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Title: Current Dependence of Harmonics in the 8 cm Aperture Dipoles for RHIC

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Current Dependence of Harmonics in the 8 cm Aperture Dipoles for RHIC

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1. Introduction

Good measurements of both the "Up Ramp" and the "Down Ramp" harmonics as a function of current are available for the central 1 m region in 53 full length RHIC dipoles of 8 cm aperture (DRG and DR8 types). The average of the "Up Ramp" and the "Down Ramp" measurements is a good indication of the "true" harmonics in the magnet, free from persistent current effects. In a given magnet, the harmonics averaged over the "Up" and the "Down" ramps should be independent of current at low fields (below ~2 T). At higher fields, the harmonics are expected to be current dependent due to saturation of the iron yoke as well as coil deformations due to Lorentz forces.

It is interesting to analyze the vast amount of data available in the RHIC dipoles to obtain a feel for typical magnet to magnet variation in the saturation behavior of various harmonics. It is also interesting to compare the saturation behavior averaged over all the magnets with the current dependence calculated using finite element codes, such as OPERA-2d.

This note summarizes the saturation data in all the DRG/DR8 dipoles and compares the measurements with results of OPERA-2d calculations. For the purpose of this comparison, the data presented in this report are corrected for persistent current effects and may not apply to actual machine operation, particularly for the allowed terms at low fields.

2. Experimental Data

For the purpose of this study, only those magnets were selected in which clean harmonic data were available for both the "Up Ramp" and the "Down Ramp". This gave a pool of 53 magnets out of a total of 63 magnets that were cold tested. In most of these magnets, the harmonics were measured at 27 different currents in the range 1 kA to 6 kA. Four of these magnets had only 16 measurements in this current range (due to test time limitations). Data below 1 kA were ignored for this study.

The "true" harmonics, free from persistent current contributions, were obtained at each current in each magnet by averaging the "Up Ramp" and the "Down Ramp" data. For a similar construction and similar iron properties, it is expected that the variation of these "true" harmonics with current will be the same for all the magnets. However, the absolute values of the harmonics may be different from one magnet to the other due to small random geometric differences. In order to facilitate comparison of harmonics from different magnets, such "geometric" terms were subtracted out from the data. These "geometric" values were obtained by averaging the "true" values in the range of 1400 A to 1600 A (0.99 T to 1.13 T) where the iron saturation and Lorentz force effects can be neglected.

3. Finite Element Calculations

The magnetic design of the RHIC arc dipoles has been presented in earlier publications [1]. The cold mass in these dipoles is offset vertically in the cryostat, which gives skew harmonics at high fields [2]. Similarly, due to the sagitta of the cold mass, it could also be offset horizontally in the cryostat, depending upon the axial location. This gives unallowed normal terms at high fields. In order to incorporate both the top-bottom and the left-right asymmetries of the magnet, a full 360-degrees computational model, shown in Fig. 1, was created using the finite element code, OPERA-2d. In this model, the cold mass is offset in the cryostat by 9 cm vertically and 2.5 cm horizontally. The harmonics were computed at a radius of 25 mm by a Fourier analysis of the vector potential at a radius of 35 mm. The calculations were done for many different currents in the range from 1 kA to 6.6 kA.

Since the coil geometry is not exactly represented in the computational model, the allowed harmonics are not exactly zero in the calculated fields. The current dependence of harmonics was therefore obtained by subtracting out the geometric terms at low fields. This is similar to what was done with the magnetic measurements data, described in the previous section.

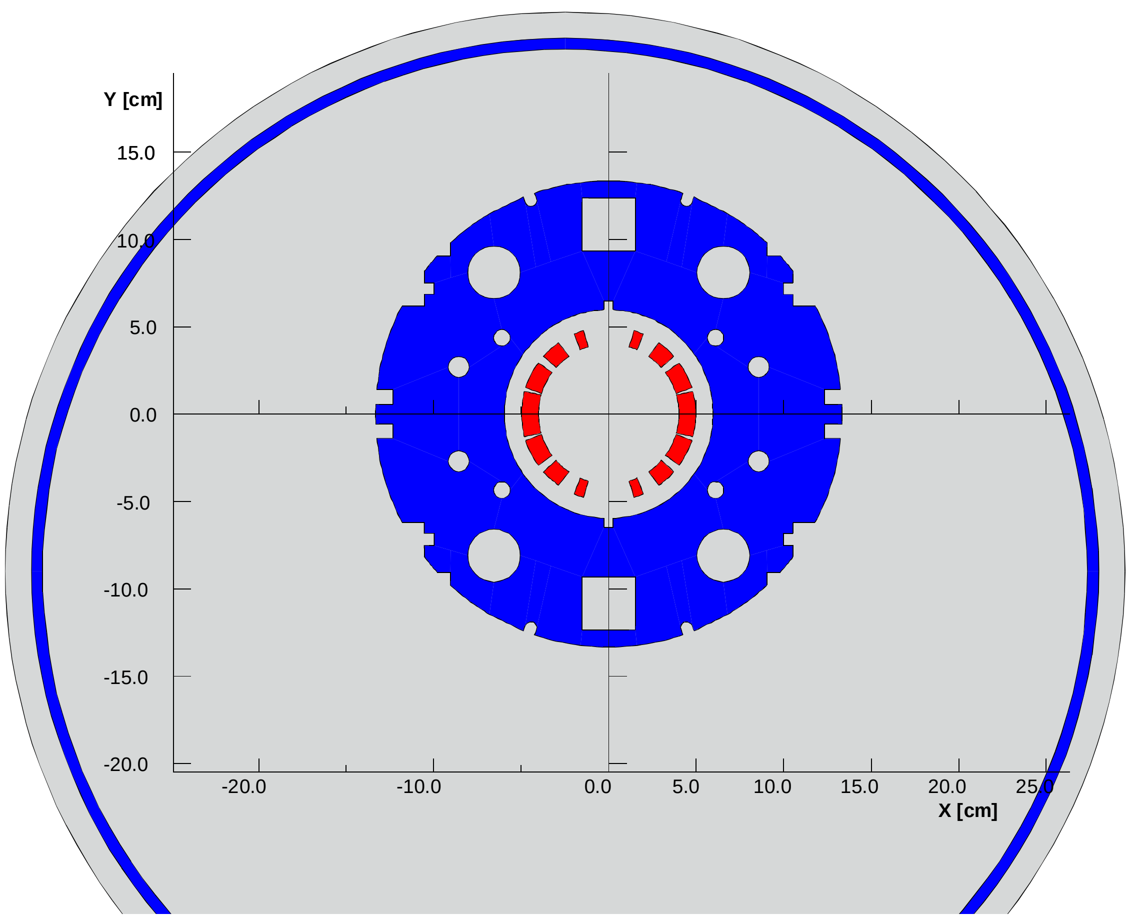


Fig. 2 OPERA-2d model used to calculate the saturation behavior. The cold mass is offset both vertically and horizontally in the cryostat. The bottom portion of the cryostat is not included in this figure.

4. Results

The mean value of transfer function, averaged over the "Up Ramp" and the "Down Ramp" data in the current range of 1400 A-1600 A in 53 magnets, is 0.7087 T/kA. The absolute value of transfer function calculated from the OPERA-2d model agrees with this value within 0.1%. This small difference is mainly due to the approximate description of the coil blocks in the model. The agreement could be improved by modeling individual turns and radially segmenting the coil to approximate the effect of keystoning. Although it could be done for the OPERA-2d model, it was not done as the model was already quite large, and this level of detail was not expected to change the saturation behavior of harmonics.

The change in transfer function with current is shown in Fig. 2 for all the 53 magnets (filled circles). At lower values of current, the standard deviation in the absolute values of the transfer function is ~0.03%. However, the magnet to magnet variation in the *change with current* is extremely small (less than 0.01% up to 3 kA, comparable to the measurement accuracy), making it impossible to see it on the plot in Fig. 3. As the iron begins to saturate, magnet to magnet variations become more apparent due to small differences in the yoke properties. However, even at 6 kA, the highest current routinely measured, the magnet to magnet variation in the change in transfer function has a total range of only 0.2% (from -6.8% to -7.0%), with a standard deviation of 0.05%. The standard deviation of the absolute values of the transfer function is ~0.06% at 6 kA. The calculated changes in transfer function are also shown in Fig. 2. The calculations agree reasonably well with the measurements.

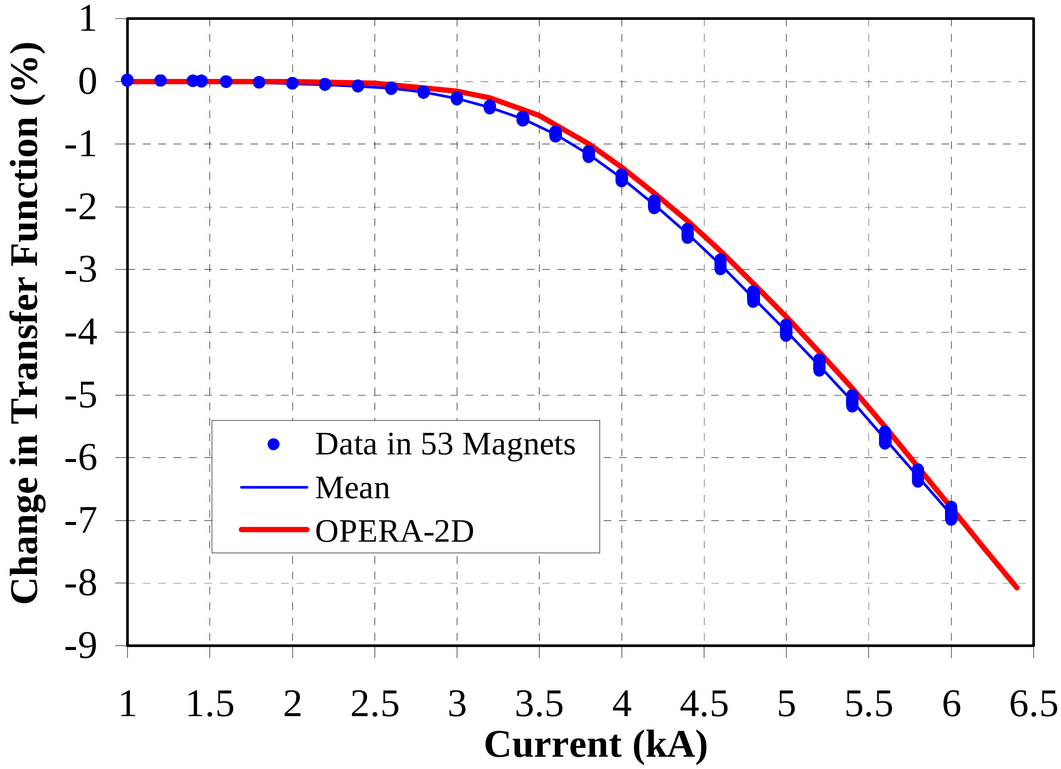


Fig. 2 Calculated and the measured current dependence of the transfer function.

The measured current dependence of various normal and skew harmonics, along with calculated values from OPERA-2d, is shown in Figs. 3 through 12 located at the end of this report. Since the higher order unallowed terms were used for centering of data, no plots are included for unallowed terms beyond the 14-pole. In any case, such harmonics are expected to be negligible at all currents.

The quadrupole terms (Fig. 3) at high fields are perhaps the most sensitive to the yoke packing density. Although the total yoke weight over the entire magnet length is well controlled in production, the local yoke density in the central 1 m region may differ significantly from the average. This is manifested in the large magnet to magnet scatter seen in Fig. 3 for both the normal and the skew quadrupole terms.

The current dependence in the normal quadrupole term arises from a horizontally offset cold mass in the cryostat due to the sagitta in the magnet (see Fig. 1). A significant magnet to magnet variation is seen at high currents, which is an indication of magnet to magnet variations in the yoke packing densities in the central 1 m region, even though the overall yoke weight and yoke length were well controlled. The calculation is in good agreement with the measured current dependence averaged over all the magnets.

The current dependence of the skew quadrupole term is mostly due to a uniform vertical offset of the cold mass in the cryostat, but is also influenced by small differences in the local packing densities of the upper and the lower yoke halves. With no top-bottom asymmetry in the yoke density, OPERA-2d calculations give a saturation of approximately -2.4 units at 5 kA. The measured skew quadrupole saturation in most magnets ranges from -4 units to +0.1 unit at 5 kA, with one exceptional magnet (DRG133) at +1.8 units. This clearly brings out the sensitivity of the skew quadrupole saturation to variations in the yoke densities. In fact, a good correlation between the yoke weight asymmetry and skew quadrupole saturation has been demonstrated in an earlier study [2]. This correlation was tracked throughout the RHIC production as a sensitive test of the accuracy of the yoke weight data. Significant departures from this correlation were traced to the use of weighing scales that were out of calibration. The average skew quadrupole saturation is in good agreement with the calculated curve (see Fig. 3). In production, beginning with dipole sequence number 63, an attempt was made to place the relatively lighter yoke packs on the top to control skew quadrupole saturation [2]. This may account for the fact that the average saturation is slightly less than the calculated value. It should be emphasized, however, that the control of yoke weight was applied to the total length of the magnet, whereas the skew quadrupole saturation depicted in Fig. 3 is sensitive to the yoke weight asymmetry in the central 1 m region, which could be very different from that for the full length.

The current dependence of the normal sextupole term (see Fig. 4) does not show large magnet to magnet variation (standard deviation of 0.22 unit at 5 kA). The average current dependence generally follows a profile similar to that calculated from OPERA-2d. The agreement is at a level of ~1.5 unit. The discrepancy may be attributed to coil deformations under the action of Lorentz forces, although no calculations were performed to estimate the deformations, and their effect on the sextupole term.

The average skew sextupole saturation is in excellent agreement with the calculations (see Fig. 4). The magnet to magnet variation is again due to variations in yoke packing densities, as discussed earlier for the normal and skew quadrupole terms.

The current dependence of the normal and skew octupole terms (see Fig. 5) has the same origin as the quadrupole terms, and a similar discussion applies. Once again, the average behavior is in excellent agreement with the calculations, and one magnet (DRG133) stands out in terms of the skew octupole saturation.

The current dependence of the normal decapole term shows some disagreement with calculations (see Fig. 6), which may again be attributed to changes in the coil geometry due to Lorentz forces. The magnet to magnet variation has a standard deviation of only 0.06 unit at 5 kA. The corresponding value for the skew decapole term is even smaller, 0.01 unit. In addition to indicating good quality control during production, such small standard deviations in the measured values are also a testimonial to the excellent accuracy of these measurements when the next higher order terms are small and feed down effects from errors in centering of the data are small.

Both the normal and the skew 12-pole terms show significant magnet to magnet variations (see Fig. 7). According to calculations, very little current dependence should have been seen. It is difficult to see a physical mechanism that would cause such magnet to magnet variations. Most of these variations appear to result from errors in the centering of data. The next higher order term, 14-pole, has a magnitude of ~1.2 unit and an error of only ~0.3 mm in centering of the data can generate ~0.1 unit of 12-pole.

The behavior of the normal 14-pole term is very well predicted by the calculations (see Fig. 8). Once again, the negligible magnet to magnet variation is evident. The standard deviation at 5kA is 0.008 unit for the normal and 0.003 unit for the skew 14-pole terms. The current dependence in the data for the skew 14-pole term is essentially measurement noise.

The unallowed normal and skew terms beyond the 14-pole have negligible current dependence, and are not shown. The plots for allowed normal terms from 18-pole through the 30-pole are shown in Figs. 9-12. In each of these cases, the magnet to magnet variation is extremely small (typical standard deviation at 5 kA is below 0.01 unit) and the calculations agree with the measurements at the level of 0.02 unit or better.

5. Conclusions

The vast amount of data on current dependence of harmonics in the 8 cm aperture dipoles for RHIC is compiled. The results presented in this report provide a good understanding of typical magnet to magnet variations in a well-controlled production run. The extremely small standard deviations for higher order allowed terms are also indicators of good measurement accuracy. Evidence of measurement errors at the level of ~0.1 unit are seen in some of the higher order unallowed terms (e.g. the dodecapole), perhaps due to uncertainties in centering of the data. The measurement results also agree very well with the predictions based on calculations using OPERA-2d finite element code. The comparison between the average measured current dependence and the predictions is indicative of typical accuracy that can be expected from such calculations.

Acknowledgements

I thank Peter Wanderer and Ramesh Gupta for several useful discussions.

References

[1] See, for example, *Field Quality Control Through the Production Phase of RHIC Arc Dipoles*, R. Gupta, A. Jain, S. Kahn, G. Morgan, P. Thompson, P. Wanderer and E. Willen, Proc. *1995 Particle Accelerator Conference*, Dallas, Texas, May 1-5, 1995, p.1423-5.

[2] *Skew Quadrupole in RHIC Dipole Magnets at High Fields*, A. Jain, R. Gupta, P. Thompson and P. Wanderer, Proc. *The 14th International Conference on Magnet Technology (MT-14)*, Tampere, Finland, June 11-16, 1995, in *IEEE Trans. Magnetics*, Vol. 32, No. 4, July 1996, p.2065-8.

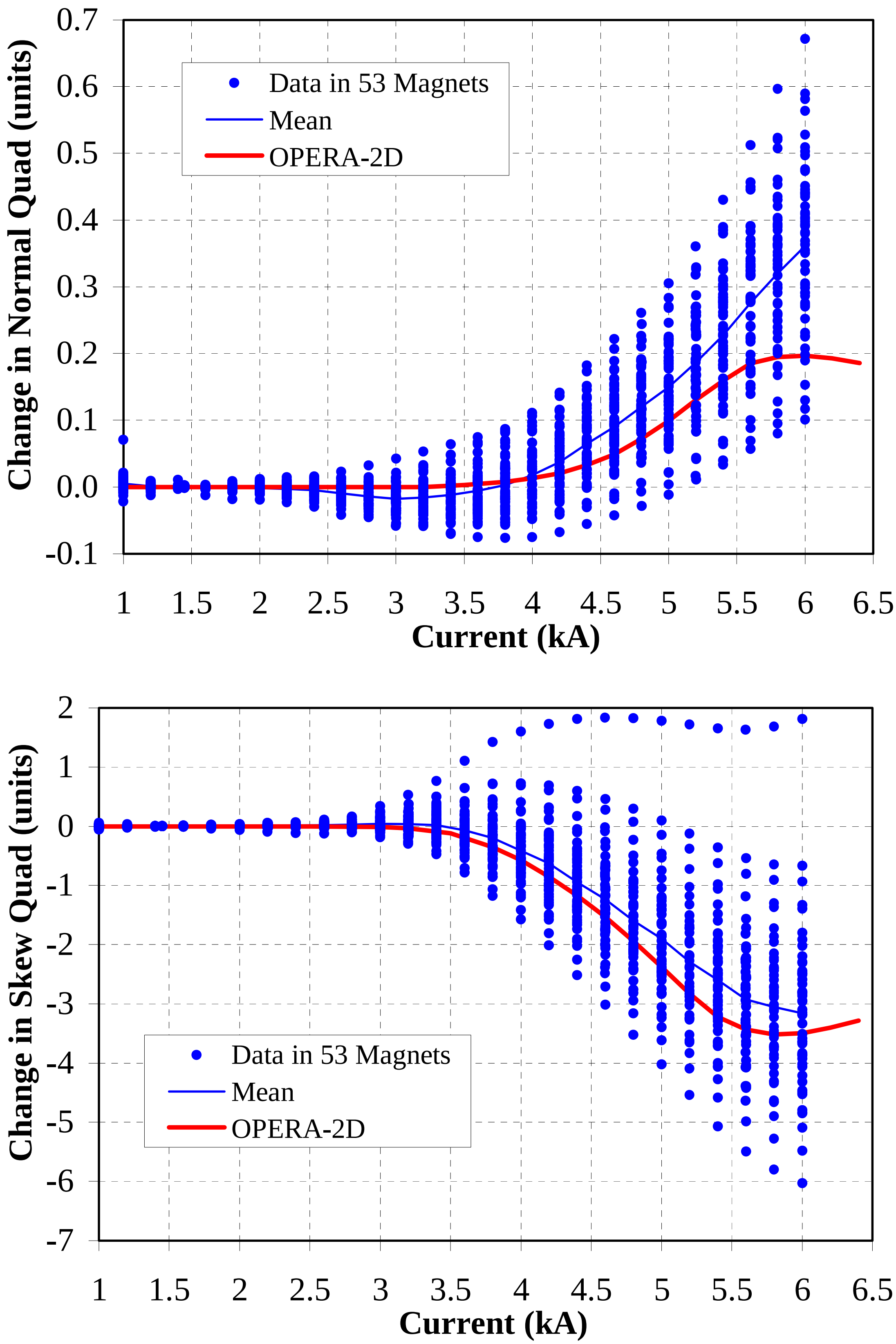


Fig. 3 Calculated and the measured current dependence of the quadrupole terms (R_{ref} = 25 mm).

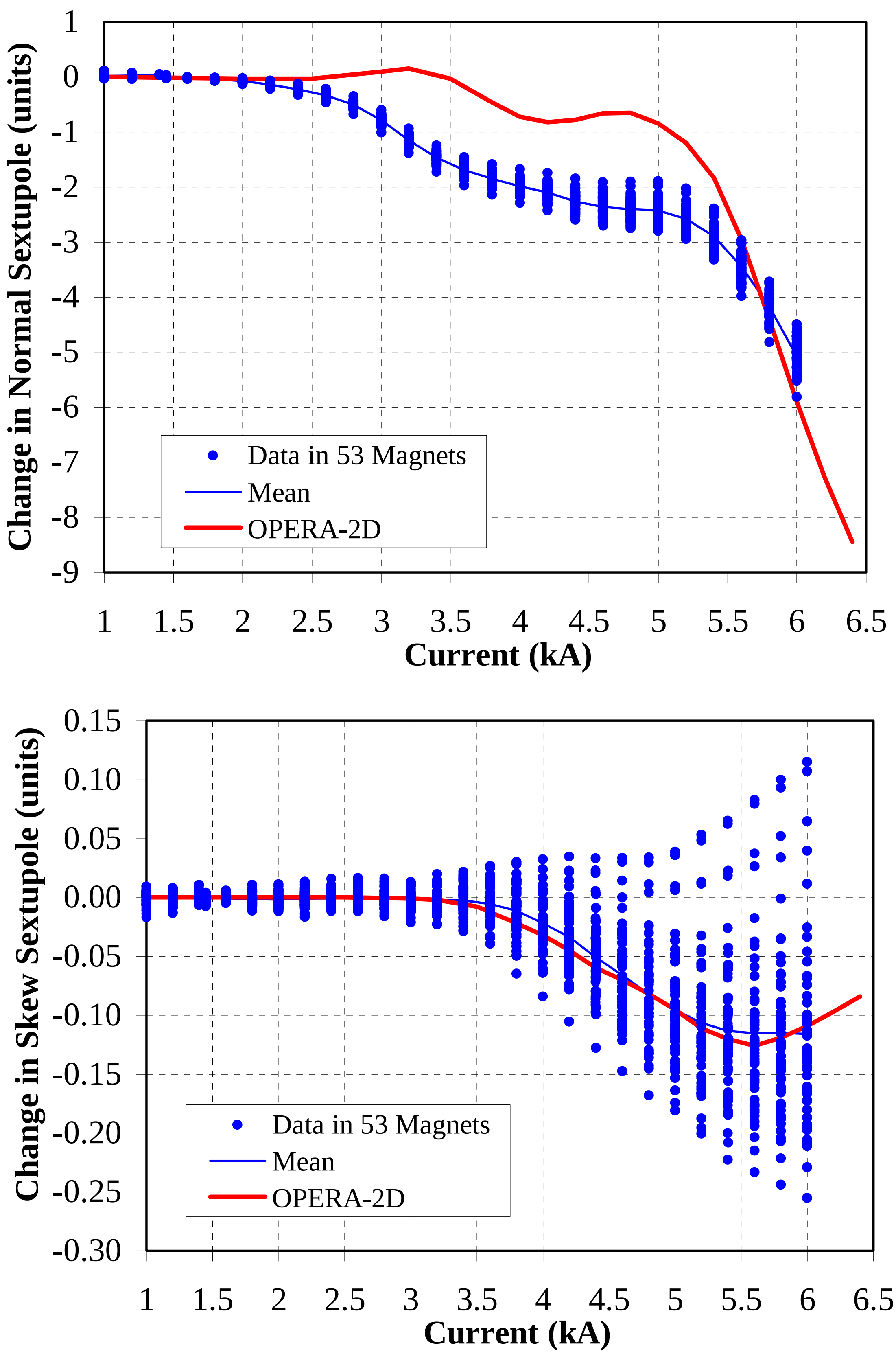
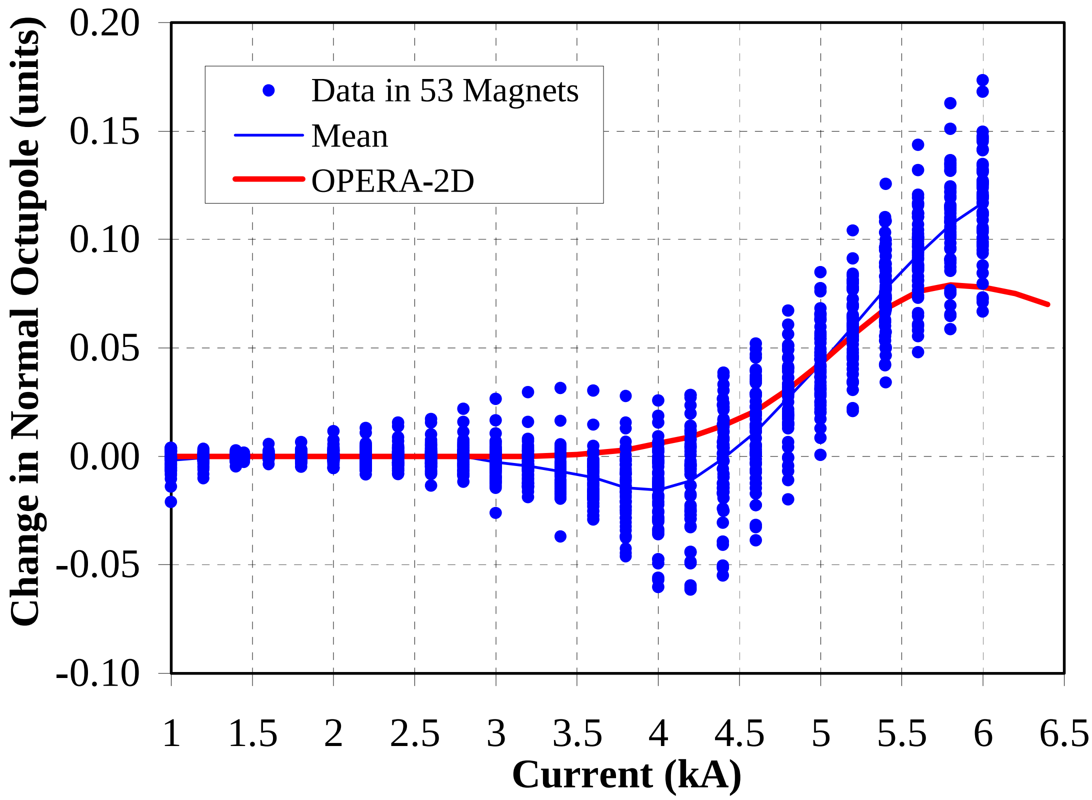


Fig. 4 Calculated and the measured current dependence of the sextupole terms (R_{ref} = 25 mm).



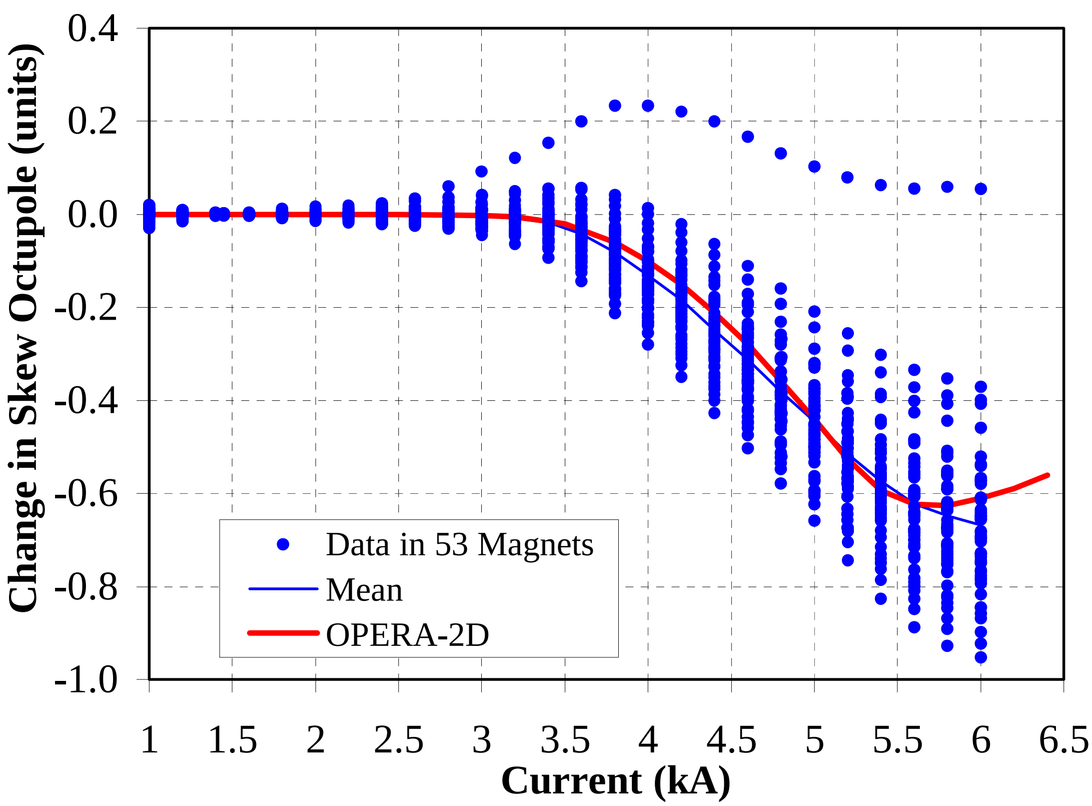


Fig. 5 Calculated and the measured current dependence of the octupole terms (R_{ref} = 25 mm).

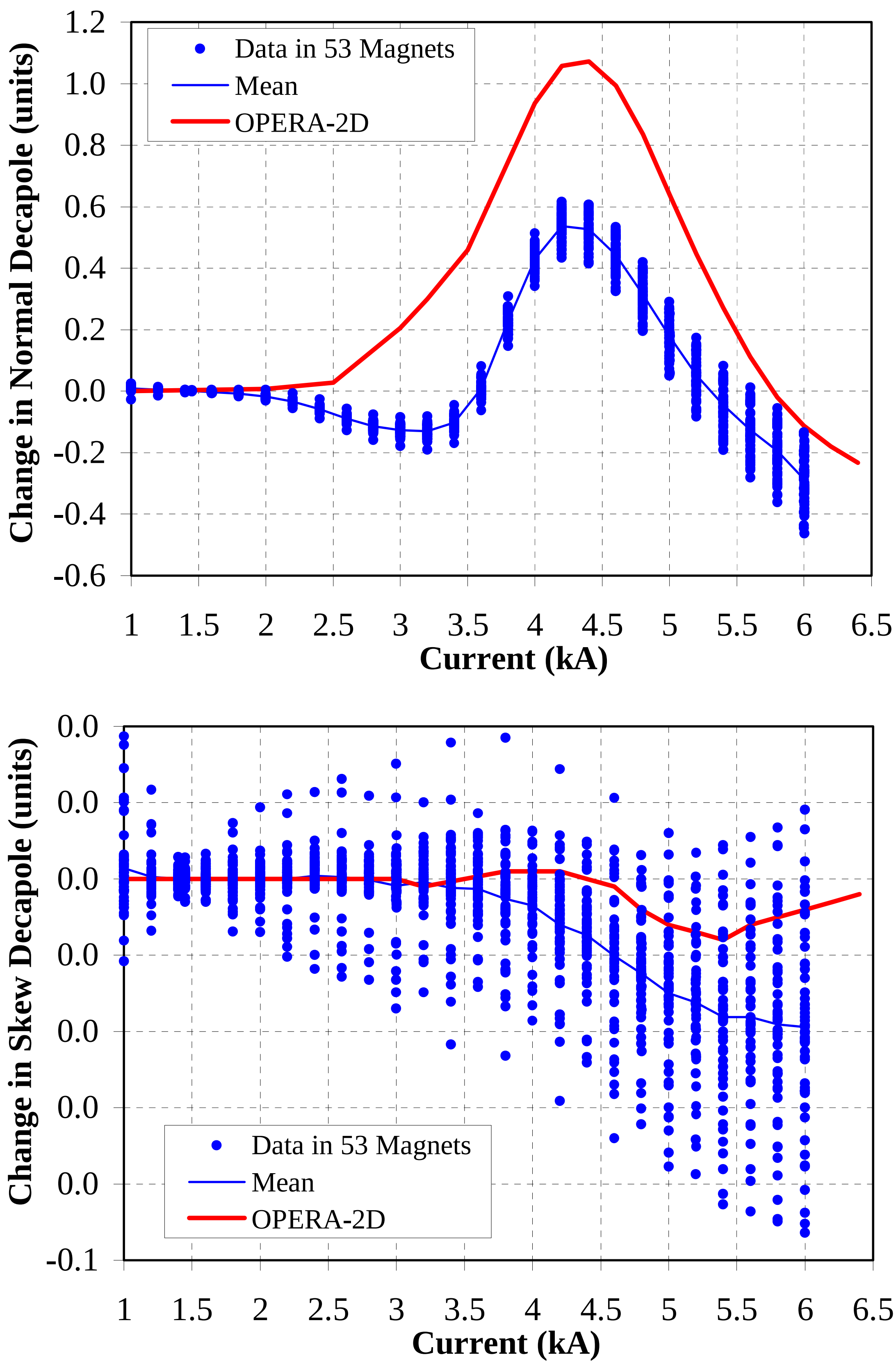


Fig. 6 Calculated and the measured current dependence of the decapole terms (R_{ref} = 25 mm).

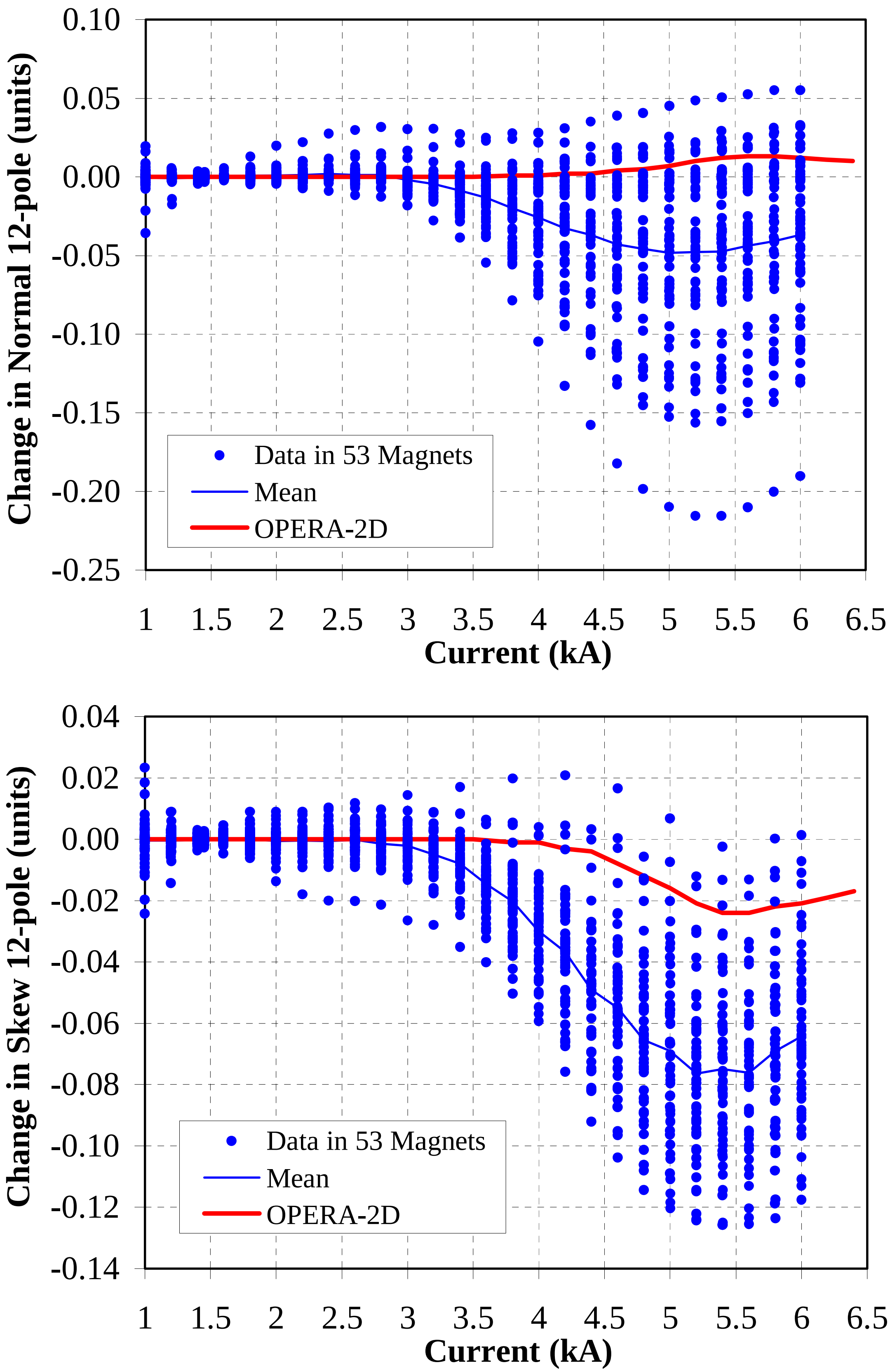
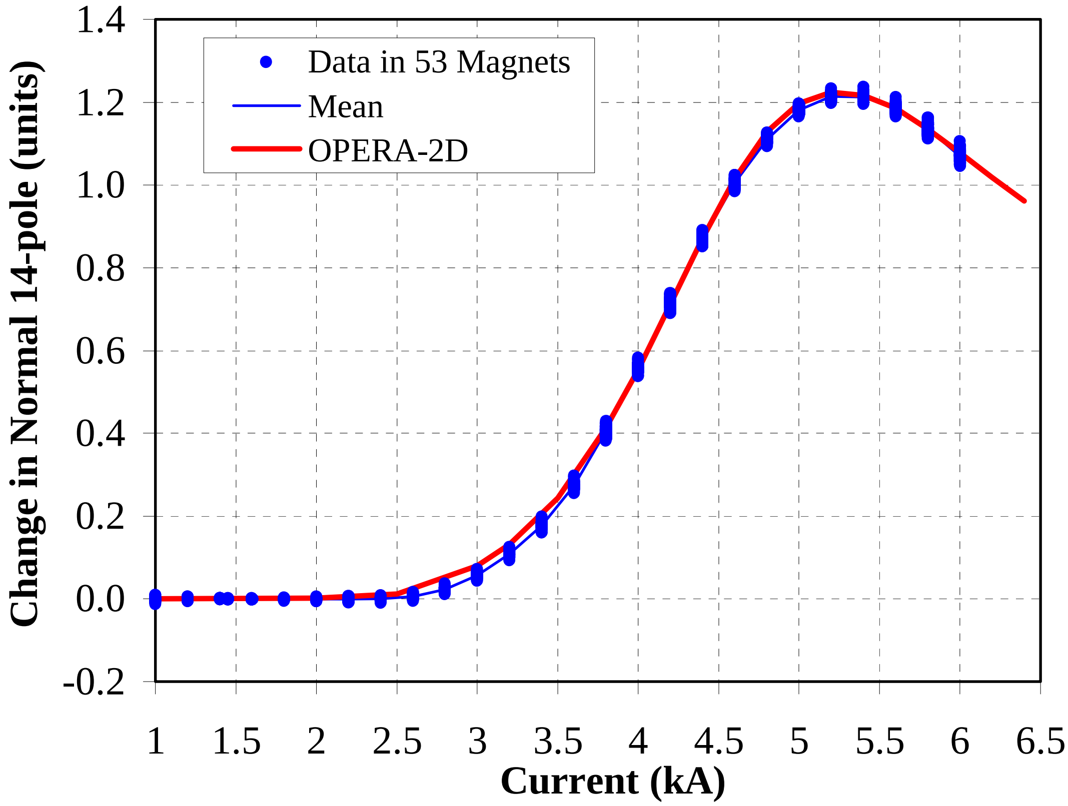


Fig. 7 Calculated and the measured current dependence of the 12-pole terms (R_{ref} = 25 mm).



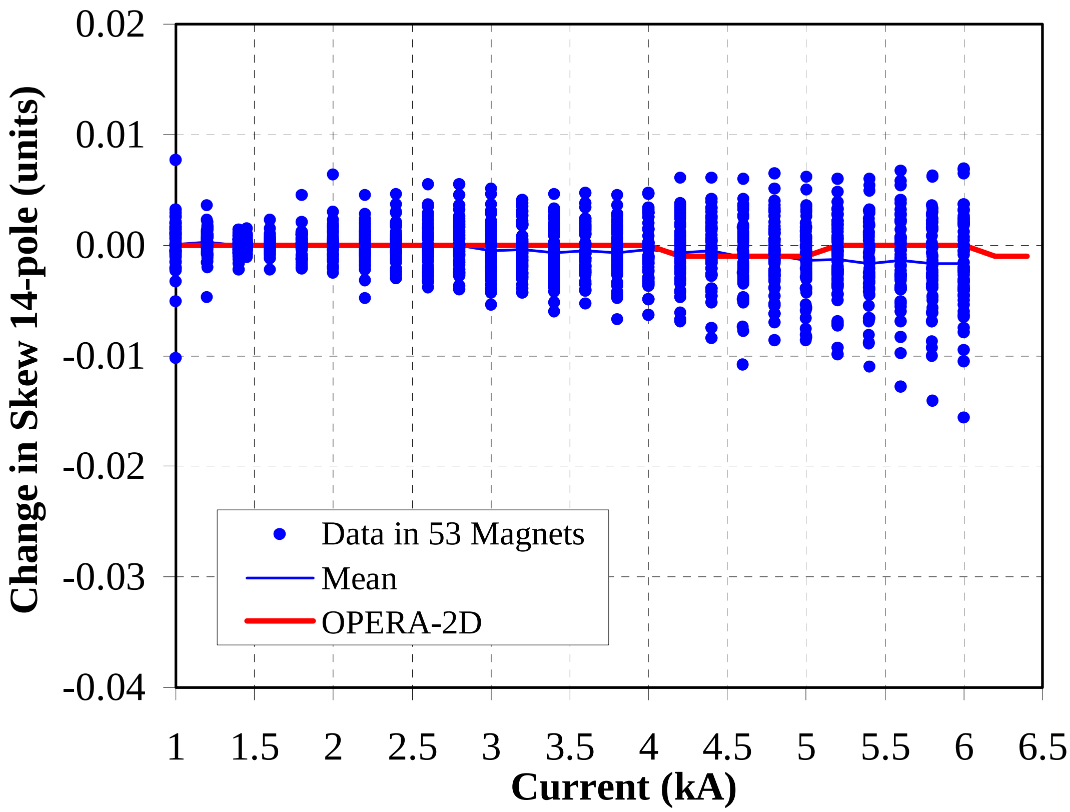


Fig. 8 Calculated and the measured current dependence of the 14-pole terms (R_{ref} = 25 mm).

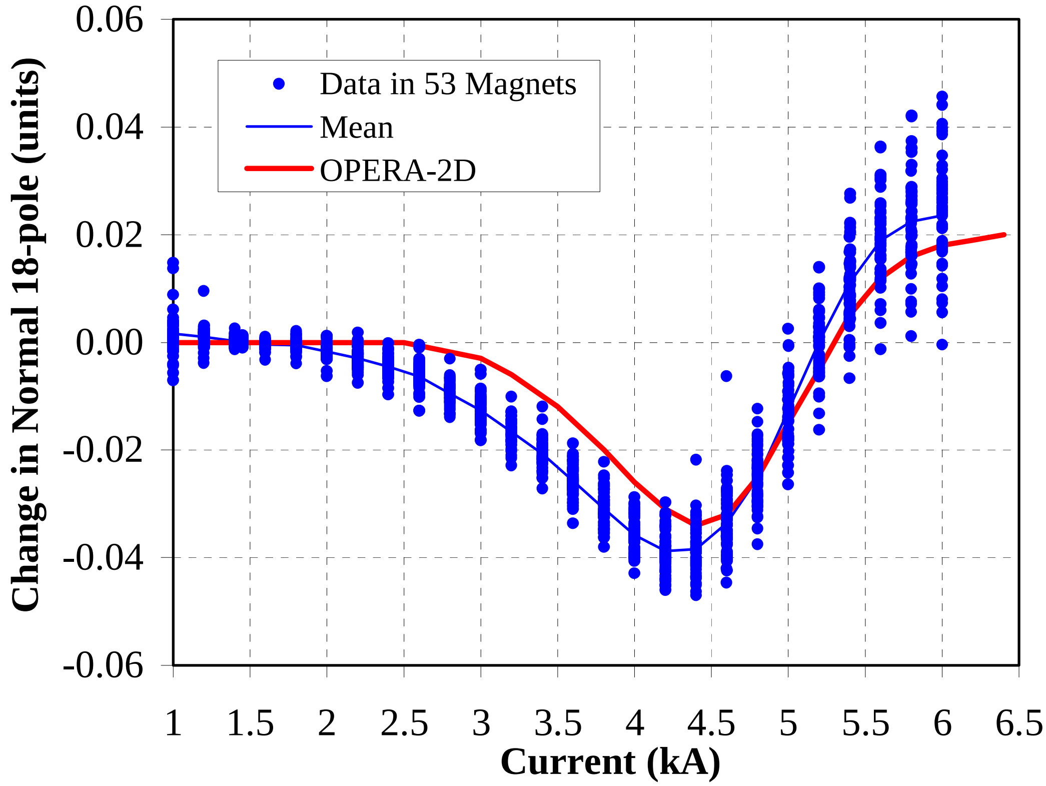


Fig. 9 Calculated and the measured current dependence of the 18-pole term (R_{ref} = 25 mm).

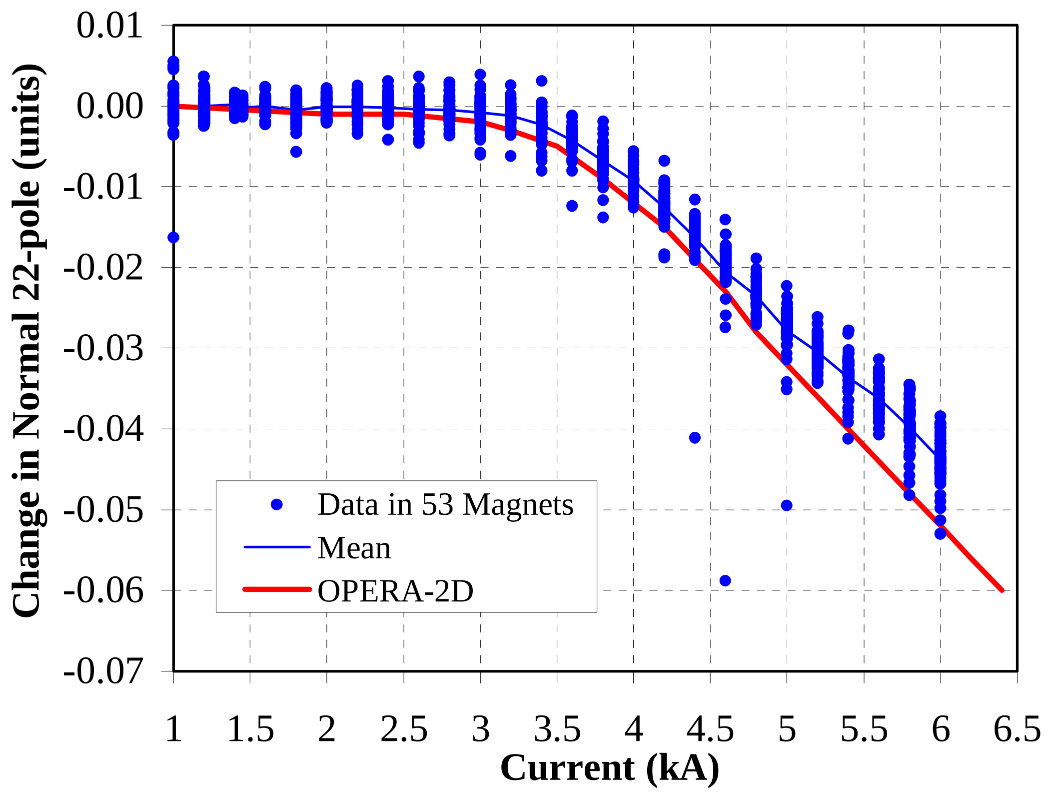


Fig. 10 Calculated and the measured current dependence of the 22-pole term (R_{ref} = 25 mm).

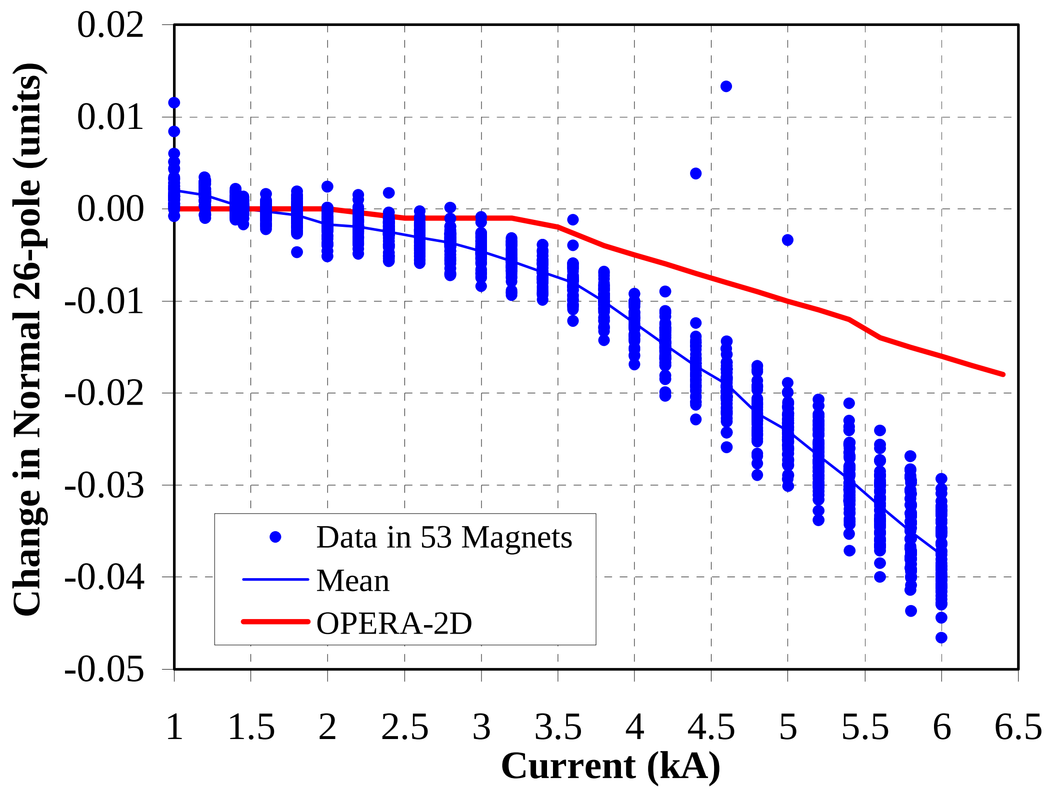


Fig. 11 Calculated and the measured current dependence of the 26-pole term (R_{ref} = 25 mm).

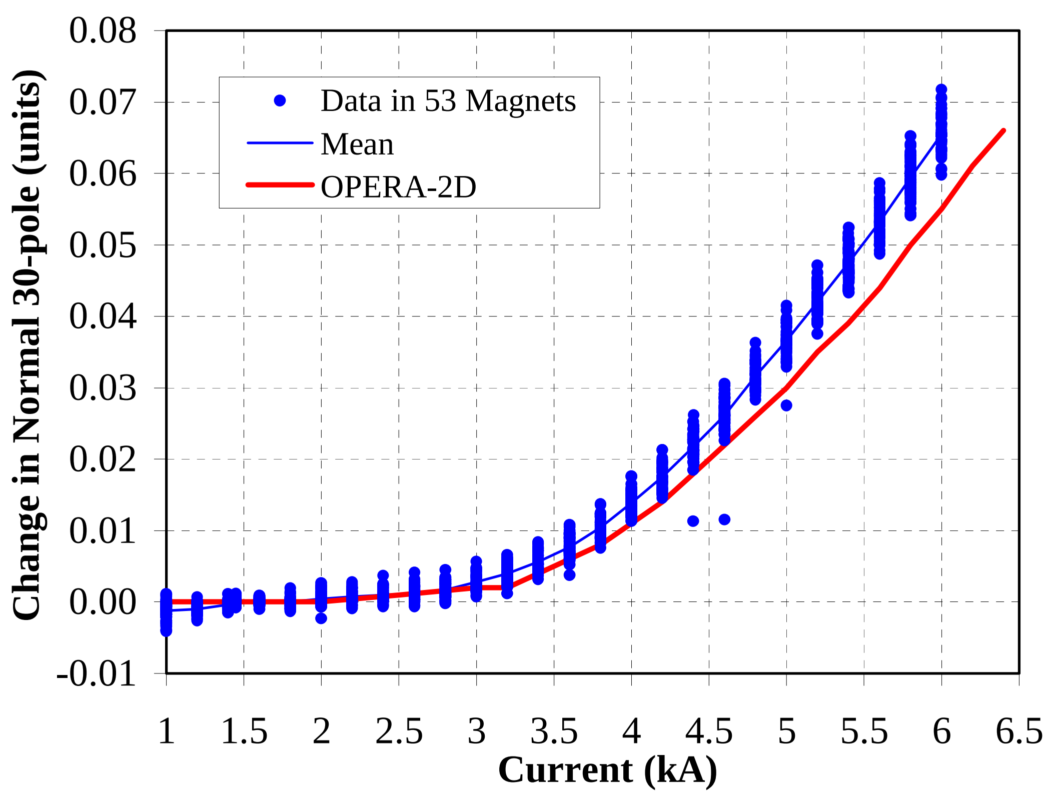


Fig. 12 Calculated and the measured current dependence of the 30-pole term (R_{ref} = 25 mm).