Application of PCB and FDM Technologies to Magnetic Measurement Probe System Development

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***Abstract*— Rotating coil probes are essential for measuring harmonic multipole fields of accelerator magnets. A fundamental requirement of these probes is their accuracy – which typically implies that the probes need to be very stiff and straight, have highly accurate knowledge of the placement of windings, and an ability to buck the fundamental fields well in order to supress the effects of vibrations. Ideally, for an R&D test environment, probe fabrication should also be easy and low-cost, so that probe parameters (type, length, number of turns, radius, etc.) can be customized to the magnet requiring test. Such facility allows measurement optimization for magnets of various multi-polarity, aperture size, cable twist pitch, etc. The accuracy and construction flexibility aspects of probe development, however, are often at odds with each other.**

This paper reports on application of printed-circuit board (PCB) and fused-deposition modelling (FDM) technologies, and what these offer in the fabrication of magnetic measurement probe systems. In particular, this paper describes a general purpose, self-contained, rotating coil device known as the 'ferret', and several other measurement probes - including two built for use at LBNL for the LARP HQ and LBNL HD programs – constructed using these techniques. Data from these devices as they have been used to measure superconducting dipole and quadrupole magnets at high fields are also presented and discussed.

***Index Terms*— magnetic measurement probes, rotating coils, printed circuit boards, fused-deposition modeling, 3D printing.**

I. INTRODUCTION

USING A rotating wire loop for the purpose of measuring magnetic fields predates Maxwell's Equations themselves [1]. Ubiquitous in laboratories and test facilities, such probes, with a variety of geometries and sensitivities, remain a workhorse for precise measurements of harmonic field quality. The manufacturing of precision probes requires careful methodologies, well-equipped facilities, and skilled technical personnel. However, even with such infrastructure at Fermilab, probes often remained behind the necessity of measurement requests: the existing array of probes providing a sub-optimal choice of diameter or length, and the construction of a new probe requiring too much cost or time. A facility and staff dedicated solely to probe fabrication and maintenance would be a solution, but difficult to justify without a project requiring a large number of such devices.

A comparable situation had existed for the alignment of different magnets: separate, specific, and costly benches would be used and maintained for the alignment of dipoles, quads and spool pieces for a particular series. However this changed with the development of the Single Stretched Wire alignment system [2] which substituted a general tool capable of flexibly meeting all alignment measurement requirements with precision technology that could be largely purchased 'off-the-shelf'. A similar paradigm seemed to be needed for the rotating coils in order to 'look around the corner' and be able to respond to future measurement needs. The idea of developing printed circuit board (PCB) magnetic measurements probes was explored with this end in mind.

Using printed circuit technology for magnetic measurements dates back to at least the 1980's. Comparable inductive loop probes of the time, however, had far larger sensitivity and/or ability to buck the main harmonic fields.

This paper describes current probe fabrication technologies using PCB and fused-deposition modeling (FDM) techniques to manufacture probes which achieve bucking, sensitivity, and accuracy at least comparable to traditional machined and hand-wound inductive pick-up loop coils.

II. PCB DEVELOPMENT

PCBs control the trace positions on a surface to very high accuracy (1-2 μm). PCB probes thus tend toward being planar, radial-type rotating coil probes. Of course they can be mounted tangentially, on the surface of a quasi-cylindrical support, but then machining and mechanics plays a more dominant role in determining e.g. bucking, and a fairly large aperture probe is needed before a large number of traces on the PCB can be implemented. We have also used the thickness of the board for winding loops (making a 'via' through the board to form a loop front and back), but the thickness of the

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board is not well-controlled at a comparable tolerance (perhaps tens of μm) – it is simply not a highly controlled parameter in the PCB industry. An example of a simple trace winding is shown in Fig. 1. The upper trace here circulates clockwise (CW) from point ‘A’, in loops of decreasing width until the via (point ‘B’). The trace would then continue in loops of *increasing* width on the reverse side (dashed line) following the original traces and maintaining the same chirality to complete a winding (in this case) of 4 planar wire loops, emerging again at C.

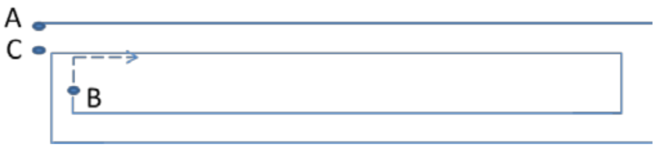

Fig. 1. Basic wire trace loop on PCB.

Although many PCB manufacturers can achieve patterns which separate traces by 0.1mm or less, a more conservative trace-to-trace separation of 0.25mm (trace width 0.1mm, with 0.15mm gap) is typically used to achieve the long lengths and multiple turns for our PCB probes without internal shorting. The number of turns can also be increased by adding identical layers (our largest so far has been 28 layers).

Dipole bucking is achieved by combining a second, identical loop at a position on the board which rotates at a smaller radius and opposite chirality. Further bucking of quadrupole and sextupole fields is achieved in a similar way [3]. Using identical radially displaced loops is by no means the only way of bucking the fundamental fields, but this tends to create very clean ends (where otherwise trace interconnections may require the formation of small loops which complicate the sensitivity). It also creates a pattern that is general and easily instantiated for different widths, number of turns/layers, etc.. Note that since each layer takes care of its own bucking, stacking misalignment of the various layers during PCB manufacturing of multi-layer boards has little impact on probe quality.

With the precision of trace patterns typically achievable, bucking residual is at the level of 0.1%. With this high suppression of the fundamental field, the probes become ‘self-calibrating’ when measurements are made in quadrupole magnets. That is, the quadrupole field as measured by the dipole bucked winding is independent of the radial position of the PCB at the level of ~0.2%, and comparison of this field with that measured by the un-bucked winding (which *does* depend on radius) yields the radial position of the PCB [4].

An example of a radial PCB probe is shown in Fig. 2. There are 4 windings with 20 turns per winding (10 front and back). The outermost un-bucked (UB) winding is combined with the third to form a dipole-buck (DB) signal, and this pair is combined with the second and fourth to form the dipole-quadrupole-bucked (DQB) signal.

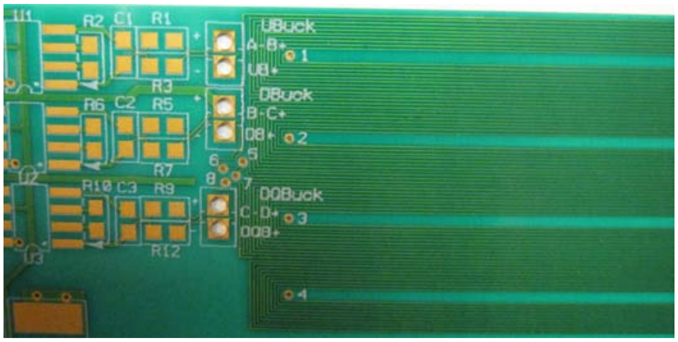

Fig. 2. Example of 20 turn (10 on front/back), 4 winding, PCB with amplifier circuit.

To increase signal amplitude upstream of the slip-rings and data acquisition electronics, low-noise pre-amplifier circuitry is sometimes placed directly on the PCB. Gain can be set up to 1000 on the bucked signal. Because of the high degree of analog bucking, this does not typically saturate ADCs.

Circuit boards can also be made with trace patterns at multiple locations per board. This effectively allows the creation of two or more separate probes, for example, with same trace pattern but different lengths for fine structure measurements.

As mentioned in [3], the analysis of the signals from the PCB probes is straightforward, if one simply accounts for the sensitivity of each wire according to

$$K_n = \sum_{j=1}^{N_{wires}} \frac{L_j R}{n} \left(\frac{(x_j + i y_j)}{R} \right)^n (-1)^j ,$$

Here L is the length of a given wire and R is the reference radius. The $(-1)^j$ gives the sign of the current flow of each wire and the (x_j, y_j) are the locations of the wires with respect to the rotation axis.

The sensitivity of a PCB probe can be compared to that of a tangential (TAN) probe in a general way. Since the opening angle of a tangential probe should be smaller than the largest harmonic it needs to measure (e.g. 12 degrees for a 30-pole (n=15) harmonic), the position of the wires of the tangential winding is known for a given probe radius. With the same radius constraint, the optimal number of trace loops for a multi-layer PCB can also be calculated. A comparison of the sensitivities is shown in Fig. 3 for a quadrupole measurement. One layer on a quadrupole PCB probe has sensitivity of about 3 turns of the tangential with probe diameter of about 32 mm. For larger diameters, the PCB gains with respect to TAN: a 64 mm diameter probe has sensitivity of about 9 windings on the TAN for each layer of the PCB for low orders, decreasing to about 5 windings per layer pair for higher orders. For a dipole probe, the equivalent windings per PCB layer is even larger. Therefore, a multiple-layer PCB in general can be made to exceed the sensitivity of the 30 or so turns usually found on tangential probes at Fermilab.

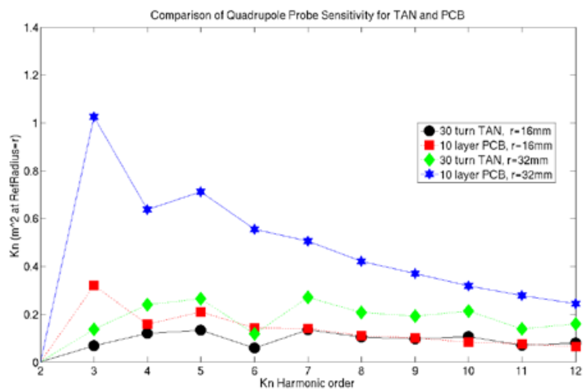

Fig. 3. Comparison of sensitivity between tangential and PCB type measurement probes for probe radius *r*.

Since the windings are rigidly coupled on the PCB, and the relative wire positions are highly precise, the harmonics obtained from the circuit board probes should be highly accurate. For this to happen, the circuit needs to be maintained planar during rotation (e.g. we sandwich it between G10 stiffeners to try to insure this) and the radial position and offset from rotation axis accounted for. The radial position calibration was described earlier. To obtain the correct harmonic phases, the phase difference between the quadrupole measured by UB and DB windings can be used to calculate an effective vertical offset of the PCB plane from rotation axis (typically this is at the level of 0.1mm and is negligible).

III. Rotating PCB Support

Several methods have been successfully developed to control the stiffness and trajectory of the PCB probe as it rotates in the magnet aperture.

A. *Probe in Tube*

Broaching the inside of a G10 cylindrical tube so that a circuit board can be inserted and held by the inside diameter proved to be a very effective way of supporting the circuit board (see Fig. 4). Since most of the non-PCB probes at Fermilab are wound directly on G10 cylinders with machined end-plugs, this also was a natural extension of our standard probe manufacturing. The two drawbacks with such a technique are that 1) the broaching needs to leave some thickness remaining on the cylinder, and thus the outermost traces of the probe (which are crucial for measurements of the higher orders) would lose ~2-3 mm of radius; and 2) every change of circuit board diameter would require a new tube and machined end plugs.

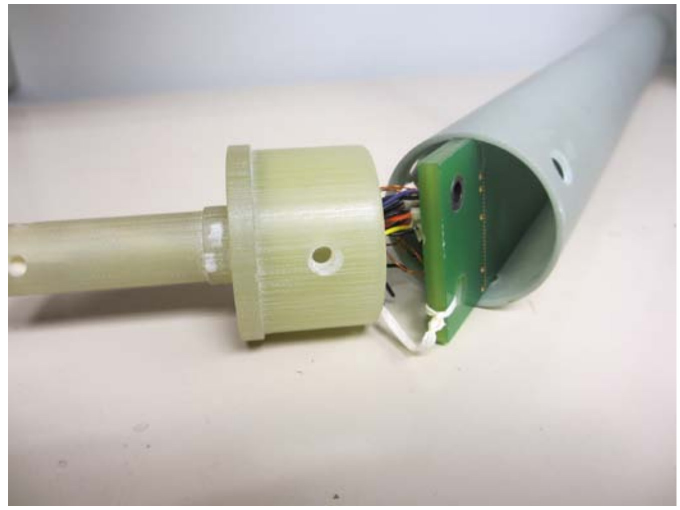

Fig. 4. PCB held within G10 via broach of the inner diameter.

B. *Strongback*

Another successful effort was to have a strongback built to support a PCB at its midplane (Fig. 5). Any width PCB with thickness less than 4mm could then be rigidly captured and rotated. This allows a variety of PCBs to be tested easily, adapting to various apertures via spacers on the bearings. The drawback here is that the strongback requires extensive machining to fabricate. Since replication is costly, PCB probes would need to be changed in and out frequently for various measurements, increasing the risk of damage to the probes or their wiring. This also causes only a single probe to be available at a given time.

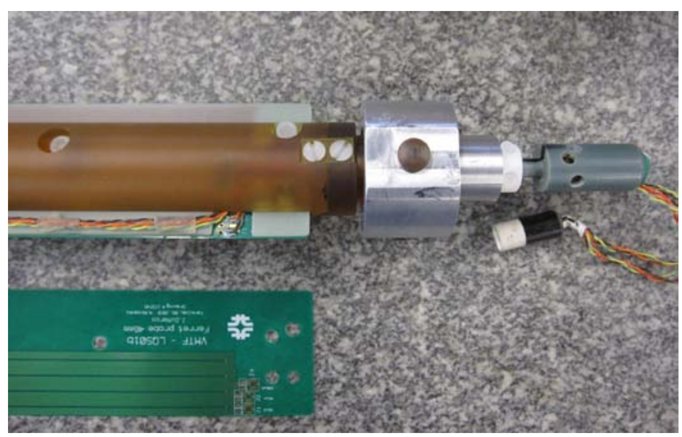

Fig. 5. Strong-back support of PCB probe which allows for different width circuit boards to be tested.

C. *Fused Deposition Modeling (FDM)*

Most recently, FDM (i.e. 3D printing) has been used to fabricate support structures for the PCB probes. The 3D printer at Fermilab uses ABS Plus thermoplastic and stereo lithography (STL) files to generate parts of cubic size up to

225 cm a side. So far, typical probe pieces have been broken up into lengths of about 100 mm and connected together with full probe length, 6.4 mm diameter, carbon fiber support rods. A sample probe support is shown in Fig. 6.

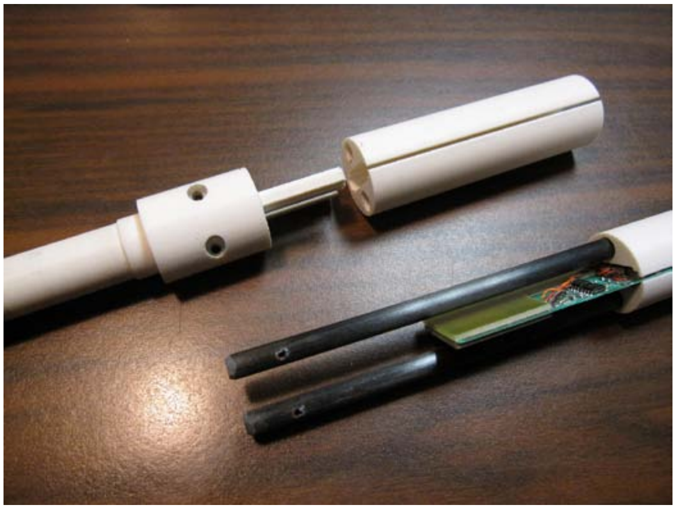

Fig. 6. A 24mm PCB probe supported within an FDM fabricated structure with carbon-fiber rods.

The stated resolution of the printer is reasonably good, 0.1-0.2 mm, but still short of high-quality machining. However, inspection of printed pieces show that the average position of a hole through a 100 mm long piece deviates from its intended position on average by less than 0.05 mm, and so with straight and stiff support rods (ceramic rods can be used to insure greater straightness and rigidity), the parts are more than adequate for rotating coil probes that incorporate bucking. The FDM enables easy replication so each PCB has its own support, and can incorporate features that would be difficult or impossible to machine. Such capability e.g. allows us to place the outer PCB traces right at the probe radius.

IV. Recent Probes and Performance

In the last couple of years, several new probes have been produced using PCB and FDM methods.

A. *Quadrupole probe for HQ magnet*

As part of the US LHC Accelerator Research Program (LARP) collaboration, LBNL requested a probe be built by FNAL for the cryogenic measurements of the LARP high-gradient HQ magnet program [7]. A 2-layer PCB with on-board amplifiers, a diameter of ~47mm and length 250mm was fabricated. The diameter of the probe was limited by the anti-cryostat available at the test facility. A second circuit with length 100 mm is also part of the same PCB and was particularly useful in characterizing the field quality along the magnet bore. The probe was supported in a G10 tube similar to Fig 4. The smooth integration of the probe into the measurement system at LBNL allowed for the detailed characterization of the magnet field quality. Sample data comparing the probe results taken during a scan along the magnet bore at 9kA to calculation is shown in Fig. 7. We note that the probe resolution was determined to be 0.006 units at the probe radius, and quadrupole bucking ratio measured at 435.

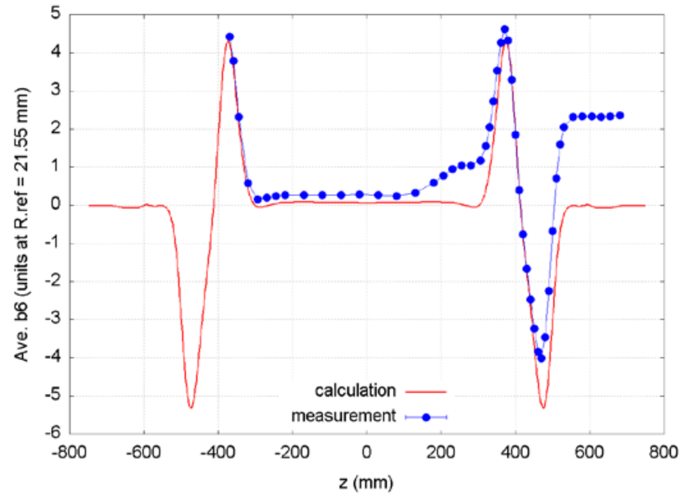

Fig. 7. 100mm long, 47mm diameter PCB measurement (DQB winding) of HQ01d quadrupole with calculation (note that the calculation did not account for the ramp splice region whose effect is seen on the measured data between 150-300mm on the z scale).

B. *Quadrupole probe for LQS magnet*

One of the spare circuit boards from the HQ probe assembly was placed in a vertical strongback and used to measure LQS03, a LARP long quadrupole magnetwith an aperture of 90mm, at the Fermilab VMTF [8]. A sample comparison between the 2-layer 100mm long PCB probe and a tangential probe of the same length is shown in Figures 8 and 9 during loops to slightly different peak currents. For these measurements, the on-board amplifiers were not used. Very good agreement is seen between the two devices in all harmonics.

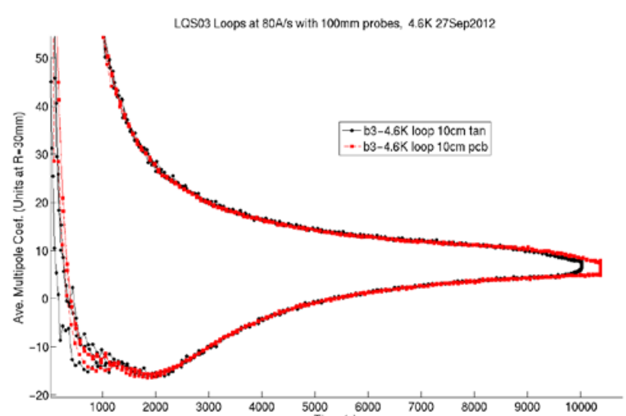

Fig. 8. Comparison of PCB and tangential probe LQS03

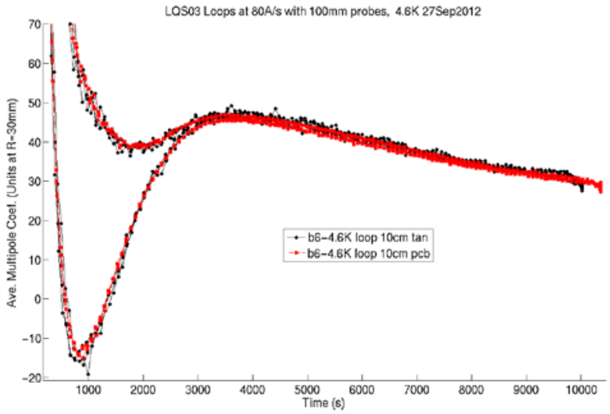

Fig. 9. PCB and tangential probe b_6 comparison, LQS03

C. Ferret Systems

The Ferret (FERmilab Rotating-coil Encapsulated Tesla-probe) was intended as a stand-alone, portable probe system similar to other 'mole' type devices [5] [6]. The Ferret features a non-magnetic phosphor-bronze flexible shaft driven by a motor which resides external to the magnet. The flex shaft spins a PCB probe (housed in an FDM support structure) within an outer tube. An internal encoder and slip-ring relate the angular position and probe signals to data acquisition electronics. A MEMS 2-axis gravity sensor chip is used to track the overall orientation with respect to gravity. All internal parts can be adapted for use in larger or smaller Ferret probes by means of spacers. The use of the flex shaft to drive the probe, together with fabrication using PCB and FDM, has made the system very robust and easy to replicate. Almost all the internal parts including bearing supports can also be fabricated with FDM. Two Ferret versions currently exist, with OD of 63.5 mm and 43 mm. The former is used for room temperature measurements of the LQS magnets, and the smaller diameter for testing in a superconducting Tevatron dipole. With a 10m flex drive, 5 m of which was in the 4 T field of the dipole, the Ferret was able to run at 6 Hz rotation rate (Fig. 10).

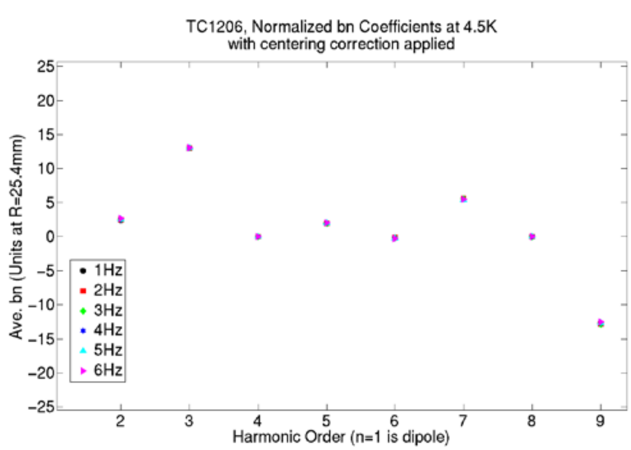

Fig. 10. Ferret measurements at various rotation rates in a superconducting Tevatron dipole.

D. HD probe and 11T dipole MBHSP01

A probe was requested by LBNL for cryogenic measurements for their High-field Dipole (HD) program. It has diameter of ~24 mm and again has two circuits, with lengths 130 mm and 26 mm to study the field profile along the magnet bore with a nominal pitch length of 130 mm. The PCB for this probe was mounted in an FDM support in order to maximize its radius. Testing in the HD magnet is expected to occur in 2013. Another set of FDM parts was printed, and using a spare PCB, a second probe was assembled. This proved timely as the LHC upgrade high-field research dipole MBHSP01 was being tested, and a cross-check of data was needed for the 25 cm long, 25 mm diameter tangential probe used for those measurements. The PCB board probe was used extensively and had comparable data quality [9]. The 26 mm long probe also provided information on local variations in magnetization that would have been otherwise missed.

V. CONCLUSION

Magnetic measurement probes using PCBs have been developed with comparable (or superior) capabilities to tangential probes in terms of sensitivity, bucking, and accuracy of winding placement. These, coupled particularly with the FDM technology for mechanical support, allow us to build a variety of probes quickly and flexibly, including the stand-alone 'Ferret' probe. The proven performance of the PCB probe has also enabled the field quality study of the LARP HQ magnet.

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