Evaluation of Magnetic and Mechanical Properties of Delta Undulator Model *

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Abstract

The paper describes a test result of a Delta undulator prototype recently built at CLASSE (Cornell Laboratory for Accelerator-based Sciences and Education). This undulator design is optimized for the linac type beam. It has a round bore, very compact, provides full polarization control and has magnetic field significantly stronger than in a conventional undulator. We are planning to use Delta undulator in the Cornell Energy Recovery Linac (ERL) facility, but it can also be employed in FEL (Free Electron Laser) and ILC (International Linear Collider) facilities.

The tested prototype was 30cm long with 5mm round gap, 24mm period magnetic structure was assembled with NdFeB (40SH) permanent magnet blocks. The model demonstrated a 1.25T maximum peak field in planar mode and 0.85T in helical. That is approximately 90% of the design value. Calculation of the photon flux spectrum for ERL type of beam using the measured field indicated less than 3% of flux degradation due to the field errors in helical mode and $\sim$ 20% in planar.

In the paper we describe results of magnetic field measurement as well as measurement of structure deformation. Analysis of the deformation suggested improvements in mechanical structure that should bring the peak field up to design value and reduce field errors. This improvement will be implemented in the next model.

Overall, the test result can be considered as a proof of principal of the Delta undulator magnets.

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I. INTRODUCTION

This paper reports followup work to the reference [1] where we presented a detailed conceptual design and future plan for a Delta undulator magnet. In the following sections we describe the test of magnetic field properties as well as mechanical structure of a short, 30cm long, Delta undulator model. The test provides a proof of principal.

The Delta undulator is quite different from a conventional design. It consists of four pure permanent magnet (PPM) arrays placed symmetrically around the beam axis. The permanent magnet blocks in arrays are fastened to copper holders using a recently developed soldering technique [2]. Arrays are mounted inside a rectangular box-like frame with miniature rails that provide for longitudinal displacement. The displacement is used for polarization and field strength control. The PM soldering [2] and box-like frame result in a very compact and mechanically stiff structure. The model can be enclosed in a 20cm diameter cylindrical vacuum vessel. The downside of this arrangement is the absent of lateral access to the magnetic field region. In conventional undulators this access is used for magnetic field measurement and field tuning. Because a Delta undulator has only axial access we adopted the following strategy. All four magnet arrays are tuned separately prior to final assembly. After assembly the field properties are verified with a small size Hall probe inserted in the bore and moved along the beam axis. This required a special magnetic field measurement setup that was designed, built and used for the field measurement as described in the following sections. Results of the field measurement confirm the feasibility of the adopted strategy.

Modeling predicted that magnetic forces between magnet arrays will cause measurable mechanical deformation of the supporting structure. Depending on the relative position of the arrays the force distribution and consequent structure deformation varies considerably. As was mentioned in ref. [1], when the arrays are positioned to create a helical magnetic field, there will only be forces between opposite arrays that produces stress toward the beam axis. In this case rectangular frame is loaded in a side-to-side direction where it has a maximum stiffness. When magnet arrays are positioned to produce a planar field, there are additional much stronger magnetic force components due to attraction and repulsion of adjoining arrays. These forces result in a significant torque applied to the frame plates and in frame deformation in the diagonal direction. Note that in this direction the deformation

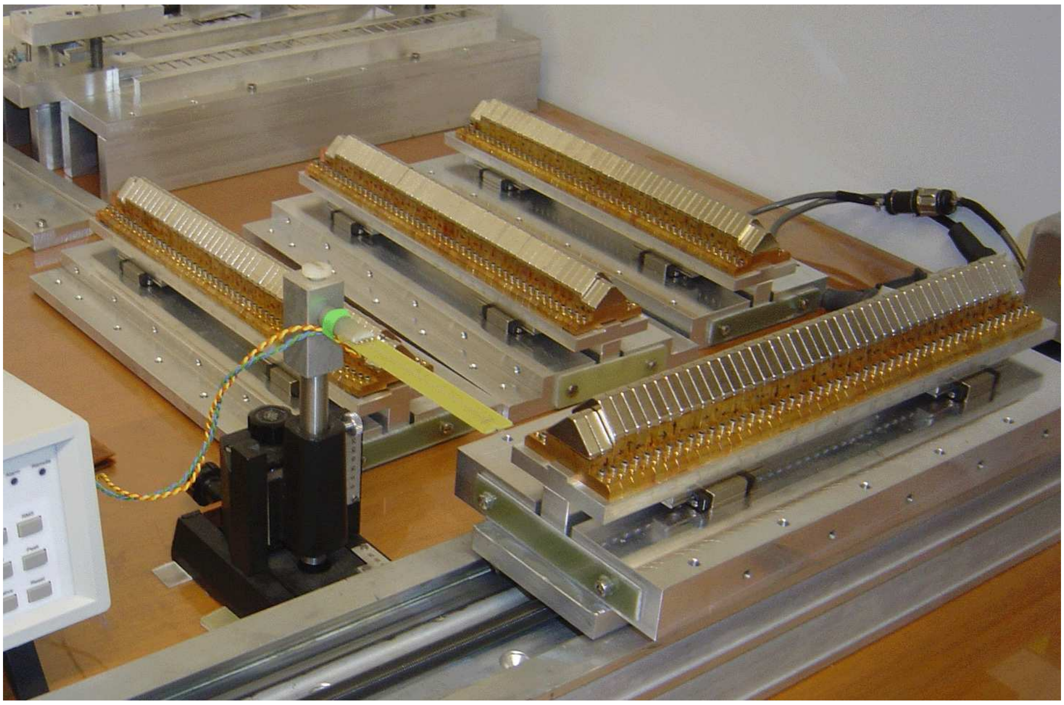

FIG. 1: "Delta" undulator magnet arrays prepared for assembly.

depends not only on the frame material and stress distribution but also on the properties of the joints between frame plates, i.e., on the joint geometry, number of bolts used to secure the joint, bolt material and size, bolt pre-load and other factors. Because of these many details a simple ANSYS stress analysis can not describe the real situation. This prompted us to measure the real structure deformation under various conditions. Results of these measurements confirm the possibility to use a rectangular box-like frame and suggest structural improvements.

II. MODEL DESCRIPTION

The tested Delta undulator model was 30cm long with 5mm round gap (bore). It consisted of two pairs of magnet arrays made with Delta-like shape NdFeB (40SH)PM blocks. One array pair generated a vertical field, the second, a horizontal field. Arrays were mounted via miniature rails on strong 20mm thickness aluminum plates that form the undulator frame. Fig. 1 shows the 4 arrays prior to final assembly. Here one can see PM blocks soldered to copper holders, rails connecting arrays to the frame plates and other details. One can notice that two end PM blocks on the end of each array are displaced relative to the others. This

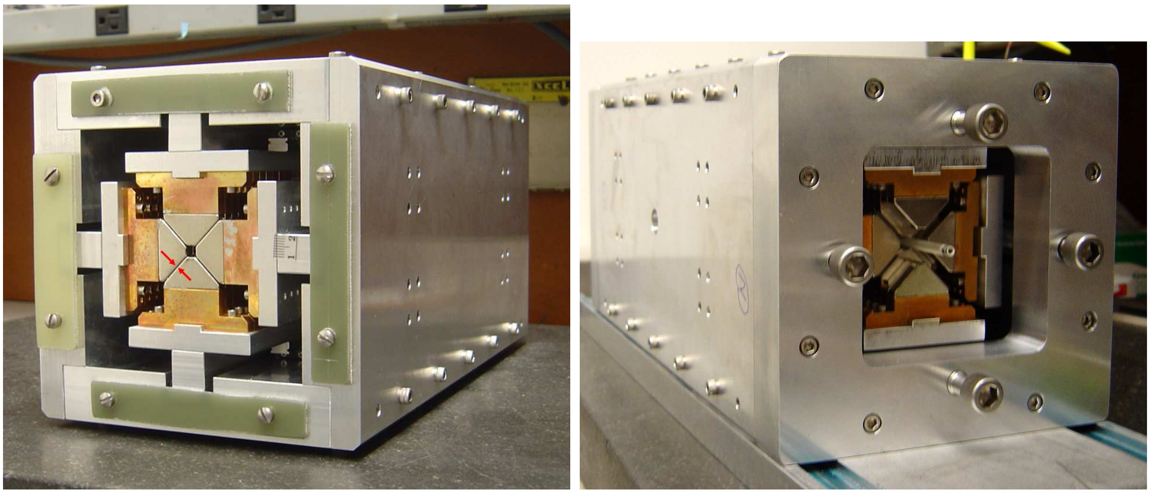

FIG. 2: On the left - the tested "Delta" undulator model with removed end plates. Arrows show the gap between adjoint arrays referred in section V B. On the right - the model with end plates and bolts used for magnet arrays displacement.

was done for proper magnetic field "end termination".

The assembled model is shown on the left side Fig. 2 with end plates removed for a better view of the internal structure. It is the rectangular box $15 \times 15 \times 30$ cm with magnet arrays inside. As a magnet array displacement mechanism we used 3/8-24 UNF bolts (two for each array) screwed through the end plates. The end plate and the driving bolts are seen on the right side of Fig. 2. When needed we employed dial gauge indicators for precise array position control. It also should be mentioned that the torque applied by fingers to the driving bolts was enough to displace the magnet arrays.

Additional details about the tested model can be found in reference [1].

III. MAGNETIC FIELD MEASUREMENT SETUP

The setup we built provides axial access to the Delta undulator field region. The setup consisted of two ceramic tubes (round single bore extrusion alumina 99.8%) with 3.96mm/2.39mm and 1.98mm/1.19mm outer/inner diameters. The larger tubing was used as a guide. It was inserted, precisely centered and fixed in the bore of the Delta undulator model.

The smaller tube fits tightly inside the guide and was used to hold a Hall probe sensor. A miniature sensor, HGT-2101 from LakeShore Cryotronics Inc., with $1.52 \times 1.52 \times 0.61$mm

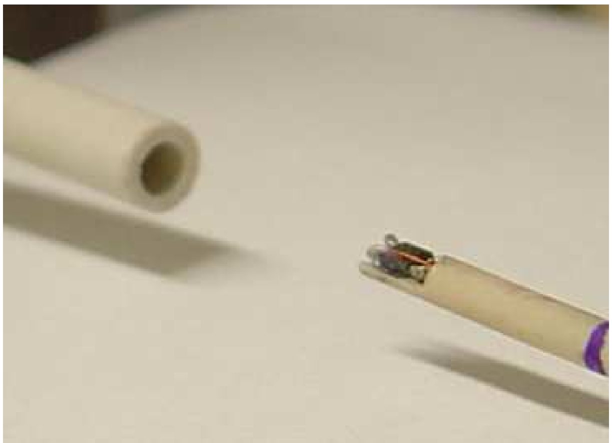

FIG. 3: Guide ceramic tubing and holding tube with the Hall sensor.

dimensions and 0.1×0.1mm active area was attached to the tip of the second tube. To align the sensor active area with the tube axis one tube end was cut with a precise step. The sensor was glued to the step and the leads were threaded through this tube. Fig. 3 depicts part of the guide ceramic tubing as well as a holding tube with the Hall sensor on the tip. The opposite end of the holding tubing was attached to the center of a rotation stage mounted on a linear translation stage. The rotary stage was used for tilting the Hall sensor. This allowed measurement of various transverse field components. The linear stage provided scans along the magnet axis.

The maximum offset of the Hall sensor center from the tested model axis was estimated as ~ 0.1mm. Taking into account the field variation across the bore calculated in ref. [1] we can estimate the possible field errors (dB/B) caused by sensor offset as 2×10^{-4} or less. This is comparable with other errors introduced by electrical noise, planar Hall effect, etc. We consider this acceptable.

The whole measurement arrangement is depicted on Fig. 4. On the left side one can see the tested Delta undulator model. The coils mounted on the top and side of the model were used for background magnetic field compensation. On the right side is a rotating stage on the linear stage. One also can see ceramic tubing used for guiding and holding the Hall sensor. The setup provides $\sim$60cm long scan.

Sensitivity of this Hall sensor was calibrated against an accurate Hall probe (HMNT-4E02VR) with absolute precision $\sim 1\%$. The sensor signal was processed with 455 DSP Gaussmeter from LakeShore Cryotronics, Inc. In typical scans the magnetic field was mea-

FIG. 4: Magnetic field measurement bench with the tested "Delta" undulator model. The seen are: background field compensating coils; ceramic tubing guiding Hall probe through the undulator bore; screws used for magnet array displacement.

sured "on-the-fly" with 0.25mm step in 1500 points.

It should be noted that because all components have a round bore (undulator model, guiding and holding tubing, rotary table) it was very convenient to use a laser beam for alignment and reference.

IV. MAGNETIC FIELD PROPERTIES

For this device a magnetic field geometry depends on the phase between magnet array pairs that create vertical and horizontal field components. For the 0^0 and 180^0 phases, 0 and 12mm displacement between pairs, the resulting field will alternate along the beam axis in two orthogonal planes, as illustrated on Fig. 5. Operation modes with these phases will be called "Planar 1" and "Planar 2". For 90^0 and 270^0 phases, 6mm and 18mm displacement, the resulting field will be helical CCW and CW, respectively. These modes will be called "Helical 1" and "Helical 2". Note that in planar modes the generated x-rays will be linearly polarized in the two orthogonal planes indicated in Fig. 5. In helical modes x-rays will be left and right circularly polarized.

The following subsections will present magnetic field measurement result first in helical

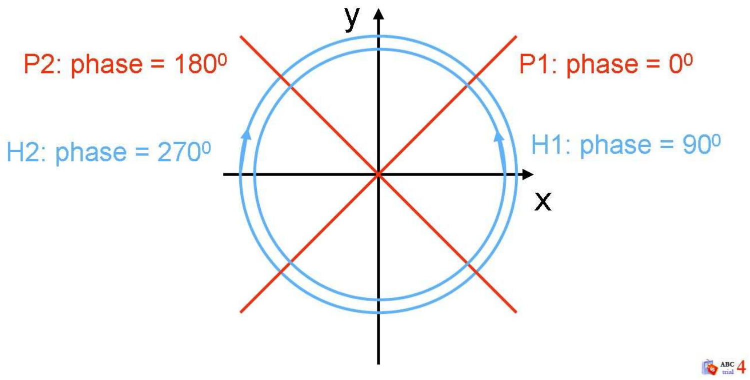

FIG. 5: Illustration for the mode identification. P1 and P2 indicate planes of alternating magnetic field for 0^0 and 180^0 phase between pairs of magnetic arrays. H1 and H2 are circulus representing helical modes for 90^0 and 270^0 phases.

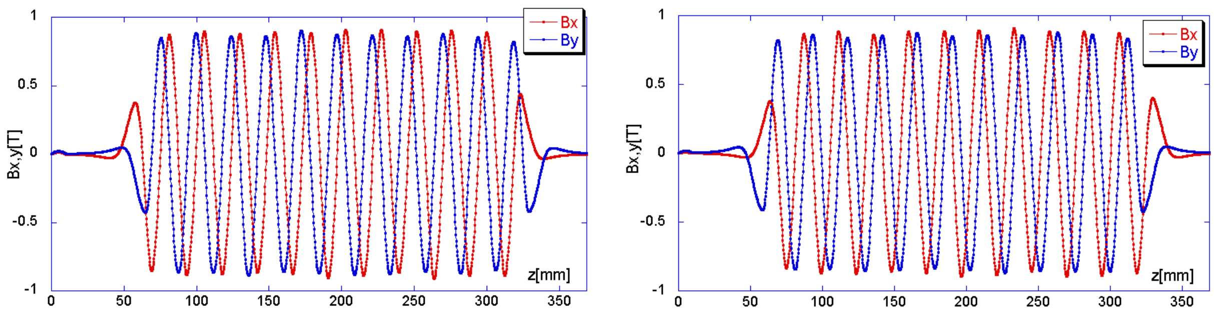

FIG. 6: Magnetic field measured in "Helical 1" (left) and "Helical 2" (right) modes.

modes then in planar modes.

A. Field in Helical modes

Results of the field measurement in "Helical 1" and "Helical 2" modes are depicted on Fig. 6. A sine wave fit applied to the horizontal (B_x) and vertical (B_y) field components in "Helical 1" mode gave 0.873T and 0.856T field component amplitudes and 88^0 phase between them. In "Helical 2" mode the field amplitudes are 0.844T and 0.857T and phase 270.5^0. Note that in both cases horizontal field component was purposely reduced from a peak value of 0.970T to match the vertical field by moving horizontal magnet arrays in opposite directions. The cause of the initial difference in these component amplitudes will be discussed in the next section.

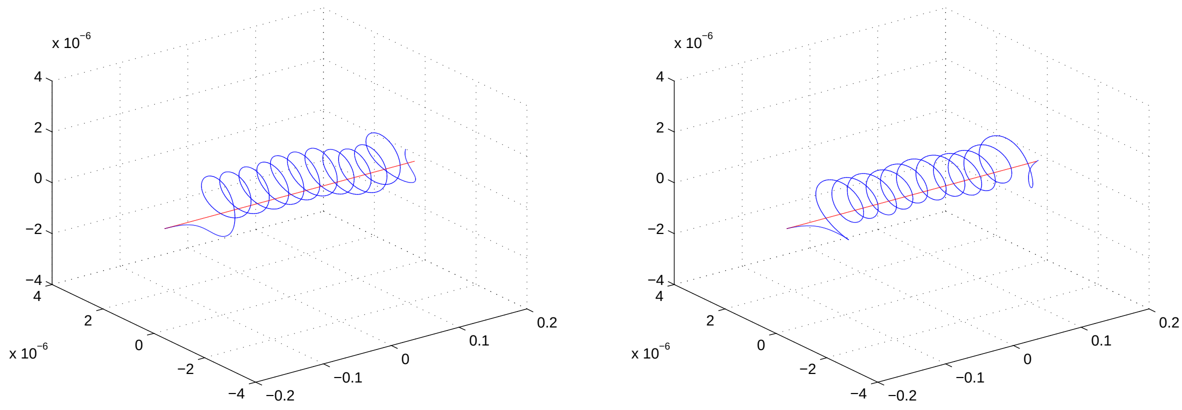

FIG. 7: 3D trajectories for 5GeV beam for "Helical 1" (left) and "Helical 2" modes (right). All scales are in meters.

Trajectories for a 5GeV beam were calculated with program SPECTRA [4] using the field distributions above and are presented in Fig. 7. The figures very clearly show left and right helical trajectory that translates into left and right x-ray circular polarization.

It should be mentioned that to improve straightness of the trajectories a current of a few amps through background field compensating coils was used to generate $\sim 10G$ constant magnetic field. At present it is not clear if this field was needed to compensate measurement field errors due to planar Hall effect or if there are other reasons for this. In any case, this effect does not seem to be a problem, because of the small amplitude and the fact that conventional undulators use similar compensating coils.

To verify the field quality we calculated flux spectra for the field distributions measured in the both helical modes and compared it with flux spectra calculated for ideal field of the same amplitude. Results are presented on Fig. 8. The negligible difference confirms a satisfactory field quality in both helical modes.

B. Field in Planar modes

The plots in Fig. 9 depict the measured vertical and horizontal field components in "Planar 1" and "Planar 2" modes. The left plot corresponds to 0^0 phase shift between pairs of magnet arrays, the right for 180^0. The accurate wave fitting in "Planar 1" mode gives horizontal field amplitude $0.97T$, vertical $0.84T$ and phase between components -0.41^0.

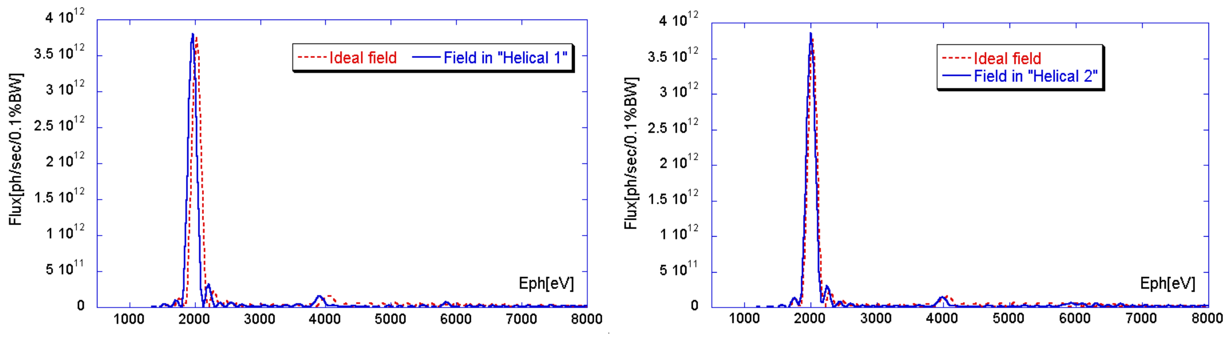

FIG. 8: Flux spectrum calculated for the field distribution measured in "Helical 1" (left) and "Helical 2" (right) modes in compare with ideal field spectrum. Calculation made with program SPECTRA [4] for Cornell ERL type beam (5GeV, 25mA current, 8pm emmitance) 0.5mm radius slit at 30m from undulator.

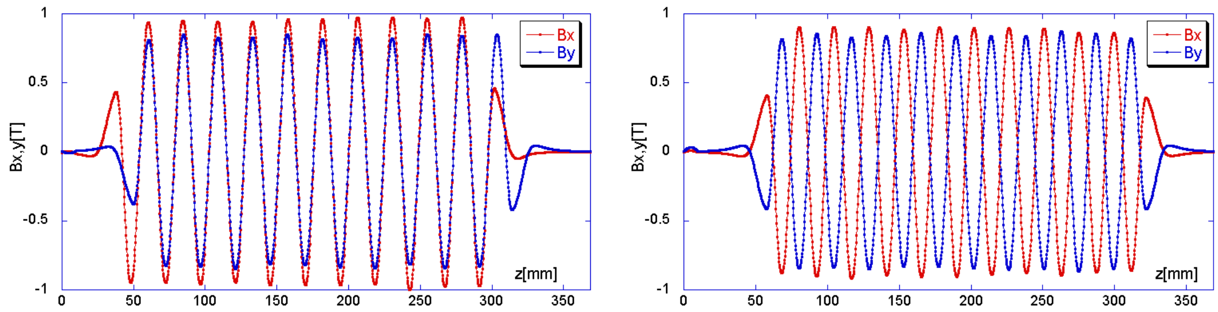

FIG. 9: Vertical and horizontal magnetic field components in "Planar 1" (left) and "Planar 2"(right) modes.

The fitting for "Planar 2" mode yielded $0.90T$ for horizontal peak field, $0.85T$ for vertical with 179.81^0 phase. The noticeable difference between vertical and horizontal field strength (horizontal is stronger) is due to enlargement of the gap between horizontal magnet arrays. The reason for this enlargement will be discussed in section V. Vertical field amplitude, in principal, should not be affected by the horizontal gap enlargement. Its measured value is between 90% to 96% of the predicted 1.01T field; see ref. [1]. A possible cause for the vertical field variation between "Planar 1" and "Planar 2" modes is mechanical structure imperfections. This will be discussed later.

The resulting magnetic field will be planar if the phase between vertical and horizontal field components is zero or 180 degrees. The measured phases differ from these values by 0.41 and 0.19 degrees. This difference will create non-planar field components at the level

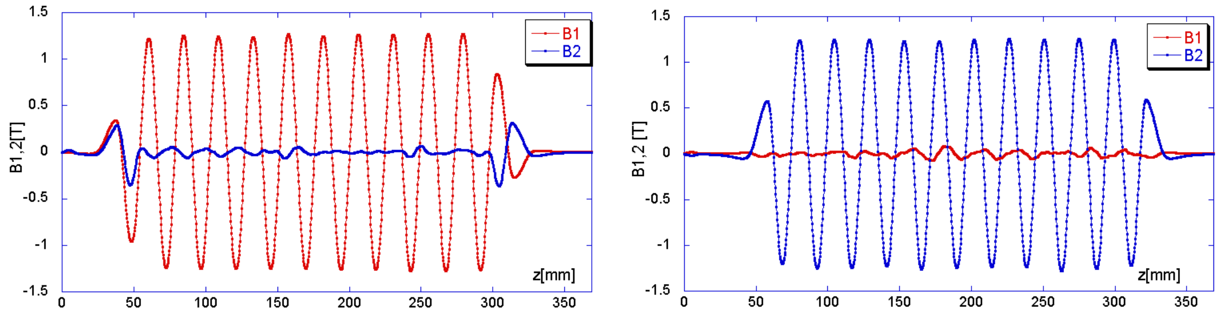

FIG. 10: Two orthogonal magnetic field components $b1$ and $b2$ in "Planar 1" (left plot) and "Planar 2" (right plot) modes.

of 7×10^{-3} of the main field which is negligible.

Plots in Fig. 10 depict two orthogonal field components $B1$ and $B2$ measured with Hall probe tilted around the beam axis by about 45^0 and 135^0.

Because vertical and horizontal field components have slightly different amplitude the actual angle in the case of "Planar 1" mode was $\theta_1 = 40.9^0$ and $\theta_2 = 130.9^0$. In "Planar 2" mode $\theta_1 = 43.4^0$ and $\theta_2 = 133.4^0$. The wave analysis indicated 1.266T peak field for $B1$ in "Planar 1" mode and 1.251T for $B2$ in "Planar 2" mode. This is approximately 87% of the expected 1.43T field strength; see ref. [1]. One reason for the peak field reduction was mentioned above.

The beam trajectories corresponding to the measured $B1$ and $B2$ field components in the planar modes are depicted on Fig. 11. For calculations we used the program SPECTRA [4]. In the case of the "Planar 1" mode, the beam trajectory undulates with ~ 1 micron amplitude in the plane orthogonal to $B1$. In the other plane the trajectory is straight and shifted from the centerline by approximately 1.5μm. This shift is due to the non-zero $B2$ field at the model ends. In the "Planar 2" mode the trajectory undulates in the plane perpendicular to the $B2$ field, and $B1$ causes a small $\sim 0.5\mu$m trajectory offset. Note that the general straightness of trajectories was optimized with background compensating coils.

The x-ray flux spectrum and the field phase errors were calculated to analyze the measured field properties. Results are presented on Fig. 12 and Fig. 13.

Fig. 12 shows the x-ray spectra calculated for the fields measured in "Planar 1" (left) and "Planar 2" (right) modes in comparison with spectrum generated for ideal fields. In "Planar 1" mode the field phase errors cause negligible degradation of the first harmonic.

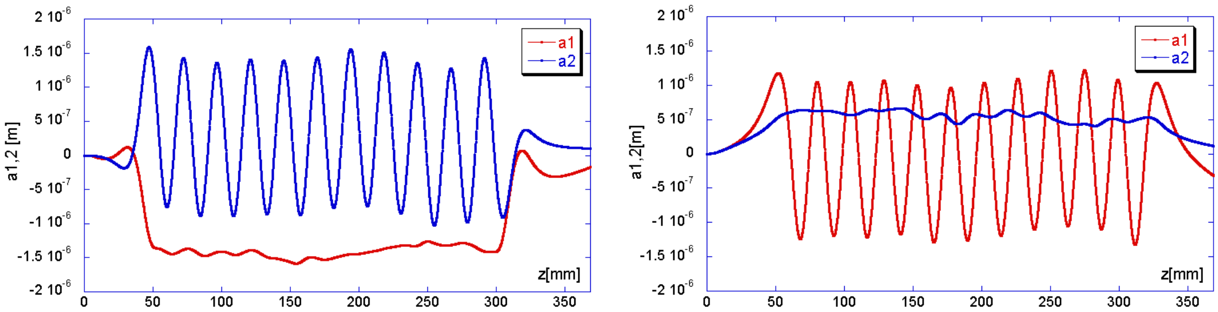

FIG. 11: 5GeV beam trajectories corresponding to the measured field in "Planar 1" (left plot) and "Planar 2" (right plot) modes.

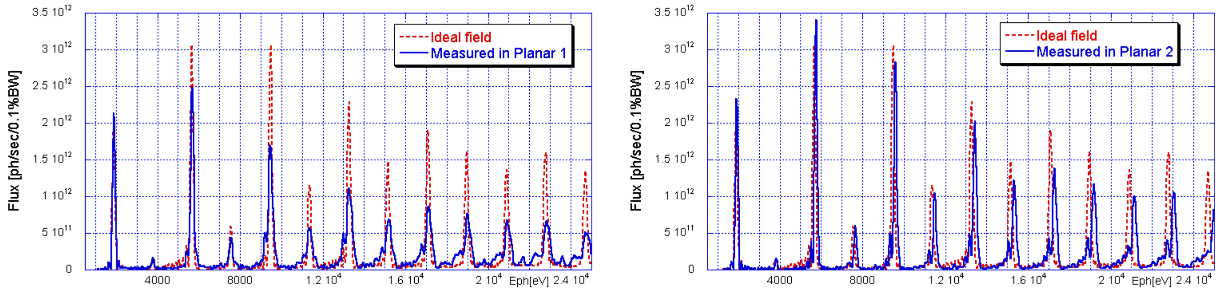

FIG. 12: X-ray flux spectrum calculated for the measured field in "Planar 1" (left plot) and "Planar 2" (right plot) modes. Dashed line is the spectrum calculated for ideal field.

Third and fifth harmonics are reduced by 14% and 36% respectively. In "Planar 2" mode the spectrum degradation is smaller with no degradation of the first and third harmonics and only a 7.7% reduction of the fifth. The better spectrum in "Planar 2" mode suggests smaller field phase errors. This was confirmed by the analysis made with software "B2E V3.3" developed by the ESRF ID group [5].

Fig. 13 depicts phase errors of the field in "Planar 1" and "Planar 2" modes. The RMS field error is 9.6^0 in "Planar 1" mode and two times smaller, 5.26^0, in "Planar 2". It should be mentioned that these errors are from 2 to 4 times larger than was expected based on individual magnet array field measurement results; see ref. [1].

One interesting observation can be made from the analysis of the phase error variation along the model. Data for "Planar 1" mode plotted on the left side of Fig. 13 clearly exhibits quadratic dependence of the phase errors with pole number. This suggests a linear variation of magnetic field strength along the test model, see dashed line, that could be the result of

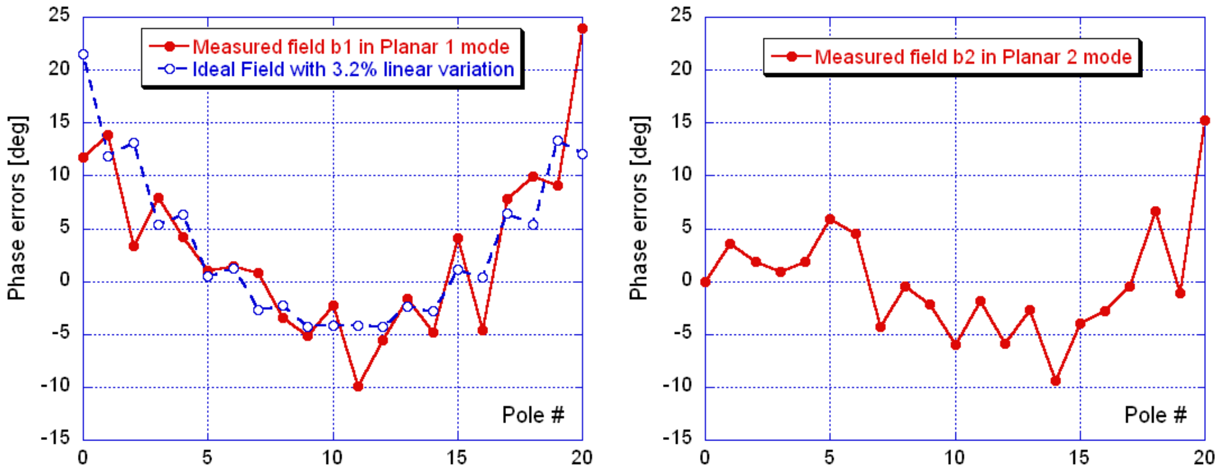

FIG. 13: The phase errors of the field in "Planar 1" (left plot) and "Planar 2" (right plot) modes.

mechanical displacement of one or more magnet arrays.

V. MECHANICAL PROPERTIES EVALUATION

In this section we report on evaluation of the supporting frame deformation, as well as magnet array displacement under the stress created by magnetic forces.

A. Frame deformation study

As mentioned in the introduction, the magnetic forces applied to magnet arrays in helical and planar modes are very different. In the first case a force $\sim$ 375N per array is directed toward the magnet center. The stress analysis under this condition carried out with programm ANSYS [3] predicted the maximum frame deformation only 0.23μm at the center of plates forming the frame, see left plot on Fig. 14. In planar modes, due to repulsion and attraction of adjoining arrays there are much stronger forces, $\sim$ 3432N in the direction perpendicular magnet axis. These forces will be transferred to the frame creating the deformation depicted on right plot Fig. 14. In this case the predicted maximum deformation $\sim$ 39μm at the upper edge.

The setup used for frame deformation tests and results are plotted on Fig. 15. The model was positioned on a solid table. Then, using an accurate gauge, we measured displacement

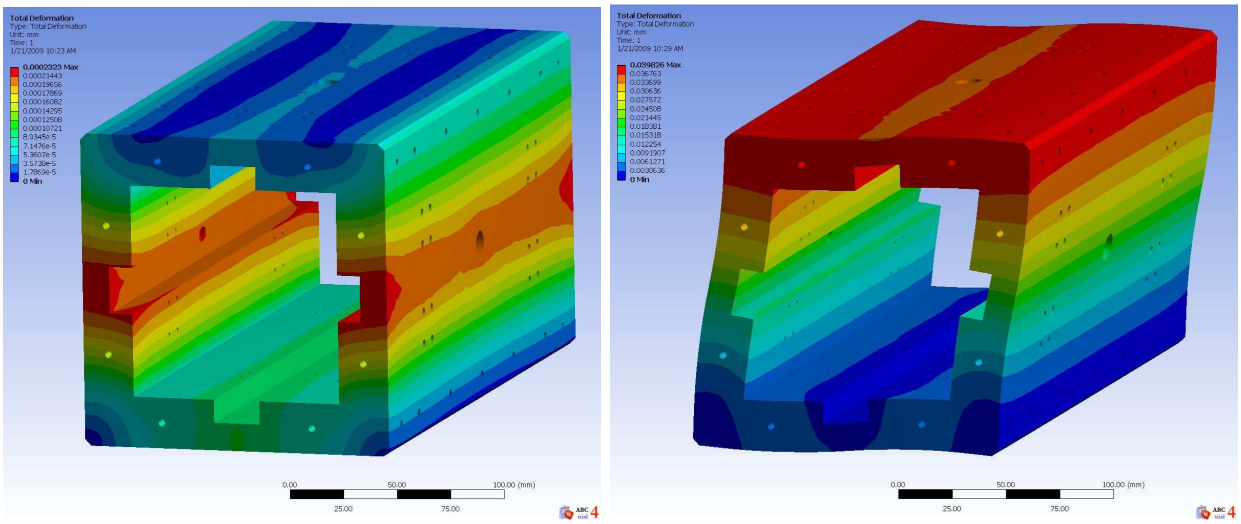

FIG. 14: Frame deformation in helical (left plot) and planar (right plot) modes predicted by program ANSYS [3].

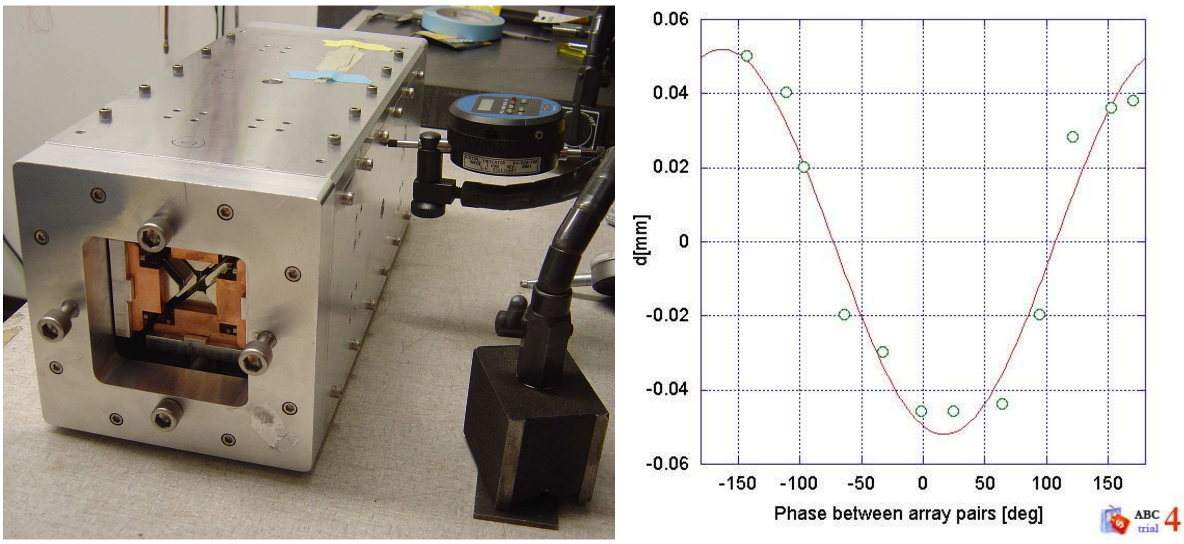

FIG. 15: The frame deformation measurement setup (left plot) and the measured deformation as function of the phase between pairs of vertical and horizontal magnet arrays.

of the upper side of the frame as a function of the relative position of the magnet arrays. Results are plotted on the right side. Here vertical axis is a edge displacement, the horizontal axis gives the phase between magnet array pairs. 0^0 and $\pm180^0$ correspond to "Planar 1" and "Planar 2" modes respectively, $\pm90^0$ phases are for "Helical 1" and "Helical 2" modes.

Confirming prediction, the data indicate maximum deformation in the planar modes and

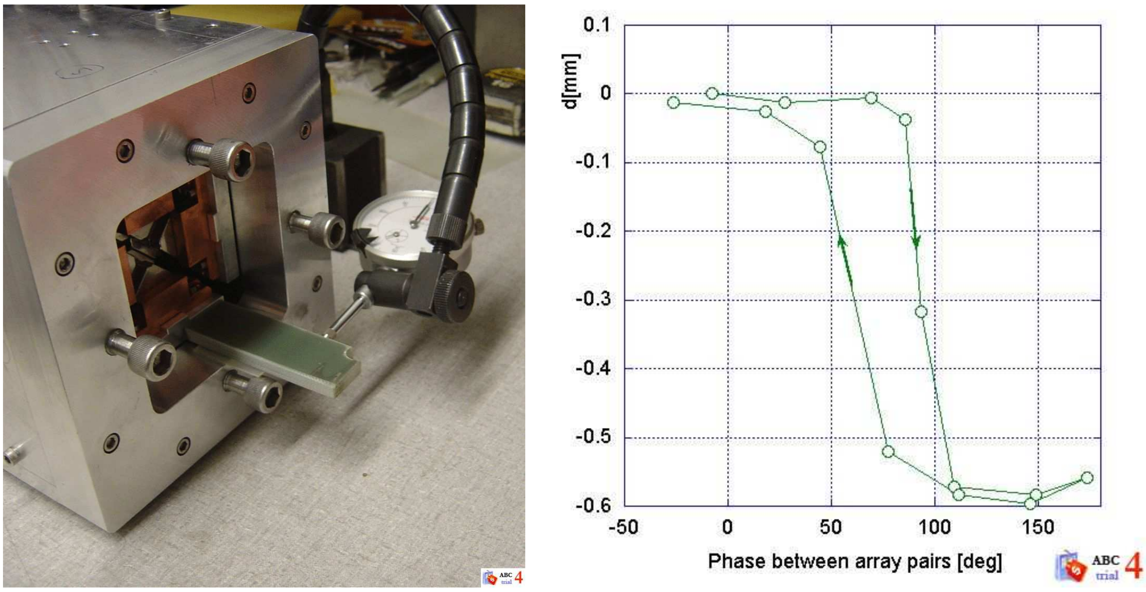

FIG. 16: The magnet array displacement measurement setup (left) and the measured displacements as a function of the phase between arrays (right).

minimum in helical. The sine wave fitting gives a $\pm 52\mu$m deformation amplitude which is consistent with the 39μm predicted. Note that consistency was archived only after bolts connecting the frame plates were tightened to their practical limit.

This frame was built with aluminum. Calculations with ANSYS predict that deformation of a frame made of stainless steel will be approximately three times less.

B. Magnet array sideways displacement

As mentioned above, in planar modes, due to interaction between adjoining arrays, there are strong forces perpendicular to magnet axis. Right after assembly of the undulator model we found that the gap between adjoining arrays varies when we move arrays longitudinally. To prevent damage to the model and to proceed with magnet field measurement we placed flat shims between frame plates. This increased the separation between vertical magnet arrays by 0.25mm, and caused a reduction of vertical magnetic field in comparison with horizontal. After the gap increased we were able to move magnet arrays freely.

To understand the cause of this problem we measured array displacement as a function of phase between vertical and horizontal pairs. Using the simple setup shown on left side

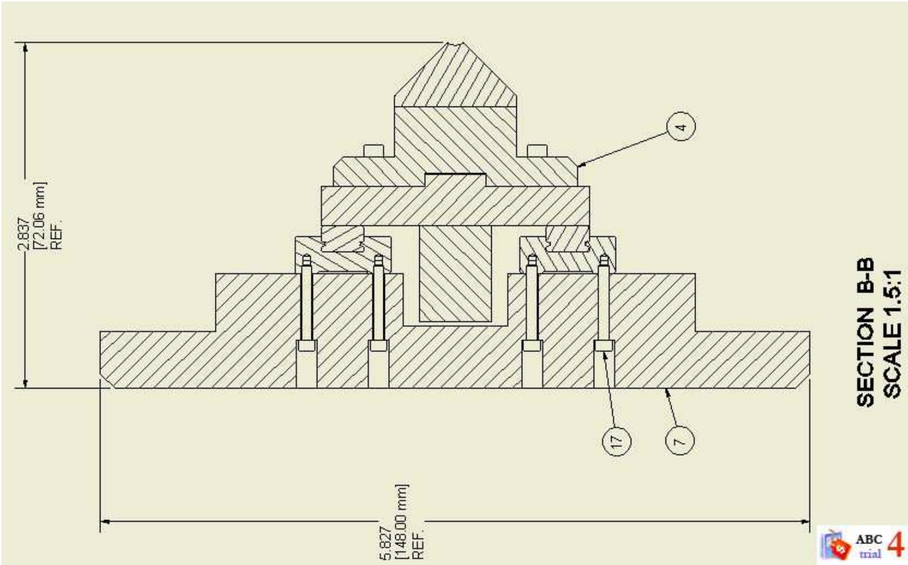

FIG. 17: Drawing of the magnet array on frame plate.

of Fig. 16 we found that a significant change in array position ($\sim$ 0.6mm) occurs when the phase crosses 90^0, see plot on the right side of Fig. 16. Note that 90^0 corresponds to helical mode with no sideways forces applied to array. When phase crosses 90^0 the sideways forces change direction to opposite. Thus we concluded that the observed change in array positions is related to the magnetic forces. However, it is too large to be explained by the frame deformation, see previous subsection.

The problem was finally traced to the connection between rails, frame plates and magnet arrays. The cross section drawing is shown on Fig. 17. Here the frame plate and array have flat surfaces. While screws used in this connection constrain the array displacement in a vertical direction there is nothing preventing sideways motion except friction. This is not enough to prevent displacement under a large sideways load. The next version of Delta undulator model will have groves in the frame plates as well as in magnet array plates to constrain such motion.

VI. DISCUSSION AND CONCLUSION

We evaluated magnetic and mechanical properties of the Delta undulator model. Evaluation shows:

1) The maximum magnetic field is close to the design value.

2) The field quality is quite satisfactory in helical modes and sufficient for proof of principals in planar modes.

3) The frame deformation is small and consistent with prediction.

4) There is a problem with magnet arrays sideways displacements in planar mode. This problem will be fixed by a minor change in the supporting structure geometry in the next model. The better design will improve the field strength and quality.

The next model support structure will be made of stainless steel instead of aluminum. This will reduce all structure deformations by a factor of three. The model will also have a provision for constraining magnet array sideways displacement. After magnetic and mechanical property testing, we plan to motorize the array motion, work out a method to cover magnet array surfaces facing the beam with a Ni coated cooper foil to smooth beam image current flow and work on the end pieces that provide a smooth transition to the standard beam pipe. The new model will also be used for development of UHV cleaning procedures.

In general, the evaluation results prove the basic principals of the Delta type undulator.

VII. ACKNOWLEDGEMENTS

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