

GY Field Homogeneity Evaluation

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T. Schulteiss of Advanced Energy Systems, Inc. (AES) has provided field profiles for the Upgrade GY dipole [1]. These are given in the magnetic midplane along a) the design orbit and b) two paths displaced by $\pm 4''$ (± 10.16 cm) from the design orbit, starting at an initial location 1.016 m upstream of the pole to the 90° point of the magnet. The reference orbits are displayed in Figure 1, the raw field profiles (and an ideal field profile) are shown in Figure 2. The downward bump in the profiles at ~ 1.15 m is generated by a notch in the pole accommodating path length correction coils, which are being made integral with the ends of this magnet. The effect of this feature is discussed elsewhere [2].

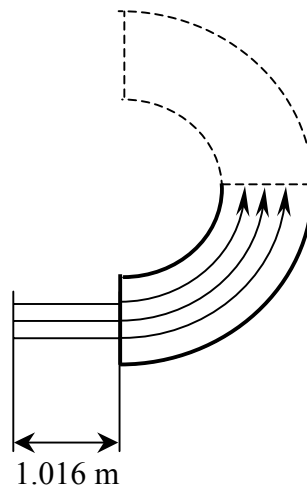


Figure 1: Reference orbits for analysis

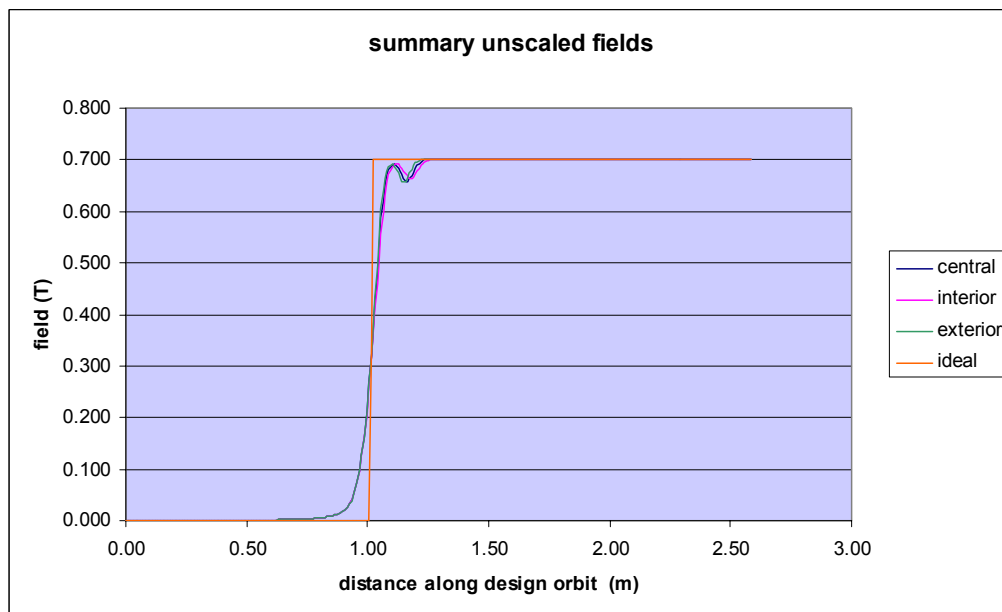


Figure 2: Computed and ideal field profiles along reference orbits

The “ideal” field is defined to be zero outside the magnet, the full 7.004846 kG required to bend a 0.210 MeV/c beam on a 1 m radius inside the magnet, and half the full field at position of the pole face ($x=1.016$ m). Prognostication of machine performance requires more careful inspection of the fields than allowed by the above figure. We therefore present, in Figure 3, deviations $(B(s)-B_{ideal})/B_{ideal}$ of the computed field data from the ideal, and in Figure 4 show the integral $\int ds(B(s)-B_{ideal})/B_{ideal}$, along each orbit, of these deviations. Were the magnet “perfect”, both the deviations and the error integral would be zero.

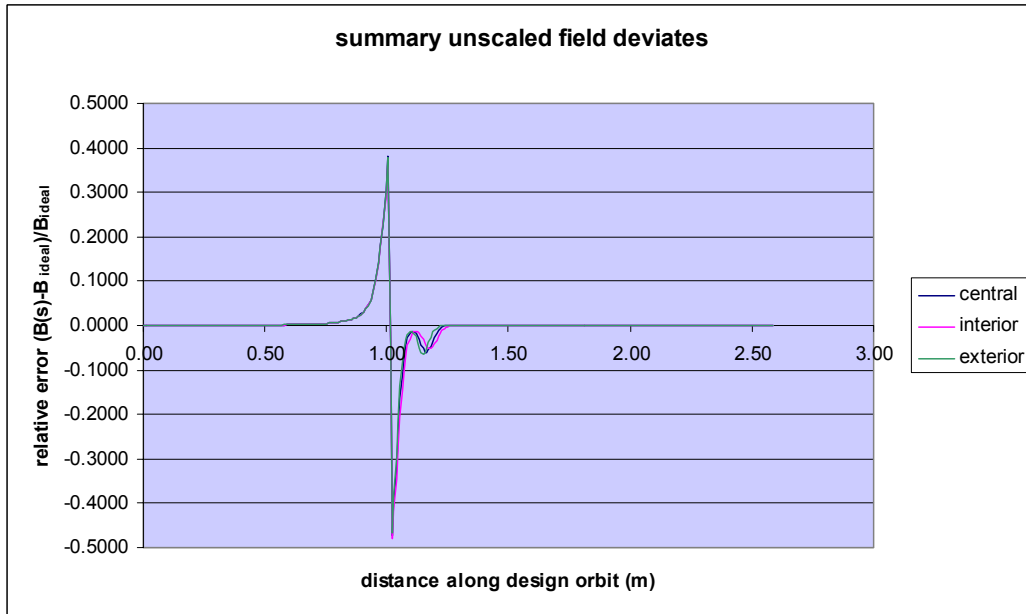


Figure 3a: Computed deviations $(B(s)-B_{ideal})/B_{ideal}$ from ideal of field on reference orbits.

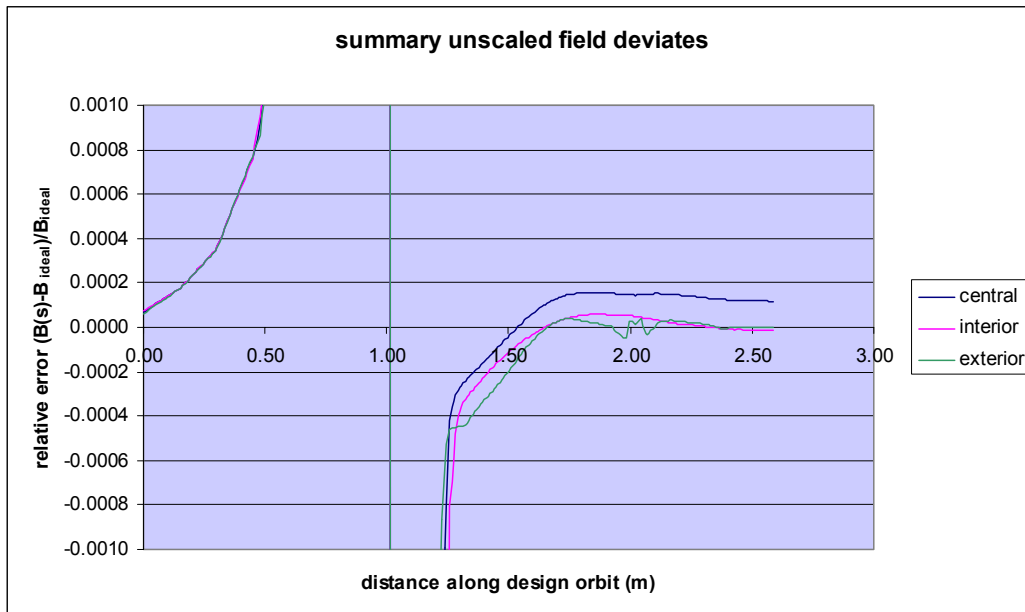


Figure 3b: As Figure 3a, with finer vertical scale to show detail.

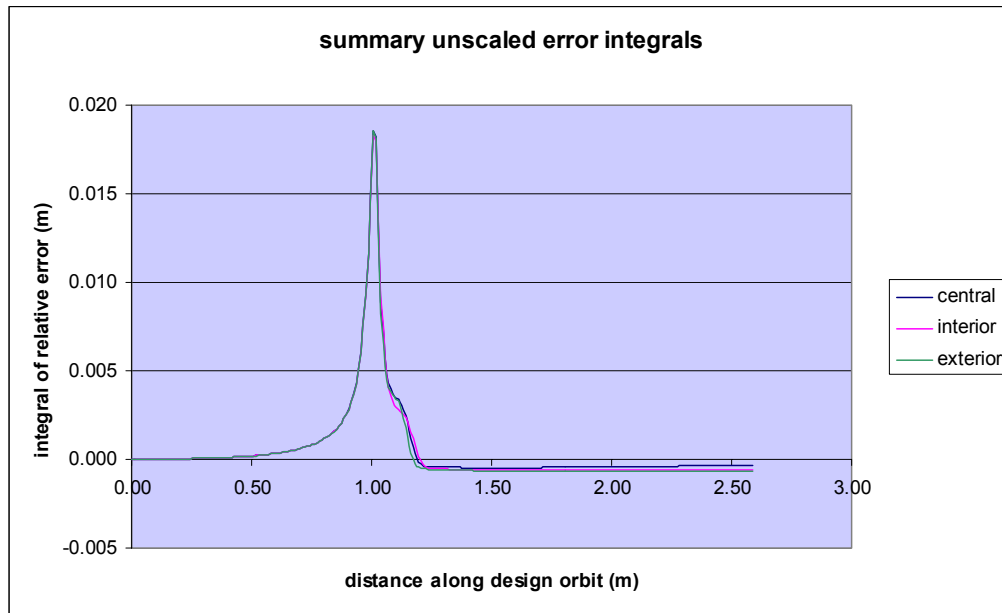


Figure 4a: Error integral $\int ds(B(s)-B_{ideal})/B_{ideal}$ along reference orbits.

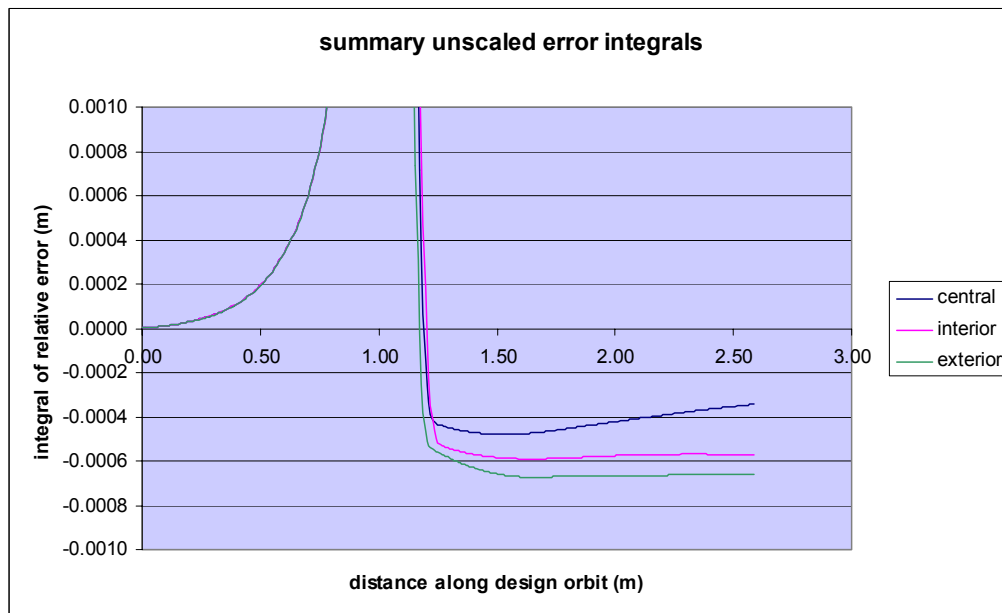


Figure 4b: As figure 4a, with expanded vertical scale.

The “real” magnet (as described by the computational model) possesses end-field field roll-off and transverse field variations, which can, in principle, degrade machine performance. Appropriate specification of error tolerances will avoid such performance problems; the Upgrade will be constrained by specifications similar to those used in the IR Demo [3]. The following requirements are relevant to this discussion:

- Core field will match ideal to 0.25 parts per thousand and be uniform to 0.1 parts per thousand
- Field integral will match ideal to 0.25 parts per thousand and be uniform to 0.1 parts per thousand

The magnet does in fact approach this performance along the preponderance of the length of each reference orbit. The field uniformity is quite good and, exclusive of the face region matches the ideal rather well. Two issues are important. The first is the correction of the error integral to the $\frac{1}{4} \text{‰}$ level. The second is the determination of the effect of the magnet end.

Error Integral Control – Operationally, the error integral will be corrected by adjusting a current shunt to correct the orbit through the dipole and to bring it onto the reference radius of 1 m. This is both readily and reasonably simulated by scaling the computed fields along each orbit by a common factor so as to zero the error integral along the central orbit. This will ensure that the bend angle matches the nominal $\pi/2$ at the 90° point of the dipole; by symmetry the outgoing beam will then undergo a bend of π radians. The results of this exercise are presented in Figure 5. A scale factor of 1.00022 is required to compensate the ~ 0.0005 m decrement in the error integral shown in Figure 4b. We note that the error integral $\int ds(B(s)-B_{ideal})/B_{ideal}$ is simply the bend radius times the angular error resulting from the field deviate, or “ $\Delta\theta = \Delta BL/B\rho$ ”. In view of the 1 m bend radius, it is thus numerically equal to the angular error in radians. The *relative* error in field integral over the region in question (90° of bending) is therefore, numerically, the Figure 5a error integrals divided by $\pi/2 \times 1$ m – meaning that the relative integral error is, exclusive of the pole region, at or below the required $\frac{1}{4} \text{‰}$ level.

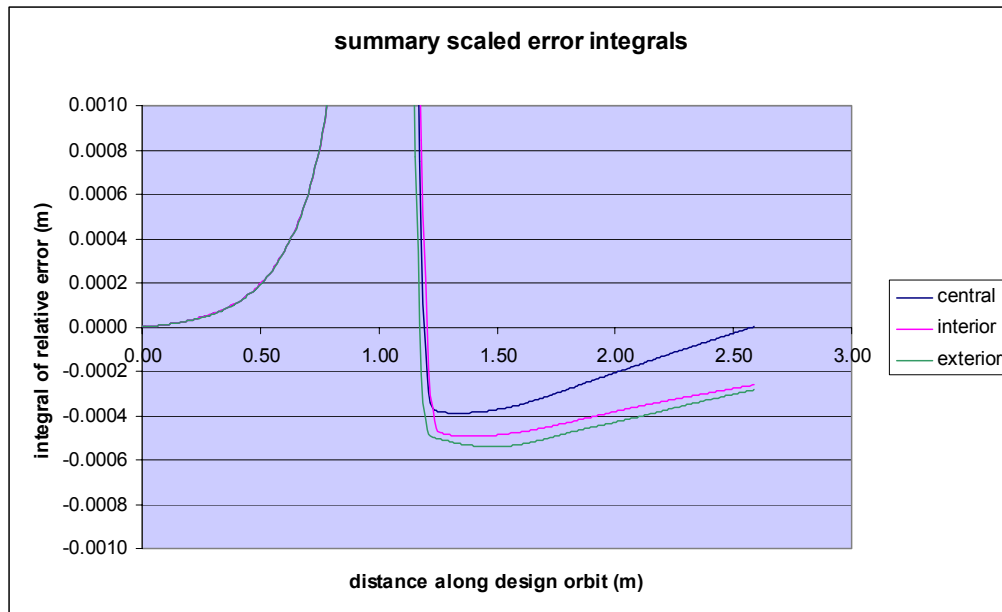


Figure 5a: Error integral with central field raised by 0.022% to zero error integral at 90° point of magnet, thereby generating overall bend of π radians.

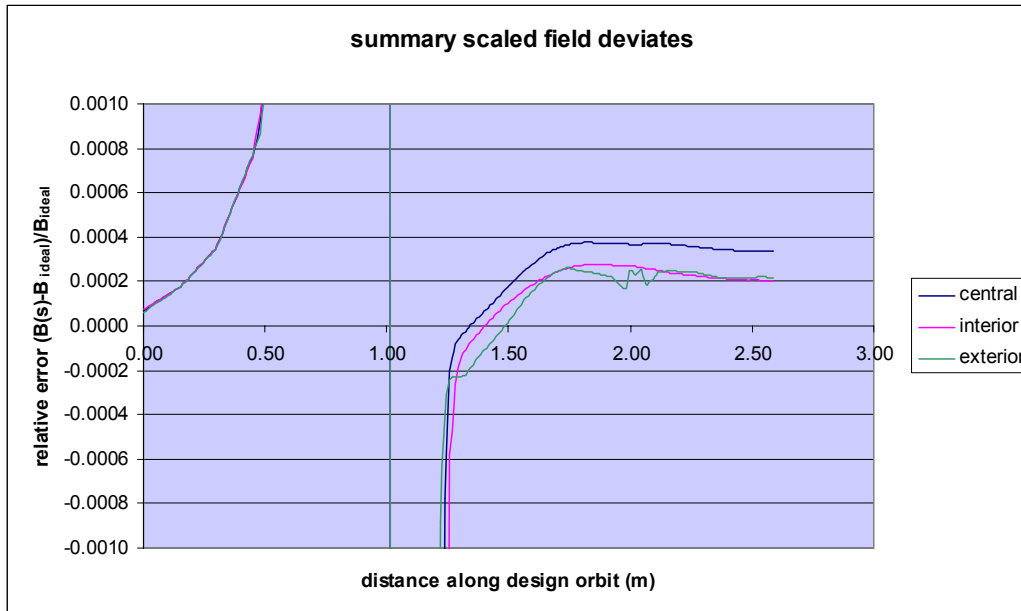


Figure 5b: Field deviations with central field scaled to zero error integral at 90° point.

The transverse variation (amongst the various reference orbits) of the error integral is of order 0.0003 m, which, when scaled to a relative angular error (relative error in field integral) by dividing by the $\pi/2$ bend angle and the 1 m bend radius, falls to 0.2‰, a factor of two greater than specification. We note however that the deviation is somewhat systematic through the magnet and is symmetric about the central orbit, suggesting that at least a portion of the variation is generated in the magnet end and can presumably be locally compensated by adjusting the adjacent trim sextupole. Noting that the associated angular error is 0.3 mrad (0.0003 m / 1 m bend radius), the required sextupole trim is

$$k_2 = B''/Br = \delta\theta / lx^2 = 0.0003 \text{ rad} / (0.15 \text{ m} \times 0.1 \text{ m} \times 0.1 \text{ m}) = 0.2/\text{m}^3,$$

which is a few percent of the nominal Upgrade trim sextupole excitation. As an alternative (it is a field deficiency, after all), additional field integral could be provided by appropriate pole-face shims.

Given the imposed field integral correction, the core field deviations (Figure 5b) are at the 0.02 – 0.04% level along the reference orbits and vary (amongst the various reference orbits) by less than 0.02% level transversely through much of the magnet. This is close to, if not actually at, the specification for core field homogeneity and will probably not represent a performance limitation.

Effect of End Fields – Some aspects of this problem have been discussed earlier [4]. Field roll-off at the magnet end manifests itself in premature bending outside the magnet, followed by under-bending in the initial portion of the magnet. The effect is then to put the beam on a trajectory inboard of, but more or less parallel to, the design orbit. The

offset can be estimated by observing that the “centroid” of the error integral exterior to the magnet (the longitudinal point at which half the error integral has accumulated) occurs at $s \sim 0.975$ m, while the centroid of the error integral interior to the magnet (the point at which the error is half corrected) occurs at $s \sim 1.04$ m. The integral is of order 0.018 m, corresponding (as noted above) to ~ 18 mrad angular error. Were this error is localized at the centroids, the beam would translate inboard by $0.018 \times (1.04 - 0.975)$ m, or 1.2 mm

A more detailed computation can be executed by numerical integration using the ideal and modeled fields. Results from such an exercise are given in Figure 6, using the geometry shown in Figure 1. Figure 6a shows the overall orbit for both “ideal” and “real” fields. Figure 6b expands on the pole face region of 6a, illustrating the translation of the beam due to field roll-off; Figure 6c illustrates the trajectories at the 90° point. Figure 6d presents the deviations of the “real” from the ideal orbit as a function of path length through the dipole. These deviations are of a magnitude and character consistent with the above simple model and estimate, and are not large enough to represent severe operational constraints or performance challenges.

As a final comment, we note the computational model presents fine detail such as the effect of the path length correction coil slot and the influence of a diagnostic port. The former generates the field suppression bump seen in Figure 3a near $s = 1.15$ m and is discussed in some detail elsewhere [5]; the latter provokes the “rattle” in the field along the exterior orbit seen in Figure 3b at $s \sim 2.0$ m. It is a small effect, worthy of comment only insofar as its appearance speaks to the quality of the model.

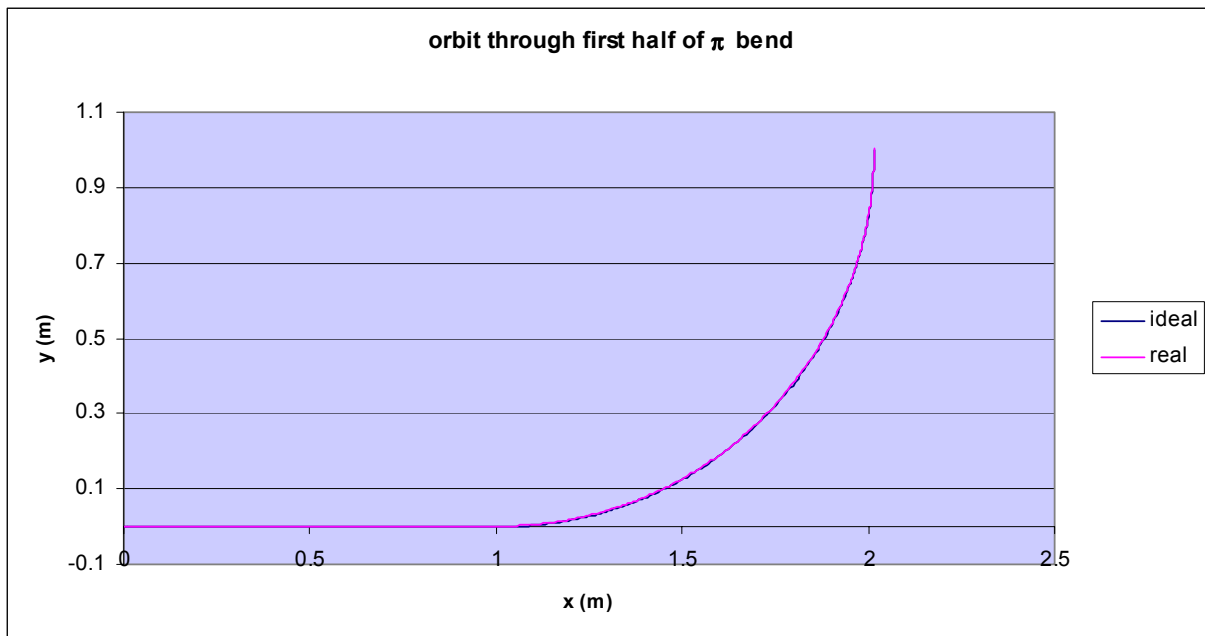


Figure 6a: Trajectories through first half of π bend computed using numerical integration through ideal and realistic (computationally modeled) fields.

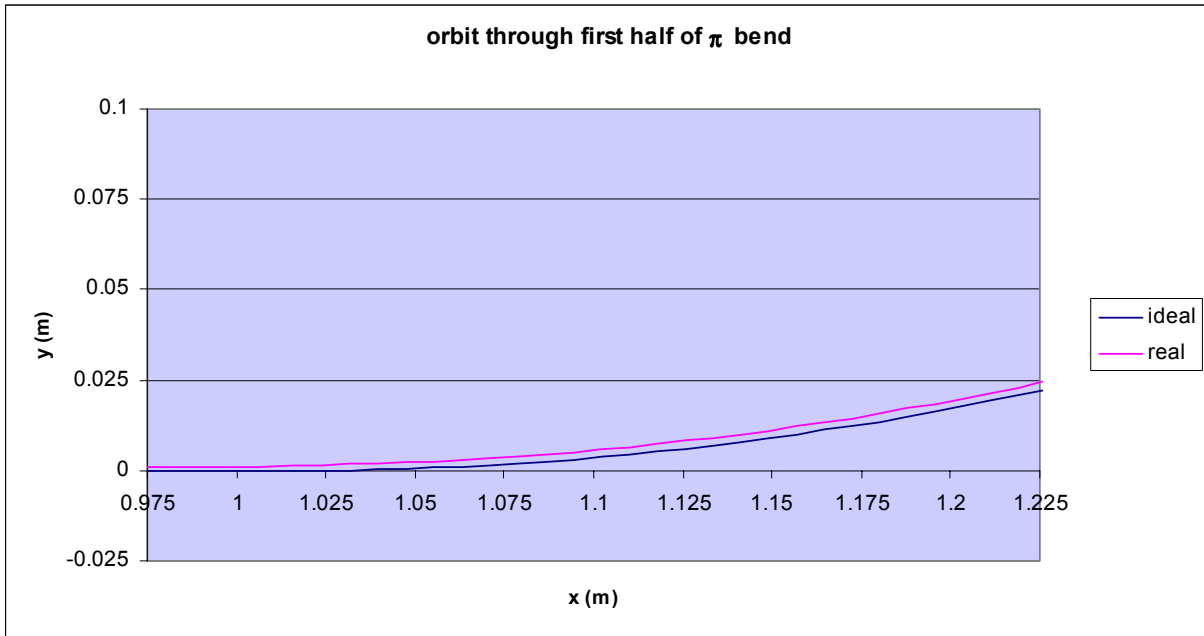


Figure 6b: Enlargement of Figure 6a in the vicinity of the pole face.

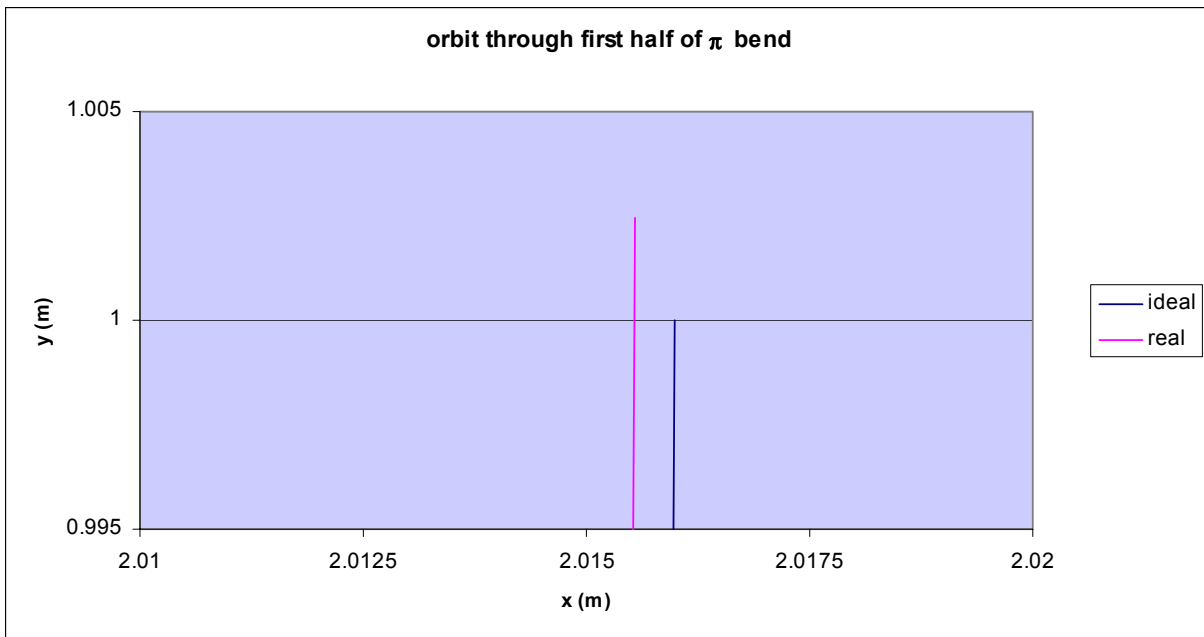


Figure 6c: Enlargement of Figure 6a in the vicinity of the 90° point.

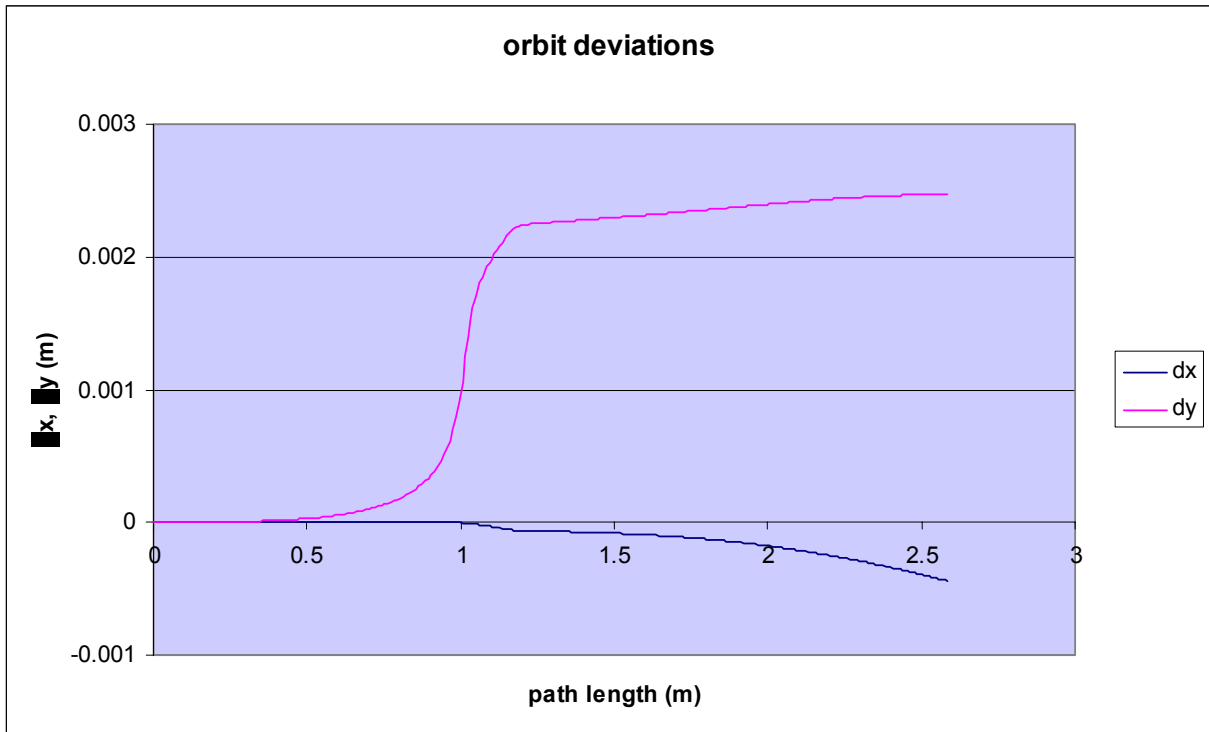


Figure 6d: Deviations of realistic from idealized orbit as a function of path length through magnet.

Conclusion

The GY design under consideration [6] meets or approaches IR Upgrade specifications and may be expected to provide adequate performance.

Acknowledgments

We thank Tom Schultheiss of AES for a superb study of, and many useful discussions regarding, GY behavior.

References

- [1] T. Schultheiss, "GY Coil, 210 MeV/c, Material 1020", 8/14/01 (unpublished).
- [2] D. Douglas, "Some Features of the FEL Upgrade π -Bends", JLAB-TN-01-024, 14 May 2001.
- [3] D. Douglas, "Error Estimates for the IR FEL Transport System", CEBAF-TN-96-035, 15 July 1996.
- [4] D. Douglas, "Some Features of the FEL Upgrade π -Bends", *op. cit.*
- [5] *ibid.*
- [6] T. Schultheiss, *op. cit.*