Higher Order Field Multipoles Dependence On Machining Defects

(Supplement to JLAB-TN-08-060)

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Abstract

The purpose of this document is to complement previous technical note JLAB-TN-08-060 [1] by using additional results on edge field participation in dipole magnets to extend the conclusions of the above mentioned technical note.

Two different evaluation methods are employed to study the field around the edges of dipole magnets in models realized under the Opera/TOSCA simulation environment. One evaluating the field by interpolation between its values at the location of the nodes of the finite element mesh, the other evaluating the field analytically in free space after numerically integrating the field values over the surface of the sources. Both methods have strong points and drawbacks which will be mentioned and taken into account.

The objective is to be able to integrate the field along the whole beam path to determine the relative importance of the fields induced by the edges on the one hand and within the body of the magnet on the other hand. A combination of the two evaluation methods cited above that makes a path integration possible, even where there are sharp field variations, is presented.

Finally, the conclusions drawn concerning skew quadrupole dependence on machining quality of the pole surfaces suggested in the previous technical note are confirmed and even extended to skew sextupole.

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I - Context

I.1 - Original concern

The purpose of [1] was to enhance accelerator dipole magnets modeling by introducing geometrical perturbations in the models in order to simulate machining defects. A correlation was then established between the amplitude of the geometrical perturbations and the skew multipole content of the magnetic field between the magnet poles. However, and although the field seemed perturbed around the edges of the magnet poles, the mesh densities reached at the time and the field evaluation techniques that were used did not allow to draw conclusions neither regarding the correlation between those 'near-edge' field perturbations and machining defects, nor regarding the relative importance of the field perturbations around the edges on the one hand and within the body of the magnet on the other. At the time, the study only concluded using the results established from field evaluations performed in the region located between the poles of the magnet.

I.2 - Purpose of this study

The purpose of this study is to develop a field evaluation method in the Opera/TOSCA simulation environment that will allow us to properly compute the field around the edges of our models, therefore allowing us to confirm the conclusions from the former study and extend their range.

I.3 - Strategy

After a presentation of the limits of the former evaluation method, the two options that are available to try and improve it will be surveyed. The first step will be to focus on mesh refining with the consequences it has on the size of the models. Then another field evaluation method available in the Opera post processor will be considered, that is less dependent on mesh quality but whose demand on CPU resources is higher. Finally, the two methods will be combined into a hybrid method that will allow us to get to our conclusions.

II - Establishing a field evaluation method along whole beam path

II.1 - Principle of the initial evaluation method

For a complete description of the method used to evaluate the fields, please refer to [1], chapter II.5.2.

II.2 - Evaluation limitations near the edges

Figure 1 shows the skew quadrupole term of the field induced by an 'ABH' dipole magnet along half of its length, evaluated using the above mentioned method. As predicted by the correlation established in [1] between machining defects and field perturbation between the poles, this non-perturbed model shows no skew quadrupole until the end of the poles. However, this plot clearly indicates that some non-null values are observed near the edges of the poles (z = 48cm).

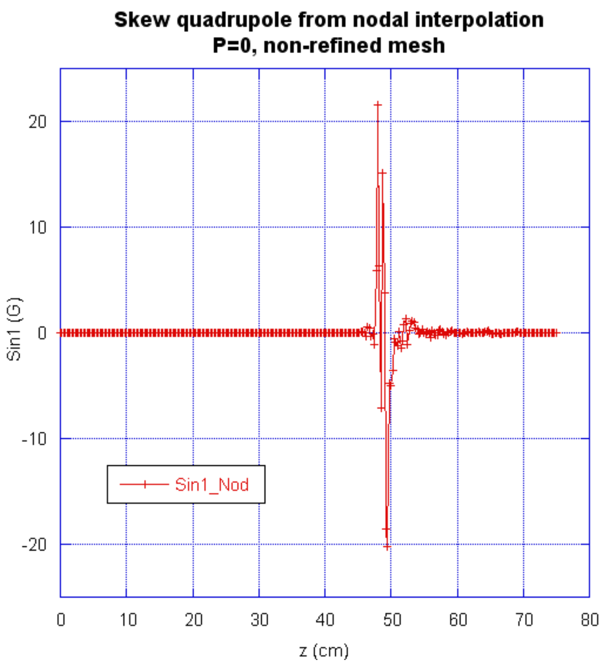


Fig. 1: Skew quadrupole term of field multipole expansion along half the length of the beam path in a classical, non-geometrically perturbed 'ABH' dipole magnet model. The origin of z (longitudinal coordinate) is located in the center of the model. Steel ends at $z = \pm 48$cm. P is the perturbation amplitude in microns (= 0 for a non-perturbed model).

Two main arguments lead to think that those results are likely non-physical and only due to some numerical noise effect:

- The model is geometrically unperturbed and although saturation in the poles may induce high order multipoles there is no reason to think that skew multipoles would be introduced, and what's more only around the edges.
- The regular shape of the magnet devoid of sharp variations cannot explain the alternative peak values that are observed on this plot.

Options to increase the accuracy of our field evaluation method will now be discussed with the intention to extract the physical content of the field around the pole edges from what is only numerical noise.

II.3 - Options to increase evaluation accuracy

II.3.1 - Mesh refining

The first option available to increase the accuracy of the data around the pole edges is to higher the finite element density in that region. Since the models of the CEBAF magnets are already pretty big (10^5 to 10^6 elements), the mesh density has to be lowered at some places in order to be made finer in the region of interest. Around 15 mesh variations were realized by the supervisor of the author and figure 2 presents the field evaluation provided by one of the densest.

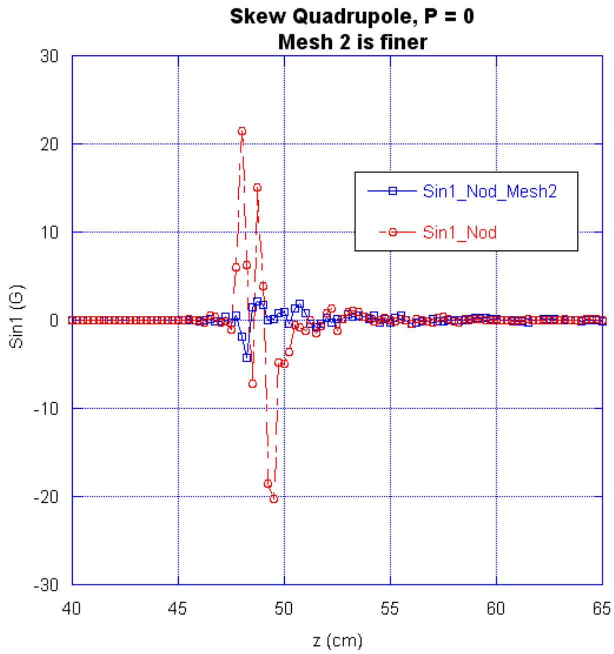


Fig. 2: A zoom around the edges' region of the skew quadrupole evaluated in two different models: one with the original mesh density (red) and the other with a mesh density as high as possible in that region (blue). Although some field oscillations are still observed even with the denser mesh, their amplitude is strongly reduced (by an order of magnitude approximately).

It can be observed that the lower value for the field peaks suggested by the denser mesh corroborates the hypothesis that a geometrically non-perturbed model should induce no skew terms in the field.

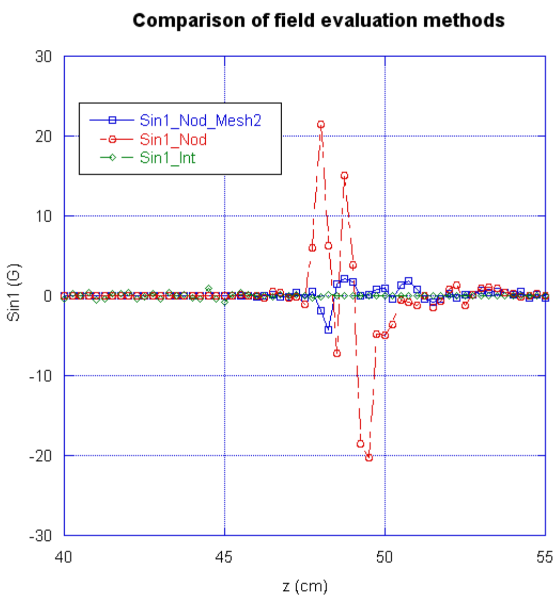
It is however technologically very difficult if not impossible to go on refining the mesh given the size reached by the last models (~20.10^6 elements).

Another option had then to be envisaged in order to try and get finer results.

II.3.2 - Surface integrals

The Opera post processor offers two ways of evaluating the field at one point in a solved model:

- the first technique, that has been used so far, is 'nodal interpolation'. The field is known from the solver's output at some determined node locations and the post processor interpolates those values when it comes to obtaining a field value at a location that is away from a node. This method is very quick but highly dependent on mesh density in the evaluated region.
- the alternate technique is called 'integration' in the code's terminology. The post processor integrates the field along the surfaces of the sources and then determines the field in free space analytically from there. It is dependent on the mesh density in the sources' region, but not around the point whose field is being evaluated. It is very useful in regions where the mesh is coarse or, in our case, not fine enough. The main drawback of this method is that it is several orders of magnitude slower than nodal interpolation.



Figures 3 exposes the same results as presented in figure 2, to which has been superposed the results obtained with the surface integrals method.

Fig. 3: Skew quadrupole evaluated in the 'ABH' magnet model by 2 different methods: nodal interpolation in red and blue (blue has finer mesh) and source surface integration (green) in the finer model.

Those results confirm that the peaks observed were due to numerical noise, which disappears when the method becomes less affected by local mesh coarseness.

Noise appears in another region though (figure 4) as the surface integration method turns out to be noisier near the sources, as explained in the following quote from one of the emails received from the code's editor support team:

> *"In many applications the integral field options available with Opera can be used to improve the accuracy of field results. Unfortunately the method depends on higher order solution errors decreasing rapidly with distance from the sources (in this case magnetisation)"*
>
> *- Vector Field Support*

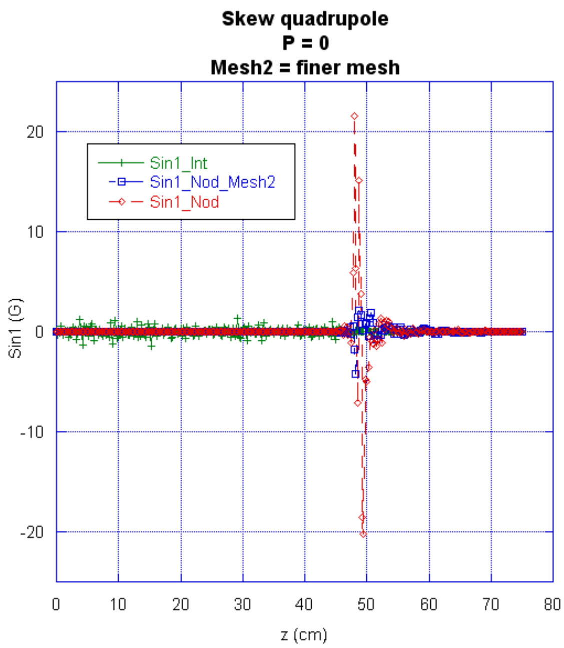


Fig. 4: Skew quadrupole along half the length of an 'ABH' dipole magnet model. Although the field evaluated by surface integrals (green) is cleaner in the region of the edges (Fig 3), it turns out here to be noisier in the region that is closer to the steel poles.

II.4 - Combination

On the one hand, we have a method of field evaluation by nodal interpolation that is accurate where the mesh is dense enough and the geometry varies little, that's to say between the poles of the dipole magnet, but which becomes very noisy when the geometry changes and the mesh is not dense enough. On the other hand, we can evaluate the field with another method, based on integration over the surfaces of the sources, that's more accurate when the evaluated region is far enough from the sources, that's to say not between the poles of the magnet.

Since those domains of efficiency seem to be complementary, the idea arose that their results could be combined so that the field evaluation resulting from that combination could take advantage of the most accurate part of each set of data.

Figure 5 focuses on the region at the very end of the steel, around $z = 46$ cm, where the nodally interpolated data starts to be noisy and the data obtained from surface integrals ceases to oscillate.

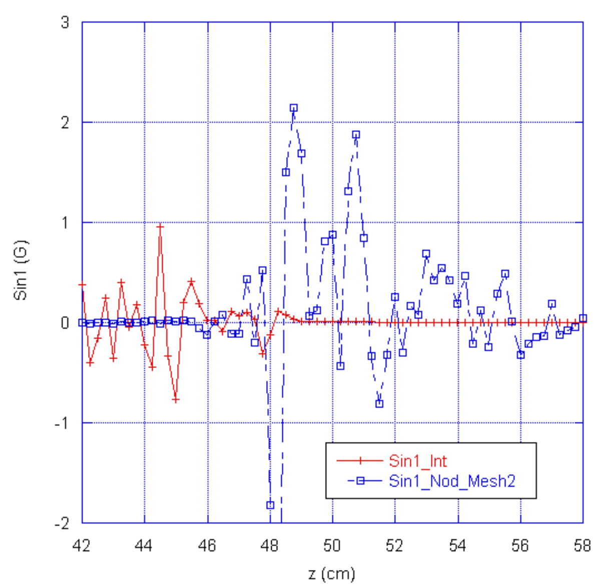


Fig. 5: Skew quadrupole evaluated along the part of the beam path that is around the end of the poles of an 'ABH' magnet model. Blue plot comes from nodal interpolation and red plot from surface integrals. Note how one method is noisy where the other is not. One method's accuracy takes over the other's around $z = 46$ cm.

Due to the complementary property of the domains of accuracy of those two methods, it was then decided to 'recombine' the data sets so as to obtain a field evaluation with a noise as low as possible. Figure 6 schematically represents the recombining operation.

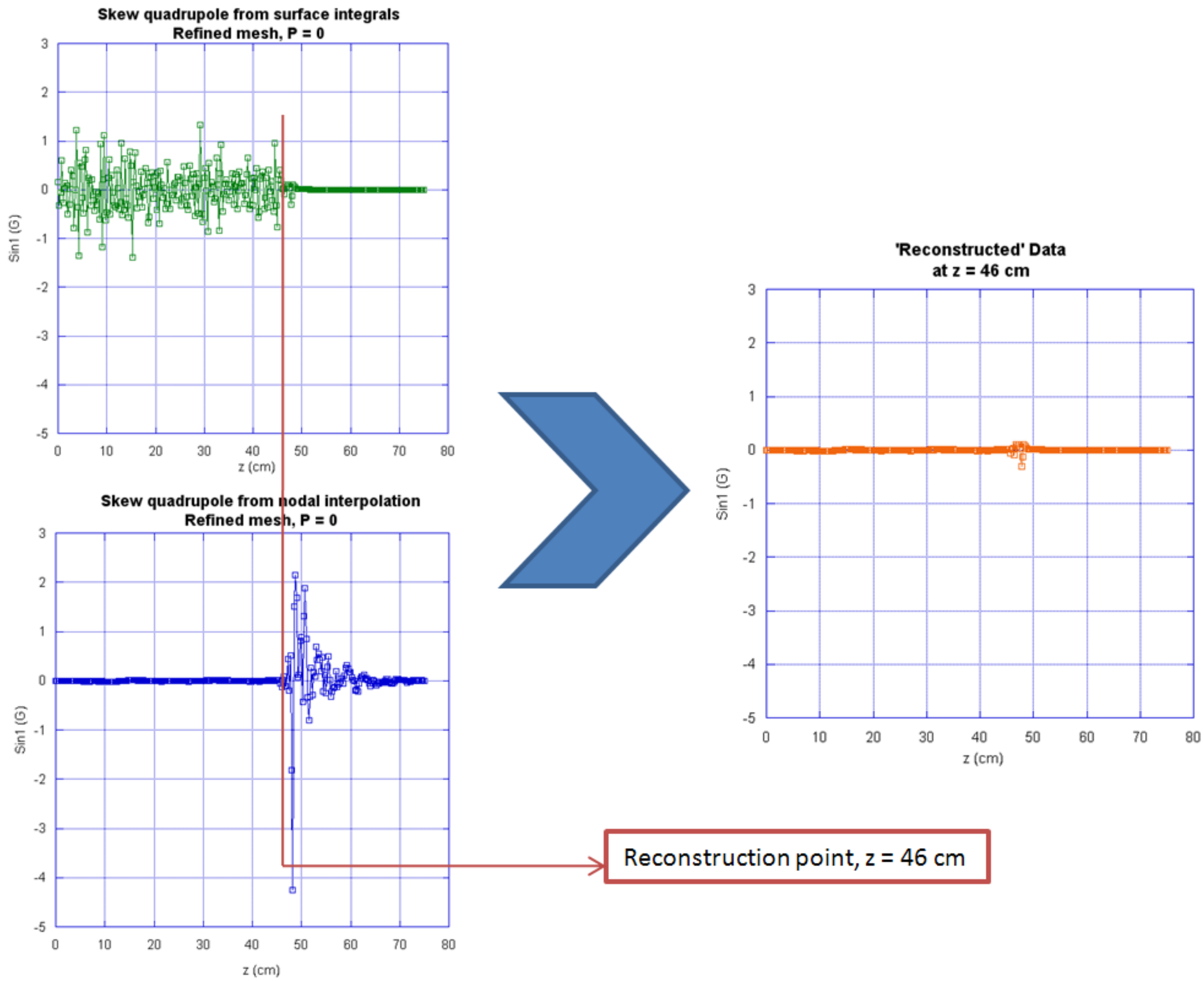


Fig. 6: Schematic representation of what is referred to as 'recombination' here. The idea is to use each evaluation method where it is most efficient: nodal interpolation between the poles and surface integrals when getting out of the magnet. The value '46 cm' for the position of the recombination point was decided in a arbitrary way within the short zone where both methods are noisy.

The interest of recombining the two sets of data is to be able to perform a numerical integration of the field values along the whole length of the beam path so that we can compare those results with the ones obtained in [1] using only a part of the beam path length. This is the purpose of the next section.

III - Implications regarding field perturbations from machining defects

III.1 - Original concern

The purpose of [1] was to establish a correlation between the undesired skew components of the field and the quality of the magnet's machining, which was to be simulated by introducing geometrical perturbations in the models.
A linear variation of the skew multipole content with regards to the geometrical perturbations was established for the skew quadrupole, sextupole and octupole that were induced within the body of the magnet. However, the field evaluation methods used at the time did not permit to conclude regarding the influence of geometrical perturbations on the field induced by the totality of the magnet, apart from the quadrupole for which the field induced around the edges seemed negligible.

This section will first show how the new field evaluation method applies to the geometrically perturbed models of [1] and then extend the conclusions that were reached then.

III.2 - Integrating the edges (example)

The following figures (7, 8, 9) show how the field data noise is reduced by the means of the recombination method in one of the perturbed models used in [1]. Here the geometrical perturbations induce a constant skew quadrupole component in the field inside the magnet and the behavior around the edges is not mere numerical noise, there is a signal that is to be isolated from this noise.

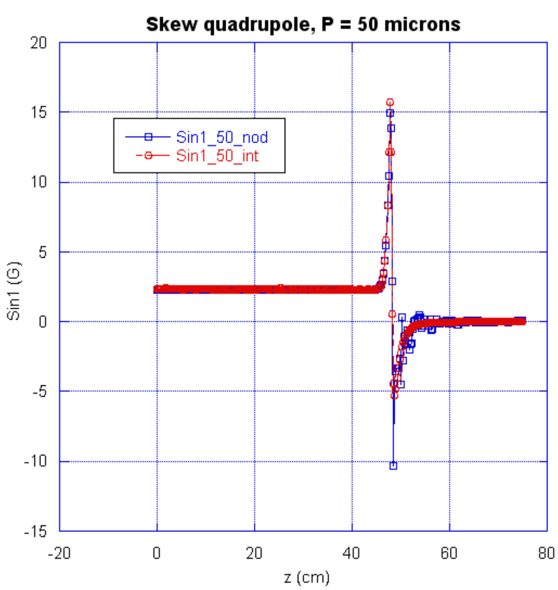


Fig. 7: Skew quadrupole plotted along the longitudinal dimension of a perturbed 'ABH' magnet. P represents the amplitude of the geometrical perturbations that stand for machining defects. See [1] for details. Red is the data from surface integrals and blue comes from nodal interpolation.

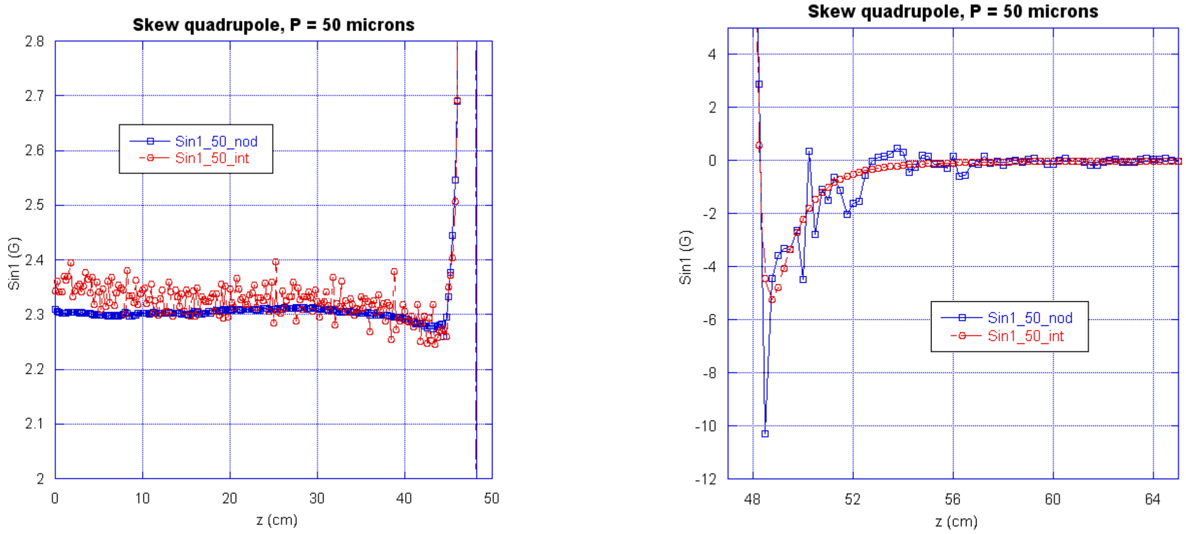


Fig. 8: Those plots still represent the skew quadrupole evaluated along the longitudinal dimension of an 'ABH' dipole magnet, but zoomed at two different places, one within the field of accuracy of the nodal interpolation method (left) and the other where the surface integrals method is accurate (right).

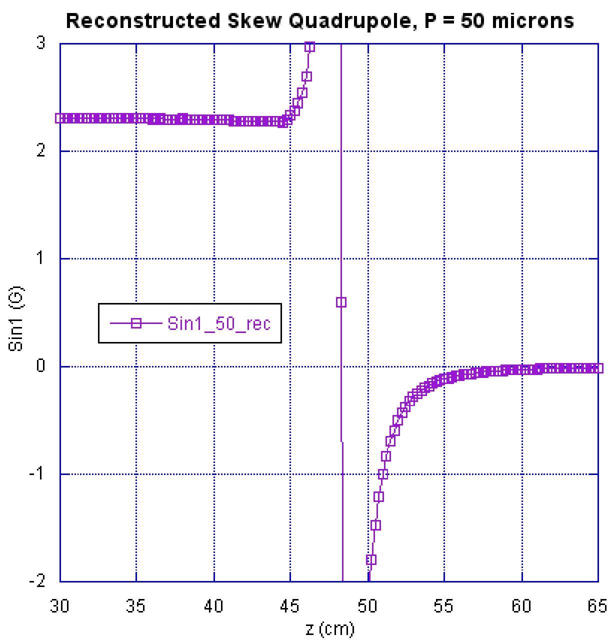


Fig. 9: Representation of the recombined skew quadrupole data around the edge of the magnet. Note how the noise is efficiently reduced.

III.3 - Final results

III.3.1 - Skew quadrupole

Once the data is treated so that the noise is reduced as much as possible, the field is integrated along the beam path to compare the results with accelerator physicists' requirements for example.

The first major point of this study is presented in figure 10. The skew quadrupole field mapped in the perturbed model of a non-ideal dipole magnet is compared to the field that would be induced in the case of a perturbed ideal dipole. In other words, assuming that the skew quadrupole component comes from the distortion of the pole shape, figure 10 compares the field obtained from a finite 3D magnet model, whose fringe field is the central interest of that study with what would come out of an ideal dipole, devoid of fringe field, whose field would be a step function of z.

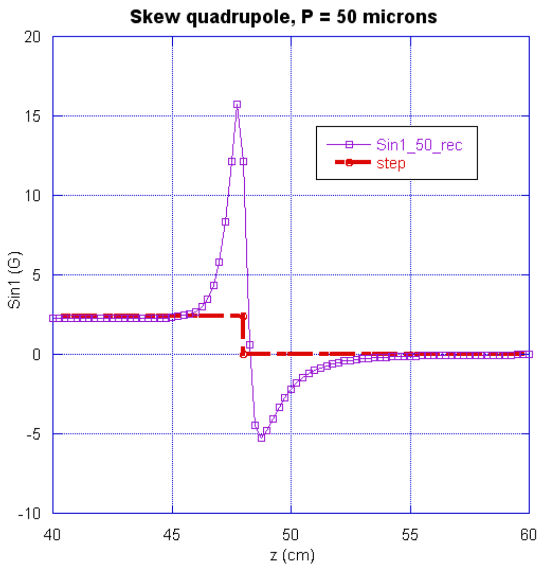


Fig. 10: Skew quadrupole around the edges of a geometrically perturbed model. Note how a 'heartbeat-shaped' series of two peaks gets added to the ideal step-function that would be induced by an ideal dipole.

After integrating the skew quadrupole along z in perturbed models with different perturbation amplitudes P, it turned out that the ratio between the integrated field from those models and from ideal dipoles whose step heights would match the field induced in the body of the dipole (fig. 10) stays constant:

$$\frac{integrated\ field\ in\ ideal\ dipole}{integrated\ field\ in\ perturbed\ magnet} = 98\%, \forall P \neq 0 \quad (1)$$

This leads to the powerful conclusion that this edge field oscillation integrates almost to zero and that all the conclusions established in [1] regarding skew quadrupole behavior with respect to geometrical perturbations are confirmed.

The correlation that has therefore been established between skew quadrupole and perturbation amplitude is presented in figure 11.

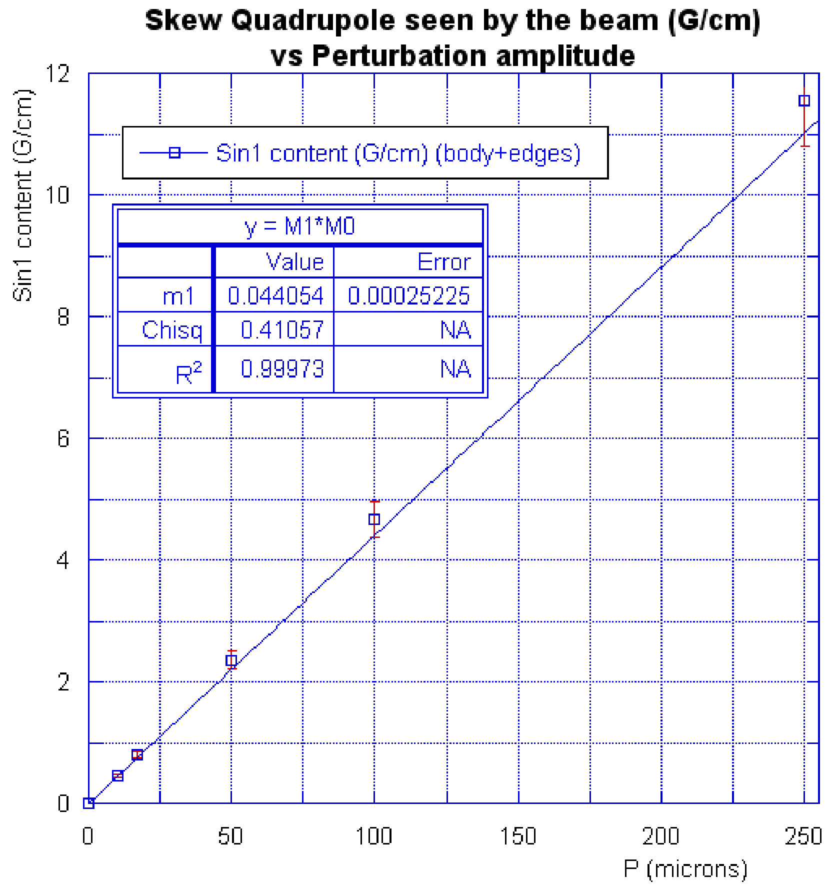


Fig. 11: Skew quadrupole versus perturbation amplitude. Error bars take into account local numerical noise and the few percent variations that can occur due to a change in the fit evaluation domain or to the fringe field participation. Practically interesting domain is reduced to P = 0..50 microns though, even if the whole range is interesting for fit accuracy.

It was established [3] that the threshold for BPM detection in the 12 GeV machine would be around 1 G/cm. Figure 11 shows that such a value would be induced for a geometrical perturbation of 22 microns. Current tolerance concerning flatness of magnet poles is 50 microns [1] [2]. A decision is therefore to be made regarding how to cope with the 2 G/cm that are to be expected if the specifications are not modified and the magnets are machined with minimum acceptable quality.

III.3.2 - Skew sextupole

Another important point of this study is that it allows to draw conclusions regarding integrated skew sextupole whereas [1] did not. Figure 12 represents the tendency that was observed at the time, using only nodally interpolated values. One can note how the tendency is clear for the field values inside the magnet but that the noisiness of the curve representing the integration along the whole path prevents any general conclusion to be drawn.

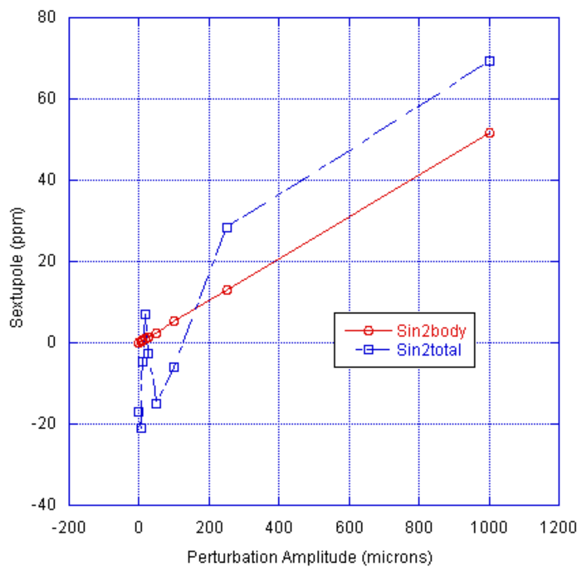


Fig. 12 (Fig. II.38 in [1]): Skew sextupole. Comparison of the integration over the inner part of the dipole (from z = -45 cm to z = 45 cm) in red with the integration over the whole length of the simulated trajectory (from z = -75 cm to z = 75 cm) in blue. Units are parts per million of the normal dipole field which is about 14kG.

Figure 13 represents the integrated values of skew sextupole that were obtained using the recombined data, where the clear tendency that was discovered in [1] in a limited region of the models is now confirmed by integrations over the entire length of the magnets.

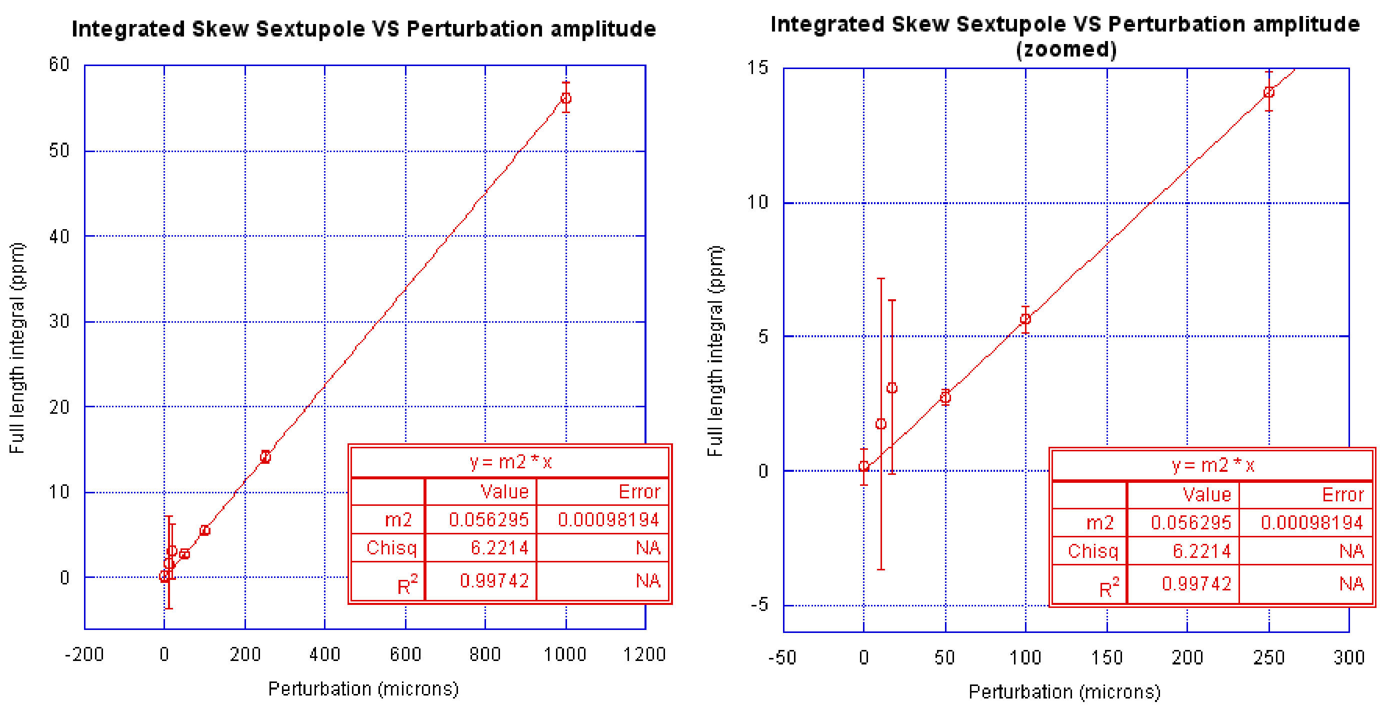


Fig. 13: Skew sextupole integrated over the whole length of the beam path in a perturbed 'ABH' magnet model, versus the amplitude *P* of geometrical perturbations. Units are parts per million of the normal dipole field (~14 kG). Linear fits have been associated with the plots. Error bars represent residual numerical noise in the field maps that were used to realize the path integration for each model.

IV - Conclusions

1. Field evaluation options offered by Opera TOSCA by nodal interpolation and by surface integrals have complementary domains of accuracy. The recombination method used here takes advantage of both in a time efficient manner.

2. Linear dependence of skew quadrupole with respect to the quality of the poles' surfaces has been confirmed. The current surface specifications appear to be twice too loose which means that either the tolerances need to be tightened or a practical means needs to be thought of to cope with this skew quadrupole component, albeit relatively low, when it is observed in the machine.

3. Linear dependence of skew sextupole with respect to the quality of the poles' surfaces has been established and is to be compared with the requirements of machine designers. The appendix contains one viewgraph from a presentation to CASA with suggestions for geometric specification of magnet steel.

References

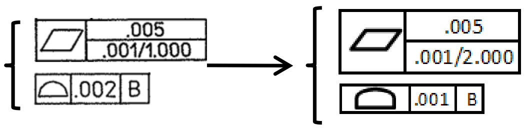
[1]: Nicolas Ruiz , JLAB-TN-08-060: *Determination of the influence of machining defects on the magnetic field as a part of the design of new magnets for the CEBAF 12-GeV upgrade*, 2008

[2]: Drawings 22161-0101 and 22161-0002 in Océ, *Electronic Job Ticket for the Web*, http://dcg4/oceweb/Oce/Main/ASP/FS_Login.asp

[3]: Yves Roblin, JLAB-TN-08-042, *Normal and skew multipole terms in the dipoles and quadrupoles of the 12GeV CEBAF upgrade*, 2008

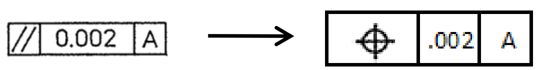
Suggestions on specification

- To stay below 1 G/cm of skew quad:
  - Tighten current specs by half:

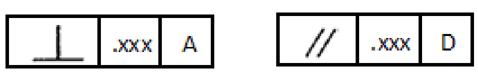


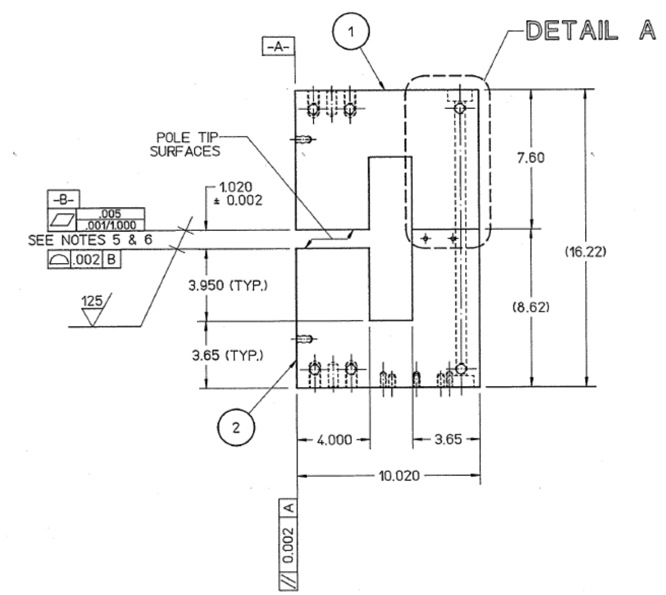
  - Accept or correct skew quad content

- To prevent pole misalignment:
  - Use location specification



- To specify pole orientation (along x AND z):
  - Specify the implicit angle tolerance
  - Use explicit specifications





Side view of the core of the 'AB' magnet.

ANSI Y14.5