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Magnetic Field Optimization of an In-Vacuum Undulator at NSLS-II

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A 3.0 m long In-Vacuum Undulator (IVU) is employed at the National Synchrotron Light Source II (NSLS-II) for the Hard X-ray Nanoprobe (HXN) beamline providing structural and X-ray fluorescence imaging with world-leading spatial resolution. On July 1st 2018 a gearbox shaft in the gap drive train assembly sheared due to corrosion fatigue caused by stress due to mechanical misalignment. The device was extracted from the storage ring and measured. The magnetic field measurements detected a degradation of the magnetic performance as well as a localized demagnetization of the first 3 upstream periods. This paper describes the mechanical repairs and the magnetic phase shimming optimization implemented to restore the spectral performance of the device.

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FIG. 1

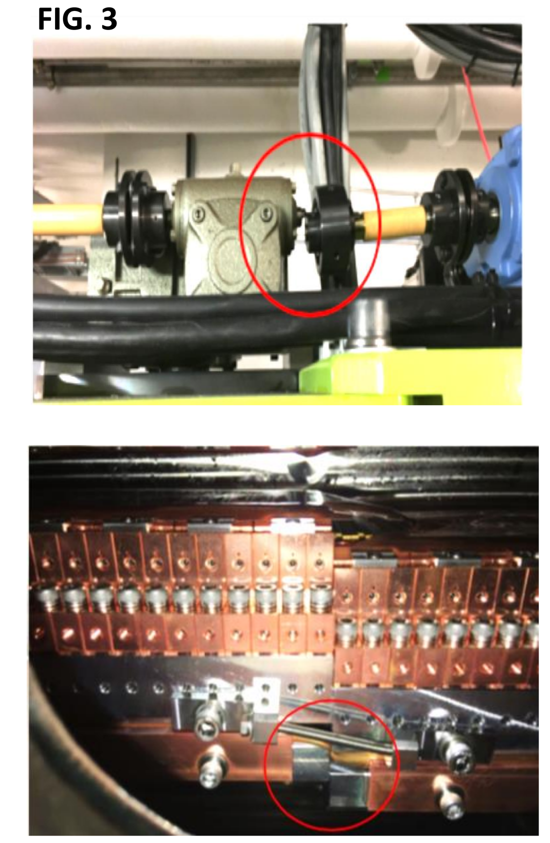
The HXN IVU was procured as turn-key device by Hitachi Metal America (Neomax) and installed into the storage ring in August 2014 in a short straight section. This device has a period length of 20 mm and a maximum effective K of 1.83 at 5.2 mm pole gap. The magnetic module consists of a half period unit with two NdFeB magnet blocks of high intrinsic coercivity and one Permendur pole piece. Figure 1 shows the IVU at the ID magnetic measurement facility (ID-MMF) for magnetic characterization and tuning

MECHANICAL ADJUSTMENTS

In July 2018 a catastrophic failure of the HXN IVU resulted in a complete severing of the horizontal drive shaft that was a common synchronous driver of all vertical axes. The fractured input shaft of the second gearbox, at the position circled red in elevation view of Fig. 2 and shown clearly at the top of Fig. 3, separated the coupled upstream and downstream magnet girders (both the out-of-vacuum structural girder and the in-vacuum cooling platen) allowing them to move independently.

The uncontrolled independent movement of these girders led instantaneously to critical secondary failures. Firstly, the loss of the gap drive synchronization corrupted the once precise relative parallelism of each magnet plane. Ring extraction, with realignment and magnetic field optimization in the ID-MMF was inevitable. Secondly, a shear failure of the copper water lines integral to the in-vacuum cooling platens breached the IVU vacuum chamber. Thankfully, its large rectangular seal could not keep the containment but rather acted to relieve the rising internal pressure (albeit onto the tunnel floor). Forensic inspection and survey of the horizontal drive train uncovered gross misalignments at the junctions of interconnecting shafts and distortion even within shaft segments. Subsequently, data from accelerometers that had been attached to the shipping container revealed the HXN IVU had experienced higher than expected accelerations, particularly along its long axis. Finite element analyses of the IVU subject to such sensor-recorded loads shows deflected shapes of the structural frame and drive shaft that closely resemble post-mortem survey data as shown in Fig. 4. Furthermore, an in-situ survey performed at the sister CHX IVU of identical construction revealed similar misalignment errors that are, in fact, of even greater magnitude at certain points in the drive train. Various measures were proposed by committee to address this serious concern (e.g., structural reinforcement with "Girder Bridge", water detection sensing, passive pressure shut-off valves, etc. The HXN IVU was extracted immediately over a long weekend and transported to the ID magnetic measurement facility. Replacement right-angle gearboxes were ordered, not just for the failed unit, but for all four vertical axes. Upon receipt, careful bench QI by CMM measurement indicated to varying degrees, a poor alignment between the horizontal input shaft and vertical output shaft on all new units. Yielding to operation demands, these new gearboxes were nevertheless installed while taking careful measures to "average out" those misalignments with existing flexible couplers, especially at critical high-stress points to minimize possible further fatigue.

FIG. 3



Vertical Magnetic Center

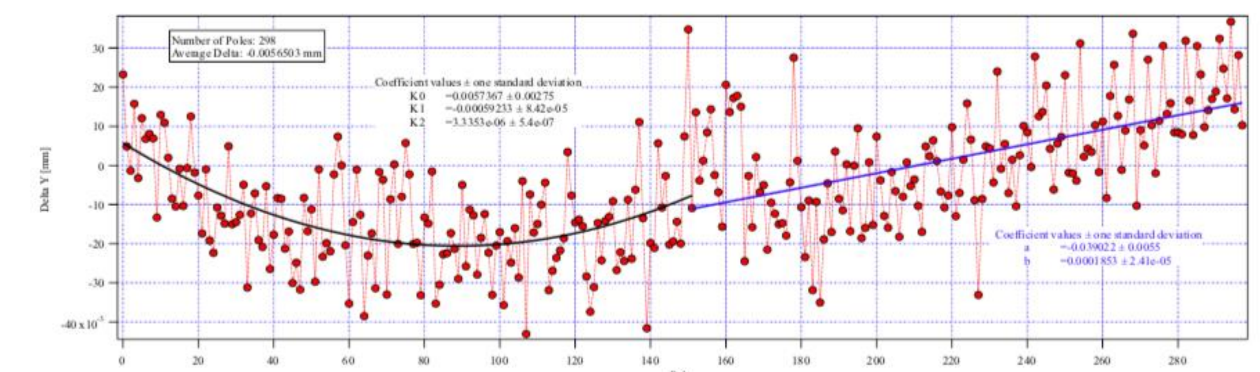
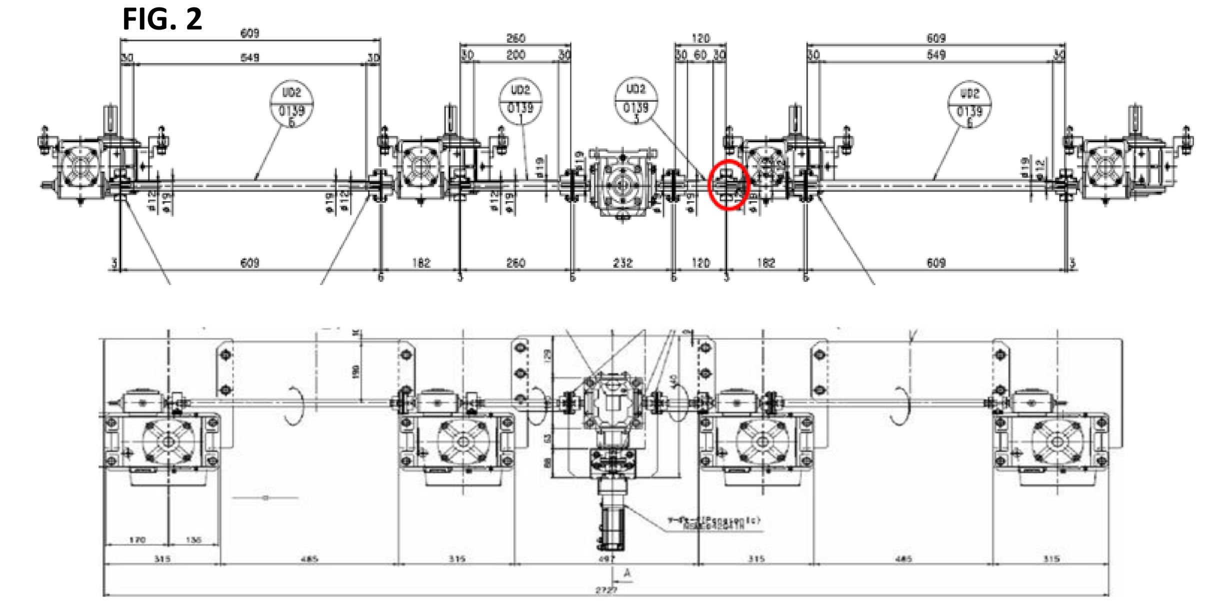


FIG. 2



MAGNETIC FIELD OPTIMIZATION

After the mechanical repair was successfully completed, a full set of measurements were performed in order to characterize the magnetic field errors of the device. These measurements revealed that the first 3 upstream periods of the device were slightly demagnetized. The Figure 5 shows a comparison of the vertical magnetic field profile at 6.2 mm gap between the original measurement taken in 2014 and the measurement after the accident. The peak field amplitude of the first 3 upstream periods has decreased by 10% due to these demagnetized modules. The first attempt to restore the magnetic field performance of the device was extract the first 6 demagnetized modules on the top and bottom arrays of the device and insert the Neomax spare modules, which were identified according to the Helmholtz measurement data provided by the vendor. The magnetization in all three directions of magnets and the N-S magnetic field measurements at a given distance were carefully chosen in order to obtain mutual cancellation of the field errors. A comparison between the magnetic field integral of a demagnetized module versus an original module is shown in the Fig. 6. A total of 12 replacement modules were installed on the magnetic girder on the upstream side of the device.

FIG. 5

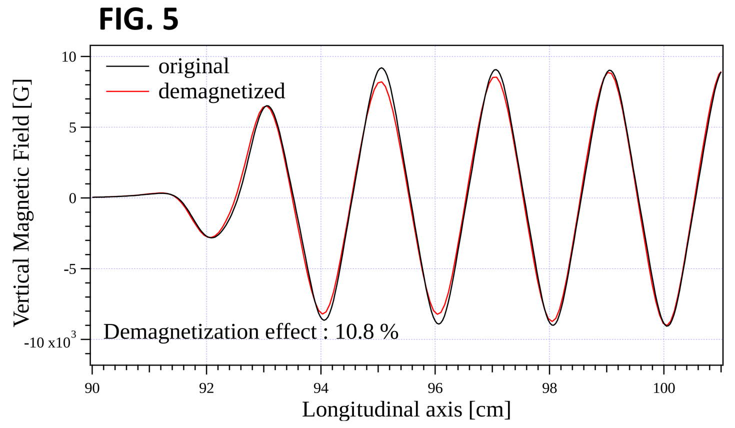


FIG. 6

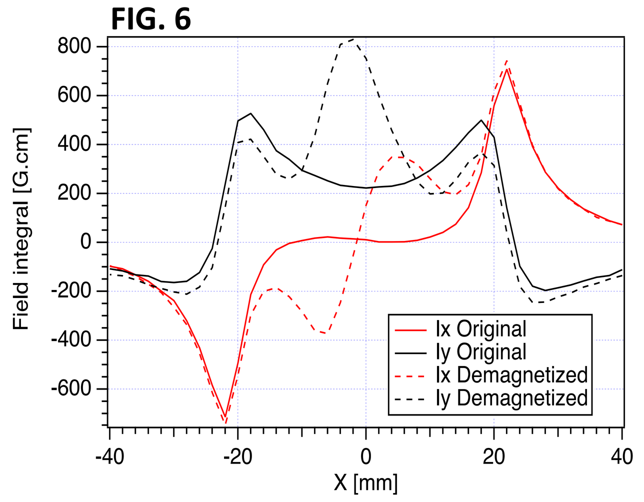
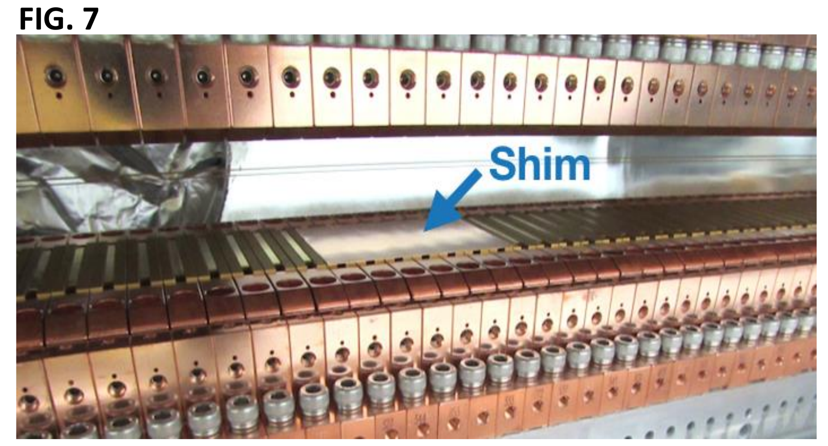
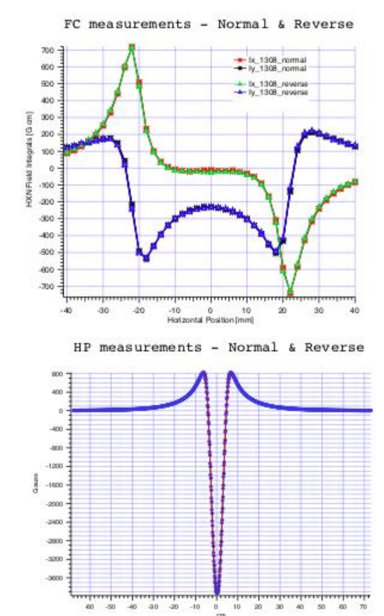


FIG. 7



Magnetic module : half period unit, consisting of 2 magnet blocks and 1 pole piece



PHASE SHIMMING OPTIMIZATION

The RMS phase error is used as figure-of-merit to quantify the effect of magnetic errors on the radiation intensity. Therefore, in order to restore the spectral performance of the device a phase shimming technique was implemented. This technique consists of increasing or decreasing locally the on axis peak field along the device without distorting the periodicity of the field. A proper tuning of the peak field advance by using magnetic shims allows the RMS phase error to be minimized. The phase shimming was implemented by placing thin Ni-Cu sheet of 100 µm thickness on the surface of the magnetic array as shown in Fig. 7. The Ni-Cu sheet becomes magnetized under the surrounding nominal field and the additional magnetization can be regarded as a small field source and enhances the field locally. The specific locations, dimensions and number of the shims necessary for the magnetic correction were determined by using an optimization script developed in-house. The shimming procedure is performed based on the measurement data and pre-measured shim-signatures, which describe the magnetic field perturbation induced by the shims located at different longitudinal positions. Given a set of shim-signatures is possible to predict the effect of any shim configuration on the magnetic field distribution and consequently on the optical phase error at a specific gap. The linear superposition of the fields generated by the shims results in the desired magnetic field profile. The phase shimming was capable to improve locally the field quality of the device reducing the phase error to the required values without impacting drastically the total first integral. The phase error distribution at different gaps after the magnetic shimming is shown in Fig. 8. This error contribution is about 0.45 deg. and it is correlated to the mechanical gap repeatability (Fig. 9).

FIG. 8

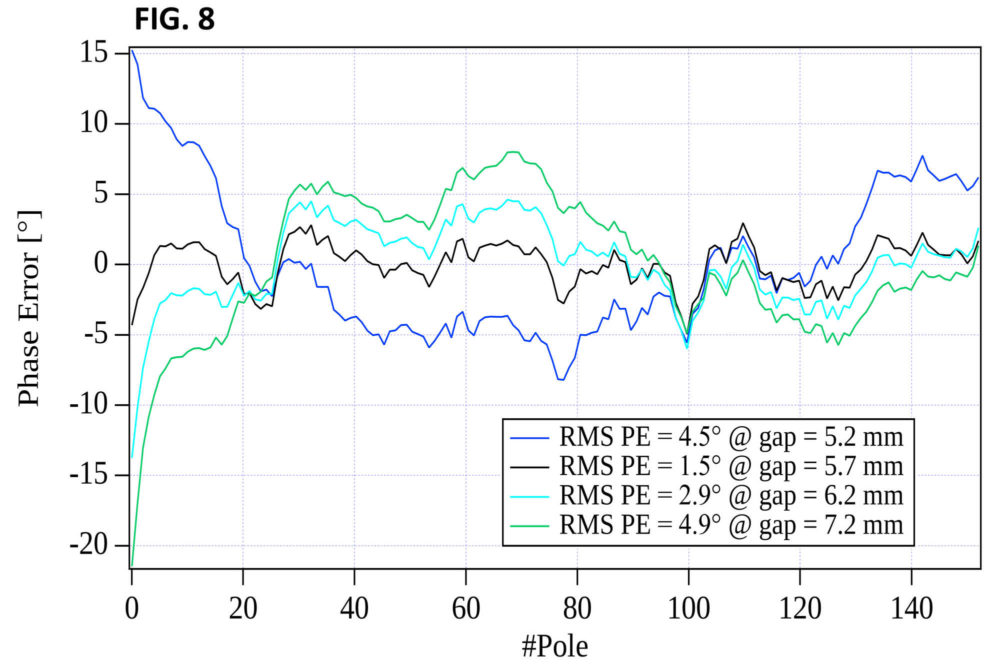
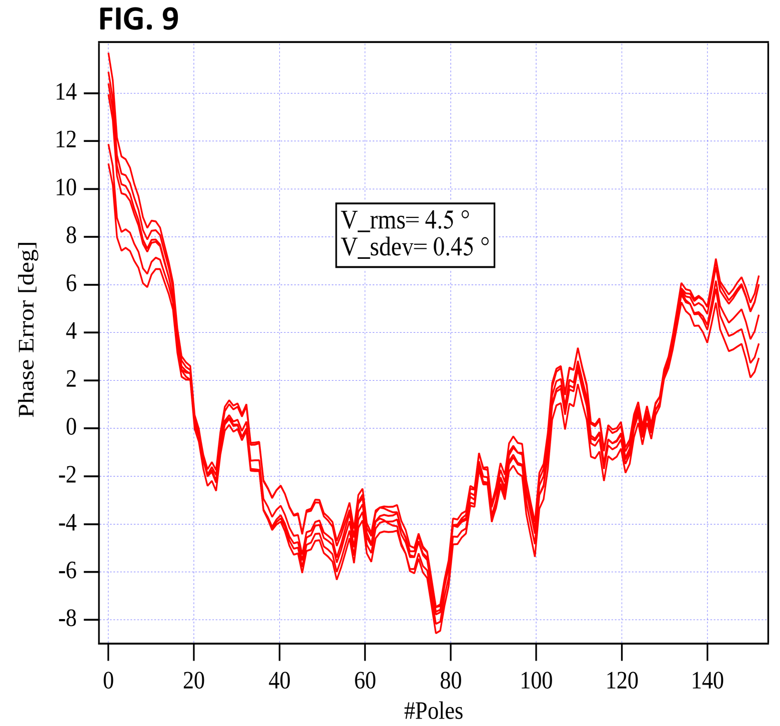


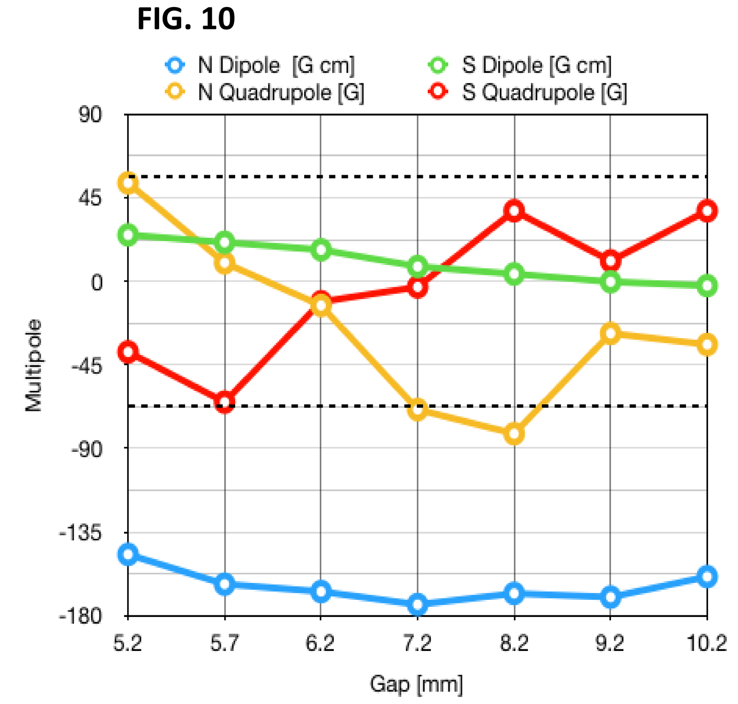
FIG. 9



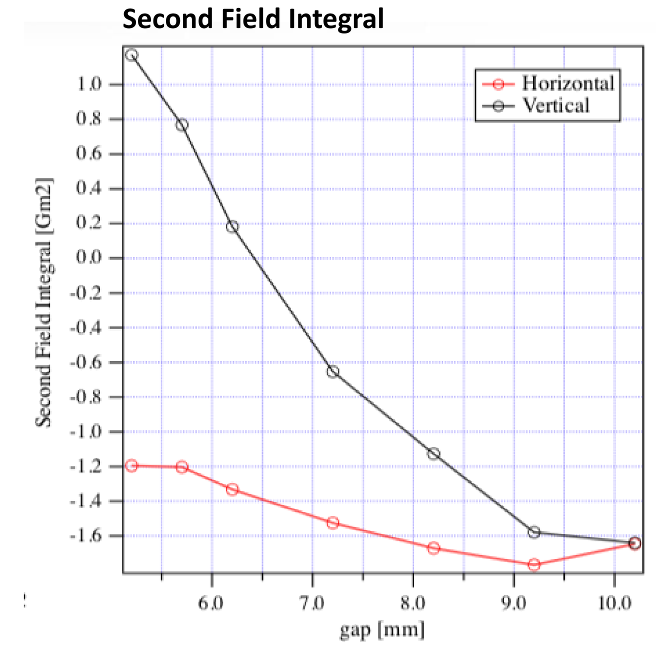
MULTIPOLE ERRORS COMPENSATION

After improving the phase error distribution, the next and final step of magnetic optimization was performed to compensate the remaining normal (N) and skew (S) integrated multipole of the device, primarily to minimize the quadrupole components. This final magnetic optimization was achieved by a rearrangement of the chip-magnets called "magic fingers" inserted into special holders and mounted to both ends of the upper and lower magnet arrays of the device. The magic fingers arrangement is a suitable method to decrease greatly the multipole errors. The final multipole values after the magic fingers tuning at several gaps are shown in Fig. 9. Even though the vertical dipole is out of the optimization range, the steering coils located upstream and downstream of the device can easily correct it.

FIG. 10

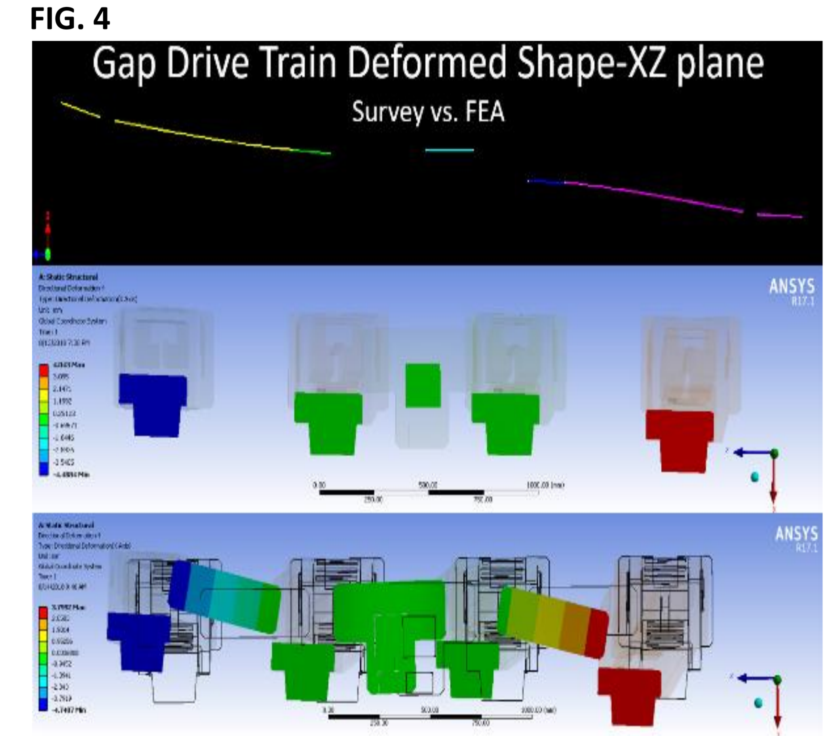


Second Field Integral



The magic fingers optimization was carried out using "IDBuilder", a genetic algorithm-based computer code for magnetic tuning of undulators.

FIG. 4



Once the drive train was assembled and aligned as best afforded by our compressed schedule, magnetic measurements and shimming operations looked to return the IVU to its original magnetic performance. Discussion of outcome of those measurements followed. Meanwhile, in parallel, the failed Cooling System (Figure 3) was reworked, this time with stainless tubing rather than copper, and including specially designed weldable re-entrant vacuum feed-throughs. This new Cooling System is expected to be more reliable benefitting from increased resistance to shear and fatigue, remaining always below the now higher material strengths and fatigue limit. To date, the thermal performance has proven to be equally efficient relative to the original copper system.

CONCLUSION

HXN-IVU suffered from a catastrophic failure and was successfully repaired in house thanks to a huge team effort by all staff of NSLS-II Accelerator Division groups. The magnetic and mechanical tuning strategies fully restored the magnetic quality of the device. The HXN-IVU is back in operation since January 2019 and no degradation of performance has been observed.