High-Resolution and Frequency, Printed Miniature Magnetic Probes

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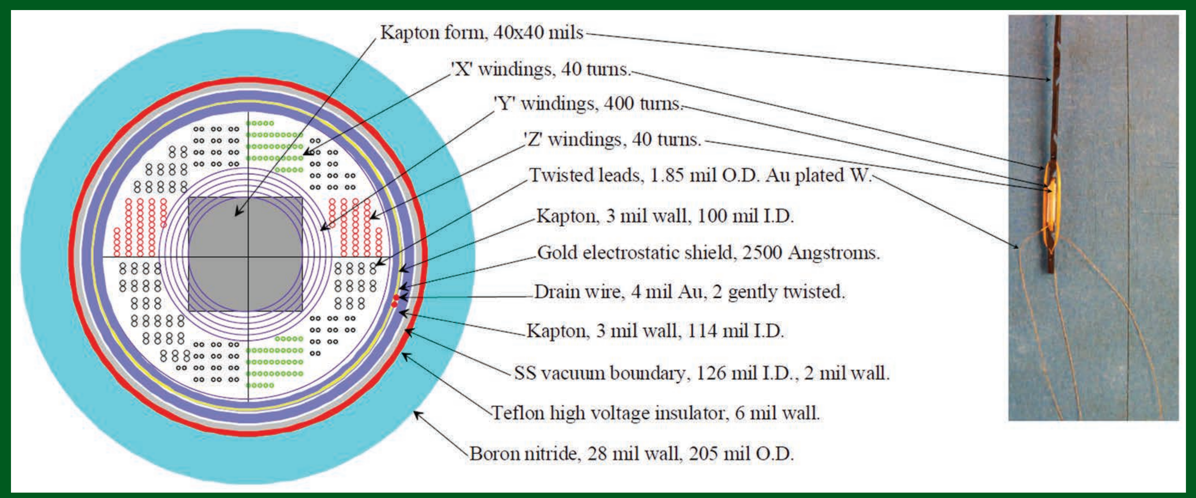
EAGLE HARBOR TECHNOLOGIES

Abstract:
Eagle Harbor Technologies, Inc. (EHT) is developing a technique to significantly reduce the cost and development time of producing magnetic field diagnostics. EHT is designing probes that can be printed on flexible PCBs thereby allowing for extremely small coils to be produced while essentially eliminating the time to wind the coils. The coil size can be extremely small when coupled with the EHT Hybrid Integrator, which is capable of high bandwidth measurements over short and long pulse durations. This integrator is currently being commercialized with the support of a DOE SBIR. Additionally, the flexible PCBs allow probes to be attached to complex surface and/or probes that have a complex 3D structure to be designed and fabricated. During the Phase I, EHT will design and construct magnetic field probes on flexible PCBs, which will be tested at the University of Washington's HIT-SI experiment and in EHT's material science plasma reactor.

Motivation:

- Countless research groups have developed internal magnetic field probes for studying magnetic fields in fusion plasmas.
- The internal magnetic probe developed at the Redmond Plasma Physics Laboratory (RPPL) served as a reference for illustrating the challenges and complexities associated with building an internal magnetic probe to operate in a plasma environment.
- There were more than 15,000 turns spread over 96 windings (not including the twisted pair leads) in this probe.
- The total time to design and construct the RPPL probe represents approximately four man-years of work, with at least half a person-year to wind the coils, half a person-year to design the connectorization, and one person-year to troubleshoot.
- The total program for this internal probe cost over $1 million.



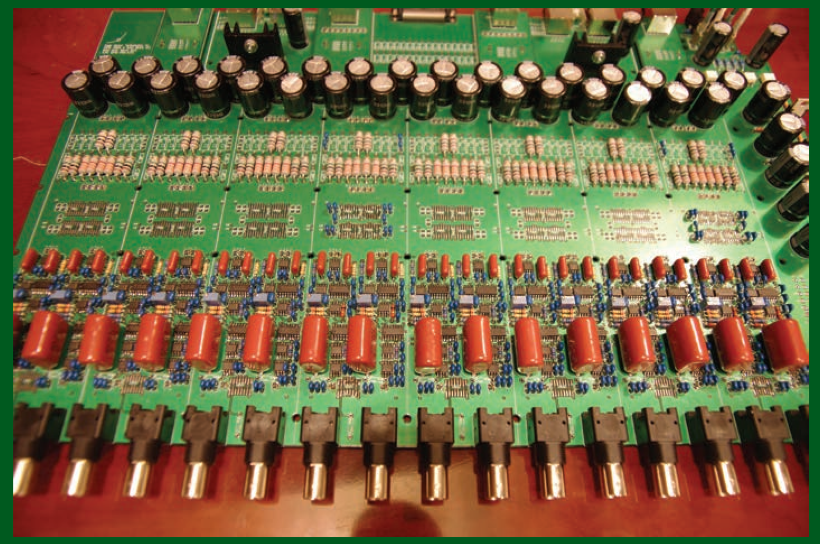
Cross section of the RPPL internal magnetic probe showing the selected materials and thicknesses. (Inset) Photo of one three-axis magnetic probe constructed at RPPL.

- The data gathered from this type of measurement can also be extremely important for diagnosing plasmas. Therefore, making inductive pickup probe technology easier to implement and cost-effective could have a major effect on understanding key physics related to fusion energy development.

- To provide simple and low-cost solutions for a wide variety of inductive probes, improved methods for probe fabrication and miniaturization need to be found.

The EHT Short Pulse Integrator:

- 5 MHz frequency response
- 1 μs to 100 ms RC time constant
- Drift Error: 5μV-s for 3600 s
- Extremely high dynamic range
- Fast, digitally controlled, reset process stabilizes analog integrator
- Auto zeroing feature eliminates trim pots
- 50 Ω to 100 kΩ input impedance
- 50 Ω output impedance
- 1U rack mountable chassis
- More info at Thursday afternoon's poster session (UP8.00023).



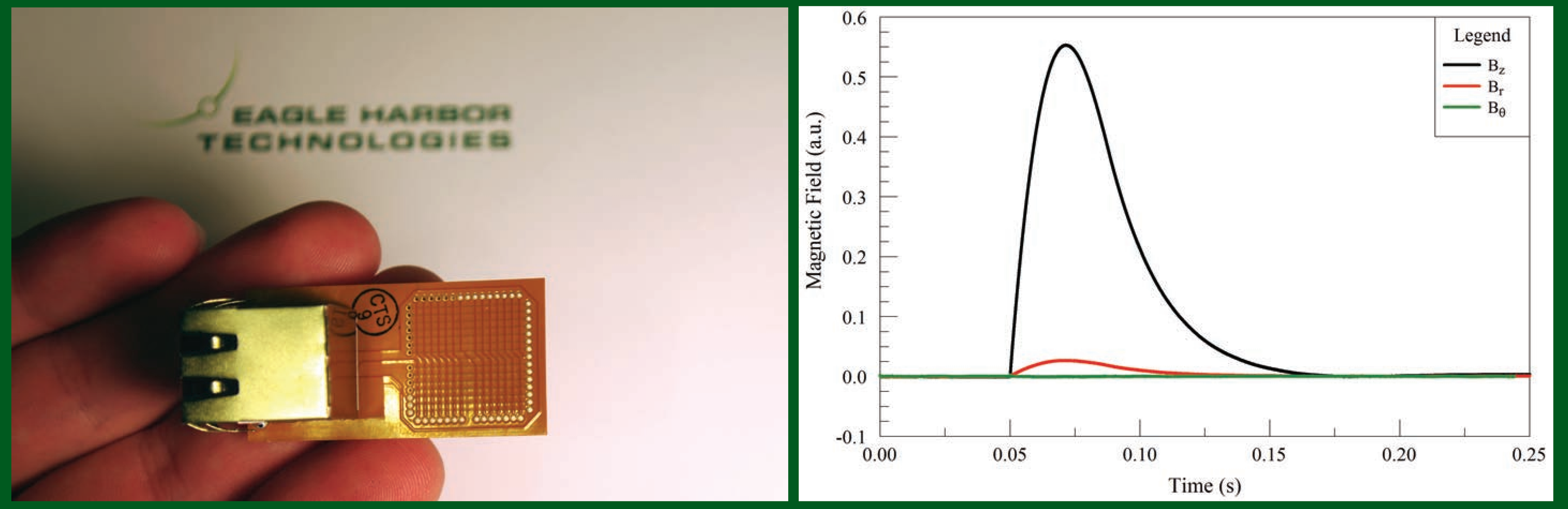
Sixteen channel, short pulse integrator developed for validation platform experiments through DOE SBIR Phase I/II.

Flexible Magnetic Probes using Flexible PCB Printing Techniques:

One style of probe is printed on a polyimide material using flexible PCB printing techniques. Depending upon the choice of connector, these probes can withstand baking temperatures up to 200 °C. Their flexible circuitry allows the probes to conform to the curvature of vacuum vessels and other experimental geometries, maximizing probe-experiment proximity.

Three-axis Surface Probe

- Ideal for applications with access to a vacuum feed-through or those requiring accurate external magnetic field measurements.
- With a board size of 2 cm^2 and just 280 μm thick, each axis has 0.5 cm^2 of area.
- Creating a network of these probes over a vacuum chamber can deliver detailed data of magnetic field profiles.
- The three channels output through a standard RJ-45 connector, which makes interfacing easy with existing hardware.

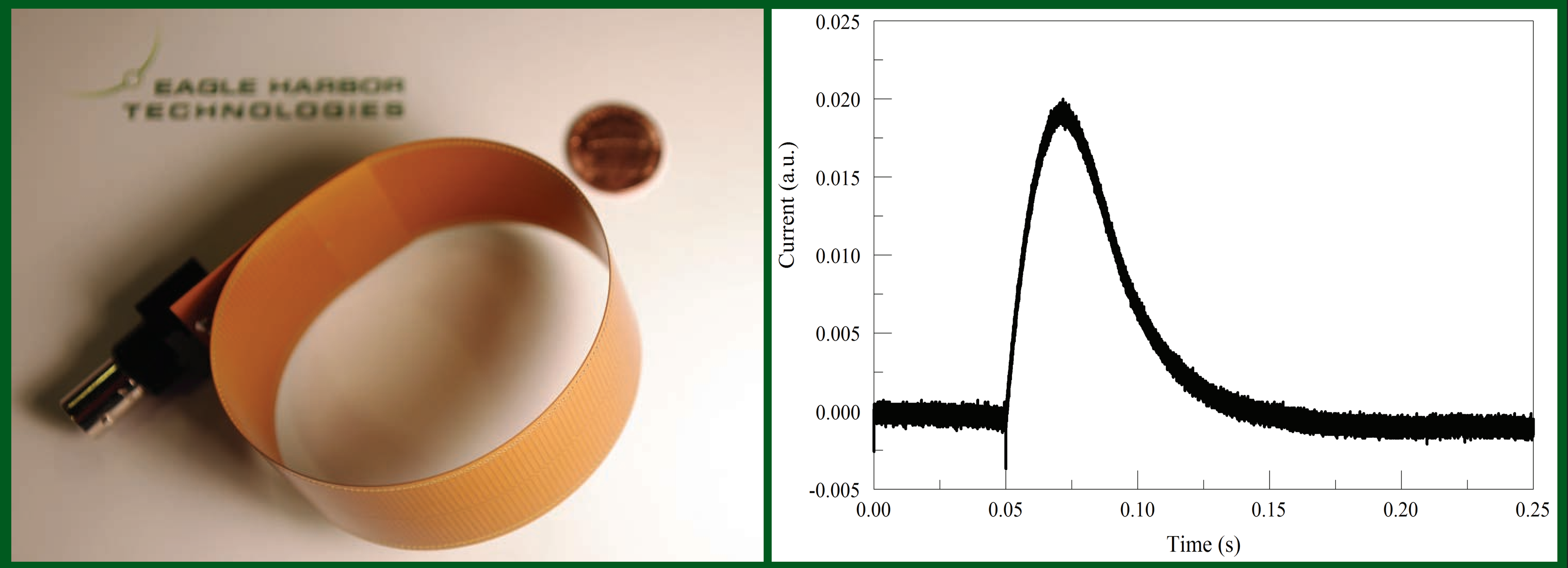


(Left) Three-axis surface probe with RJ-45 connector made using flexible PCB printing techniques. (Right) Magnetic field inside a pulsed solenoid measured off-axis using the three-axis surface probe.

Rogowski Coil

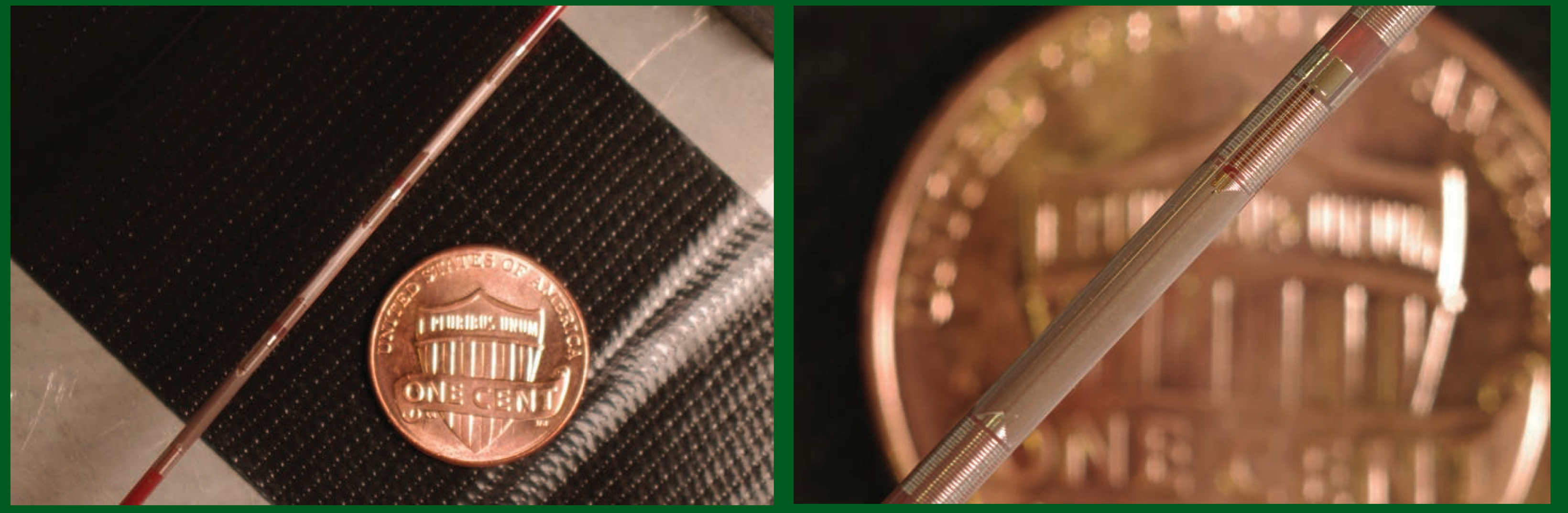
- Prototype Rogowski probe has a total thickness of only 280 μm
- The probe has a field-sensitive area greater than 1 cm^2.
- The dimensions of the probe allow for insertion into smaller regions than possible with other probes.
- Frequency response in the tens of megahertz.
- When compared to pulse current transformers, this probe is significantly smaller and does not suffer from droop or a limitation in the total amp-seconds that it can be operated.
- Outfitted with a BNC connector, this custom current diagnostic tool easily interfaces with existing data acquisition systems.

(Upper Left) Rogowski coil with BNC connector made using flexible PCB printing techniques. (Lower Left) Rogowski coil shown in coiled configuration. (Lower Right) Current in a pulsed solenoid magnet as measured by the flexible Rogowski coil.

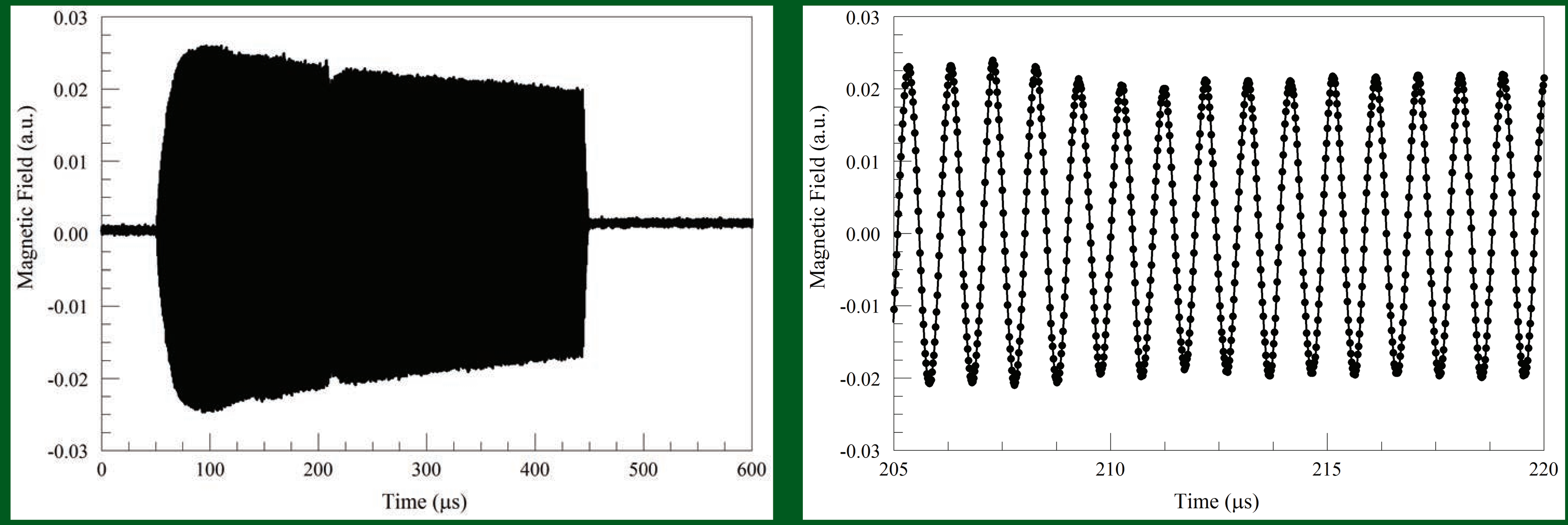


3D Printed Three-axis Magnetic Probe:

- Printed on flexible polyimide tube substrate (1 mm diameter).
- Thermal characteristics of the polyimide and printing process make this probe highly functional in a baked environment (up to 200 °C), such as ultra-high vacuum plasma experiments.
- Each three-axis probe is roughly 1.5 cm long. This high spatial resolution is ideal for internal measurements of large-scale plasma experiments.
- Traces printed in silver nanoparticles have a width of 25 μm, which enables accurate packing of traces on the substrate surface to keep each probe axis within 10 μm of the common center.
- The probe area is 1 cm^2 in each orthogonal direction. In addition, stray area of each direction is limited to less than 0.3 mm^2, or 0.3%.
- Future designs will increase layer count and reduce trace width to 10 μm in order to increase and optimize the probe area.
- Frequency response of this probe is in the tens of megahertz.



(Left) Three-channel, three-axis probe (nine coils total) on polyimide tube made using 3D printing techniques. (Right) Zoomed in photo of the probe showing a single three-axis channel with 25 μm trace widths visible.



(Left) Internal magnetic field in an RF inductive plasma source (no plasma present) as measured with the 3D printed magnetic probe. The antenna frequency is 1 MHz. (Right) Zoomed in magnetic field trace showing that the individual field oscillations are cleanly resolved. The signal was digitized at 50 MS/s.

Phase II Objectives:

- Investigate issues related to improving probe sensitivity.
  - Build in 3D printed electrostatic shielding.
  - Minimize area in each direction.
- Investigate issues related to simplifying probe construction and replication.
  - Probe connectorization.
  - Wiring probe to integrators.
  - Jig to improve 3D printing.
- Build a chain probe containing 25 three-axis probes (75 coils total) with suitable vacuum vacuum hardware.
- Test probes in a validation platform experiment environment (HIT-SI).
- Test probes in a tokamak experiment environment (DIII-D).

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