture 1).

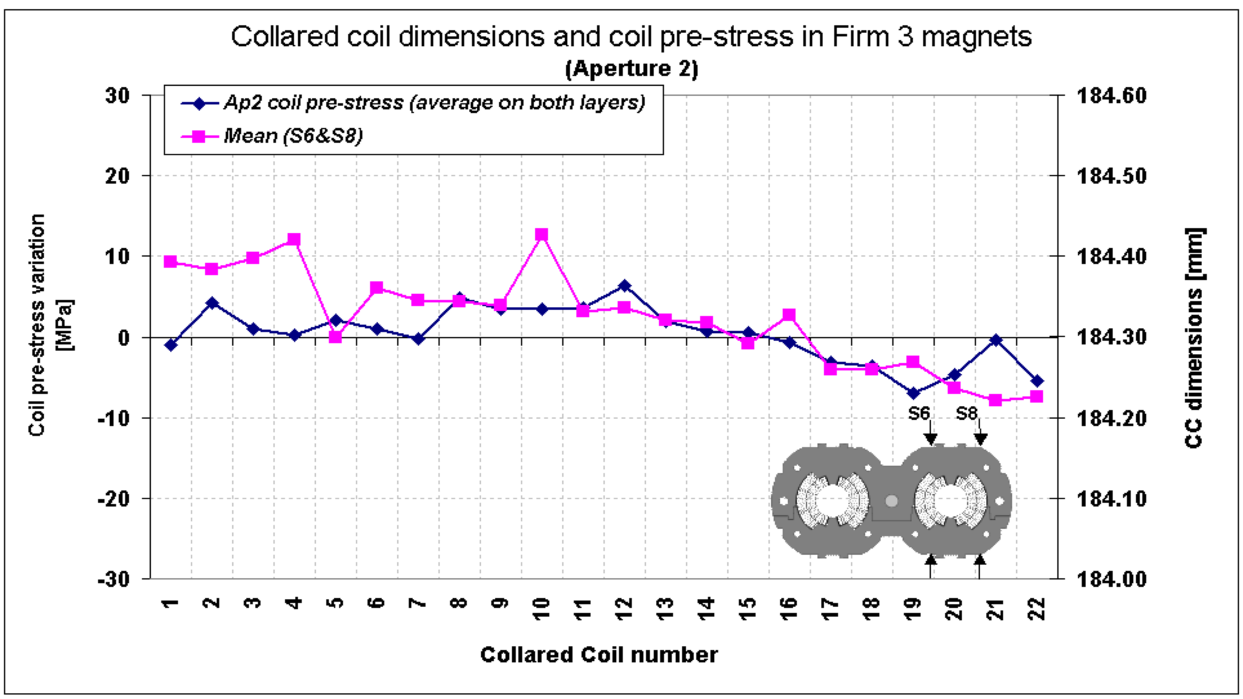

Fig. 26 Firm 3. Collared coil dimensions and estimated from the coil size measurements data coil pre-stress variation in the collared coils (aperture 2).

3. Acknowledgments

We wish to acknowledge B. Bellesia, P. Fessia, F. Savary, G. De Rijk, L. Rossi, W. Scandale, E.Todesco, D. Tommasini, C.Vollinger and E.Wildner for comments, discussions and valuable help.