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**Magnetic Field Design, Optimization,
Physical Assembly and Characterization
for High-Power ECR Thruster**

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Abstract

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This thesis presents the design, manufacturing, and magnetic characterization of a hybrid solenoid–permanent magnet field source for a high-power electron cyclotron resonance (ECR) thruster. The magnetic assembly was developed to support a Space Force high-power ECR thruster concept requiring an approximately 875 gauss resonance region near the base of a boron nitride discharge chamber while maintaining a field topology that guides plasma through the chamber. The final design combines a large-radius solenoid with a fourteen-element permanent magnet array. The permanent magnets provide a static bias field that reduces the solenoid current requirement, while the solenoid provides an approximately axisymmetric contribution that tunes the ECR surface location and improves axial field-line guidance.

The design evolved from an initially permanent-magnet-dominated concept into a manufacturable hybrid assembly. Early radial permanent magnet concepts were rejected because they were cost prohibitive, mechanically complicated, and incompatible with the need for a split assembly. The final permanent magnet architecture instead uses fourteen

off-the-shelf rectangular N42 magnets arranged around a tetradeccagonal inner boundary. A key design improvement was increasing the magnet dimensions from $1 \times 1 \times 1$ in. to $1 \times 1 \times 2$ in.; this increased the useful field contribution while preserving nearly the same chamber-facing magnetic boundary. The solenoid was moved outward to a larger radius to improve field-line straightness, and the final coil was manufactured with 648 turns in a 27-turn by 24-layer winding. The measured coil resistance was approximately 1Ω , consistent with pre-manufacturing estimates.

Magnetic characterization was performed using a gaussmeter probe at a fixed solenoid current of 8.5 A. The measured centerline axial field reached 877.4 gauss at the upstream measurement location, satisfying the 875 gauss ECR target. A two-component $B(r, z)$ field map confirmed that the measured field structure was consistent with the intended magnetic nozzle-like topology, with a strong upstream field, downstream decay, and controlled outward field-line divergence. A 37-point backplate honeycomb measurement showed that the axial field varied smoothly in azimuth and followed the same general trend as the simulated field. The resulting characterization verified that the manufactured hybrid magnetic assembly achieved the required ECR-strength field, preserved the intended field shape, and maintained acceptable backplate axial-field uniformity despite the use of discrete permanent magnets.

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ECR THRUSTER BACKGROUND

1.1 Electron Cyclotron Resonance

Electron cyclotron resonance occurs when the angular frequency of an applied electromagnetic wave matches the gyrofrequency of electrons in a magnetic field. For an electron in a magnetic field of magnitude B , the electron cyclotron angular frequency is

$$\omega_{ce} = \frac{eB}{m_e}, \quad (1.1)$$

where e is the elementary charge and m_e is the electron mass. Equivalently, the electron cyclotron frequency is

$$f_{ce} = \frac{eB}{2\pi m_e}. \quad (1.2)$$

The resonance condition may therefore be written as

$$B_{\text{ECR}} = \frac{2\pi m_e f}{e}. \quad (1.3)$$

For a microwave frequency of 2.45 GHz, this gives

$$B_{\text{ECR}} = \frac{2\pi m_e (2.45 \times 10^9 \text{ Hz})}{e} \approx 0.0875 \text{ T} = 875 \text{ gauss}. \quad (1.4)$$

This value is a standard ECR field strength for 2.45 GHz microwave systems and follows directly from the electron charge-to-mass ratio [1, 6]. In this project, the magnetic design was therefore required to generate an approximately 875 gauss region near the base of the boron nitride chamber.

The magnetic design problem is not simply to create a strong magnetic field. The field must reach the required magnitude in the correct physical region, and the field topology must be compatible with plasma formation, particle transport, microwave coupling, and surrounding thruster hardware. A field that satisfies the resonance condition in the wrong location, or with field lines that rapidly intersect the chamber wall, would not satisfy the practical ECR thruster requirement.

1.2 Microwave Power Absorption in an ECR Plasma

In an ECR plasma, electrons absorb energy efficiently when their cyclotron motion is resonant with the applied microwave field. Near resonance, the microwave electric field can transfer energy into electron gyromotion, increasing electron energy and promoting ionization of the neutral propellant. The resulting plasma can then be guided and expanded by the magnetic field.

The resonance region is therefore one of the most important magnetic design features. If the 875 gauss region is too far upstream, microwave energy may be absorbed before it reaches the intended discharge volume. If it is too far downstream, the discharge may not form efficiently near the injection region. For the thruster considered in this thesis, the desired ECR region was near the base of the boron nitride chamber, close to the microwave injection region.

The ECR surface is not a physical surface, but a magnetic-field contour. In three dimensions, it is the set of spatial locations where the magnetic field magnitude is approximately equal to the resonant value. Because the plasma occupies a finite volume and the field varies continuously, the useful resonance region is better understood as a spatial zone rather than a single point. The design objective was therefore to position the ECR-strength region in a useful part of the chamber while maintaining an acceptable field shape through the rest of the discharge volume.

1.3 Role of the Magnetic Field in an ECR Thruster

The magnetic field in an ECR thruster performs several coupled functions. First, it determines where microwave energy is preferentially absorbed by electrons. Second, it influences electron confinement and ionization by affecting charged-particle motion. Third, it shapes the plasma expansion through the discharge chamber and into the downstream region. Because of these coupled functions, the magnetic field magnitude and magnetic field geometry are both design-critical.

Electron motion perpendicular to the magnetic field is constrained by gyromotion, while motion parallel to the magnetic field is comparatively less restricted. Field lines therefore provide a useful way to visualize the preferred direction of charged-particle transport. In the design considered here, the field lines were required to guide plasma through the boron nitride chamber rather than strongly into the chamber wall.

This requirement motivated the emphasis on field-line straightness. In this thesis, “straight” does not mean perfectly uniform or mathematically parallel. Instead, it means that the field lines through the chamber remain predominantly axial and avoid strong curvature into the wall. This distinction is important because an ECR thruster does not require a perfectly uniform magnetic field. It requires a magnetic field that places the resonance region correctly and guides the resulting plasma in a useful direction.

1.4 Magnetic Nozzle Behavior

A magnetic nozzle is a diverging magnetic-field structure that guides plasma expansion downstream. In electric propulsion, magnetic nozzle concepts are used to influence plasma acceleration, plume shape, and wall interaction. The field does not act on ions and electrons in exactly the same way at all scales, but the magnetic topology remains an important part of the discharge and plume design [3, 5].

For this project, the desired field structure was not a highly divergent nozzle im-

mediately at the chamber base. Instead, the goal was to produce an ECR-strength region near the upstream side of the chamber while maintaining field lines that remain as axially directed as practical through the boron nitride volume. Farther from the centerline and farther downstream, some controlled divergence is expected and useful. The final $B(r, z)$ measurements therefore evaluated not only field magnitude, but also the radial component of the field and the overall field-line shape.

The radial component B_r is especially useful for evaluating divergence in a two-dimensional meridional plane. A field that is nearly axial near the centerline and becomes more radial at larger radius has the magnetic nozzle-like structure expected from the final design. This is why the magnetic characterization included both centerline B_z measurements and two-component $B(r, z)$ field mapping.

1.5 Motivation for a Hybrid Magnetic Source

A permanent magnet array is attractive for an ECR thruster because it provides magnetic field without continuous electrical power or ohmic heating. Permanent magnets can therefore reduce the current required from an electromagnetic coil. However, permanent magnets alone are difficult to tune after assembly, and a discrete permanent magnet array introduces azimuthal nonuniformity.

A solenoid has the opposite advantages and disadvantages. It produces an approximately axisymmetric field and can be tuned by changing current, but it also generates heat through electrical resistance. For a solenoid with resistance R carrying current I , the resistive heat load is

$$P = I^2 R. \tag{1.5}$$

As a result, a solenoid-only design can become thermally undesirable if high current is required. The hybrid approach used in this thesis combines the strengths of both methods.

The permanent magnet array supplies a static bias field, while the solenoid supplies the tunable and approximately axisymmetric contribution needed to place the ECR region and improve field-line shape.

The total magnetic field can be written as

$$\mathbf{B}_{\text{total}} = \mathbf{B}_{\text{PM}} + \mathbf{B}_{\text{solenoid}}. \quad (1.6)$$

This superposition is central to the design. The permanent magnet field does not need to be perfectly uniform by itself because the solenoid field reduces the fractional importance of the discrete magnet variation. The resulting hybrid field can therefore meet the ECR magnitude requirement while remaining manufacturable and tunable.

1.6 Relevance to Microwave ECR Thruster Design

Microwave ECR thrusters and ECR ion sources have been investigated because they can produce plasma without conventional cathodes or internal electrodes in the discharge region [4, 2]. This can be attractive for long-duration electric propulsion systems because removing or reducing electrode erosion mechanisms can improve lifetime. The magnetic field design remains a central challenge because the same field must support resonance, confinement, and plasma transport.

The magnetic source developed in this thesis was designed for a high-power ECR thruster concept. The design used a 875 gauss ECR target corresponding to 2.45 GHz microwave operation, placed the resonance-strength region near the chamber base, and used a hybrid solenoid–permanent magnet architecture to balance field strength, tunability, manufacturability, and thermal load. The following chapters describe the specific requirements, design evolution, manufacturing process, and magnetic characterization of that field source.

Chapter 2

SPECIFIC REQUIREMENTS

2.1 ECR Field Magnitude Requirement

The primary magnetic requirement was that the field magnitude reach approximately 875 gauss in the desired ECR region. This requirement followed directly from the microwave resonance condition. The design was evaluated by examining the location of the 875 gauss surface in simulation and, later, by planning magnetic field measurements of the manufactured assembly.

The field magnitude requirement was not treated as a single-point requirement. Because the discharge occupies a finite volume, the useful ECR region is a surface or volume within the chamber rather than an isolated point. The target design placed this region near the chamber base, where it could interact with injected microwave power and seed the discharge.

2.2 Field-Line Straightness Requirement

The second major requirement was that the magnetic field lines through the boron nitride chamber be as straight as practical. In this thesis, “straight” does not mean perfectly parallel or mathematically uniform. Rather, it means that the field lines in the chamber should predominantly guide particles axially and should not rapidly diverge into the chamber wall.

This requirement became one of the dominant design drivers. Early compact-field designs could produce strong local fields, but the field lines curved substantially near the magnetic sources. The design therefore evolved toward a larger-radius solenoid, which produced a more useful field topology in the chamber even though it increased the outer diameter of the magnetic assembly.

2.3 Azimuthal Uniformity Requirement

The permanent magnet array contains fourteen discrete magnets. This means the field produced by the permanent magnets cannot be perfectly azimuthally symmetric. The design therefore required that any fourteen-fold variation be small enough that the total superposed field remained acceptable.

The relevant quantity is not the nonuniformity of the permanent magnet field alone, but the nonuniformity of the combined field:

$$\mathbf{B}_{\text{total}} = \mathbf{B}_{\text{PM}} + \mathbf{B}_{\text{solenoid}}. \quad (2.1)$$

The solenoid contribution is nearly axisymmetric, so it reduces the fractional azimuthal variation of the total field. This principle allowed a practical discrete magnet array to be used without requiring a custom radially magnetized ring.

2.4 Mechanical and Manufacturing Requirements

The magnetic field source also had to satisfy several mechanical requirements. The assembly had to fit around the waveguide converter and boron nitride chamber. It had to be compatible with the thicker quartz window and waveguide extension introduced later in the design. It also had to be manufacturable with available resources and assembled without requiring a continuous ring to be slid over the thruster.

The need for split assembly was especially important. A custom radial permanent magnet ring would have been attractive electromagnetically, but it would have complicated assembly and increased cost. The final design therefore used a split permanent magnet holder containing discrete rectangular magnets. The solenoid was wound separately on a mandrel and then integrated with the magnet assembly.

2.5 Thermal and Electrical Requirements

The solenoid needed to operate at a current low enough to keep heat generation manageable. Resistive heating is estimated by

$$P = I^2 R, \tag{2.2}$$

where I is the solenoid current and R is the coil resistance. Early estimates placed the coil resistance near $1\,\Omega$, making current reduction important. For example, operation near $14\,\text{A}$ would generate approximately

$$P \approx (14)^2(1) = 196\,\text{W}. \tag{2.3}$$

The final hybrid design reduced the simulated current requirement to approximately $10.86\,\text{A}$, corresponding to a heat load on the order of $100\text{--}125\,\text{W}$. This reduction was a direct benefit of including the permanent magnet array.

Chapter 3

DESIGN

3.1 Initial Magnetic Architecture

The earliest design concept established the basic spatial relationship between the microwave hardware, boron nitride discharge chamber, permanent magnet array, and solenoid. The magnetic source had to fit around the waveguide converter and chamber while producing an ECR-strength region near the upstream chamber base. This made the magnetic design a coupled field-strength, field-shape, thermal, and packaging problem rather than a simple requirement to generate a large magnetic field.

The initial architecture first considered whether the required field could be produced primarily by permanent magnets located close to the chamber. This approach was attractive because permanent magnets provide field without electrical power or ohmic heating. However, the magnets could not be placed arbitrarily close to the ECR region because they had to remain outside the required clearance envelope for the waveguide and surrounding hardware. At this distance, the permanent magnet field contribution was not sufficient by itself. Across the permanent magnet configurations tested in simulation, no permanent-magnet-only arrangement produced more than approximately 700 gauss at the target location, which was below the 875 gauss ECR requirement.

The first permanent magnet concepts were based on a more continuous radial magnet arrangement. After that approach proved difficult to manufacture and source, the design study shifted toward discretized magnet arrays. A highly discretized array was tested first, as shown in Figure 3.1, because it approximated the radial magnet concept while using individual magnet elements. However, the additional discretization did not provide a meaningful advantage once the field was evaluated at the chamber scale. The field behavior was dom-

inated more by the overall magnet radius, clearance constraints, and solenoid contribution than by fine angular segmentation of the permanent magnet array.

The design therefore moved toward simpler off-the-shelf rectangular magnets. This substantially improved manufacturability, cost, and ease of sourcing while still preserving the useful magnetic field structure. The first practical version used commercially available $1 \times 1 \times 1$ in. rectangular magnets arranged around the chamber. This layout provided a much more realistic path to hardware while maintaining the chamber-facing magnetic boundary needed for the hybrid design.

The final permanent magnet layout extended the magnet length from $1 \times 1 \times 1$ in. to $1 \times 1 \times 2$ in. This change increased the available magnetic field strength without substantially altering the field structure at the chamber. Simulation showed that magnetic shunting through the permanent magnets themselves allowed the longer magnets to improve field strength while preserving nearly the same chamber-facing field topology. This made the $1 \times 1 \times 2$ in. rectangular magnet layout the best compromise between field strength, manufacturability, cost, and availability of off-the-shelf components.

Overall, the initial architecture showed that the magnetic source had to be designed as a complete system rather than as separate magnet and coil components. The final direction therefore kept the permanent magnets, solenoid, chamber, waveguide clearance, thermal limits, and manufacturability coupled throughout the design process. This system-level approach led to the hybrid magnetic assembly used in the final hardware.

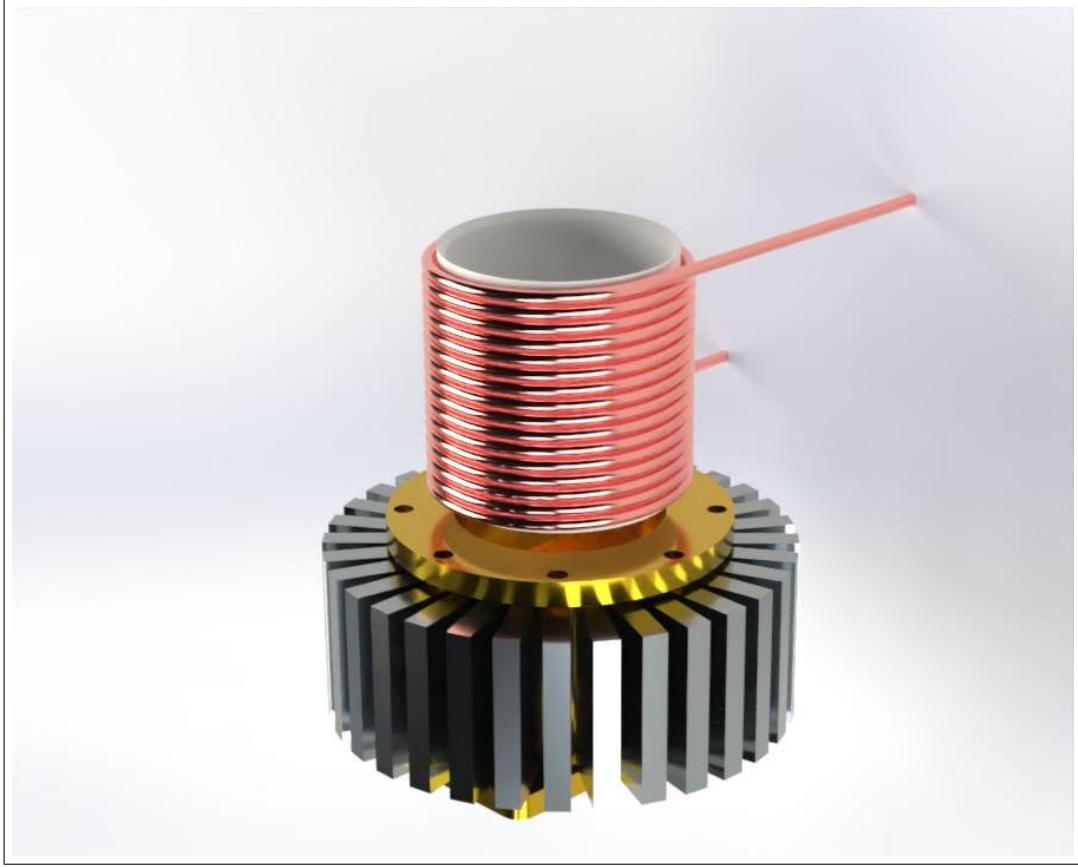


Figure 3.1: Initial magnetic architecture showing the relationship between the waveguide converter, boron nitride chamber, permanent magnet array, and solenoid. The render shows an early highly discretized permanent magnet concept, which was later simplified into an off-the-shelf rectangular magnet array for improved manufacturability, cost, and sourcing.

3.2 Evolution Away from Radial Permanent Magnets

The first preferred permanent magnet concept used radial permanent magnets. Radial magnetization was attractive because it could approximate a more continuous annular magnetic source and reduce the angular variation associated with discrete block magnets. In principle, a radially magnetized ring or segmented radial magnet assembly could have produced a cleaner permanent magnet field.

In practice, the radial magnet concept was rejected because it conflicted with the manufacturing and assembly constraints of the thruster. Custom radially magnetized magnets were cost prohibitive, and a continuous or near-continuous radial magnet structure

would have complicated assembly around the chamber and waveguide hardware. The magnetic assembly also needed to split apart for installation and maintenance. A custom radial magnet ring would have made this requirement difficult to satisfy.

The design was therefore redirected toward commercially available rectangular magnets. This changed the design philosophy. Instead of requiring the permanent magnet field to be ideal by itself, the permanent magnet array was designed to provide a strong and manufacturable bias field that became acceptable after superposition with the solenoid. The total field, not the permanent magnet field alone, was the relevant design object.

3.3 Fourteen-Magnet Tetradecagonal Array

The selected permanent magnet layout uses fourteen rectangular magnets arranged around the chamber. The chamber-facing boundary of the magnet array forms a regular fourteen-sided polygon, or tetradecagon, which approximates a circular magnetic boundary while remaining straightforward to machine and assemble.

This geometry was selected as a compromise between magnetic uniformity, part count, cost, and mechanical simplicity. A larger number of magnets would have reduced the angular spacing between magnetic sources, but it would also have increased the number of pockets, retainers, assembly steps, and opportunities for tolerance stack-up. A smaller number of magnets would have simplified the hardware but increased azimuthal variation. Fourteen magnets provided a practical balance between these competing requirements.

The original off-the-shelf magnet concept used $1 \times 1 \times 1$ in. magnets. The design was later changed to $1 \times 1 \times 2$ in. N42 magnets. This change increased the amount of magnetic material while preserving the same chamber-facing pole geometry. Because the inner boundary remained a tetradecagon, the magnet extension improved the useful field contribution without substantially changing the angular structure imposed on the chamber-facing field.

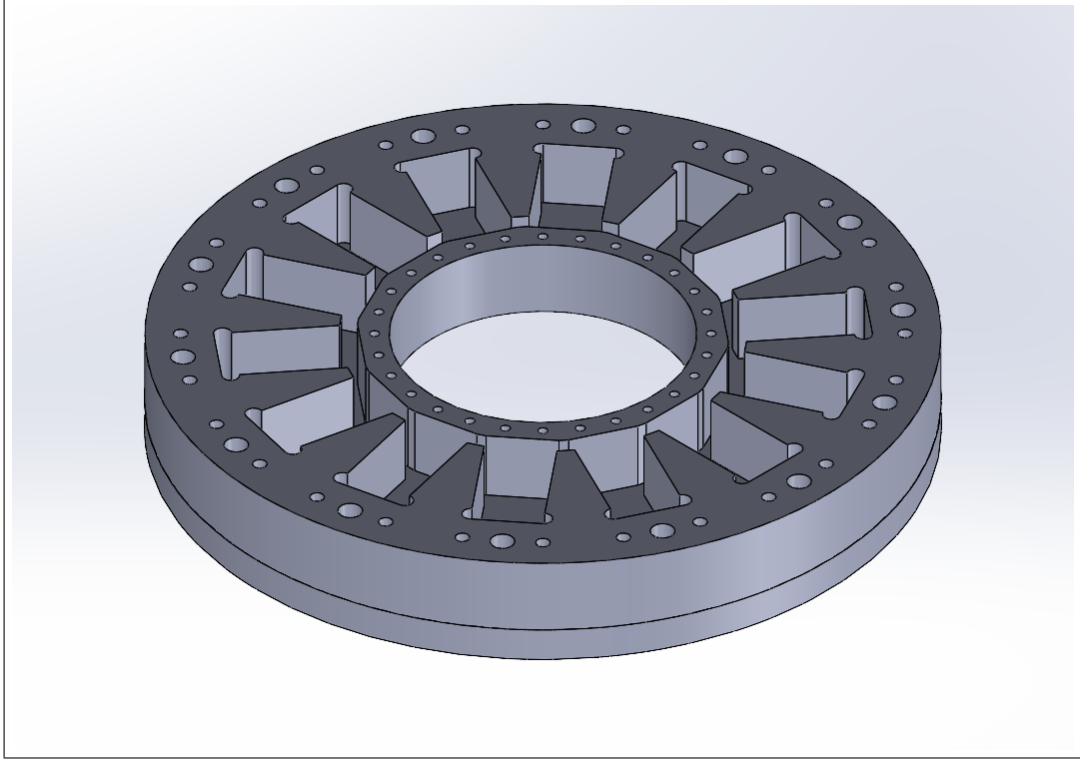


Figure 3.2: Fourteen-magnet permanent magnet array arranged around a tetradecagonal chamber-facing boundary.

3.4 Magnet Length Increase and Magnetic Shunting Insight

Increasing the magnet length from $1 \times 1 \times 1$ in. to $1 \times 1 \times 2$ in. was one of the major design improvements. The change was not simply a brute-force increase in magnet volume. The important insight was that the added magnet length increased the magnetic material behind the same inner pole geometry. The magnets therefore acted partly as their own magnetic flux paths, increasing the effective field contribution without introducing a new chamber-facing shape.

This was valuable because the chamber-facing magnetic boundary controls much of the field structure seen by the plasma. Extending the magnets outward preserved the fourteen-sided inner boundary while increasing the available magnetic field. The resulting design improved the field strength contribution from the permanent magnet array while maintaining a similar field shape near the discharge chamber.

This effect became especially useful after superposition with the solenoid field. The permanent magnet array inevitably introduces some fourteen-fold azimuthal variation because it consists of discrete magnets. However, the solenoid contribution is nearly axisymmetric. When the two fields are added, the same absolute angular variation from the magnet array becomes a smaller fraction of the total field. This is one of the main reasons the discrete magnet architecture was acceptable: the permanent magnets supplied useful field strength, and the solenoid reduced the fractional nonuniformity of the combined field.

3.5 Solenoid Radius and Field-Line Straightness

The solenoid radius study was performed to determine how the coil diameter affected the field-line shape through the boron nitride chamber. A compact solenoid initially appeared attractive because it reduced the overall magnetic assembly size and placed the current closer to the chamber. However, simulation showed that the compact configuration produced field lines with stronger curvature in the discharge region. This curvature increased the tendency of field lines to intersect or approach the chamber wall.

Increasing the solenoid radius improved the field-line topology. Moving the winding outward produced a more gradual field variation through the chamber and reduced the sharp curvature near the magnetic source. The larger-radius solenoid therefore improved axial guidance even though it increased the outer diameter of the assembly.

This result changed the role of the solenoid in the design. The solenoid was not only a field-strength booster; it was also a field-shaping component. Its radius, axial position, and winding geometry were selected to support the desired magnetic topology. The final design uses the solenoid to tune the ECR region while also helping the field lines guide plasma away from the chamber walls.

3.6 Simulation Model

The magnetic design was evaluated primarily in Ansys Maxwell 3D. The permanent magnets were modeled as explicitly magnetized N42 blocks arranged in the fourteen-magnet geometry. The solenoid was modeled using an annular current representation to reduce mesh complexity while preserving the dominant axisymmetric field contribution of the winding.

This modeling approach made it possible to evaluate the full three-dimensional field without requiring a conductor-by-conductor mesh of the 648-turn solenoid. The simplified solenoid representation was appropriate because the winding behaves as a distributed current source at the scale of the discharge chamber. The permanent magnets, by contrast, were modeled individually because their discrete spacing was directly relevant to azimuthal uniformity.

The simulations were used to evaluate the following design quantities:

1. the location of the 875 gauss ECR surface,
2. field-line shape through the boron nitride chamber,
3. azimuthal variation caused by the fourteen discrete magnets,
4. sensitivity of the field topology to solenoid radius,
5. interaction between the permanent magnet field and solenoid field,
6. solenoid current required to place the ECR region at the chamber base.

Cross sections of the superposed field were evaluated at multiple axial locations through the chamber. These cross sections showed how the magnetic structure changed from the upstream region to the downstream region and confirmed that the field topology remained acceptable throughout the relevant discharge volume. The simulation results placed the ECR-strength field near the chamber base and showed field lines guiding plasma away from the chamber walls.

3.7 Final Magnetic Design

The final magnetic design consists of a large-radius solenoid combined with a fourteen-element permanent magnet array. The permanent magnet assembly uses $2 \times 1 \times 1$ in. N42 rectangular magnets in a split aluminum enclosure. The solenoid uses 9 AWG square magnet wire and contains 648 turns arranged as 27 turns by 24 layers. Figure 3.3 shows the final magnetic assembly layout.

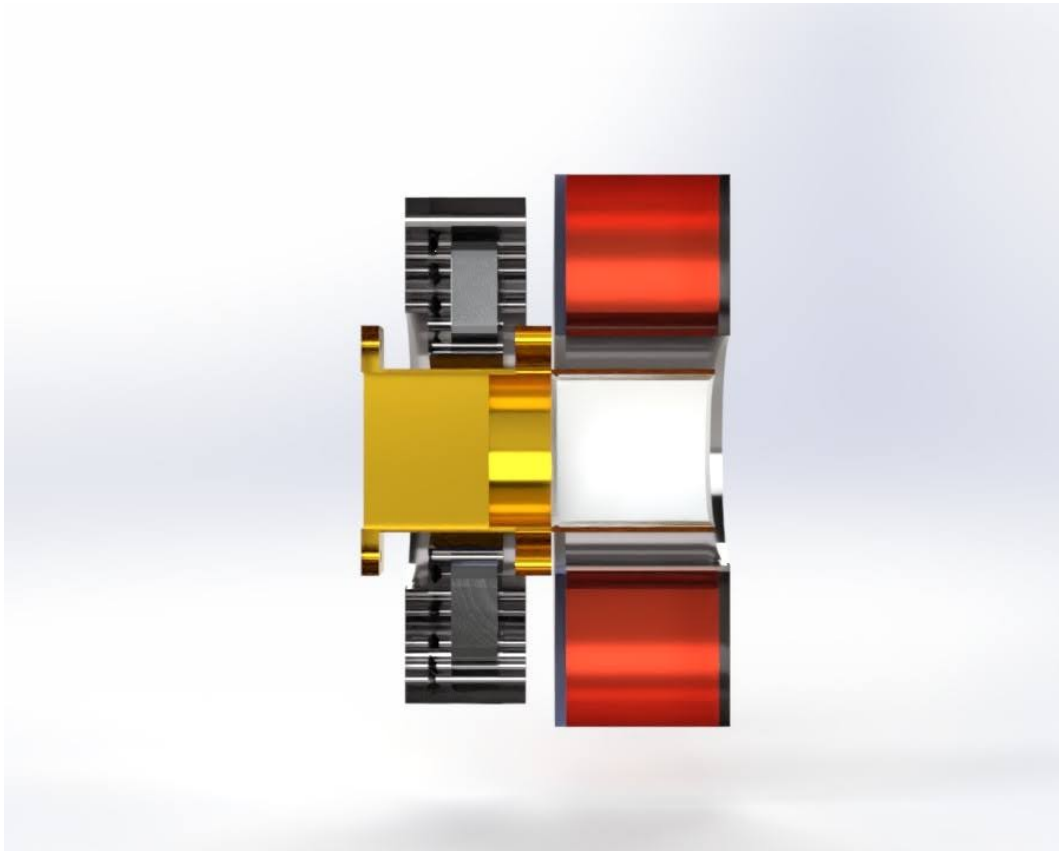


Figure 3.3: Final hybrid magnetic assembly showing the large-radius solenoid, fourteen-element permanent magnet array, and surrounding mechanical structure. In the final hardware configuration, the permanent magnet array and solenoid were shifted downstream onto a lengthened waveguide extension to satisfy packaging requirements, while the relative magnetic geometry of the solenoid, magnet array, and chamber-facing field source remained unchanged.

The final simulated operating point placed the ECR-strength region near the base of the boron nitride chamber at a solenoid current of approximately 10.86 A. This current

was lower than the approximately 14 A operating point that would likely have been required with the earlier $1 \times 1 \times 1$ in. permanent magnet layout. Assuming a solenoid resistance near 1Ω , the final operating heat load is on the order of

$$P = I^2 R = (10.86 \text{ A})^2 (1 \Omega) \approx 118 \text{ W}. \quad (3.1)$$

By comparison, a 14 A, 1Ω operating point would dissipate approximately 196 W. The final $1 \times 1 \times 2$ in. permanent magnet layout therefore reduced the expected solenoid current and heat load relative to the earlier $1 \times 1 \times 1$ in. magnet configuration.

The final design satisfied the major magnetic and mechanical requirements. The ECR region was positioned near the chamber base, the field lines guided plasma through the chamber rather than directly into the wall, the permanent magnet assembly remained compatible with split installation, and the discrete magnet nonuniformity was reduced by the axisymmetric solenoid contribution.

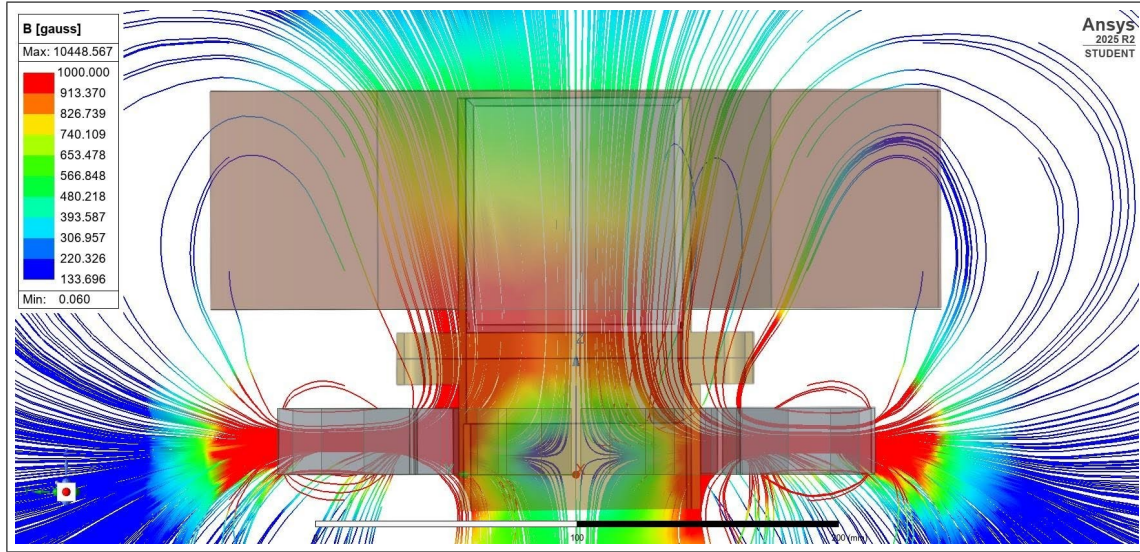


Figure 3.4: Final simulated magnetic field configuration showing the ECR-strength region near the chamber base and field lines guided through the discharge chamber.

MANUFACTURING METHODS

4.1 Permanent Magnet Enclosure

The permanent magnet enclosure was designed as a split aluminum assembly containing fourteen rectangular magnet pockets. The enclosure was machined from 11 in diameter aluminum stock. The required operations included milling the magnet slots, drilling the mounting holes, and turning the center bore.

The split design was required because the magnet assembly needed to be installed around the thruster geometry. A continuous closed ring would have complicated assembly and reduced maintainability. The split holder also made it possible to install magnets in controlled groups, which was important because the magnets exerted strong forces during assembly.

The enclosure served two functions. First, it located the permanent magnets at the angular positions required by the magnetic design. Second, it provided a mechanically secure structure that could retain the magnets during handling, assembly, and operation. Because the magnetic design depends on the relative position of the magnets, the enclosure was a field-critical component rather than only a structural support.

The fourteen magnet pockets were arranged to produce the tetradecagonal inner boundary described in the design chapter. This geometry preserved a practical approximation to a circular magnetic boundary while remaining compatible with conventional machining and split assembly. The aluminum body also provided a nonmagnetic structure for holding the magnets without significantly redirecting the intended magnetic field.



Figure 4.1: Machined aluminum permanent magnet enclosure containing the split-ring geometry and rectangular magnet-pocket layout.

4.2 Permanent Magnet Retention

The completed permanent magnet array used vented screws and oversized washers to retain the magnets. The vented screws were selected to reduce the risk of virtual leaks in vacuum operation, while the oversized washers provided improved mechanical capture of the magnets. This retention method was selected because the magnets needed to remain secure during handling, assembly, and operation while remaining compatible with vacuum practice.

Permanent magnet retention was an important manufacturing concern because the magnets experience strong forces during installation. The array uses N42 permanent magnets, and adjacent magnets interact strongly enough that uncontrolled handling can cause sudden motion, impact, or misalignment. The enclosure and retention hardware therefore needed to allow the magnets to be installed in a controlled sequence and then held securely

after placement.

Oversized washers were used because they distributed the retaining force over a larger area and provided a more forgiving capture feature than a small screw head alone. This was especially useful because the magnet faces are smooth and the available retaining features are constrained by the surrounding geometry. The vented screws provided a vacuum-compatible fastening method by reducing trapped gas volumes.

The retention design also preserved serviceability. The magnets were mechanically captured without permanently bonding the entire array into a single closed structure. This maintained the split-assembly philosophy of the magnetic design and allowed the permanent magnet hardware to remain compatible with installation around the thruster.

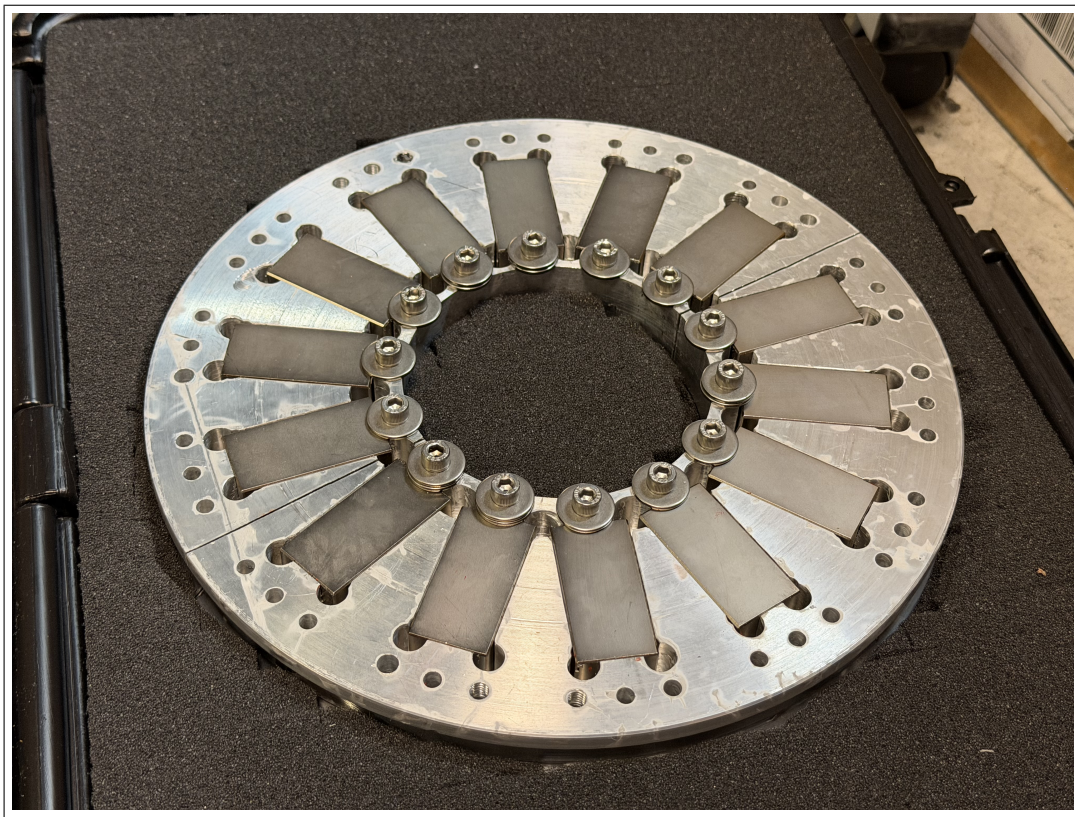


Figure 4.2: Completed permanent magnet array with rectangular magnets retained by vented screws and oversized washers.

4.3 Solenoid Mandrel

The solenoid was wound on a dedicated mandrel. The mandrel defined the coil radius, axial length, and winding window. Because the magnetic field shape depended strongly on solenoid radius, the mandrel was a field-critical component rather than a simple manufacturing aid.

The mandrel geometry controlled the final position of the 648-turn winding. This was important because the solenoid radius was selected through simulation to improve field-line straightness through the boron nitride chamber. Any significant deviation in mandrel radius or axial length would have changed the magnetic field produced by the solenoid and reduced the accuracy of the simulated design.

The mandrel also provided the mechanical reference for winding the large square magnet wire. The wire stiffness made it difficult to form a uniform coil without a rigid and dimensionally stable support. The mandrel therefore needed to resist winding loads, maintain alignment with the winding jig, and provide a repeatable surface for building the coil layer by layer.

The solenoid was ultimately manufactured with 27 turns per layer and 24 layers, for a total of 648 turns. The mandrel and winding setup were therefore required to maintain consistent layer placement over a large number of turns. This was especially important because irregular winding geometry would affect both the electrical resistance and the local magnetic field distribution.

4.4 Winding Jig

A custom winding jig was developed to wind the solenoid. The jig used two bearings, a central axle, and a ratchet/winch interface. The purpose of the jig was to control the high stiffness and stored energy of the 9 AWG square magnet wire during winding. Because the wire was large and difficult to handle, the jig needed to provide controlled rotation, resist back-driving, and maintain alignment.

The winding jig converted the solenoid from a difficult hand-winding task into a controlled manufacturing process. The bearings allowed the mandrel to rotate smoothly, while the axle maintained the alignment of the mandrel through the winding operation. The ratchet interface allowed the winding position to be advanced incrementally and prevented the coil from unwinding when the operator released force.

The stiffness of the square magnet wire was one of the main challenges in manufacturing the solenoid. Large wire stores mechanical energy when bent around the mandrel, and uncontrolled release of that energy can damage the winding or create a safety hazard. The jig reduced this risk by keeping the winding motion constrained and repeatable.

Adapters were 3D printed and fitted into place to interface the mandrel with the winding hardware. The ratchet mechanism was tested before the final winding operation, and test winding was performed using damaged wire to confirm the process without risking the final conductor. These tests verified that the jig could control the wire and maintain the winding geometry required for the final solenoid.



Figure 4.3: Winding jig used to control the mandrel, bearings, axle, ratchet interface, and wire feed during solenoid manufacturing.

4.5 Spool Stand and Wire Handling

The magnet wire spool was approximately 90 lb at the beginning of winding. A spool stand was built from 80/20 aluminum extrusion with an axle through the center of the spool. Two 50 lb sandbags were used to stabilize the stand. The friction between the aluminum support and the spool provided enough resistance to prevent uncontrolled unwinding during the winding operation.

Wire handling was a major manufacturing concern because uncontrolled spool motion could damage the wire, disturb winding tension, or create a safety hazard. The final setup allowed the spool to feed wire into the winding jig while maintaining enough friction to prevent runaway unwinding.

The spool stand also helped isolate the winding process from the large mass of the

wire spool. Rather than requiring the operator to support or redirect the full spool load by hand, the stand allowed the wire to feed from a fixed location into the mandrel. This improved control of the winding path and reduced the likelihood of kinks or sudden changes in tension.

The wire feed path was arranged so that the conductor entered the winding region in a controlled direction. This was important for maintaining a clean layer structure. Because the wire was square, twist and misalignment could affect how each turn seated against the previous turns. Careful wire handling therefore improved both the mechanical quality of the coil and the repeatability of the winding geometry.



Figure 4.4: Spool stand and wire-feed setup used to support the large magnet-wire spool during solenoid winding.

4.6 Solenoid Winding Procedure

The solenoid was wound using 9 AWG square magnet wire. The winding target was 27 turns per layer and 24 layers, giving a total of

$$N = 27 \times 24 = 648 \tag{4.1}$$

turns. This turn count was selected to provide the required magnetic field contribution at the target operating current while maintaining a manageable resistance and heat load.

The winding process began by securing the wire to the mandrel and establishing the first turn position. The first layer was especially important because it set the alignment for all later layers. Each turn was placed adjacent to the previous turn to maintain a compact and repeatable winding pack. After completing each layer, the next layer was wound on top of the previous one while preserving the intended turn count and axial span.

The square wire geometry helped the turns pack into a stable winding structure, but it also made the wire stiff and difficult to manipulate. The winding jig and spool stand were therefore essential for controlling the process. The ratchet mechanism prevented back-driving, while the spool stand reduced uncontrolled spool motion. Together, these tools allowed the solenoid to be wound with the intended geometry.

The completed solenoid contained precisely 648 turns. This agreement with the design turn count was important because the solenoid field is directly related to the ampere-turns of the winding. For a fixed current, an incorrect turn count would produce a proportional error in the solenoid contribution to the total magnetic field.

4.7 Electrical Resistance and Thermal Check

After winding, the solenoid resistance was measured to verify that the conductor length and winding quality were consistent with design expectations. The measured resistance was approximately $1\ \Omega$. This value agreed with the pre-manufacturing estimate and confirmed that

the electrical properties of the completed coil were consistent with the intended operating point.

The resistance measurement is important because the solenoid heat load is determined by

$$P = I^2 R, \tag{4.2}$$

where P is the resistive heat generation, I is the solenoid current, and R is the coil resistance. At the simulated operating current of approximately 10.86 A, the measured resistance corresponds to

$$P \approx (10.86 \text{ A})^2 (1 \Omega) \approx 118 \text{ W}. \tag{4.3}$$

This heat load is consistent with the intended hybrid design. The permanent magnet array reduces the solenoid current required to reach the ECR field strength, and the reduced current keeps the solenoid thermal load more manageable than higher-current solenoid-only concepts.

The resistance result also provided a check on manufacturing quality. A resistance significantly higher than expected would have indicated excessive conductor length, poor electrical connections, or damage to the conductor. A resistance significantly lower than expected would have suggested an incorrect turn count or possible shorting. The measured value near 1Ω supported the conclusion that the solenoid was manufactured according to the intended design.

4.8 Final Winding Retention

After the solenoid was wound, the final winding was secured using Loctite EA 1C, a TorrSeal-equivalent epoxy. The epoxy prevented the outer layers from shifting and helped maintain the final winding geometry. This was important because the square wire stores mechanical

strain energy, and the completed winding could loosen if not retained.

The epoxy retention also improved handling robustness. The solenoid needed to be moved, installed, and integrated with the rest of the magnetic assembly after winding. By locking the final layer in place, the epoxy reduced the risk that the coil would unwind, shift, or change shape during later assembly steps.

Maintaining the winding geometry after manufacturing was important for both mechanical and electromagnetic reasons. Mechanically, a stable coil is easier to handle and less likely to be damaged. Electromagnetically, the simulated solenoid field assumes a fixed winding geometry. Retaining the final coil shape therefore helps preserve agreement between the manufactured hardware and the simulated design.

4.9 Completed Solenoid

The completed solenoid contained precisely 648 turns, arranged as 27 turns by 24 layers. Loctite EA 1C was used to secure the final winding. The measured resistance was approximately $1\ \Omega$, consistent with the design prediction.

This agreement between predicted and measured resistance validated the conductor length estimate and supported the expected thermal model. Since the solenoid heat load scales with I^2R , a measured resistance near the predicted value increased confidence in the expected operating heat load.

The completed solenoid satisfied the main manufacturing requirements. It achieved the target turn count, maintained the intended winding geometry, and produced the expected electrical resistance. These results confirmed that the solenoid could be used as the tunable field component in the final hybrid magnetic assembly.

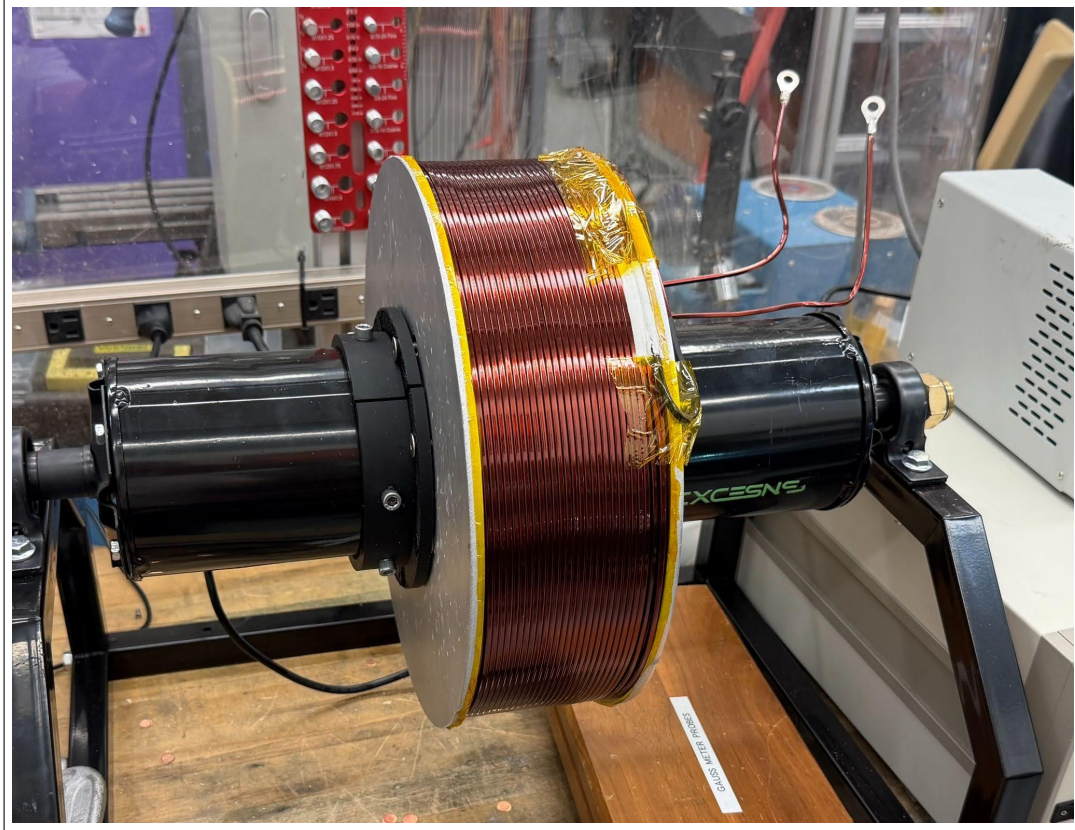


Figure 4.5: Completed 648-turn solenoid after winding and epoxy retention.

MAGNETIC MEASUREMENTS AND CHARACTERIZATION

5.1 Characterization Overview

Magnetic characterization was performed to verify that the manufactured hybrid solenoid–permanent magnet assembly satisfied the field requirements for the high-power ECR thruster. The primary requirement was to produce an approximately 875 gauss ECR-strength field near the upstream/base region of the boron nitride chamber. The secondary requirements were to preserve a useful magnetic field topology through the chamber and to avoid severe azimuthal nonuniformity from the discrete permanent magnet array.

All measurements reported in this chapter were taken with the solenoid operated at 8.5 A. The current was intentionally held fixed for the centerline scan, the $B(r, z)$ field map, and the backplate honeycomb measurement. This made the measurement sets directly comparable and ensured that the characterization represented one consistent solenoid operating condition.

The characterization consisted of three measurements. First, a centerline B_z scan was used to verify the ECR field magnitude and axial location. Second, a two-component $B(r, z)$ map was used to evaluate the field shape and compare the measured field structure to simulation. Third, a higher-resolution backplate honeycomb measurement was used to evaluate the azimuthal uniformity of the axial field component B_z over the chamber-facing plate region.

5.2 Coordinate System and Field Components

The field-profile measurements used a cylindrical coordinate system. The z direction is the axial direction through the chamber, and r is the radial distance from the centerline. The

magnetic field may be written as

$$\mathbf{B} = B_r \hat{\mathbf{r}} + B_\theta \hat{\boldsymbol{\theta}} + B_z \hat{\mathbf{z}}. \quad (5.1)$$

The centerline measurement uses B_z because the field near the centerline is primarily axial. The two-dimensional field map uses B_r and B_z , with the meridional field magnitude computed as

$$|\mathbf{B}_{rz}| = \sqrt{B_r^2 + B_z^2}. \quad (5.2)$$

The positive-radius field profile was measured over

$$r = \{0, 0.5, 1.0, 1.5, 2.0\} \text{ in} \quad (5.3)$$

and

$$z = \{0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0\} \text{ in.} \quad (5.4)$$

For the main field-structure visualization only, the measured positive-radius field was mirrored about the centerline. The axial component was mirrored with the same sign,

$$B_z(-r, z) = B_z(r, z), \quad (5.5)$$

and the radial component was mirrored with sign reversal,

$$B_r(-r, z) = -B_r(r, z). \quad (5.6)$$

This mirrored plot is used only to visualize the full magnetic nozzle-like field shape. The quantitative component comparisons use the actually measured positive-radius domain.

The simulated $B(r, z)$ field was exported from Maxwell as an EnSight vector field,

converted to CSV, and interpolated onto the measurement grid. The exported simulation coordinates were mapped to the measurement coordinates using the exported transverse coordinate as r and the relative exported axial coordinate as z .

5.3 Centerline B_z Verification

The centerline axial field was measured at nine axial positions from $z = 0$ in to $z = 4$ in. The measured centerline values were compared with simulated values extracted from Maxwell and interpolated to the same axial locations. The measured and simulated values are listed in Appendix A.2, and the corresponding profiles are shown in Figure 5.1.

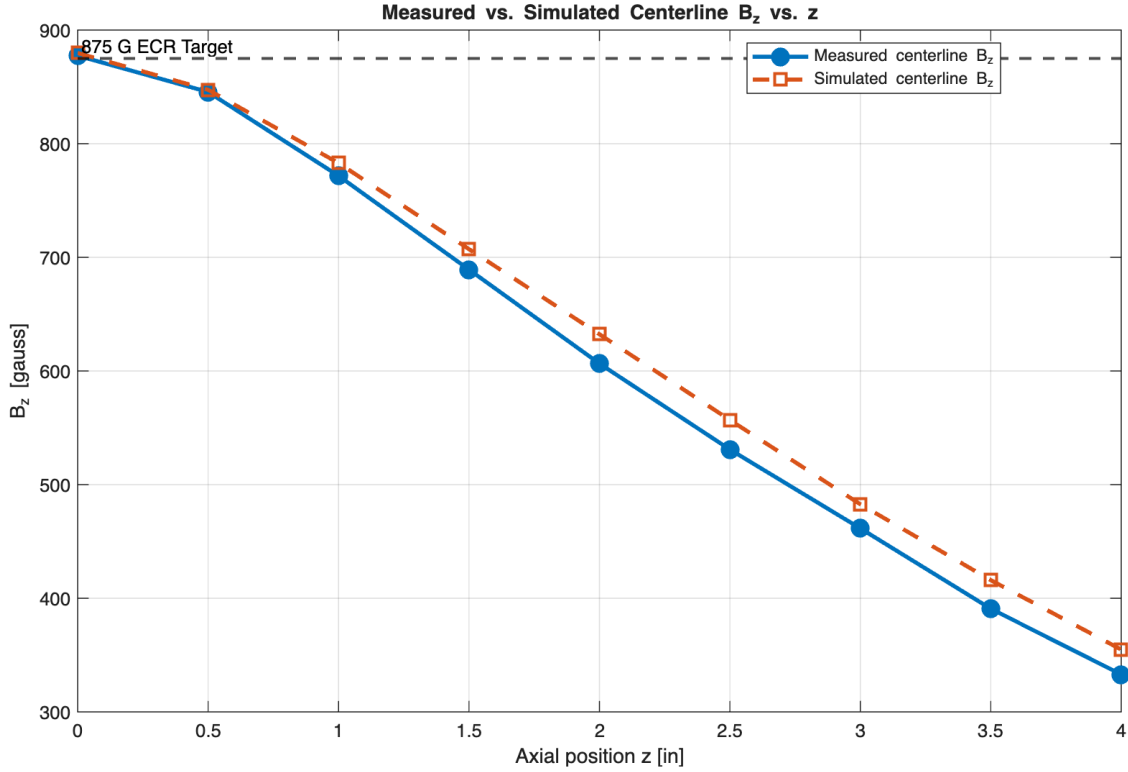


Figure 5.1: Measured and interpolated simulated centerline B_z as a function of axial position z . The 875 gauss ECR target is shown for reference.

The measured centerline field at $z = 0$ in was 877.4 gauss, which satisfies the 875 gauss ECR target at the 8.5 A characterization current. The field then decreased downstream, reaching 771.7 gauss at $z = 1$ in, 606.5 gauss at $z = 2$ in, and 332.9 gauss at $z = 4$ in. This

confirms that the ECR-strength field was localized near the intended upstream chamber region rather than shifted downstream.

Figure 5.2 shows the difference between the measured and simulated centerline field. The measured profile follows the same decay trend as the simulated profile. The agreement is strongest near the ECR region, where the field requirement is most important. The downstream differences are acceptable for the purpose of this design because the downstream region is below the ECR target and primarily confirms the expected field decay.

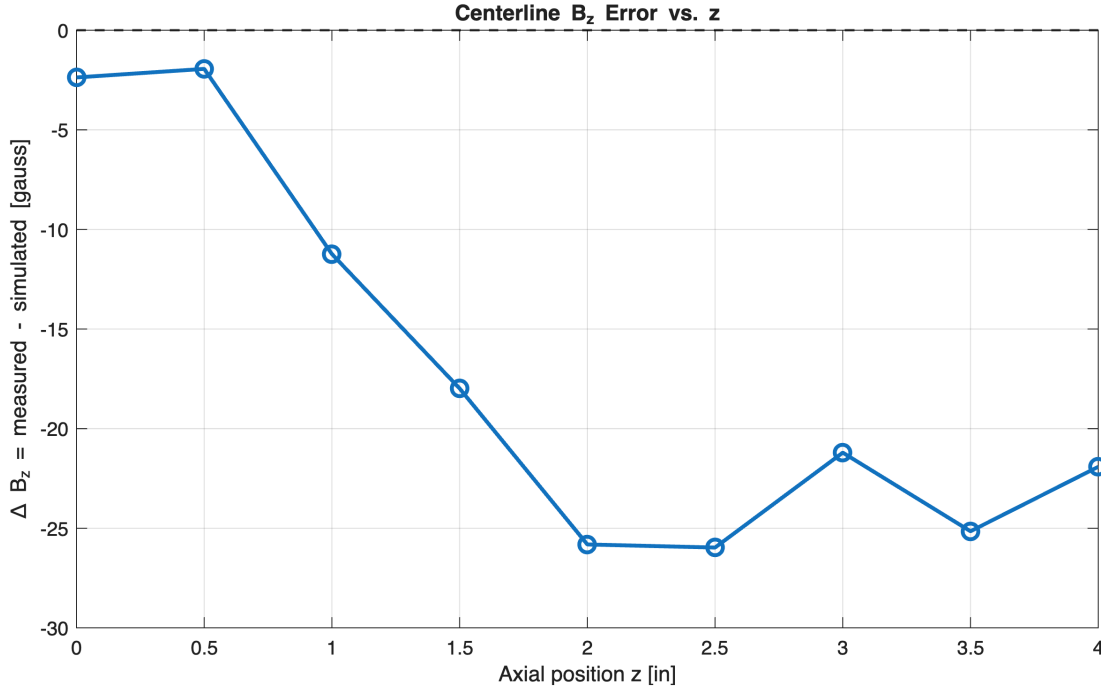


Figure 5.2: Centerline B_z error, calculated as measured minus interpolated simulated field.

5.4 Measured and Simulated $B(r, z)$ Field Structure

The centerline scan verifies that the field reaches the ECR magnitude, but it does not by itself verify the shape of the field through the chamber. For that reason, a two-component $B(r, z)$ map was measured using B_r and B_z . The purpose of this measurement was to confirm that the field has the intended magnetic nozzle-like topology: strong axial field near the upstream region, downstream decay, and controlled outward divergence at larger radius.

Figure 5.3 shows the measured and simulated $B(r, z)$ field structures. The heatmap

shows $|\mathbf{B}_{rz}|$, the arrows show the vector field, and the streamlines show the interpolated field direction. The magenta contours show the ECR-strength region, defined here as 875 gauss $\pm$ 2.5 gauss. The black dashed box shows the approximate boron nitride chamber inner diameter and axial length. The figure is mirrored about $r = 0$ only for visualization.

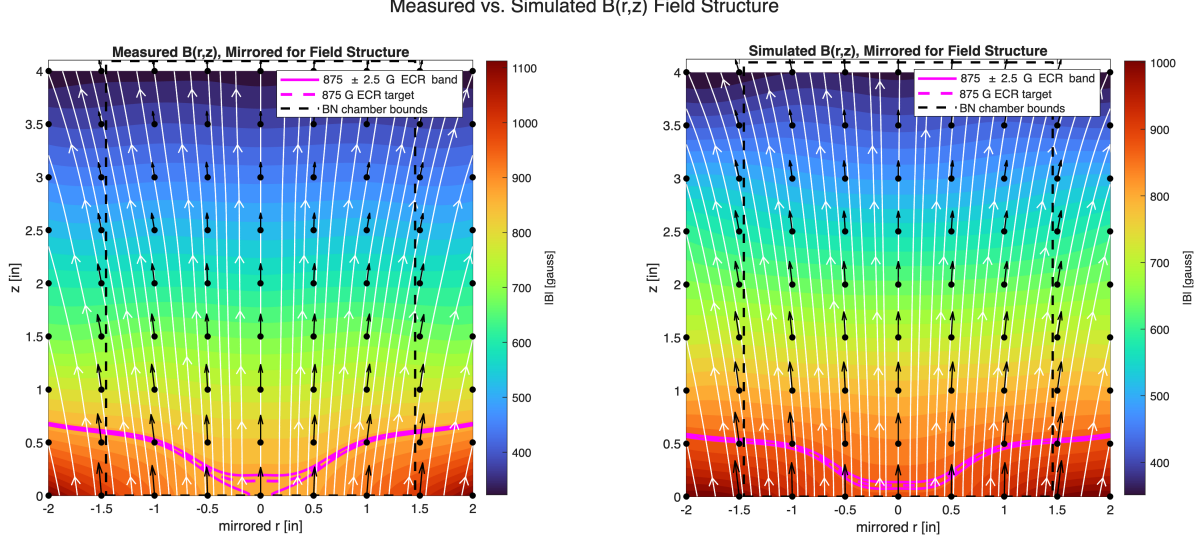


Figure 5.3: Measured and simulated $B(r, z)$ field structure. This figure is mirrored about $r = 0$ only for visualization. The heatmap shows $|\mathbf{B}_{rz}| = \sqrt{B_r^2 + B_z^2}$, arrows show the vector field, and streamlines show the interpolated field direction. The magenta contours indicate the 875 gauss $\pm$ 2.5 gauss ECR region, and the black dashed box indicates the approximate boron nitride chamber inner diameter and axial length.

The measured field reproduced the main features predicted by simulation. Near the centerline, the field remained primarily axial. At larger radius, the radial component increased and the field lines expanded outward. This is the desired behavior because the magnetic field should guide plasma through the chamber while allowing controlled divergence downstream.

The streamlines also provide a useful way to interpret potential wall interaction. A streamline that originates near the ECR-strength region can be followed downstream to estimate whether accelerated plasma is guided through the chamber or toward the chamber wall. In both the measured and simulated maps, the field lines near the center of the chamber remain mostly axial through the upstream region, while the outer field lines diverge toward

the chamber boundary. This indicates that the design forms the intended magnetic nozzle-like structure rather than a field topology that immediately drives plasma into the wall near the ECR region.

The measured field also showed the same qualitative topology as the simulated field. Exact point-by-point agreement is not expected because B_r is sensitive to probe angle, and small positioning errors are most important in regions with steep field gradients. Even with these limitations, the measured vector field confirmed the intended spatial structure of the final magnetic design and showed that the ECR-strength region is located where the magnetic field lines can guide the plasma through the chamber.

5.5 Positive-Radius Field Component Comparison

The component comparisons were performed over the actual positive-radius measurement domain. This avoids treating the mirrored visualization as independent measured data.

Figure 5.4 compares the measured and simulated $B_z(r, z)$ distributions. Both fields are strongest near the upstream measurement plane and decay downstream. The field is also larger near the outer radial positions close to the upstream region, where the measurement points are closer to the solenoid's inner wall.

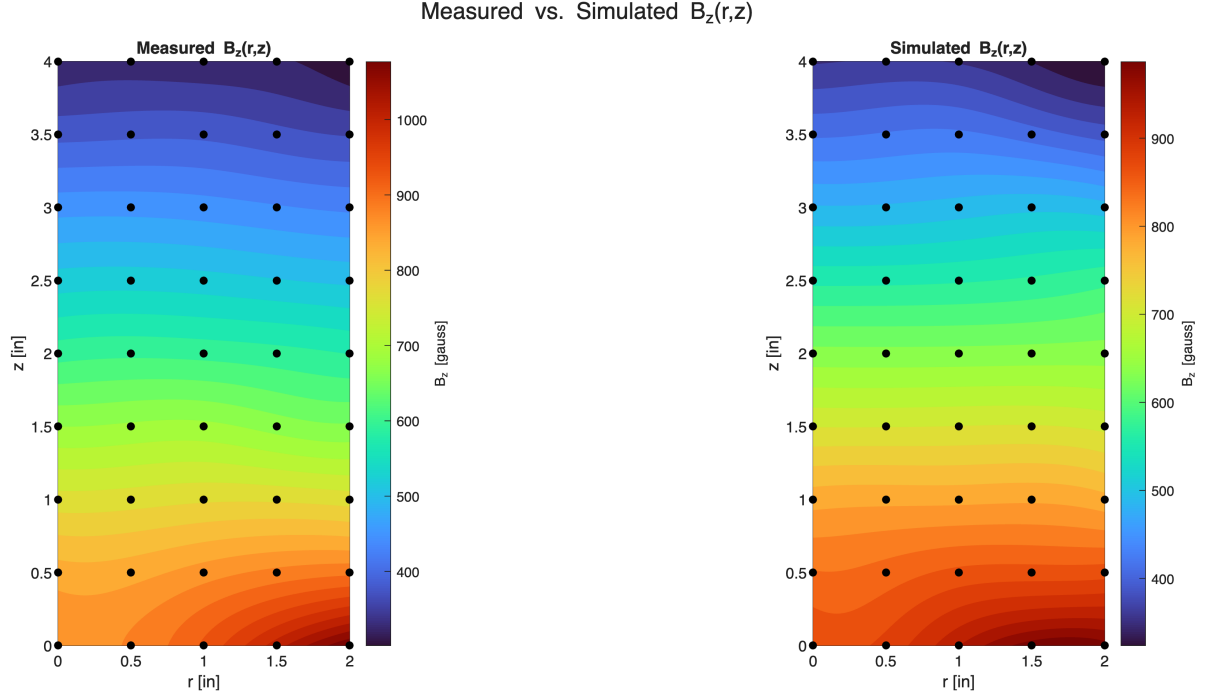


Figure 5.4: Measured and simulated $B_z(r, z)$ over the positive-radius measurement domain. The simulated data were interpolated from the exported Maxwell vector field onto the measurement grid.

Figure 5.5 compares the measured and simulated $B_r(r, z)$ distributions. The measured radial component is small near the centerline and increases toward larger radius, which agrees with the expected structure of a diverging magnetic field. The strongest radial field appears near the outer upstream region, where the magnetic field bends outward most strongly.

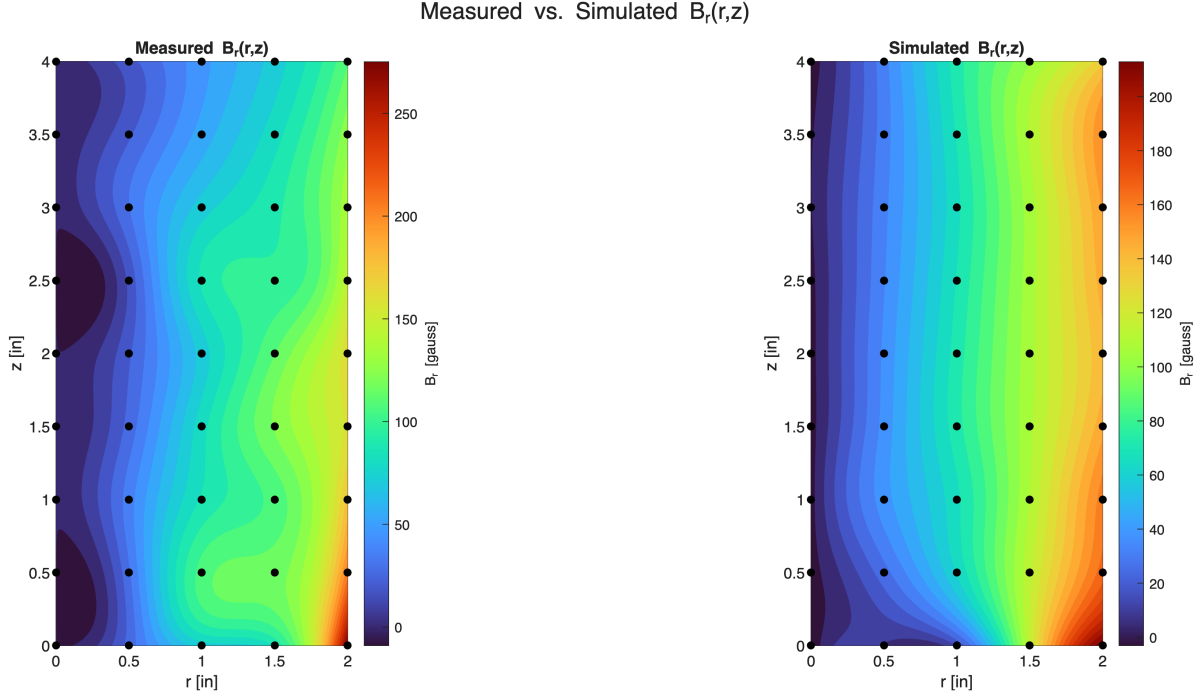


Figure 5.5: Measured and simulated $B_r(r, z)$ over the positive-radius measurement domain. The simulated data were interpolated from the exported Maxwell vector field onto the measurement grid.

The peak measured axial field in the mapped region was approximately 1101 gauss near $r = 2.0$ in and $z = 0.0$ in. The maximum measured radial component was approximately 284 gauss near $r = 2.0$ in and $z = 0.0$ in. These values are consistent with the physical layout of the magnetic assembly: the permanent magnet array contributes strongly near the outer upstream region, while the solenoid provides the smoother axial contribution through the chamber.

Additional coordinate tables, point layouts, and error definitions for the $B(r, z)$ measurement are provided in Appendix A.3.

5.6 Backplate B_z Azimuthal Uniformity

The backplate axial-field uniformity was evaluated using a 37-point honeycomb measurement pattern. The physical target region was selected to match the boron nitride chamber inner diameter as closely as practical. The boron nitride chamber diameter is approximately

74 mm, or 2.9 in. The honeycomb therefore used an outer radius of 1.45 in, corresponding to an outer measurement diameter of 2.90 in.

The honeycomb included one center point at $r = 0$ in, 15 inner-ring points at $r = 0.725$ in, and 21 outer-ring points at $r = 1.45$ in. The inner ring provided intermediate-radius information, while the outer ring sampled the field near the chamber inner diameter. This measurement pattern provided strong chamber coverage and enough angular resolution to evaluate azimuthal trends associated with the fourteen-magnet array.

Only B_z was used for the final backplate analysis. The radial and azimuthal components were not included because they were difficult to measure repeatably with the available probe setup and were sensitive to small changes in probe angle and alignment. The axial component was the most reliable component and was also the most relevant for evaluating the ECR-strength field near the backplate.

Figures 5.6 and 5.7 show the measured and simulated backplate B_z heatmaps. The dotted circle represents the approximate boron nitride chamber inner diameter, and the dashed circle represents the inner honeycomb measurement ring radius. The outer ring lies approximately on the chamber inner-diameter boundary.

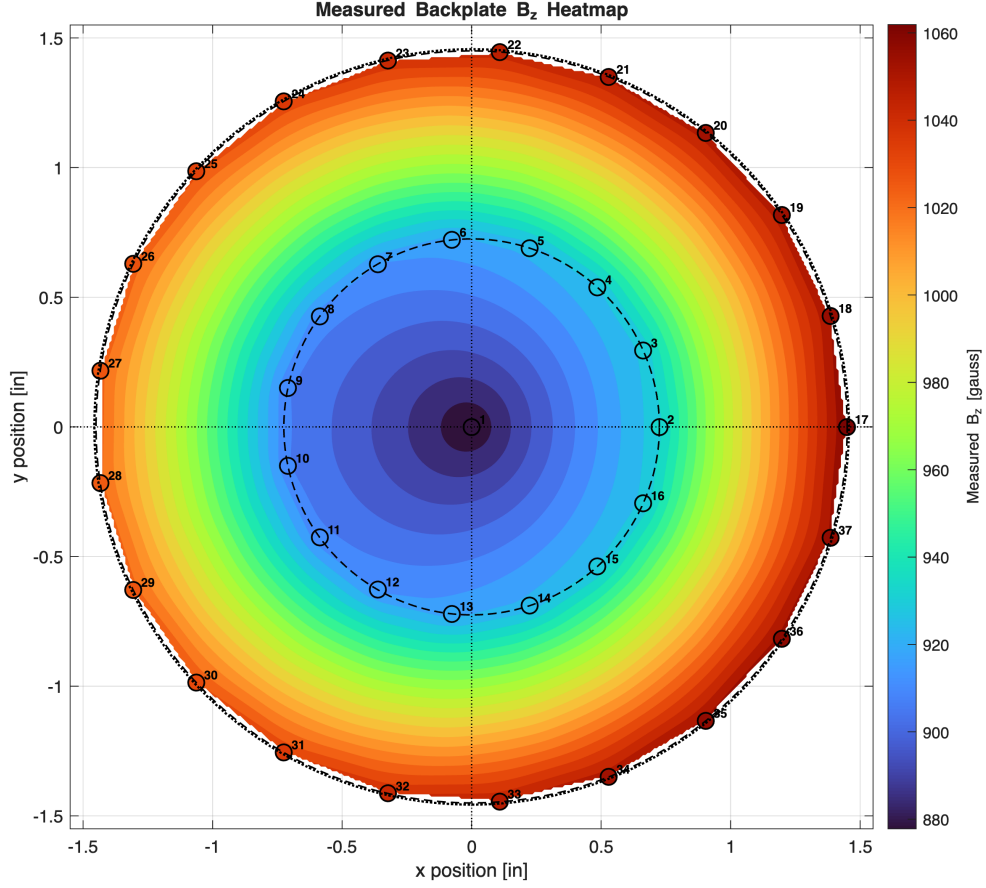


Figure 5.6: Measured backplate B_z heatmap from the 37-point honeycomb measurement. The dotted circle shows the approximate chamber inner diameter, and the dashed circle shows the inner honeycomb ring radius. The outer honeycomb ring lies approximately on the chamber inner-diameter boundary.

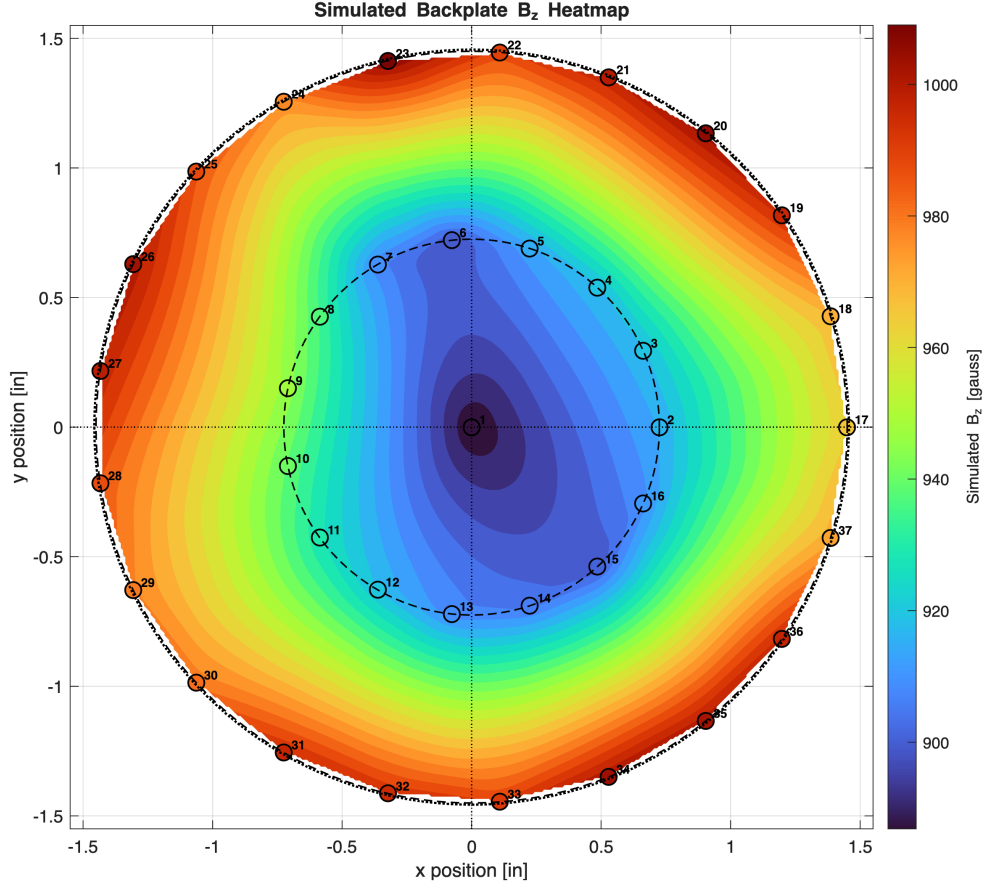


Figure 5.7: Simulated backplate B_z heatmap sampled at the same 37 honeycomb locations. The dotted circle shows the approximate chamber inner diameter, and the dashed circle shows the inner honeycomb ring radius.

The measured backplate field followed the same broad radial trend as the simulated field. The center point was measured at approximately 877.8 gauss, which is consistent with the ECR target. The inner-ring mean was approximately 920.8 gauss, and the outer-ring mean was approximately 1043.5 gauss. The higher field on the outer ring is expected because the outer ring is closer to the permanent magnet array. This confirms that the measured field behavior is consistent with the geometry of the magnetic assembly.

Figure 5.8 shows the azimuthal variation on the inner and outer rings. The measured field varies smoothly around both rings. The inner ring remains near the ECR-strength region, while the outer ring is stronger because it is closer to the permanent magnets. The measured data show a slight angular skew, which is likely due to the solenoid not being

perfectly centered over the permanent magnet array during testing. Even with this alignment effect, the measured outer ring is especially smooth, indicating that the discrete permanent magnets did not create severe local axial-field defects around the chamber-facing boundary.

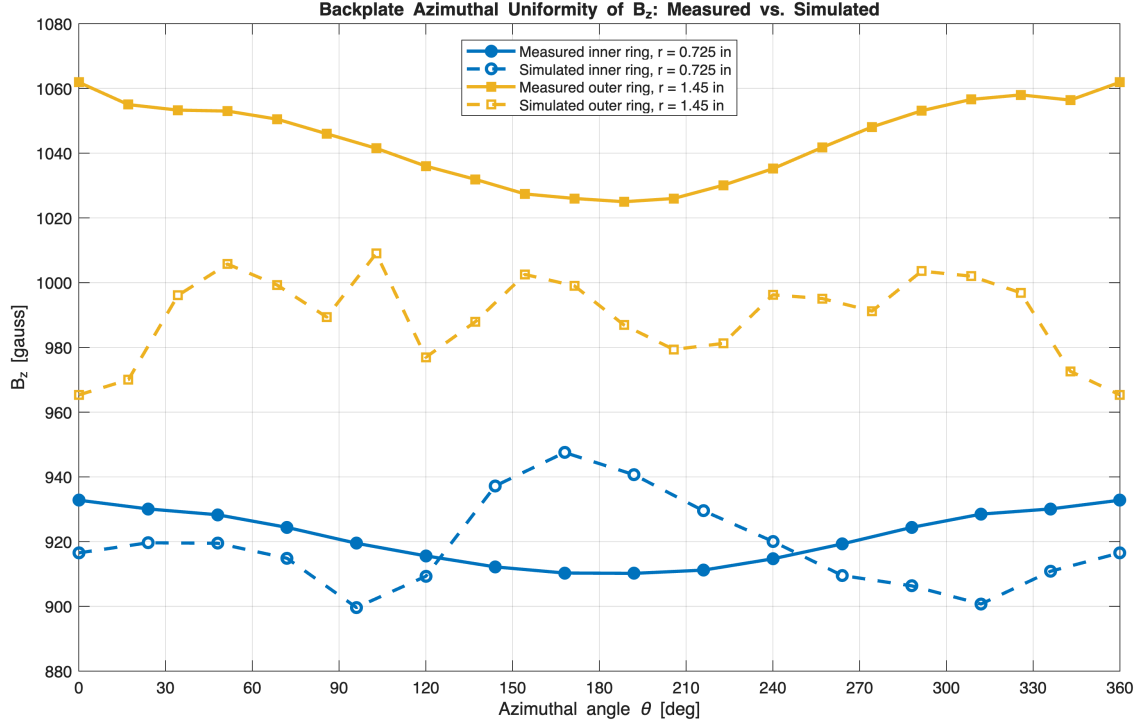


Figure 5.8: Measured and simulated backplate B_z azimuthal uniformity for the inner ring at $r = 0.725$ in and the outer ring at $r = 1.45$ in.

The simulated data show the same general ring-to-ring behavior, although the detailed angular shape differs from the measured field. The larger error on the outer ring is likely related to the solenoid current approximation used in the Maxwell model. In the physical solenoid, each wire turn carries the same current, so the current does not vary as a function of radius. In the simulation, however, the coil was approximated as a large cylindrical current region with a constant current distribution. Because the circumference increases with radius, this approximation can introduce a slight radial dependence in the effective current contribution, making the simulated field less accurate near the inner edge of the coil. This effect is less important farther from the solenoid boundary, but it can influence the simulated field near the outer backplate radius. In addition, some of the azimuthal field

structure appears smeared into a slightly elliptical pattern. This is likely associated with the way current is introduced into the Maxwell simulation region, which can introduce small non-axisymmetric components into an otherwise axisymmetric solenoid contribution.

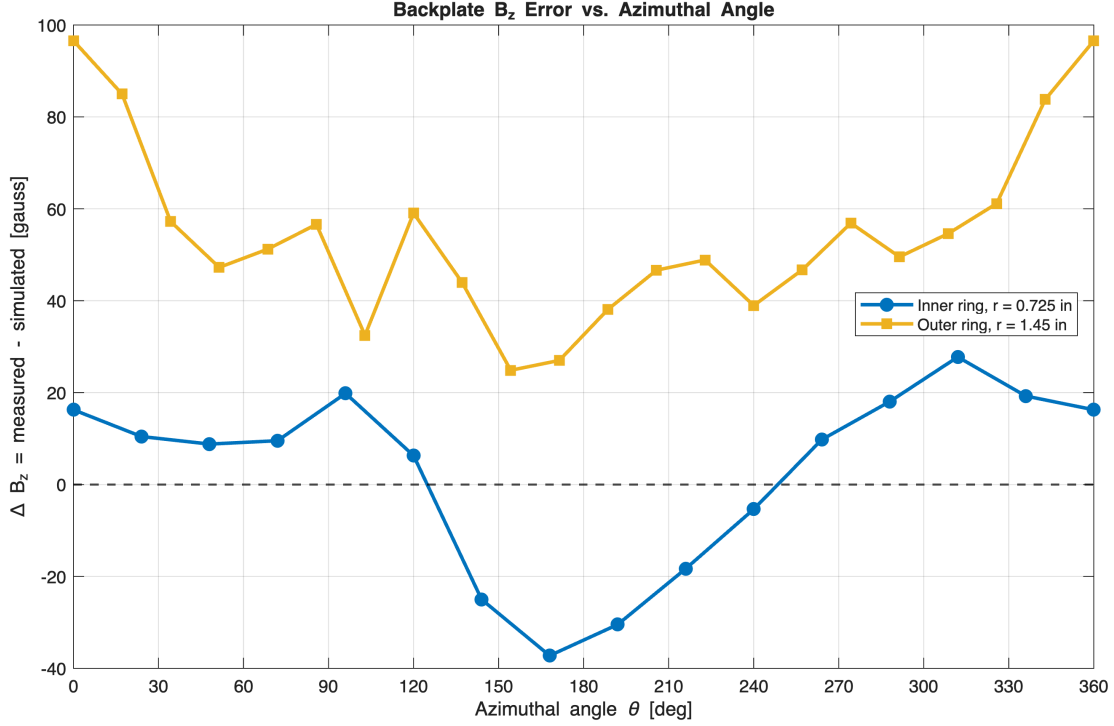


Figure 5.9: Backplate B_z error versus azimuthal angle, calculated as measured minus simulated field.

The measured field does not indicate a severe azimuthal defect. The inner ring varied by approximately 2.45% peak-to-peak relative to its mean, and the outer ring varied by approximately 3.54% peak-to-peak relative to its mean. These values are acceptable for the purpose of this design because the variation is smooth and does not show a localized field collapse. The result supports the design decision to use a fourteen-magnet tetradeccagonal array rather than a custom radially magnetized ring.

5.7 Measurement Limitations

The main considerations in interpreting the characterization data are probe positioning, probe angular alignment, interpolation of the simulation data, and the finite spatial resolu-

tion of the backplate scan. These effects are typical of manual magnetic field mapping and do not change the main conclusions of the characterization.

Probe positioning uncertainty is most relevant in regions where the magnetic field changes rapidly with position, especially near the upstream outer-radius region close to the permanent magnet array. In most of the chamber region, the field varies smoothly enough that small placement differences do not significantly affect the interpretation of the field topology. Probe angular alignment is most important for B_r , since the axial component B_z is dominant through much of the chamber. For this reason, the B_r data were used primarily to confirm the field-line shape and outward divergence rather than as a high-precision component measurement.

The simulated field data were interpolated onto the same measurement locations used in the experiment. This was necessary because the Maxwell export and the physical measurement grid did not contain identical node locations. Since the fields vary smoothly over the regions of interest, this interpolation provides a reasonable basis for measured-simulation comparison.

The backplate honeycomb scan used one center point, 15 inner-ring points, and 21 outer-ring points, as shown in Figure 5.10. This improved the angular resolution compared with the earlier 15-point scan and reduced the risk of aliasing the fourteen-fold angular structure of the permanent magnet array. Because both rings used more angular samples than the fourteen magnet sectors, the scan was able to resolve azimuthal trends associated with the discrete magnet geometry rather than undersampling them. The heatmaps should still be interpreted as interpolated visualizations of the measured trend rather than exact continuous field maps.

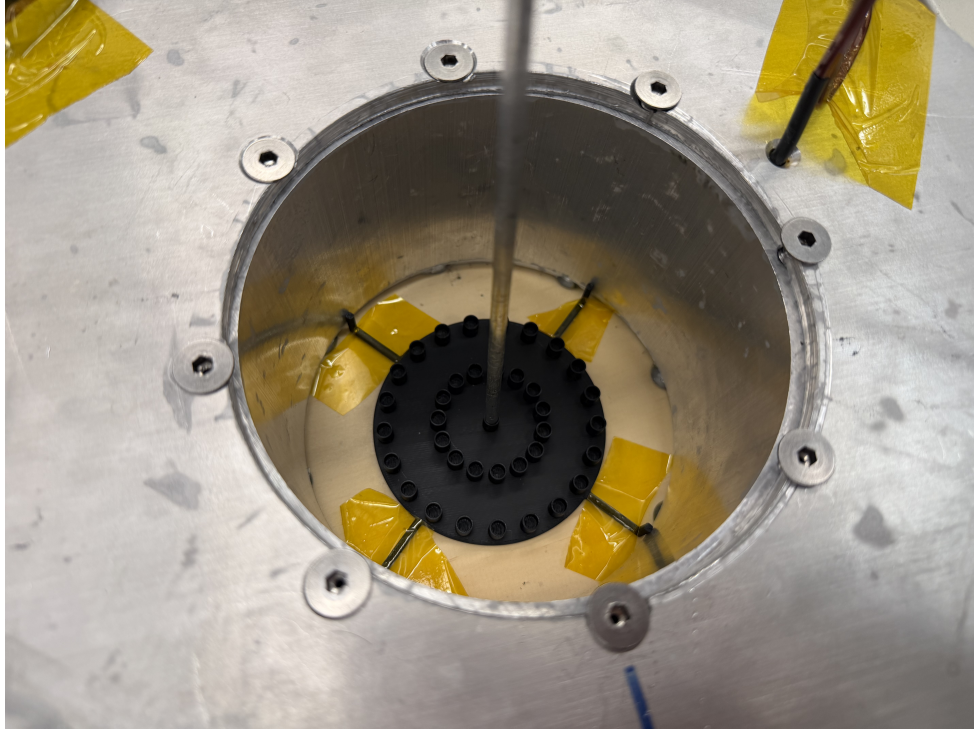


Figure 5.10: Backplate honeycomb measurement fixture installed inside the magnetic assembly. The fixture provided repeatable probe locations for the center point, inner ring, and outer ring used in the B_z azimuthal uniformity measurement.

The permanent magnet array also showed some magnetic-history behavior during testing. At one point, the measured field appeared lower after exposure to the opposing solenoid field, but after the assembly was left undisturbed for several days the measured field returned to approximately its original strength. All characterization data in this chapter were collected at a fixed 8.5 A solenoid current, so the results document the field produced by the hardware under a consistent test condition.

5.8 Summary

The magnetic characterization verified that the manufactured hybrid solenoid–permanent magnet assembly met the main field requirements. At a fixed solenoid current of 8.5 A, the measured centerline field reached 877.4 gauss at $z = 0$ in, satisfying the 875 gauss ECR target. The centerline field decayed downstream, confirming that the ECR-strength region

was located near the intended upstream chamber region.

The measured $B(r, z)$ field map confirmed the intended magnetic field topology. The field was primarily axial near the centerline and became more radially divergent at larger radius, matching the desired magnetic nozzle-like structure. The measured and simulated field maps showed the same qualitative behavior, confirming that the manufactured assembly preserved the simulated field shape.

The backplate honeycomb measurement showed that B_z varied smoothly in azimuth and followed the expected radial trend. The scan used one center point, 15 inner-ring points at $r = 0.725$ in, and 21 outer-ring points at $r = 1.45$ in, giving substantially better angular resolution and chamber coverage than the earlier 15-point scan. The measured center point was approximately 877.8 gauss, the inner-ring mean was approximately 920.8 gauss, and the outer-ring mean was approximately 1043.5 gauss. The field increased smoothly with radius and did not show a severe localized azimuthal defect.

Overall, the characterization confirmed that the final magnetic assembly achieved the required ECR field strength, produced the intended field shape, and maintained acceptable backplate axial-field uniformity despite the use of discrete permanent magnets and the practical limitations of the measurement method.

CONCLUSIONS

This thesis presented the design, manufacturing, and magnetic characterization of a hybrid solenoid–permanent magnet field source for a high-power electron cyclotron resonance (ECR) thruster. The magnetic field source was required to place an approximately 875 gauss ECR region near the base of the boron nitride chamber while maintaining a field topology that guides plasma through the chamber rather than directly into the chamber wall.

The final design uses a fourteen-element permanent magnet array and a large-radius solenoid. The permanent magnet array provides a static magnetic bias field, while the solenoid provides a tunable and approximately axisymmetric contribution to the total field. The design evolved from more idealized radial permanent magnet concepts to a practical array of commercially available rectangular magnets. This change was driven by cost, manufacturability, and the need for a split assembly that could be installed around the thruster hardware.

Two design insights were central to the final architecture. First, increasing the permanent magnet dimensions from $1 \times 1 \times 1$ in. to $1 \times 1 \times 2$ in. improved the available field strength while preserving the same chamber-facing tetradecagonal magnetic boundary. This allowed the permanent magnet contribution to increase without substantially changing the angular field structure seen by the chamber. Second, increasing the solenoid radius improved field-line straightness through the boron nitride chamber. The solenoid therefore acted not only as a field-strength booster, but also as a field-shaping component.

The final solenoid was manufactured with 648 turns arranged as 27 turns by 24 layers using 9 AWG square magnet wire. The measured resistance was approximately $1\ \Omega$, consistent with the design estimate. The permanent magnet array was assembled using fourteen

N42 rectangular magnets retained in a split aluminum enclosure with vented screws and oversized washers. The completed hardware satisfied the main manufacturing requirements: it used available materials, remained compatible with split installation, achieved the intended solenoid turn count, and produced the expected electrical resistance.

Magnetic characterization was performed with the solenoid operated at 8.5 A. This current was held fixed throughout the centerline scan, the $B(r, z)$ field map, and the backplate azimuthal measurement so that all results represented a consistent operating condition. At this current, the measured centerline axial field at $z = 0$ in was 877.4 gauss, which satisfied the 875 gauss ECR target. The centerline field decayed downstream, confirming that the ECR-strength region was localized near the intended upstream chamber region.

The measured $B(r, z)$ field map confirmed the intended magnetic field structure. The field was primarily axial near the centerline and became increasingly radial at larger radius, forming the magnetic nozzle-like topology predicted by simulation. The measured and simulated vector-field plots showed the same qualitative behavior: strong upstream field, downstream decay, and controlled outward field-line divergence. This verified that the manufactured assembly preserved the field-shape intent of the design.

The backplate honeycomb measurement showed that the axial field varied smoothly in azimuth and followed the expected radial trend. The final 37-point measurement pattern used one center point, 15 points on an inner ring at $r = 0.725$ in, and 21 points on an outer ring at $r = 1.45$ in. The outer ring corresponded to a 2.90 in measurement diameter, closely matching the approximately 74 mm boron nitride chamber inner diameter. The inner and outer rings both used more angular samples than the fourteen permanent magnet sectors, reducing the risk of aliasing the discrete magnet geometry. The measurement confirmed that no severe localized azimuthal defect was present and that the fourteen-magnet array produced acceptable backplate axial-field uniformity across the chamber-facing region.

During characterization, the permanent magnet array showed one apparent magnetic-history anomaly after exposure to the opposing solenoid field. The apparent reduction in

measured field strength was likely caused by a slight upward tilt of the permanent magnet magnetization vectors, which would move the local magnetic null point upward and reduce the field measured at the original probe location without requiring permanent demagnetization of the magnets. This anomaly only appeared once and did not continue to be a repeatable issue. When the effect was later tested intentionally, the measured field decreased by only about 1 %, or approximately 10 gauss, over roughly three hours before the test was stopped because the solenoid became too hot. When the field was checked again the next day, the measured strength at that location had returned to its previous value. The solenoid current was kept fixed at 8.5 A throughout the characterization data reported in this thesis, so the results document the field produced by the hardware under a consistent test condition.

Overall, the project demonstrated that a hybrid solenoid–permanent magnet architecture can satisfy the magnetic requirements of the high-power ECR thruster while remaining manufacturable. The permanent magnet array reduced the solenoid current requirement, the solenoid provided tunability and improved field-line shape, and the superposition of the two fields reduced the effect of discrete magnet nonuniformity. The final assembly achieved the required ECR-strength field, produced the intended magnetic nozzle-like topology, and maintained acceptable axial-field azimuthal uniformity at the backplate.

The completed design and characterization process also established a practical workflow for future magnetic field development. Simulation was used to select the magnet geometry, solenoid radius, and operating point; manufacturing translated the simulated geometry into physical hardware; and characterization verified the field magnitude, field shape, and azimuthal behavior. Future improvements should focus on higher-coercivity permanent magnets, reduced exposure of the magnets to reverse field, and more rigid probe-positioning fixtures. These refinements would improve robustness and measurement precision, but they do not change the main conclusion of this work: the manufactured hybrid magnetic assembly met the core magnetic design objectives for the ECR thruster.

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Appendix A

MAGNETIC CHARACTERIZATION DATA REDUCTION

A.1 Purpose of the Appendix

This appendix documents the data organization and reduction methods used to process the magnetic characterization measurements. Chapter 5 presents the physical interpretation of the measured magnetic field, while this appendix provides the supporting coordinate definitions, measurement-point tables, field-magnitude calculations, error metrics, and plotting workflow.

Three characterization data sets were processed:

1. the centerline B_z scan used to verify the ECR field strength;
2. the $B(r, z)$ field map used to evaluate the magnetic nozzle-like field structure;
3. the 37-point backplate honeycomb measurement used to evaluate azimuthal uniformity.

All data sets correspond to the same solenoid operating current of 8.5 A.

A.2 Centerline Data

The centerline scan measured the axial field component B_z from $z = 0$ in to $z = 4$ in in 0.5 in increments. The simulated values were extracted from the Maxwell centerline field curve and interpolated onto the same axial locations. The first simulated point corresponded directly to the measured $z = 0$ in location, so no interpolation was required for that point.

Table A.1: Measured and interpolated simulated centerline B_z values.

z [in]	Measured B_z [G]	Simulated B_z [G]	Error [G]
0.0	877.4	879.8	-2.4
0.5	845.5	847.4	-1.9
1.0	771.7	782.9	-11.2
1.5	689.2	707.2	-18.0
2.0	606.5	632.3	-25.8
2.5	530.9	556.9	-26.0
3.0	461.5	482.7	-21.2
3.5	390.8	416.0	-25.2
4.0	332.9	354.8	-21.9

The pointwise error was calculated as

$$\Delta B_z(z_i) = B_{z,\text{meas}}(z_i) - B_{z,\text{sim}}(z_i). \quad (\text{A.1})$$

The root-mean-square error was calculated as

$$\text{RMSE}_{B_z} = \sqrt{\frac{1}{N} \sum_{i=1}^N [B_{z,\text{meas}}(z_i) - B_{z,\text{sim}}(z_i)]^2}. \quad (\text{A.2})$$

The normalized RMS error was calculated as

$$\text{NRMSE}_{B_z} = \frac{\text{RMSE}_{B_z}}{B_{z,\text{sim}}} \times 100\%. \quad (\text{A.3})$$

A.3 $B(r, z)$ Field-Map Coordinates

The $B(r, z)$ field map used a positive-radius measurement grid. The measured radial positions were

$$r = \{0, 0.5, 1.0, 1.5, 2.0\} \text{ in}, \quad (\text{A.4})$$

and the measured axial positions were

$$z = \{0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0\} \text{ in}. \quad (\text{A.5})$$

At each point, B_z and B_r were measured. The meridional field magnitude was calculated as

$$|\mathbf{B}_{rz}| = \sqrt{B_z^2 + B_r^2}. \quad (\text{A.6})$$

For the field-structure visualization in Chapter 5, the positive-radius data were mirrored about the centerline. The mirrored radial grid was

$$r = \{-2.0, -1.5, -1.0, -0.5, 0, 0.5, 1.0, 1.5, 2.0\} \text{ in}. \quad (\text{A.7})$$

The mirrored field used

$$B_z(-r, z) = B_z(r, z) \quad (\text{A.8})$$

and

$$B_r(-r, z) = -B_r(r, z). \quad (\text{A.9})$$

This convention was used only to visualize the approximate axisymmetric field topology. Quantitative comparisons were performed on the positive-radius measured domain.

A.4 $B(r, z)$ Measured Field Data

The measured positive-radius B_z values are listed in Table A.2. Rows correspond to axial position z , and columns correspond to radial position r .

Table A.2: Measured $B_z(r, z)$ values in gauss over the positive-radius field-map grid.

z [in]	$r = 0$	$r = 0.5$	$r = 1.0$	$r = 1.5$	$r = 2.0$
0.0	877.4	886.6	936.5	1017.0	1101.0
0.5	845.5	848.6	870.6	890.4	901.2
1.0	771.7	774.9	782.2	782.1	775.0
1.5	689.2	693.8	695.9	679.2	668.9
2.0	606.5	611.4	608.4	601.2	591.6
2.5	530.9	533.4	529.4	521.5	514.5
3.0	461.5	462.3	458.0	449.5	442.0
3.5	390.8	394.1	393.2	382.2	372.5
4.0	332.9	337.1	331.1	328.8	301.6

The measured positive-radius B_r values are listed in Table A.3. The centerline radial component was set to zero because the radial component is zero on the axis of an approximately axisymmetric field.

Table A.3: Measured $B_r(r, z)$ values in gauss over the positive-radius field-map grid.

z [in]	$r = 0$	$r = 0.5$	$r = 1.0$	$r = 1.5$	$r = 2.0$
0.0	0	30	75	90	284
0.5	0	34	110	120	210
1.0	0	40	90	110	180
1.5	0	30	85	125	162
2.0	0	25	75	115	165
2.5	0	20	90	100	150
3.0	0	35	75	95	140
3.5	0	25	57	85	130
4.0	0	23	50	75	114

A.5 Maxwell Simulation Interpolation

The Maxwell simulation data were exported as vector-field data and converted into a CSV file containing node coordinates and magnetic field components. For the $B(r, z)$ field map, the exported transverse coordinate was interpreted as the radial coordinate, and the exported axial coordinate was shifted so that the upstream measurement plane corresponded to $z = 0$ in.

The simulation data were interpolated onto the measurement grid using scattered interpolation. The interpolated quantities were

$$B_{r,\text{sim}}(r_i, z_j) \tag{A.10}$$

and

$$B_{z,\text{sim}}(r_i, z_j). \tag{A.11}$$

The field magnitude from simulation was then calculated as

$$|\mathbf{B}_{rz,\text{sim}}| = \sqrt{B_{r,\text{sim}}^2 + B_{z,\text{sim}}^2}. \quad (\text{A.12})$$

The same calculation was applied to the measured data. This produced directly comparable measured and simulated values at the same physical coordinates.

A.6 Field-Map Error Metrics

Measured and simulated values were compared at identical positive-radius grid locations. The component errors were calculated as

$$\Delta B_r(r_i, z_j) = B_{r,\text{meas}}(r_i, z_j) - B_{r,\text{sim}}(r_i, z_j), \quad (\text{A.13})$$

$$\Delta B_z(r_i, z_j) = B_{z,\text{meas}}(r_i, z_j) - B_{z,\text{sim}}(r_i, z_j). \quad (\text{A.14})$$

The field magnitude error was calculated as

$$\Delta |\mathbf{B}_{rz}(r_i, z_j)| = |\mathbf{B}_{rz,\text{meas}}(r_i, z_j)| - |\mathbf{B}_{rz,\text{sim}}(r_i, z_j)|. \quad (\text{A.15})$$

For any field component Q , the root-mean-square error over the grid was calculated as

$$\text{RMSE}_Q = \sqrt{\frac{1}{N} \sum_{k=1}^N (Q_{\text{meas},k} - Q_{\text{sim},k})^2}, \quad (\text{A.16})$$

where N is the number of measurement points in the positive-radius grid.

A.7 Backplate Honeycomb Coordinates

The backplate honeycomb measurement used 37 points: one center point, 15 points on an inner ring, and 21 points on an outer ring. The inner ring was located at $r = 0.725$ in, and the outer ring was located at $r = 1.45$ in. The outer ring therefore corresponds to a measurement diameter of 2.90 in, which closely matches the approximately 74 mm boron nitride chamber inner diameter.

The center point was located at $r = 0$ in. The inner ring used 24 deg angular spacing, while the outer ring used approximately 17.14 deg angular spacing. This provided more angular samples than the fourteen permanent magnet sectors and reduced the risk of aliasing the discrete magnet geometry.

A.8 Backplate B_z Data and Uniformity Metrics

The final backplate analysis used only B_z . The radial and azimuthal components were excluded because they were more sensitive to probe orientation and were not needed for the axial-field azimuthal uniformity analysis. The measured and simulated B_z values are listed in Tables A.4, A.5, and A.6.

Table A.4: Measured and simulated center-point backplate B_z value.

Point	Radius, r [in]	Azimuth, θ [deg]	Measured B_z [G]	Simulated B_z [G]
1	0.000	0.000	877.8	886.8

Table A.5: Measured and simulated inner-ring backplate B_z values at $r = 0.725$ in.

Point	Radius, r [in]	Azimuth, θ [deg]	Measured B_z [G]	Simulated B_z [G]
2	0.725	0.000	932.8	916.5
3	0.725	24.000	930.1	919.7
4	0.725	48.000	928.3	919.5
5	0.725	72.000	924.4	914.9
6	0.725	96.000	919.5	899.7
7	0.725	120.000	915.6	909.3
8	0.725	144.000	912.2	937.2
9	0.725	168.000	910.3	947.5
10	0.725	192.000	910.2	940.7
11	0.725	216.000	911.2	929.5
12	0.725	240.000	914.7	920.1
13	0.725	264.000	919.3	909.5
14	0.725	288.000	924.4	906.3
15	0.725	312.000	928.5	900.7
16	0.725	336.000	930.1	910.8

Table A.6: Measured and simulated outer-ring backplate B_z values at $r = 1.45$ in.

Point	Radius, r [in]	Azimuth, θ [deg]	Measured B_z [G]	Simulated B_z [G]
17	1.450	0.000	1061.9	965.3
18	1.450	17.143	1055.0	970.0
19	1.450	34.286	1053.3	996.1
20	1.450	51.429	1053.0	1005.7
21	1.450	68.571	1050.5	999.3
22	1.450	85.714	1046.0	989.4
23	1.450	102.857	1041.5	1009.0
24	1.450	120.000	1036.0	977.0
25	1.450	137.143	1031.9	988.0
26	1.450	154.286	1027.4	1002.5
27	1.450	171.429	1026.0	999.0
28	1.450	188.571	1025.0	986.9
29	1.450	205.714	1026.0	979.4
30	1.450	222.857	1030.1	981.2
31	1.450	240.000	1035.2	996.2
32	1.450	257.143	1041.8	995.1
33	1.450	274.286	1048.1	991.2
34	1.450	291.429	1053.1	1003.6
35	1.450	308.571	1056.6	1002.0
36	1.450	325.714	1058.0	996.9
37	1.450	342.857	1056.4	972.6

Azimuthal uniformity was calculated separately for the inner and outer rings. The center point was excluded because azimuthal angle is undefined at $r = 0$. The mean field on a ring is

$$\overline{B_z} = \frac{1}{N} \sum_{i=1}^N B_{z,i}. \quad (\text{A.17})$$

The peak-to-peak variation is

$$\Delta B_{z,\text{pp}} = B_{z,\text{max}} - B_{z,\text{min}}. \quad (\text{A.18})$$

The percent peak-to-peak nonuniformity is

$$U_{\text{pp}} = \frac{B_{z,\text{max}} - B_{z,\text{min}}}{\overline{B_z}} \times 100\%. \quad (\text{A.19})$$

The 37-point honeycomb pattern provided improved angular resolution compared with the earlier 15-point pattern. The inner ring used 15 angular samples and the outer ring used 21 angular samples, both exceeding the fourteen angular sectors associated with the permanent magnet array. This reduced the risk of aliasing the fourteen-fold magnet geometry and allowed the measurement to resolve the main azimuthal trends around the chamber-facing region.

A.9 MATLAB Data-Reduction Workflow

The magnetic characterization figures were generated using MATLAB. The data-reduction workflow consisted of three scripts:

1. `centerline_Bz_vs_z.m`, used to compare the measured and simulated centerline axial field;
2. `Brz_field_profile.m`, used to generate the measured and simulated $B(r, z)$ field maps;
3. `backplate_Bz_azimuthal.m`, used to analyze the 37-point backplate honeycomb measurement.

The scripts imported measured gaussmeter data, converted exported Maxwell field values to gauss, interpolated simulated values onto the measurement locations, generated the figures used in Chapter 5, and exported pointwise comparison CSV files.

The complete scripts and generated CSV files are retained with the project data archive.