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NON-LINEAR MAGNETIC INSERTS FOR THE INTEGRABLE OPTICS TEST ACCELERATOR*

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Abstract

We present here a status update of the manufacture and magnetic measurements of the non-linear inserts for the Integrable Optics Test Accelerator. RadiaBeam Technologies is designing the 2-meter structure from magnetic field specifications, including pole design, measurement systems and alignment fiducialization. Herein, we will describe the current state of the project.

STATE OF THE PROJECT

The goal of the Integrable Optics Test Accelerator (IOTA) is to serve as a proof of principle experiment of the integrable optics technique. Briefly, the technique seeks to improve accelerator intensity by deliberately violating the assumption of linear motion that has two invariants: particle emittance and energy [1, 2]. The IOTA ring will be constructed at the Advanced Superconducting Test Accelerator facility at Fermi National Lab [3]. While a great many of the components for the IOTA ring are being recommissioned from other projects, the non-linear inserts are entirely new and must be designed exclusively for the IOTA ring because the magnetic field of the insert depends on the configuration of the other optical elements in the ring.

Unlike magnets typically found in circular accelerators, both the magnetic field strength and the mechanical aperture of the non-linear insert are explicit functions of the longitudinal coordinate [1–3]. To reduce the complexity of manufacturing the magnets for this insert and allow flexibility for assembly, we have decided to segment the insert such that the magnetic field properties are constant along a fixed short length of the insert, but the magnetic properties vary between segments along the length of the insert in accordance with the requirements of the integrable optics theory. An example of a segmented prototype can be seen in Fig. 1. The constraints on the field quality are specified by tracking simulations to be:

1. The magnetic axes of all of the segments may not deviate from each other by more than 50 μm.
2. The field may not deviate from the theoretical field by more than 1% within some good field region.
3. The good field region should cover as much of the physical aperture as practicable.

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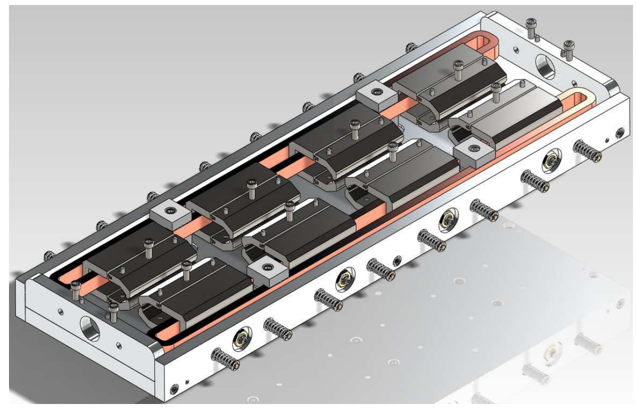

Figure 1: Isometric view of the initial IOTA insert prototype. A plate on top has been hidden to show detail below. The copper items are the excitation coils, the dark grey items are the steel poles and return yokes, and light grey items are aluminum.

In previous proceedings we reported the construction of an initial prototype to test a simple tuning mechanism to allow adjustment of the magnetic fields in the insert [4]. RadiaBeam Technologies is now moving forward with the design of a full scale prototype non-linear insert that will be installed on the IOTA ring. We have advanced the design of the full scale prototype to take advantage of the experience gained during manufacture of the initial prototype. In addition to reporting the results of the magnetic measurement of the initial prototype, we report on the design and engineering strategy for the full scale insert. Specifically, we cover the design of the vacuum system, a manufacturing strategy for the magnets, and the alignment technique we will use to align the many segments of the insert.

MEASUREMENT OF THE PREVIOUS PROTOTYPE

Previously, we had planned to measure the magnetic field of the initial prototype insert (see Fig. 1) via a custom Hall probe bench to accommodate the very small aperture of the magnets [4]. This measurement system was constructed, but it turned out to be impractical. The very small Hall probes, of total size in the mm range, required very fine wires which easily broke. In addition, the connections to the Hall effect sensor were sensitive to movement and produced spurious signals on the order of the measurement signal. As a result, we decided on a more conventional rotating

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coil measurement that was performed at Argonne National Lab [5]. The measurement was performed using a stretched rotating wire system in which the wire is displaced from the origin by 3.82 mm.

To make this measurement the pair of coils used to excite all four segments simultaneously was replaced with a pair of coils for each segment so they can be energized independently. Preliminary results of this measurement are reported here.

For the full scale insert, there are 10 different segment types which we denote by 1 . . . 10. Additionally, the full scale insert is mirror symmetric longitudinally such that the segment order is given by 10 . . . 2, 1, 1, 2 . . . 10 when enumeration begins from either end of the insert. The prototype has two 1 segments, a 2 segment and a 3 segment, in that order; these segments are further numbered #1, #2, #3 and #4, respectively.

The first constraint on the magnetic field is that the axes of the segments must not deviate by more that 50 μm from each other. The axis of each segment was calculated using feed down of the expected harmonics in to lower harmonics [6]. As we can see from Table 1, the axes of the segments do not meet the required tolerance. The measurement was made particularly difficult by the lack of repeatability. The segments are tuned by changing the reluctance gaps between the yokes and pole tips on each side of the segments - see Ref. [4] for more details. While it was intended that the yokes should only move in the horizontal direction, they were not sufficiently constrained and changed in vertical position, pitch and yaw while being adjusted in the horizontal direction. This made repeating measurements impossible.

Table 1: Location of the different segment axes (**x** and **y**) and the deviation of the axes from the mean axis of all of the segments (Δ**x** and Δ**y**). The standard deviation of the measurement is $\sim$10 μm.

Segment	**x**	**y**	**Δx**	**Δy**
#1	$-17\,\mu$m	$-10\,\mu$m	$8\,\mu$m	$-48\,\mu$m
#2	$-77\,\mu$m	$109\,\mu$m	$-50\,\mu$m	$71\,\mu$m
#3	$16\,\mu$m	$66\,\mu$m	$42\,\mu$m	$28\,\mu$m
#4	$-26\,\mu$m	$-13\,\mu$m	$0\,\mu$m	$-51\,\mu$m
Range	-	-	$50\,\mu$m	$122\,\mu$m

In addition to a mobile magnetic axis in each segment, the extraneous motion of the yokes also produces a number of unwanted harmonics in the magnetic field. In rotating coil measurements the field is typically specified in terms of the harmonic content such that

$$B_y + iB_x = \sum_{n=1}^{\infty} [B_n + iA_n] \left(\frac{x+iy}{R_{ref}}\right)^{n-1} \quad (1)$$

where R_{ref} is a specified reference radius and B_n and A_n are the upright and skew harmonics of the field, respectively.

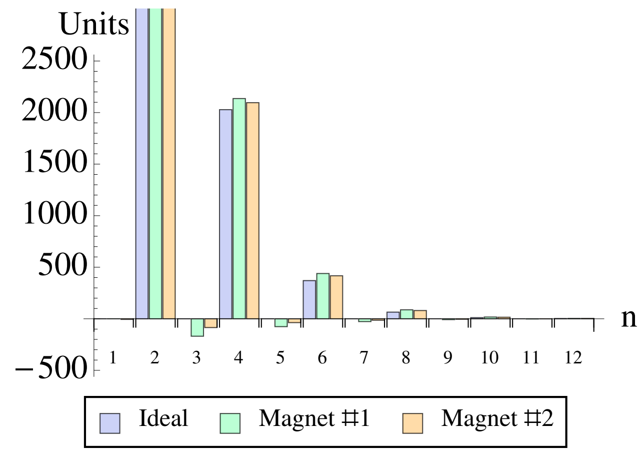

Figure 2: Upright harmonic content of the 1 segments of the IOTA insert prototype, B_n, in units of 10^4 where $B_2 \equiv 10^4$ (and has been intentionally clipped). Measurement error is less than 2 units. The values have been corrected for feed down.

Using this notation, the harmonics of an ideal segment of the insert are given by

$$B_{2n} = \frac{\sqrt{\beta(s)}c}{2R_{ref}} \frac{2^{2n-1}n!(n-1)!}{(2n-1)!} \left(\frac{R_{ref}}{\sqrt{\beta(s)}c}\right)^{2n-1} \quad (2)$$

where $c = 0.009$ m$^{1/2}$ is a constant for the entire insert and $\beta(s)$ is the beta function of the beam at the location of the insert if the insert was not present. In this case, $\beta(s) = \beta^* + s^2/\beta^*$, with $\beta^* = 0.727$ m. For the ideal insert, we have $A_n = 0$ for all n and only the even upright harmonics are allowed.

Table 2: Skew harmonic content, A_n, of the different segments of the initial insert prototype in units of 10^4 where $B_2 \equiv 10^4$ and $A_n \equiv 0$. Measurement error is less than 2 units. The values have been corrected for feed down.

n	**#1**	**#2**	**#3**	**#4**
1	-1	-4	-1	-1
2	0	0	0	0
3	143	-88	-29	-19
4	4	9	13	10
5	52	-28	-5	-6
6	-3	1	-3	-2
7	13	-8	0	2
8	3	0	-2	-2
9	3	-2	0	-1
10	1	1	0	0
11	0	-1	1	-1
12	0	0	0	0

It can be seen in Table 2 that the skew harmonics are clearly and strongly non-zero. Because the feed down corrections were calculated using the quadrupole and the dipole

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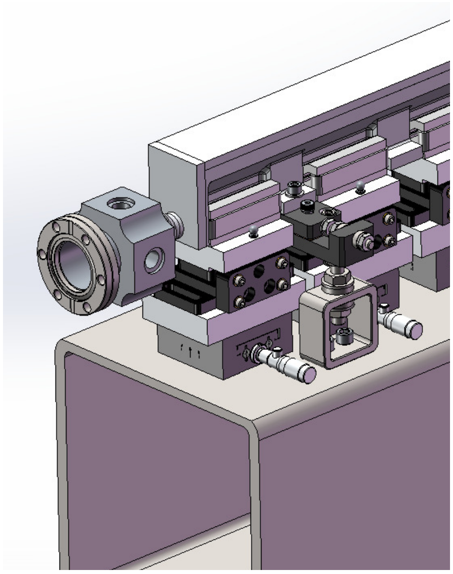

Figure 3: Truncated view of the engineering model of the IOTA insert.

harmonics, the upright and skew dipole terms are small. However, because the feed down terms for higher order harmonics (octupole and higher) are non-zero, we conclude that the axes of the different harmonics are not coincident in each segment. In addition, the upright harmonics differ from the intended values (see Fig. 2). The specified constraint on the field quality, that it not deviate from ideal by more than 1%, is violated for radii greater than ∼1 mm. Compared to the physical aperture of approximately 4 mm radius, this is quite small

STRATEGIES FOR PRODUCTION OF THE IOTA INSERT

While we have long since started the design of full scale prototype employing a different strategy for construction, the results from the rotating coil confirmed that the previous strategy would not produce an acceptable result. Unfortunately, we cannot tell from the above results whether the harmonic content is of sufficiently high quality because the symmetry that we designed for was very clearly broken. Even so, the desired harmonics appear to be close to the desired values. In this section, we outline the strategies we are planning on using to improve the magnetic field quality as well as the vacuum system that will be constructed.

Vacuum System

In order to maximize the physical aperture of the vacuum chamber, we are making a custom vacuum chamber in which the thin walls of the chamber conform to the shape of the poles in the magnetic gap. To facilitate vacuum pumping, we have built in a larger secondary chamber which will be pumped. The first electron beam welding test piece can be seen in Fig. 4. The weld joints on the test piece are solid,

Figure 4: End on view of the welded vacuum chamber test part.

however, the surfaces opposite of the welds showed spatter. In future fabrication we will use a throwaway tool part to catch the spatter.

The vacuum system will be supported separately from the magnetic segments (see Fig. 3). This should provide enough degrees of freedom to allow alignment of the vacuum chamber to the segments, which will be adjusted slightly to ensure the segments are co-axial. We will be performing a vacuum test of a second chamber prototype in the coming months.

Magnet Manufacture and Alignment

It is clear from the rotating coil measurement that fixing the magnets in place is not enough to ensure that each segment is sufficiently co-axial with the others. To increase the chances of success we are planning both secondary cuts to ensure that the pole faces are true to the design and individual alignment of the segments to alleviate tolerance stack up. To perform the secondary cuts, the magnets will be rough cut to near final shape, assembled and then the final pole shapes will be finish cut, in-situ, using wire EDM. This manufacturing process and the fact that the yokes and poles will now be one piece rather than three (see Fig. 3) will certainly improve the harmonic content as well.

For alignment, we will use the vibrating wire technique [7]. Each segment will use off-the-shelf optical alignment components to align the segments in five dimensions - all except longitudinal position, which simulation has shown to be non-critical. The current engineering model for two segments can be found in Fig. 3. The vibrating wire measurement is currently being developed at RadiaBeam using a permanent magnet quadrupole that results in similar measurement characteristics expected from the IOTA segments.

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