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Designing and Building STAR_Lite at Hampton University

Introduction

The quest for clean and sustainable energy is driving innovation across the globe, and stellarator research is rapidly advancing, poised to potentially dominate the future of fusion power [1,2]. Hampton University, a pioneering Historically Black College and University (HBCU) and home to the Center for Fusion Research and Training (CFRT), brings a unique perspective to this exciting landscape. Just an hour from the future site of Commonwealth Fusion Systems' groundbreaking power plant, Hampton is committed to fusion research and education, with seminal publications in the field [3] and a unique dedication to student mentorship through the CFRT. Now, the university is embarking on an exciting experimental endeavor: STAR_Lite. Short for Stellarator for Training And Research – Learn Interesting Things Every day, STAR_Lite is a student-driven initiative conceived and built by undergraduate and even high school students. Its ambitious dual goal is to provide unparalleled hands-on education while contributing meaningfully to cutting-edge stellarator research, particularly in the field of non-resonant divertors, a concept advanced by Hampton's own Dr. Alkesh Punjabi. STAR_Lite embraces innovative modular coil designs and simplified manufacturing techniques. It aims to forge a practical and accessible path in stellarator development, empowering students to learn and contribute to the future of fusion, one experiment at a time.

Origins and Guiding Principles

In this issue . . .

Designing and Building STAR_Lite at Hampton University

STAR_Lite, Hampton University's new stellarator experiment, puts students at the forefront of fusion research and development. This cost-effective, education-focused project utilizes innovative manufacturing and targets key stellarator physics, including non-resonant divertors, fostering practical skills and advancing the path to fusion energy. ...1

STAR_Lite emerged from the vision of Dr. Calvin Lowe at Hampton University, driven by the recognition of the vital need for hands-on training in fusion technology and the potential of small-scale stellarators for impactful research. As exemplified by university-scale machines throughout stellarator history, Dr. Lowe conceived STAR_Lite as an accessible and educationally focused device. Initial parameters were practically determined by existing resources at Hampton, including two 15-kW microwave systems operating at 2.45 GHz, establishing a target axial magnetic field of 87.5 mT. Inspired by helical field coil designs in configurations similar to CFQS [4], the project formally began in Fall 2023. Figure 1 shows a full-scale illuminated model representing the initial helical coil concept, used to aid visualization and student understanding during these early design phases. From its inception, STAR_Lite has been guided by key principles to ensure its educational effectiveness and practical feasibility:

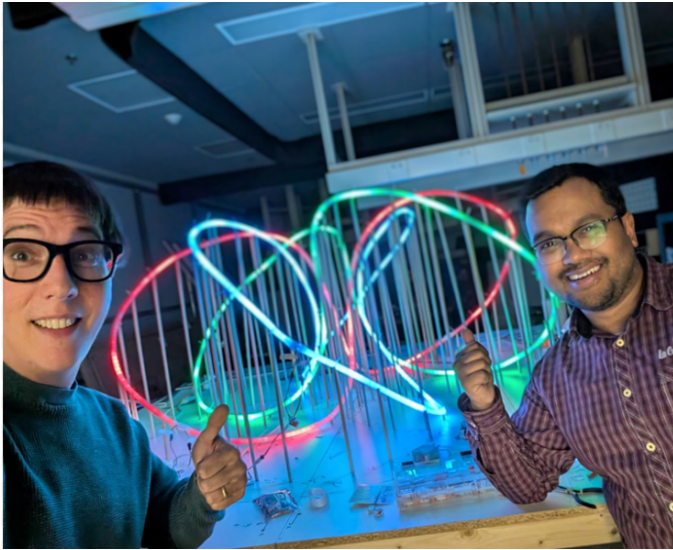


Fig. 1. Finished construction of a full scale model of the initial helical coil STAR_Lite configuration.

Hands-on Student Training:

Foremost was the commitment to student-led design, construction, and operation. Emphasizing practical skill development, the guiding principle became “Coils will be made, not bought,” prioritizing in-house fabrication.

High Plasma Access:

The design prioritized extensive diagnostic and experimental access to the plasma to maximize research and educational opportunities, favoring open helical coil geometries.

Simplified Manufacturing and Cost-Effectiveness:

Construction methods would utilize readily accessible and student-friendly techniques, initially focusing on bending tubes or rods for coil creation. Acknowledging resource constraints, the project adopted a cost-conscious approach. Exploring aluminum coils exemplifies this, balancing performance goals with budgetary realities.

Modular Coils and Manufacturing Innovation

STAR_Lite's initial coil manufacturing plan centered around collaboration with the industry partner Type One Energy, which possesses a freeform bending machine. The envisioned process involved the partner bending

half-windings from aluminum rods according to the design specifications. These half-windings would then be shipped to Hampton University, where students would weld them together to form complete windings. Connection boxes, designed for on-site assembly, would link the windings into finished coils with a triangular winding pack geometry. The entire coil system was initially conceived to reside within a large, single vacuum chamber.

However, seeking to accelerate the project timeline and enhance self-sufficiency in manufacturing, the team developed the “spine winding” technique. This innovative approach, illustrated in Fig. 2, reduces reliance on external bending services by requiring only one pre-bent rod per coil. It allows for coils to be constructed in-house at various sizes, enabling precise magnetic field measurements at each stage of development. Students then wind readily available 4-0 AWG cable around this spine, securing it with clamps to create modular coil segments. This method directly empowers students to participate in coil fabrication in-house and enables a staged construction and testing process, beginning with smaller-scale prototypes like “STAR_little.”

To facilitate these detailed field measurements, the team designed a Hall probe diagnostic system featuring 16 probes aligned on one axis and mounted on a high-precision x,y,z manipulator. This system is designed to map the magnetic field with micro-Tesla sensitivity and sub-

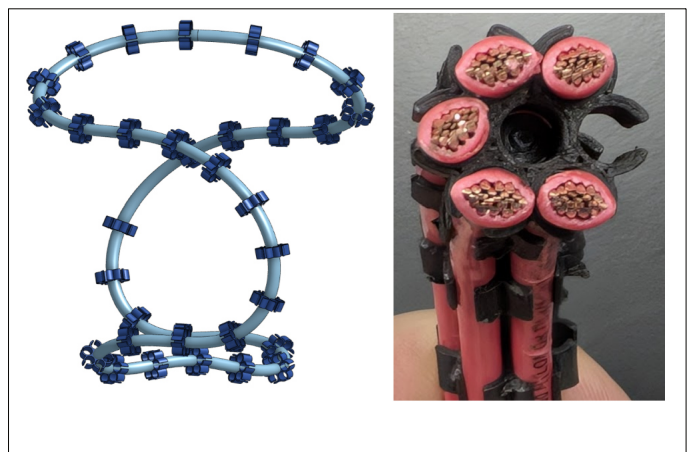


Fig. 2. The innovative “spine winding” technique. left: CAD visualization showing cables wound around a central spine. Right: Prototype cross-section demonstrating 10 AWG cable secured around a 3D-printed spine component.

millimeter precision, starting with single coils and scaling up to the full STAR_Lite configuration.

Furthermore, concurrent with the shift from helical to modular coils and adopting the QUASR [5] configuration, the winding pack geometry evolved to a hexagonal arrangement. This adaptation, driven by the spatial constraints of the QUASR 104183 configuration, further streamlined the implementation of modular coils with spine winding.

Embracing QUASR: A Strategic Pivot

Efforts to optimize the initial helical coil design, generated using the SIMSOPT code [6], encountered significant challenges. Field error analysis revealed relatively high errors on the order of 10%, and Poincaré plots failed to consistently demonstrate well-nested flux surfaces. A pivotal moment in the STAR_Lite project occurred during a design review meeting in December 2024. Feedback from the broader stellarator community and insights from initial Blender field visualizations prompted a strategic re-evaluation of the chosen magnetic configuration. This transition was further accelerated by the successful funding of the RENEW project, a collaborative effort between Hampton University, PPPL, and NCSU, which necessitated a more rapid project timeline. While this custom helical coil design was a valuable starting point, the aforementioned factor motivated a strategic pivot towards exploring existing, well-characterized configurations.

The first idea was to investigate the publicly accessible QUASR database developed by Andrew Giuliani at the Flatiron Institute, which led to adopting the QUASR 104183 configuration. A three-dimensional (3D) CAD design of the 6 coils of this configuration is shown in Fig. 3. While the size and field strength of QUASR configurations are pre-defined within the database, the team's attention was drawn to configuration 104183 specifically through a paper by Bob Davies et al. [7]. This paper highlights a novel method for characterizing non-resonant divertors using unpaired X-points, and QUASR 104183 stood out for its desirable tokamak-like X-point geometry, positioned consistently on the outboard side of the plasma, top, and bottom. This configuration offered a

computationally optimized design with compelling features. Crucially, scaling the coil filaments and magnetic field down to a major radius of $R = 0.5\text{m}$ and an axial field of $B = 0.1\text{T}$ demonstrated that QUASR 104183 was buildable using the discussed manufacturing techniques, with coil currents remaining within the operational capabilities of the designated power system.

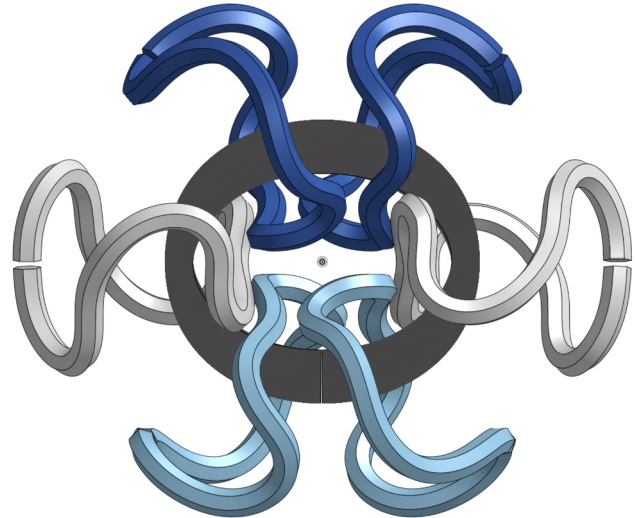


Fig. 3. The computationally optimized QUASR 104183 modular coil configuration adopted for STAR_Lite, leveraging publicly available designs to accelerate the project.

This strategic pivot to QUASR 104183 offers several key benefits: Firstly, it significantly accelerates the project timeline by leveraging a pre-existing, optimized design, bypassing the complexities of de novo configuration development and the optimization challenges encountered with the initial helical coil approach. Secondly, it aligns STAR_Lite's research focus squarely with Hampton's strengths in non-resonant divertor physics, promising high-impact scientific contributions by experimentally investigating the intriguing X-point divertor geometry. Finally, the inherent modularity of the QUASR design, with its discrete coil sets, synergized effectively with the team's decision to transition to modular coils and the spine winding manufacturing technique, creating a cohesive and efficient pathway for student-led construction. While representing a significant change in design direction, the embrace of QUASR 104183 ultimately focuses

STAR_Lite's educational and research potential, maximizing the project's impact within available resources and expertise.

Student Powerhouse: Hands-on and Theoretical Contributions

STAR_Lite is, at its heart, a student-driven endeavor, with undergraduates and even high schoolers playing integral roles in all aspects of the project. Hampton University students are not just assisting; they take ownership of key subsystems and research areas, gaining invaluable practical and theoretical expertise in fusion science and technology.

Experimental Subsystems and Fabrication:

- **Poloidal Coil Construction:**

Undergraduate students Krystal Scott and Zach Meggett have taken the lead in designing and constructing planar field coils. Aiming at 0.5 m radius and 20 kA-turns, Krystal and Zach are mastering in-house winding techniques using 4-0 AWG cable and developing cost-effective fabrication methods, aiming for a cost of \$700 per coil. These coils will be used as reference fields and test loads for the power supply system.

- **Power System Development:**

Electrical Engineering freshmen Brenden Forrest and Kamar Mann are pioneering STAR_Lite's innovative and budget-conscious power system. Experimenting with a resourceful combination of pre-existing 48V 200A batteries, repurposed 750 A welding power supplies, and refurbished Cisco 40 V 200 A server power supplies, Brandon and Kamar are gaining hands-on skills in high-current power electronics, system integration, and creative engineering solutions to meet STAR_Lite's demanding power needs. (Fig. 4 (a))

- **STAR_little: A High School Stellarator Prototype:**

Extending STAR_Lite's educational impact to younger students, talented high schoolers Yuna Chung and Karen Hu from the New Horizons Governor's School for Science and Technology are constructing "STAR_little," a 1/5th scale stellarator

model. This ambitious project provides Yuna and Karen with an accelerated introduction to fusion concepts, vacuum technology, and practical experimental physics, with the exciting goal of measuring fields (Fig. 4 (b)) and finally achieving plasma discharges in their student-built device (Fig. 4 (d)).

- **Ferrofluid Field Visualization:**

Chemical Engineering student Laura James is exploring a novel diagnostic approach using ferrofluid field visualization. By building a ferrofluid cell and experimenting with polarized light, Laura is investigating a visually compelling and cost-effective method for magnetic field mapping, adding a unique interdisciplinary dimension to STAR_Lite's diagnostics (Fig. 4 (c)).

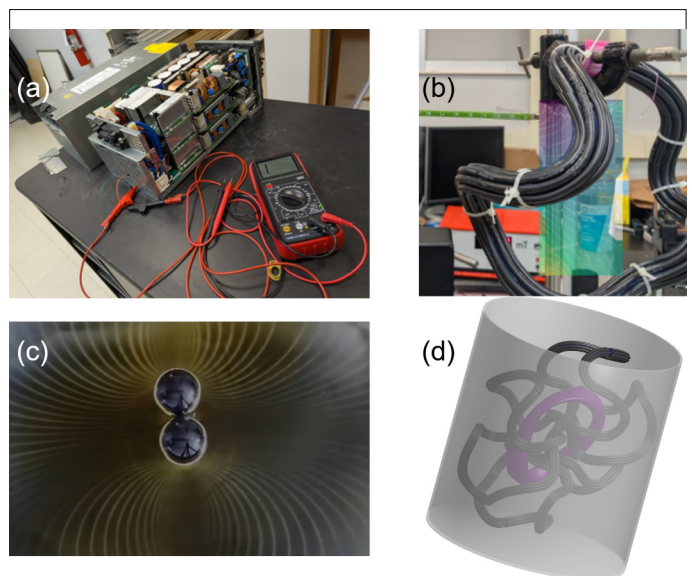


Fig. 4. Students leading key STAR_Lite subsystems. (a) Power system integration (Brenden Forrest & Kamar Mann). (b) STAR_little construction (Yuna Chung & Karen Hu). (c) Ferrofluid field visualization (Laura James). (d) First Hall probe Field measurements

- **Theoretical Non-Resonant Divertor Research:**

Undergraduate students Leila Alston, Jayla Higgs, and Angel Gayles are making significant contributions to the theoretical understanding of non-resonant divertors (NRDs), a central research focus for STAR_Lite. Supported by Dr. Naik, Leila, Jayla, and Angel are delving into the complex physics of NRDs, per-

forming simulations and analysis that will directly inform the experimental program and contribute to Hampton's long-standing expertise in this critical area of stellarator physics.

Powering Fusion on a Budget

A defining characteristic of the STAR_Lite project is its commitment to resourcefulness and cost-effectiveness, and this is particularly evident in the innovative approach to the power system. Meeting the demanding current requirements of stellarator coils necessitates expensive, high-current power supplies. However, the STAR_Lite team, driven by budgetary constraints and creative engineering spirit, has adopted a multi-faceted strategy to “power fusion on a budget.”

This strategy leverages a combination of readily available and repurposed components:

- **Pre-existing Battery Bank:** STAR_Lite benefits from a foundation of seven 48 V 200 A batteries already available at Hampton University. While representing a significant initial investment, these batteries provide a substantial baseline power capacity.
- **Repurposed Welding Power Supplies:** Two 750 A welding power supplies, salvaged from within the university, offer a high-current capability at minimal cost, albeit with potentially older technology requiring careful integration.
- **Refurbished Server Power Supplies:** A Cost-Effective Innovation: Perhaps the most innovative element is the exploration of refurbished Cisco 40 V 200 A server power supplies. At only 100\$ per piece, these power supplies offer a modular and scalable solution. Students are actively testing and integrating these units, aiming to create a high-current power supply “stack” that rivals the performance of commercial systems at a fraction of the cost.
- **Brushed DC Motor Controllers** are used to digitally control the current provided by the above systems.

This resourceful power system design addresses budgetary limitations and provides invaluable hands-on

learning opportunities for electrical engineering and power electronics students. By creatively combining diverse components and embracing a “make-do-and-mend” engineering philosophy, the STAR_Lite team demonstrates that cutting-edge fusion research can be pursued effectively and affordably at the university level.

Vacuum Vessel and Future Horizons

With the coil and power systems advancing rapidly, the STAR_Lite team is diligently developing the vacuum vessel, a crucial component for achieving and sustaining plasma confinement. Initial designs considered a large, monolithic vacuum chamber enclosing all coils. However, the transition to modular coils and the QUASR configuration has broadened the design space, allowing for more tailored and potentially innovative vacuum vessel solutions.

Current vacuum vessel development focuses on designs closely conforming to the QUASR 104183 geometry, optimized for plasma performance and cost-effective manufacturing. The team is evaluating several fabrication pathways, some of which are illustrated in Fig. 5:

- **3D-Printed Stainless Steel:** Additive manufacturing of the vacuum vessel using stainless steel, potentially via Wire Arc Additive Manufacturing (WAAM), remains a promising option for creating complex shapes with reduced material waste and manufacturing costs compared to traditional subtractive methods (Fig. 5 (a)).
- **Welded Pipe Segments:** A more conventional approach, constructing the vessel from welded stainless steel pipe segments, offers a balance of established vacuum technology and cost-effectiveness for vessel geometries (Fig. 5 (b)).
- **Bridged or Lofted Wall Design:** This option explores maximizing in-vessel space for potential plasma-facing components by creating the largest possible vacuum vessel that still fits within the coil volume. However, the manufacturing feasibility of this complex geometry remains under investigation (Fig. 5 (c)).

- **Exploratory Hybrid Glass and Steel Design:** The team is investigating a hybrid vessel design incorporating both stainless steel and glass segments in a more exploratory and visually compelling direction. While still conceptual, a glass segment could provide visual access to the plasma for diagnostic observation and public outreach, complemented by the structural robustness of steel in critical areas (Fig. 5 (a)).

Looking ahead, the STAR_Lite team is pursuing a focused research and development roadmap:

- **Detailed Field Mapping and Validation:** A near-term priority is comprehensive magnetic field mapping and validation using the Hall probe diagnostic system. The laboratory setup for these measurements is shown in Fig. 6. This staged approach will begin with individual coils, progress to sub-assemblies, and culminate in full STAR_Lite configuration measurements, ensuring precise field generation and alignment with computational models.
- **Optimization of the configuration and extending capabilities:** In parallel to the smaller scale test coil manufacturing, the SIMSPOT optimization of configuration 104183 will continue simplifying the coils, adding toroidal field coils to change the iota profile and adding divertor coils to manipulate the x-point positions.
- **Coil Manufacturing and Placement Sensitivity Studies:** Recognizing the importance of coil accuracy, the team will conduct sensitivity studies to assess the impact of manufacturing tolerances and coil placement variations on magnetic field quality and plasma performance and experimentally test the robustness of the configuration to errors.
- **Non-Resonant Divertor Studies and Magnetic Island Mapping:** With fully operational STAR_Lite coils, the team will directly address its core research objectives: in-depth experimental studies of non-resonant divertor fields, leveraging the QUASR 104183 configuration's unique X-point geometry. Furthermore, mapping the inherent magnetic islands in the vacuum field, such as those simulated in Fig. 7, will provide valuable insights into the robustness of fixed points in an actual device.
- **STAR_little First Plasma:** Achieving initial plasma discharges in the smaller STAR_little device is an imminent goal. These early experiments, potentially utilizing a glowing tungsten electrode and noble gases at low magnetic fields, will serve as a valuable testbed for plasma generation and diagnostic development and provide a unique opportunity for outreach.
- **STAR_Lite First Plasmas and Discharge Optimization:** Achieving and optimizing plasma dis-

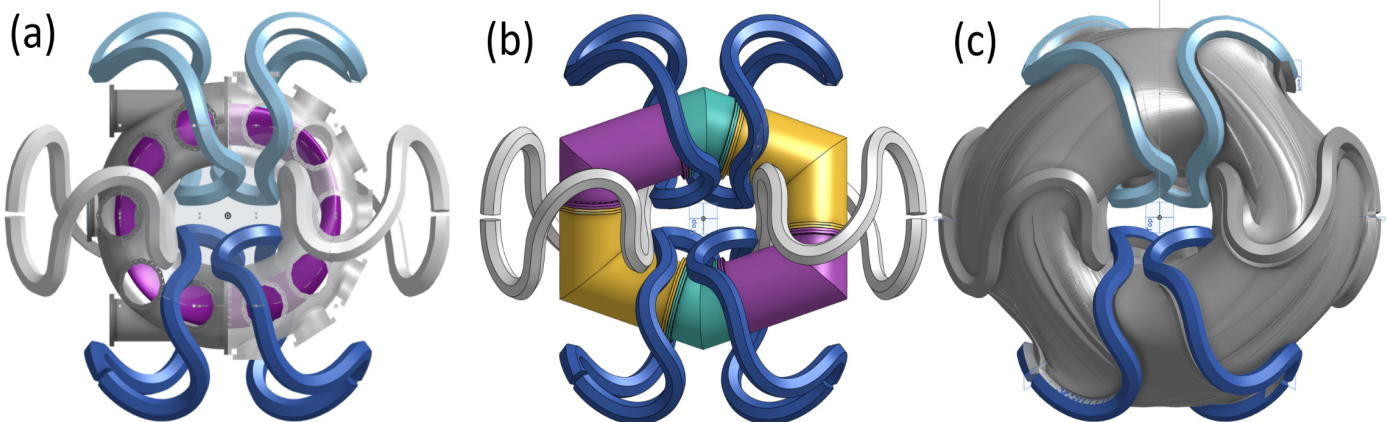


Fig. 5. Vacuum vessel concepts being evaluated for STAR_Lite. (a) A complex geometry suitable for Wire Arc Additive Manufacturing (WAAM). (b) A simpler approach using welded standard pipe segments. (c) A 'lofted' design maximizing internal volume.

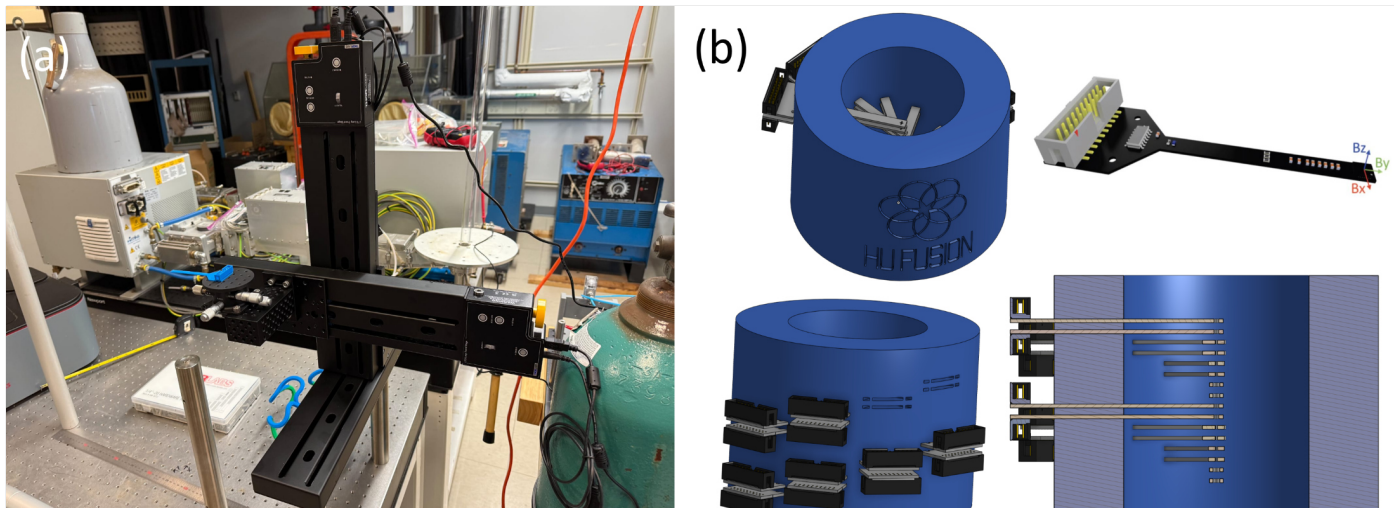


Fig. 6. (a) The laboratory setup for precise magnetic field mapping, utilizing a 1D Hall probe mounted on high-precision translation stages. (b) Design of the 16 3D Hall probe diagnostic for rapid field mapping.

charges in the full-scale STAR_Lite device will be a subsequent major milestone, requiring higher magnetic fields and more refined plasma control techniques.

STAR_Lite's future is bright with exciting potential. By integrating student innovation, cost-conscious engineering, and a well-defined research agenda, Hampton University is strategically positioned to contribute significantly to the growth of a skilled fusion workforce and to advancing cutting-edge stellarator science, accelerating the global pursuit of clean and sustainable fusion energy.

Conclusion

STAR_Lite represents more than just a small stellarator experiment; it embodies a novel approach to fusion research and workforce development. By placing students at the heart of the design, construction, and operation process, Hampton University is cultivating a new generation of fusion scientists and engineers equipped with practical skills, innovative mindsets, and a deep understanding of stellarator technology.

STAR_Lite's journey, marked by a commitment to cost-effectiveness, open-source principles, and strategic pivots like the adoption of modular coils, spine winding, and the QUASR 104183 configuration, underscores a key message: impactful fusion research is achievable at the university scale through resourcefulness and ingenuity.

STAR_Lite's focused research agenda, targeting non-resonant divertor physics and magnetic island studies, promises to contribute valuable experimental data to the global stellarator community, validating theoretical concepts and advancing the collective quest for fusion energy.

As STAR_Lite progresses from component fabrication to plasma discharges and beyond, it stands as a testament to the power of student-driven innovation and a beacon for the future of fusion energy—a future built, quite literally, by students, one coil, one plasma discharge, and one “interesting thing learned every day” at a time.

As we build our experimental program, we are looking for opportunities to expand our diagnostic and opera-

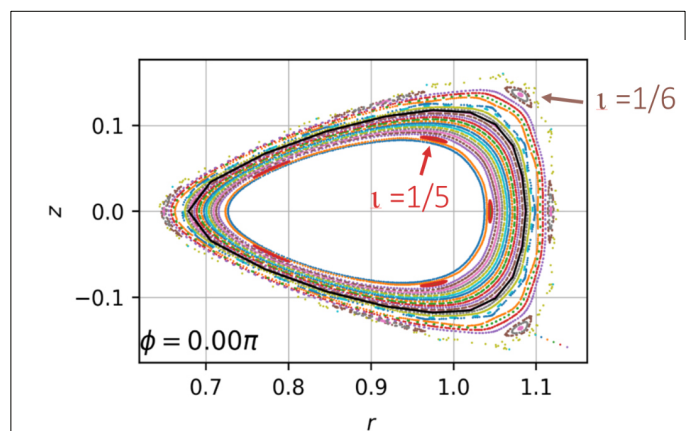


Fig. 7. Simulated magnetic islands (e.g., $\iota = 1/5$, $\iota = 1/6$) within the STAR_Lite vacuum field. Experimental mapping of these structures is a key research objective.

tional capabilities efficiently. We are particularly interested in acquiring functional equipment, including legacy diagnostics, that other institutions may be phasing out or replacing, allowing these assets to continue contributing to the field.

Separately, we are keen to foster the next generation of researchers. Our highly motivated students will be seeking challenging summer internships where they can apply their skills and contribute meaningfully to ongoing stellarator research. We believe collaborations on equipment and student training can be mutually beneficial for the community.

Acknowledgments

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