Construction and Calibration of a Tri-Directional Magnetic Probe

for the VASIMR experiment on mini-RFTF

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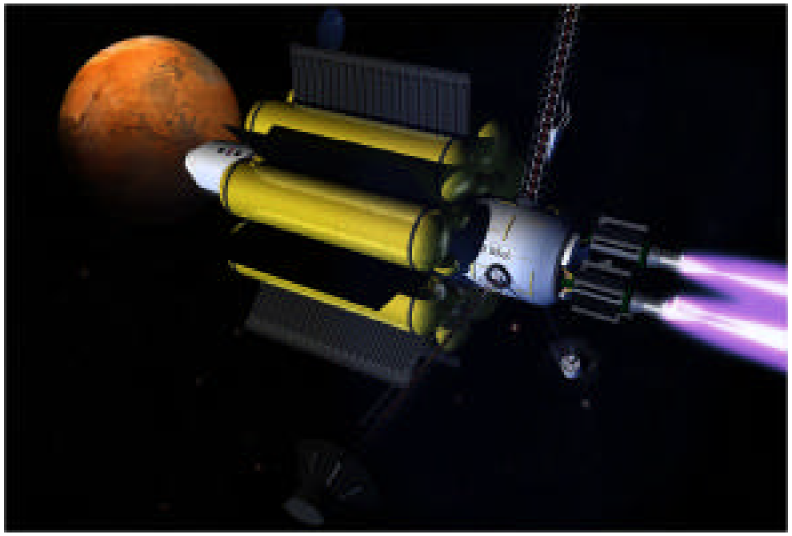
Abstract

Development and Calibration of a Tri-Directional Magnetic Probe for Investigation of Field Structure in the VASIMR Helicon Plasma Source, HANNA SMITH (Smith College, Northampton, MA 01063) R. H. Goulding (Oak Ridge National Laboratory, Oak Ridge, TN 37830).

The performance of a helicon plasma source as a propulsion device depends upon the structure of the magnetic fields generated by the rf antenna that ignites and maintains the plasma. The EMIR2 code predicts the configuration of these fields in three dimensions for the helicon plasma source on mini-RFTF. Due to a lack of appropriate diagnostics, however, the theoretical results from EMIR2 still await experimental confirmation. Inductive loop probes provide a convenient means of investigating magnetic fields inside experimental plasmas of moderate energy density. Conventional single loop probes sample one component of *dB/dt*, the time-rate-of-change of the magnetic field. Acquisition of data in three dimensions for comparison with EMIR2 results demands the use of three mutually perpendicular (and physically proximate) inductors. Moreover, mapping the fields associated with the helicon source on mini-RFTF requires a small probe of high frequency response. This presentation details the design, construction and calibration of a tri-directional magnetic probe for the VASIMR experiment on mini-RFTF.



Introduction

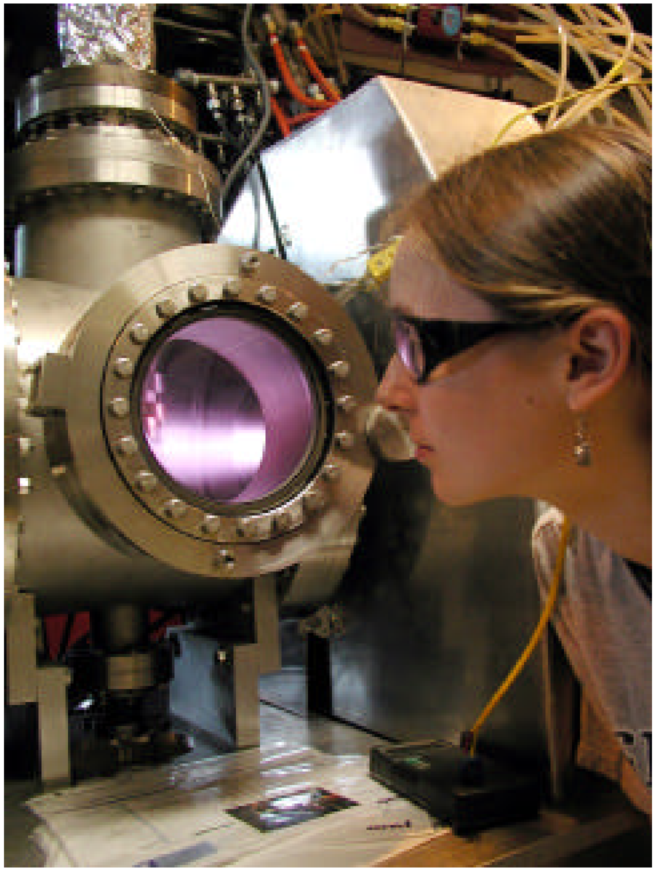
The Variable Specific Impulse Magneto-plasma Rocket (VASIMR) is a next- generation space propulsion device currently under development at both Oak Ridge National Laboratory and NASA's Johnson Space Center. In the early eighties plasma physicist and astronaut Franklin Chang-Diaz began investigating asymmetric magnetic mirrors with space propulsion in mind. Effectively, a magnetic mirror is a leaky plasma containment device that can provide a shaped flow of charged particles -- and therefore thrust. Chang-Diaz hopes that VASIMR will one day carry human passengers to Mars.

The rocket's basic design is that of a three-cell mirror device. In the first cell, neutral gas (hydrogen or helium) is injected and ionized by radio frequency (rf) power, creating a plasma discharge. The cold dense plasma flows into a larger chamber where the ions are heated and accelerated. The heated ions are accelerated still further as they move through the final cell, or magnetic nozzle. Although the concept is straight forward, twenty years of low level research have not untangled the complex physics that governs VASIMR's behavior.

Many factors influence the speeds and trajectories of individual particles in the plasma exhaust, including the shape of the confining magnetic field, the relative masses of the ions and electrons in the exhaust, and the structure of the waves launched by the antenna that ignites the discharge. The VASIMR plasma source consists of two dual half turn antennas, connected by two helical straps. The waves launched by this and similar antennas are generically termed "helicon waves" because of the twisted antenna geometry from which they are produced. The high ionization efficiency and high density of helicon discharges makes them well suited for semi-conductor processing as well as space propulsion. The physics that gives helicons these useful characteristics, however, is poorly understood. Mapping the fields generated by the VASIMR antenna is critical to understanding the behavior of the plasma source, both in the lab and in outer space.

An inductive loop probe provides the simplest means of sampling the magnetic fields inside a moderately dense plasma. A diagnostic of this type will be an important addition to the VASIMR experiment at ORNL.

Objectives



- **Design a magnetic probe** compatible with the VASIMR experiment on mini - RFTF.

- **Fabricate the probe**. The probe must be:
  - *Extremely* small (diameter < 0.25”, height < 0.5”)
  - Capable of sampling fields in three mutually perpendicular directions
  - Able to compensate for electrostatic potentials in the plasma

- **Fabricate a probe casing**. The casing must:
  - Be vacuum tight
  - Protect the probe from hot dense plasma
  - Interfere minimally with plasma
  - Allow the probe to be scanned axially along the plasma column

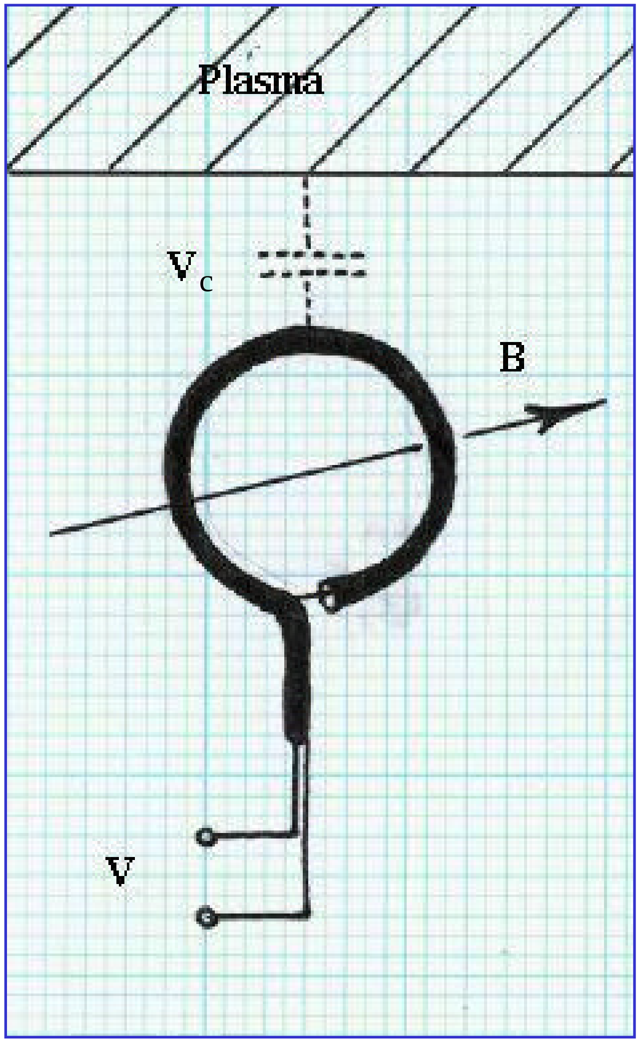
- **Calibrate the probe**

Simple Inductive Probe

The most basic inductive probe consists of a rigid coaxial line wrapped into a single loop. The inner conductor is shorted to the outer conductor. When the loop is inserted into the plasma, the signal produced is

$$V_B = nA\frac{dB}{dt}$$

where A is the area of the loop in square meters, n is the number of turns (in this case one) and dB/dt is the time rate of change of the magnetic field, or B-dot.



Electrostatic Pickup

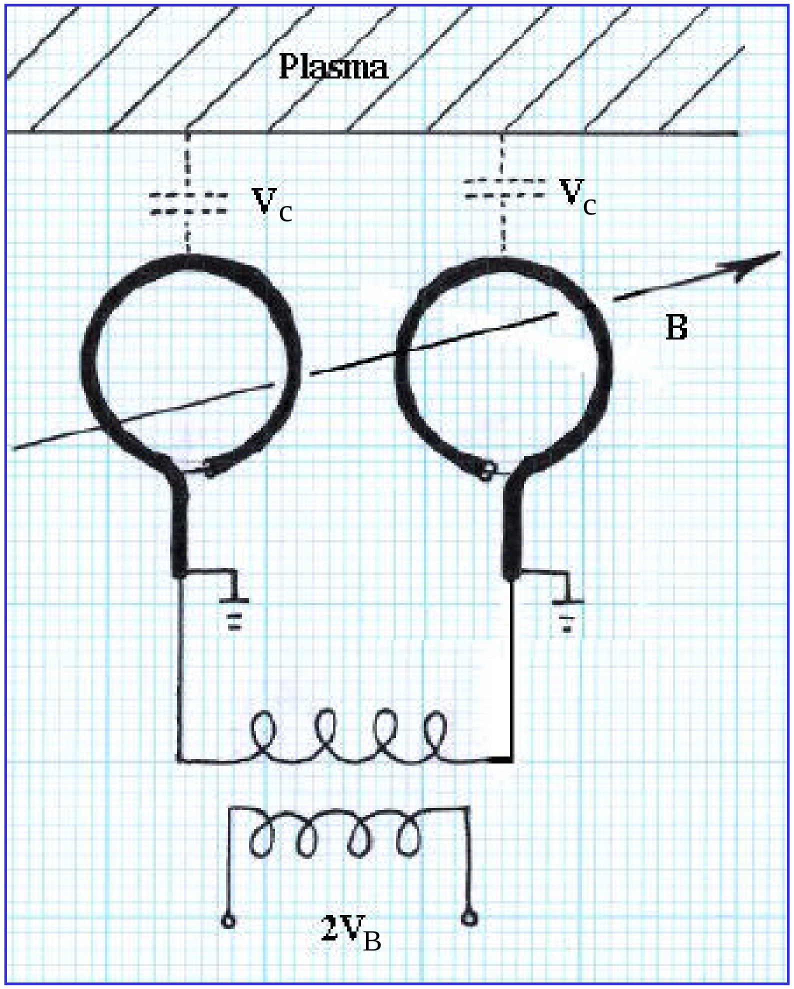
Although the relationship between the probe output and the internal magnetic field is quite direct, complications arise in the presence of electric fields. Electrostatic coupling causes the B-dot probe to act as a Langmuir probe, resulting in the output signal

$$V = V_B + V_C$$

where V_c is the voltage due to the electrostatic rf pickup. In order to remove the electrostatic component a second loop, wound in the opposite direction, is placed next to the first. By Ampere's Law, the polarity of the magnetic pick-up in each loop is opposite to that of the neighboring loop. The direction in which a loop is wound, however, does not affect the polarity of its capacitive signal. Thus the output from the second loop is

$$V = V_c - V_B$$

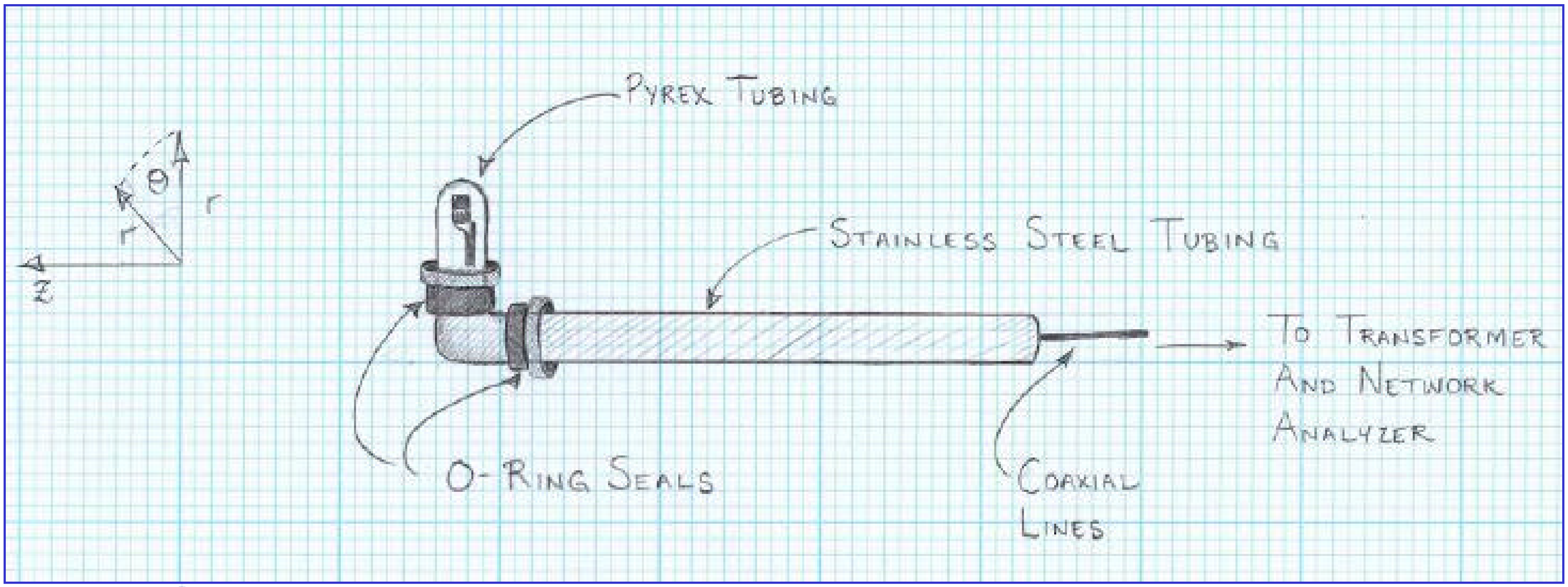
The signals from the two loops are subtracted by connecting the center conductors to opposite ends of a transformer winding. The output from the total probe is then $2V_B$



Probe Design -- Schematic Diagram

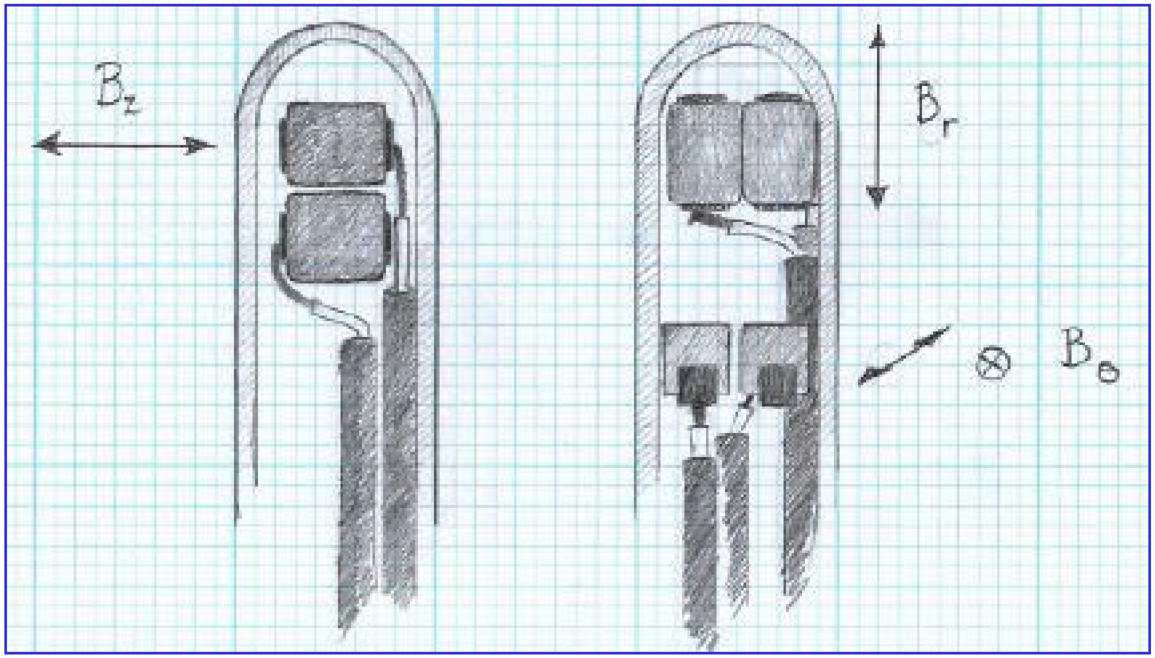
- The objective of my project was to design, build and calibrate a B-dot probe for the VASIMR experiment on mini-RFTF.

- Size was the major constraint on the probe's design. The probe casing measures < 1" vertically and the outer diameter of the steel tubing is 0.25".



Early design concept sketch -- *not to scale*

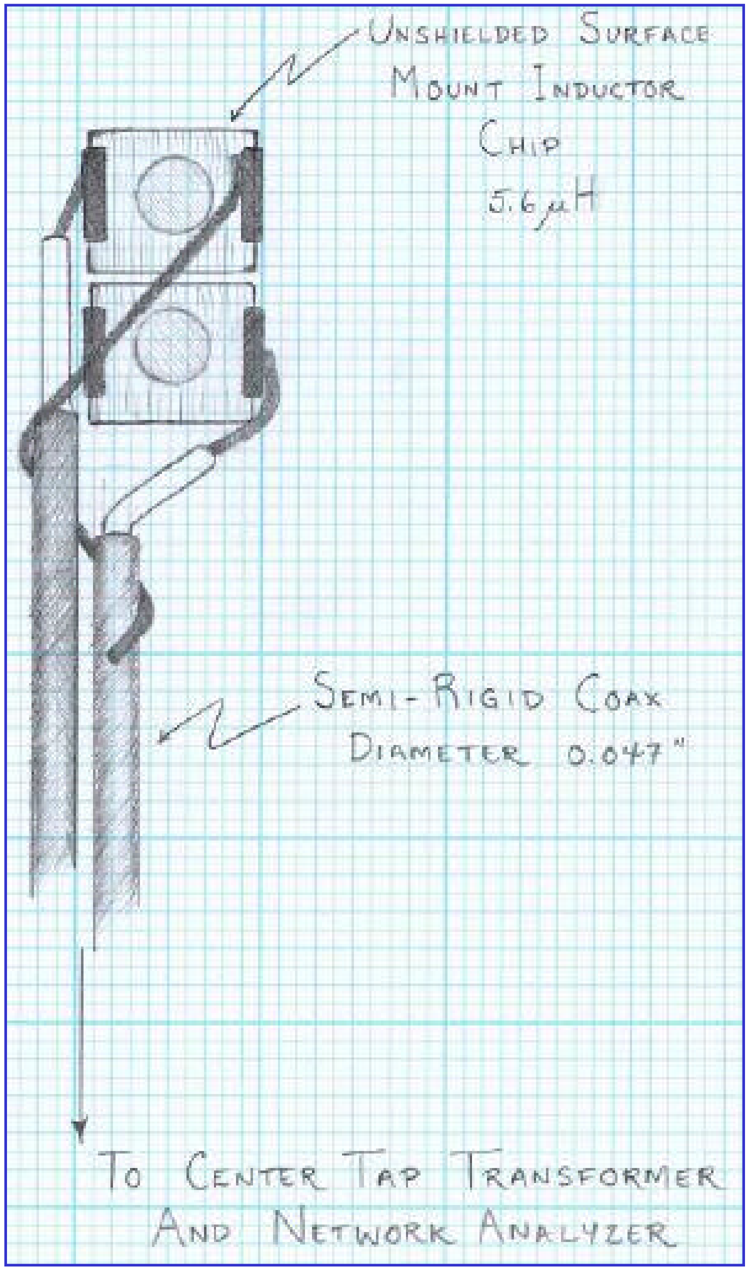
Probe Design -- Schematic Diagrams
(Continued)



(Drawings not to scale)

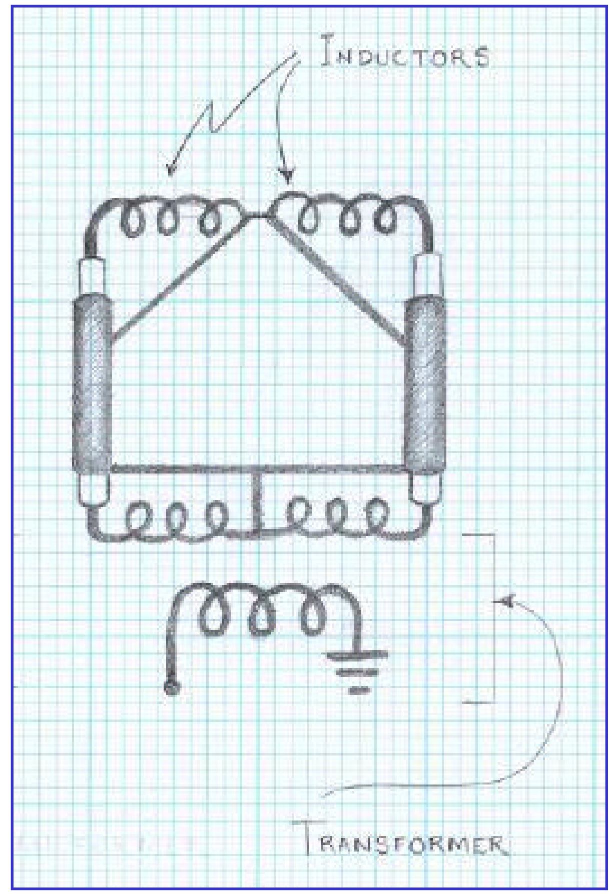
- Due to size constraints it proved impossible to fabricate a single probe that could sample all three mutually perpendicular components of B-dot simultaneously. Instead, two nearly identical probes were built. One samples the axial field; the other samples the radial and azimuthal fields. The probes can be swapped to obtain data in all three coordinate directions.

Compensation for Electrostatic Pickup



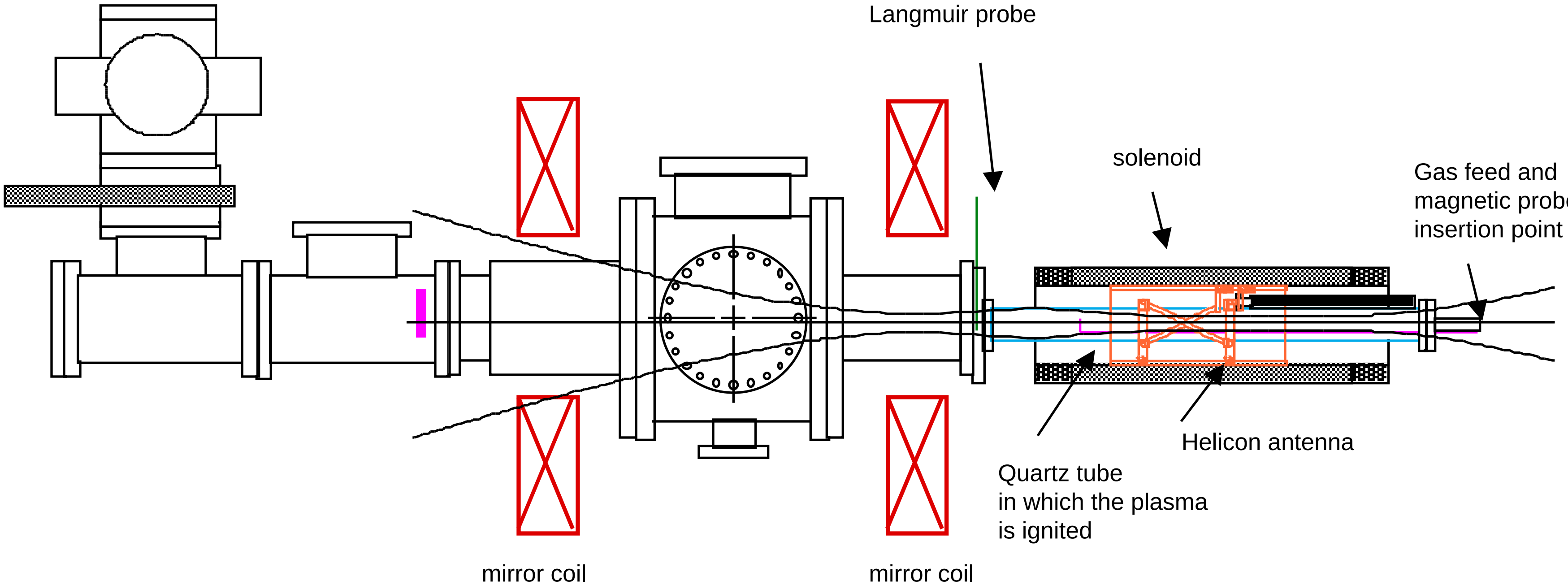
Electrostatic pickup was subtracted from the probe signal in a manner similar to that described for the single loop probe. The figures show a schematic of the probe circuit (including a center tap transformer for electrostatic subtraction) and a detailed view of the chip connections for a single component of the probe. Note that the chips are connected in series and positioned to drive current in the same direction.

Note also that the left hand drawing is to scale. The width of each probe component is less than 0.16 inches or 4 mm.



Mini-RFTF/STX schematic

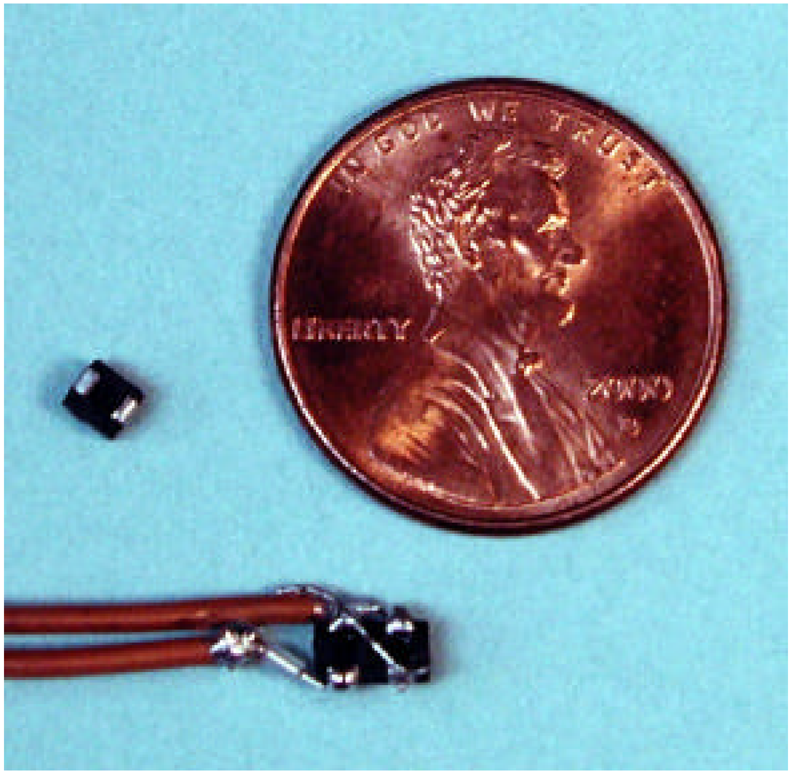
✷ VASIMR experimentation at ORNL is conducted on the Fusion Energy Division's mini-Radio Frequency Test Facility (mini-RFTF). Test stand dimensions mandate the use of a very small probe.



✷ The magnetic probe is inserted at the extreme right of the diagram beside the gas feed. The metal probe casing lies horizontally inside the vacuum chamber and the Pyrex casing extends vertically into the plasma column. (See probe schematic.)

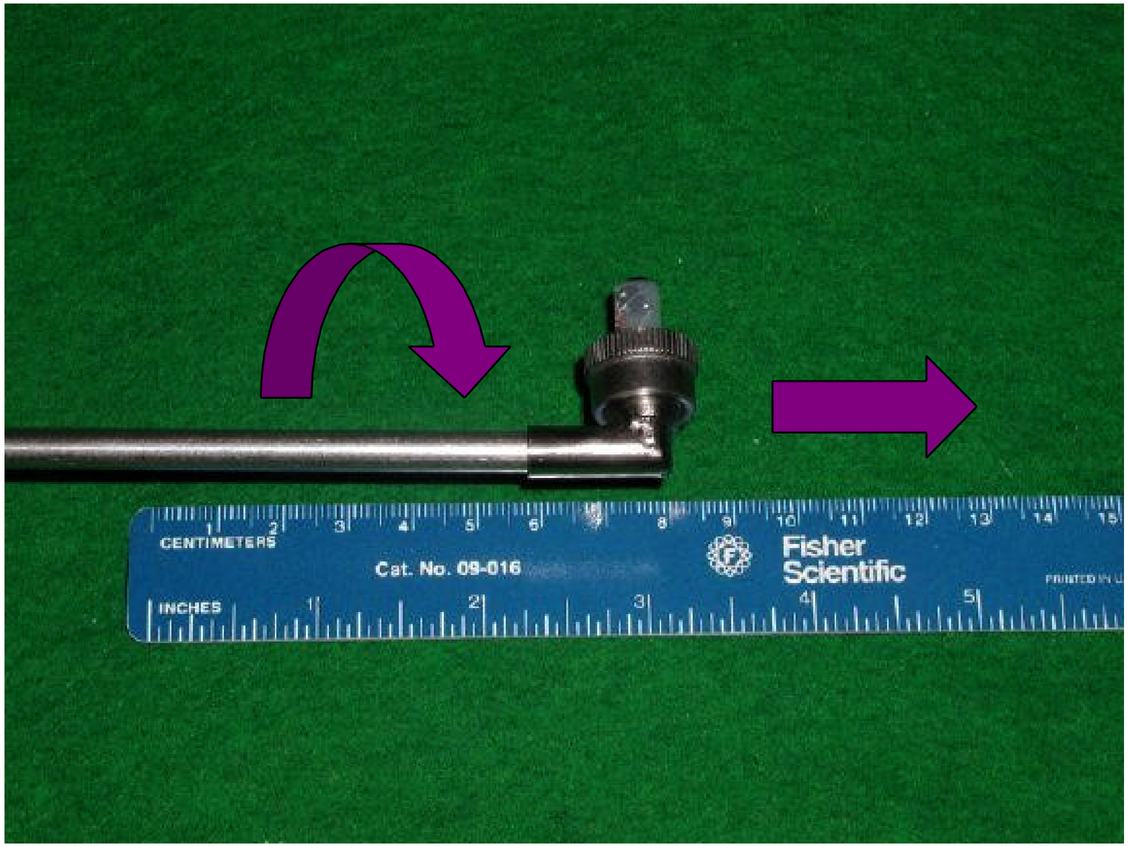
Probe Materials

- Surface mount inductors
  - Dimensions: 2.75 x 2.36 x 2.2 mm
  - Inductance: 5.6 μH
  - Self-resonant frequency: > 44 MHz
- Semi-Rigid Coax -- Diameter: 0.047”
- Pyrex tubing -- Outer diameter: 0.275”
- Stainless steel tubing -- Outer diameter: 0.25”
- Stainless steel elbow joint with o-ring vacuum seals
- Dow Corning 3140 RTV coating
- Center tapped transformer chips
- Good eyes, steady hands ☺



Single inductor with z-component probe and penny

The Completed Probe



✸ Photograph of the completed z-component probe. Both this probe and the r/θ-component probe can be scanned axially and rotated azimuthally to sample fields in all three coordinate directions. The axial range of motion for both probes is 27 inches.

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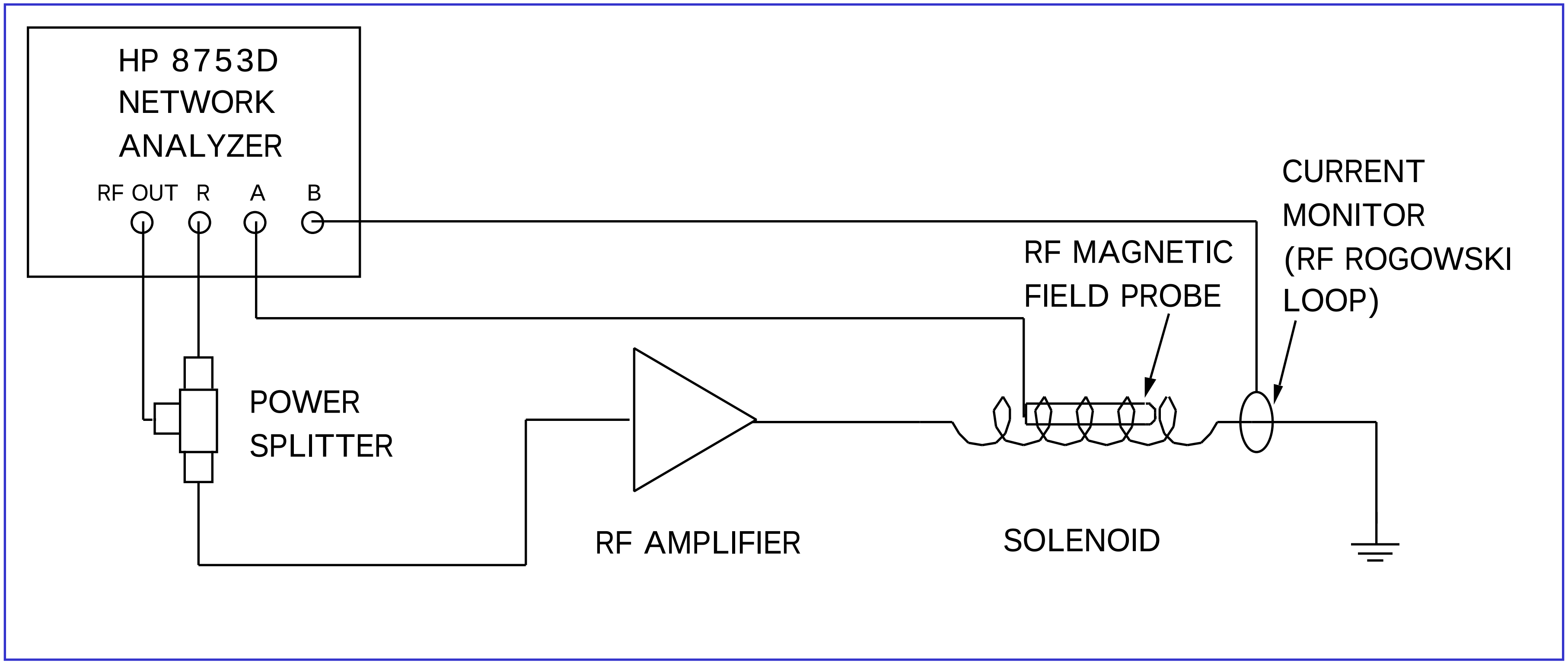
Calibration -- Materials

- Helmholtz Coils:
  - D/2 = coil separation = 1.25”
  - resonant frequency ~37 MHz
- Hewlett Packard 8753D 30 kHz - 6 GHz network analyzer
- Current Monitor (RF Rogowski Loop)
- RF amplifier
- Power splitter
- Solenoid -- alternative to Helmholtz coils
  - Diameter 1.5 cm, Length = 4.5 cm, N = 7
  - $$B_z = \frac{\mu_o N I}{L}$$

- Helmholtz coils were fabricated specifically to calibrate the new probe. The coils produce a uniform magnetic field on axis, described by the simple relation

$$B_o = \frac{32\pi N \; I_H}{5^{3/2} \, D \; 10}$$

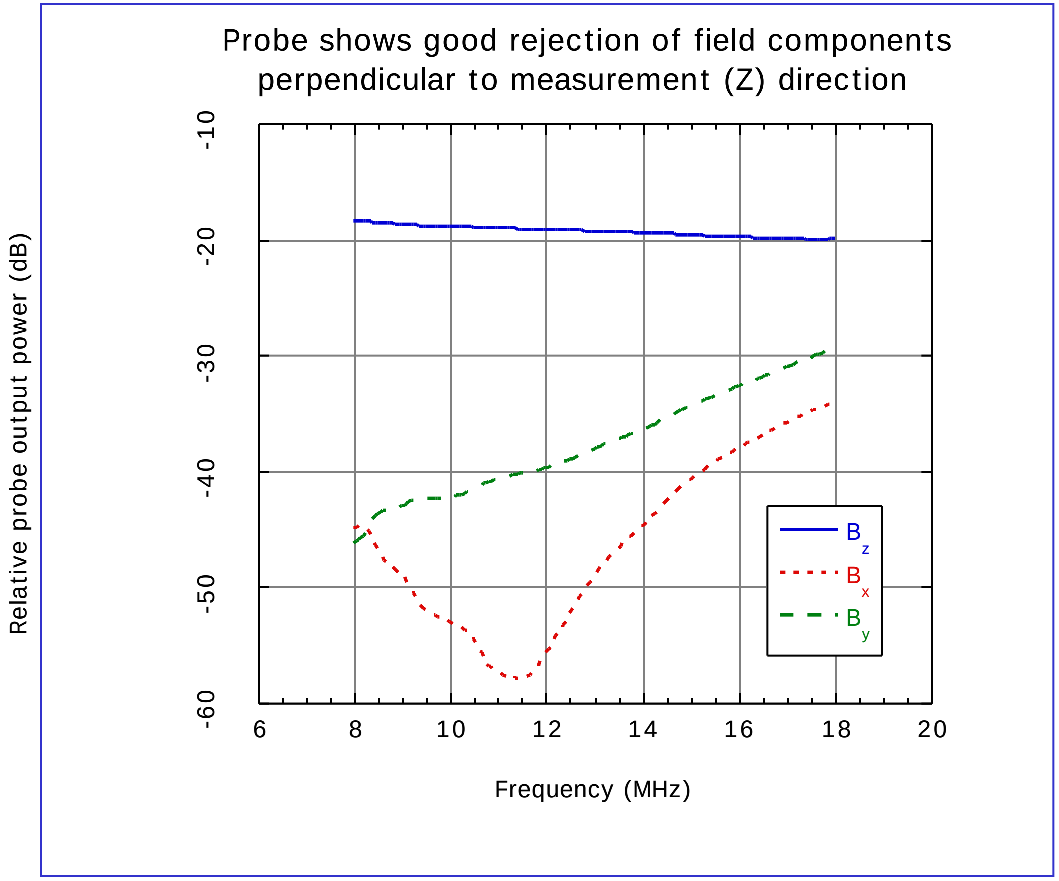
RF Probe Calibration Schematic



- Probe calibration factor in Volts/Tesla = $\dfrac{V_A}{V_B} \times \dfrac{V_{Rogowski}}{I_{Solenoid}} \times \dfrac{I_{Solenoid}}{B_{Solenoid}} = C$

- At 10 MHz C is in the range 260 V/T -- 284 V/T
- At 16 MHz C is in the range 225V/T -- 313 V/T

Calibration
(continued)



Absolute calibration (see previous slide) required that the probe inductors be aligned as well as possible with the magnetic field produced by the solenoid. After the absolute calibration was complete the probe inductors were deliberately misaligned by 90 degrees from the magnetic field to demonstrated that each component of the total probe was insensitive to perpendicular field components.

Results and Conclusions

✷ The probe produces adequate signal to sample the fields generated by the VASIMR rf antenna

✷ Each component of the probe is highly directional -- i.e.the z-component probe does not pick up the r-component or θ-component fields, etc.

✷ The probe is sufficiently small for use on the VASIMR experiment, but may interfere with the plasma. *Smaller probes are still desirable!*

Future Work

✷ Install the probe on mini - RFTF

✷ Begin taking data for comparison with EMIR codes

✷ Design smaller more stream-line probe casings for future use

References

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Acknowledgements

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