COVER PAGE

Project Title: Identifying the Regimes and Acoustics of Cryogenic Boiling heat Transfer for Accelerator Applications	
Federal Award Identification Number: DE-SC0025808	
Agency Code: 8900	**Organization:** Office of High Energy Physics
Recipient Award Identification Number: DE-SC0025808	**Project Period:** 01/01/2025 - 12/31/2027
Reporting Period: 01/01/2025 - 12/31/2025	**Budget Period:** 01/01/2025 - 12/31/2025
Report Term: Once per Budget Period	**Submission Date and Time:** 10/02/2025 11:28 AM ET
Principal Investigator Information: Kourosh Shoele	**Recipient Organization:** Florida A&M University MailStop Code: 400 Foote-Hilyer Admin 1700 Lee Hall Drive Tallahassee, FL 32307-3200 Country: USA **UEI:** W8LKB16HV1K5

ACCOMPLISHMENTS

Major Goals and Objectives

The project aims to tackle thermal management challenges in next-generation high-energy linear accelerators that use cryogenically cooled copper technology. These accelerators are expected to be compact, cost-effective, and operate at high RF gradients.Our goals are:

1. **Understanding Heat Distribution:** Explore how heat spreads in copper accelerator components under cryogenic conditions, particularly in specific geometries, to reduce thermal stress and optimize RF performance.
2. **Investigating Cryogenic Boiling:** Study boiling behavior of liquid nitrogen (LN2) in various configurations and thermodynamic conditions, including alternative cryocoolers. This includes analyzing bubble formation, growth, and collapse, which can impact accelerator stability.
3. **Quantifying Acoustic Disturbances:** Measure and model pressure fluctuations and noise caused by boiling cryogens to identify safe operating conditions.

Technical Approach

- Developed a **numerical framework** combining thermoelastic modeling, multiphase flow, and phase-change physics.
- Applied **adaptive mesh refinement** and **parallel computing** to simulate boiling dynamics of LN2 over complex copper geometries.
- Implemented **single- and multi-site nucleation algorithms** to capture realistic bubble formation and growth in cryogenic conditions.
- Coupled **acoustic analysis** with fluid dynamics to quantify the impact of boiling on pressure fluctuations and noise in accelerator structures.

Accomplishments to Date

- **Heat Distribution Models:** Built and validated coupled thermoelastic models to predict heat transfer in copper blocks under cryogenic conditions.
- **Boiling Dynamics:** Developed multi-seed boiling models, validated against experiments, to capture bubble growth, departure, and acoustic signatures.
- **Acoustic Footprint Analysis:** Calculated natural frequencies of LN2 bubbles under various wall superheat and contact angle conditions, revealing trends relevant for minimizing vibration in accelerators.
- **High-Fidelity Simulations:** Performed 3D multiphase simulations showing bubble formation, growth, and collapse in copper linac geometries.

Key Results and Outcomes

- Smaller wall superheat and contact angles produce higher-frequency bubble oscillations, while higher superheat and angles lead to lower-frequency bubbles.
- Developed guidelines for safe operation of copper linacs cooled by LN2, balancing heat removal and minimizing acoustic disturbances.
- Demonstrated that LN2 cooling can potentially reduce thermal management costs by up to 20% compared to superfluid helium.

Next Steps

- Extend simulations to full-scale accelerator geometries and varied cryocooler configurations.
- Conduct benchtop experimental validation of simulation predictions.
- Develop detailed design guidelines for local safe thermal management in LN2-cooled copper accelerators.

Opportunities for Training and Professional Development

- Graduate students and postdoctoral researchers have gained experience in advanced computational modeling, multiphase flow simulations, and cryogenic thermal management techniques.
- Collaborative interactions with SLAC researchers provided hands-on training in accelerator technology and experimental methods.

Dissemination of Results

- Results have been shared with the accelerator physics and thermal management communities through internal reports, conference presentations, and collaborations with SLAC.

- Data and modeling insights are being incorporated into design guidelines for future high-energy accelerators.

PRODUCTS

PUBLICATIONS
There are no publications to report.

INTELLECTUAL PROPERTIES
There are no intellectual properties to report.

PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

The table below only contains participants who have identified an affiliation with the Awardee Institution. Participants from any associated subawards may not be included in this count.

PARTICIPANTS DETAIL

Project Role	Number of People	Total Person Months Worked
Co-Investigator	1	1
Postdoctoral (scholar, fellow or other postdoctoral position)	1	12
Principal Investigator/Project Director	1	1
Total Responses	**3**	**14**

PARTNERS DETAIL

Partner: Florida State University, Tallahassee, FL, USA

IMPACT

- **Impact on the development of the principal discipline(s) of the project**
  This project directly advances the fields of cryogenic heat transfer, multiphase flow modeling, and accelerator physics. By developing and validating adaptive computational tools for predicting boiling-induced noise and heat transfer dynamics, the study addresses a long-standing challenge in accelerator design: the integration of thermal management with beam dynamics. The research fills a critical gap by moving beyond empirical correlations toward first-principles modeling that can be applied across cryogenic conditions . This progress lays a scientific foundation for the reliable use of liquid nitrogen and other cryogens in high-gradient accelerators, which until now has lacked systematic treatment.
  In doing so, the project strengthens the principal discipline by combining experimental validation with large-scale simulations, setting new methodological standards. The results will be particularly impactful for DOE initiatives such as the Cool Copper Collider (C3), potentially redefining design practices for future compact, cost-effective accelerators

- **Impact on Other Disciplines**
  While rooted in accelerator physics, the project's outcomes extend to several adjacent fields. Materials science benefits from the analysis of thermoelastic stresses induced by cryogenic boiling, offering insights for designing resilient structures exposed to extreme cooling cycles. In applied acoustics, the project pioneers methodologies for linking bubble dynamics to measurable noise spectra, which can influence noise control strategies in both industrial and medical technologies.
  Cryogenic engineering also gains from the project's advances. Predictive tools for identifying boiling regimes in liquid nitrogen or mixed cryocoolers can inform the design of sustainable cryogenic refrigeration systems used in space exploration, superconducting magnets, and even energy storage. Moreover, the computational fluid dynamics (CFD) community gains a robust case study in adaptive mesh refinement (AMR) applied to multiphase cryogenic systems, advancing the general practice of high-fidelity CFD in complex thermal environments.

- **Impact on Physical, Institutional, and Information Resources**
  On the physical infrastructure side, the project significantly enhances the capabilities of Florida A&M University (FAMU) and Florida State University (FSU). Students and faculty are granted access to the National High Magnetic Field Laboratory's cryogenic facilities and extensive HPC clusters with GPU acceleration. These resources build institutional capacity for conducting world-class cryogenic and accelerator research, aligning with FAMU's aspiration to transition from an R2 to an R1 research institution.
  Institutionally, the collaboration between FAMU and SLAC strengthens ties between universities and national laboratories, ensuring sustained pipelines of talent and shared expertise. In terms of information infrastructure, the project is committed to open science: all validated datasets, simulation codes, and experimental results will be archived, version-controlled, and made publicly available through repositories such as GitHub and DOE archives. This ensures reproducibility, long-term preservation, and broad dissemination of knowledge well beyond the life of the grant.

- **Impact on Technology Transfer**
  The potential for technology transfer is substantial. In the government sector, the DOE and SLAC can apply the computational models and validated data to optimize cryomodule design, shortening development cycles and reducing costs of large-scale accelerator facilities. The guidelines generated on boiling acoustics and thermal stresses will directly inform the design of the Cool Copper Collider, ensuring both performance and cost-effectiveness.
  Commercial opportunities also exist. The project's methodologies for coupling cryogenic simulations with experimental validation may translate into advanced CFD software tools tailored to industrial cryogenic systems. This could benefit industries in aerospace propulsion, semiconductor cooling, and medical device manufacturing. While no spin-off company is pursued here, the groundwork laid here positions the research for adoption in both federal R&D programs and private-sector innovation, particularly in cryogenics and thermal management industries.

- **Impact on Society Beyond Science and Technology**
  The societal impact of this research extends beyond the accelerator community. By lowering the cost and improving the reliability of high-energy physics facilities, the project indirectly accelerates progress in medical imaging, cancer radiation therapy, and security screening technologies—all of which rely on accelerator advancements. Broader public benefit lies in democratizing access to high-impact technologies by making their underlying infrastructure more cost-efficient.
  Another significant is the project's commitment to integrating talents in the universities into DOE missions. Conducted at a Joint College between FAMU and FSU in partnership with a leading national lab, it ensures brightest students gain direct exposure to cutting-edge research. This facilitates new workforce development by enriching the pool of talent engaged in national energy security and advanced technology development. By showcasing the role of

involving institutions in frontier science, the project fosters a productive and exemplary research ecosystem that benefits society at large.

- **Impact on the Development of Human Resources**
  Human resource development is central to the project. Undergraduate, graduate, and postdoctoral students are directly embedded into every phase of the research, from running simulations and conducting experiments to presenting results at national conferences. This ensures hands-on training in DOE-critical fields, such as cryogenic engineering and accelerator physics. Through internships and annual visits to SLAC, trainees gain professional experience in large-scale, mission-driven research environments.
  Particular emphasis is placed on supporting students in STEM. By combining technical training with mentorship and career development, the project nurtures the next generation of scientists and engineers who will advance DOE's mission in both research and national security contexts.
- **Percentage of the Award's Budget Spent in Foreign Countries**
  All resources, collaborations, and facilities are based within the United States, specifically at Florida A&M University, Florida State University, and SLAC National Accelerator Laboratory. No foreign expenditures are indicated in the project. Thus, **0% of the award's budget is expected to be spent in foreign countries**, ensuring that all funds contribute directly to U.S. research capacity, workforce training, and infrastructure development.