RESEARCH PERFORMANCE PROGRESS REPORT

1. COVER PAGE DATA ELEMENTS

a. **Federal Agency: US Department of Energy**

b. **Federal Grant: DE-SC0012036T**

c. **Project Title: Microscopic Investigation of Materials Limitations of Superconducting RF Cavities**

d. **PD/PI: Steven M. Anlage, Professor of Physics, anlage@umd.edu, (301) 405-7321, Toll Physics Building, University of Maryland, College Park, MD 20742-4111**

e. **Submission Date: 4 August, 2017**

f. **DUNS Number: 790934285**

g. **Recipient Organization: University of Maryland, College Park, MD**

h. **Project/Grant Period (05-01-2014, 03-31-2016)**

i. **Reporting Period End Date: 05-01-2014 to 03-31-2016 and a 1 year No-cost extension**

j. **Report Term: FINAL**

k. **Signature of Submitting Official (electronic signatures (i.e., Adobe Acrobat) are acceptable)**

Steven M. Anlage

2. ACCOMPLISHMENTS:

What was done? What was learned?

a. What are the major goals and objectives of this project?
Our overall goal is to contribute to the understanding of defects that limit the high accelerating gradient performance of Nb SRF cavities. Our approach is to develop a microscopic connection between materials defects and SRF performance. We developed a near-field microwave microscope to establish this connection. The microscope is based on magnetic hard drive write heads, which are designed to create very strong rf magnetic fields in very small volumes on a surface.
Our original goals are summarized in this proposed timeline of activities.

Timetable of Activities:

Year	RF B-Field Microscope Activities
1	Further study of $P_{3f}(T)$ and $P_{3f}(P_f)$ and 'extreme linear' response of bulk Nb at fixed locations Implement tuning-fork feedback mode for controlled probe-sample separation; Limited-area 2D images of P_{3f} and 'extreme linear' response on bulk Nb; Commissioning of 'dry' cryogenic microwave microscope system; Fabrication of weak-link RF magnetic field imaging samples; Preparation of Ta-inclusion samples on bulk and thin film Nb
2	Imaging of contrast from Ta-inclusion samples; Imaging of dislocation tangle bulk Nb contrast Measurement of RF critical fields of high-quality Nb single and multi-layer films; Measure of absolute RF magnetic field strength and distribution produced by the probes; RF critical field maps (from 'extreme linear' response) on bulk Nb
3	Measurement of bulk Nb materials with EP and BCE surface treatments; Measurement of critical fields of Nb and Nb/insulator multilayer samples; Identify new bulk Nb defect candidates, prepare samples, fully image P_{3f} and 'extreme linear' response

We had several goals outlined:

1) **Developing a probe-sample distance feedback control to apply a fixed-magnitude B_{RF} excitation to the sample surface while raster scanning the probe.**
    a. **Tuning Fork AFM based Probe/Sample separation control method was developed. We used a commercially available Tuning Fork Sensor Controller from nanoandmore.com. Then we integrated our Magnetic Writer into a tuning fork in a well-known "q-plus sensor" design. The Tuning Fork with fully integrated Magnetic Writer Probe has a resonance frequency of 21018 Hz and a quality factor of 106. We will do further testing for resolution and sensitivity of this probe when we get our new cryogenic scanning system.**
    The Schematic of the "Integrated Probe" is shown in Figure 1.

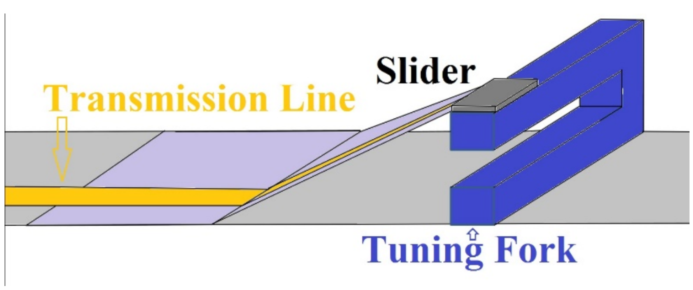

Figure1. Magnetic Probe attached to Tuning Fork. The writer pole is housed on the slider.

2) **Measuring the absolute magnitude and spatial distribution of the RF magnetic fields impressed on a superconducting surface by our different magnetic probes.**
   a. **An attempt was made to scan over an array of Josephson Junction (JJ) to measure the rf current spatial distribution. Due to the limited functionality of our existing scanner and inability to precisely locate the JJ array on the chip we were not able to get this scheme to work.**
   b. **Ansys Finite Element Simulation Software (HFSS) was used to get a precise calculation of the surface current distribution. The model is based on publicly available patents for various perpendicular magnetic recording probe designs. We concluded that the screening currents generated on the surface of the superconductor are confined to < 200 nm lateral distance.**
      The design of the probe used in the simulation is shown in Figure 2.

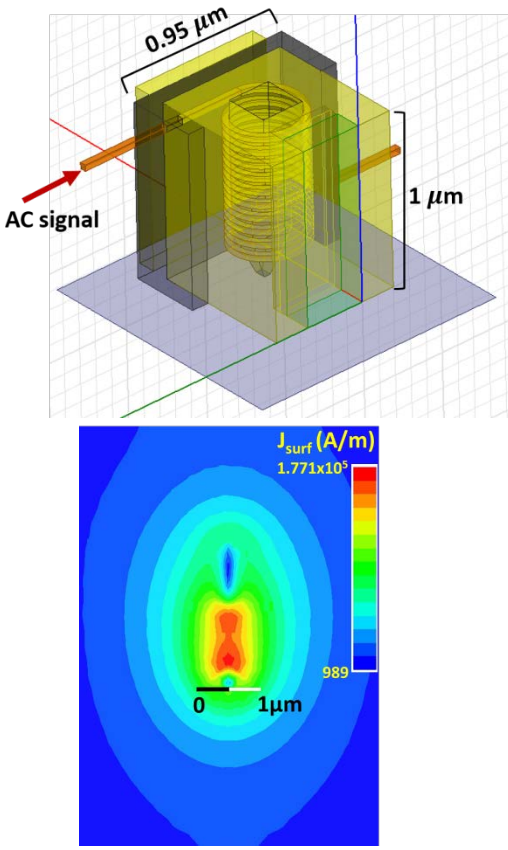

Figure2. (top) Design of Magnetic Probe used for HFSS simulation, inspired by information that we gleaned from published patents. (bottom) Example calculated surface current distribution corresponding to a maximum rf magnetic field of 223 mT, enough to exceed the critical field of bulk Nb.

   c. **We collaborated with Seagate to get a new generation of perpendicular magnetic writer probes and the actual spatial distribution of RF field generated by the probe per design specifications. Figure 3 shows the perpendicular field generated by the probe 17 nm away from sample under 60 mA excitation current.**

3) **Obtain spatially-resolved images of bulk Nb surface nonlinear and "high-power linear" response with sub-micron spatial resolution.**
    a. **Spatially-resolved images of Bi-Sr-Ca-Cu-O (BSCCO Flake) Sample was measured. We were able to measure a 10 dB difference in nonlinearity response while scanning perpendicular to the edge of the sample. The scanned image and location of the scan is shown in Figure 4.**

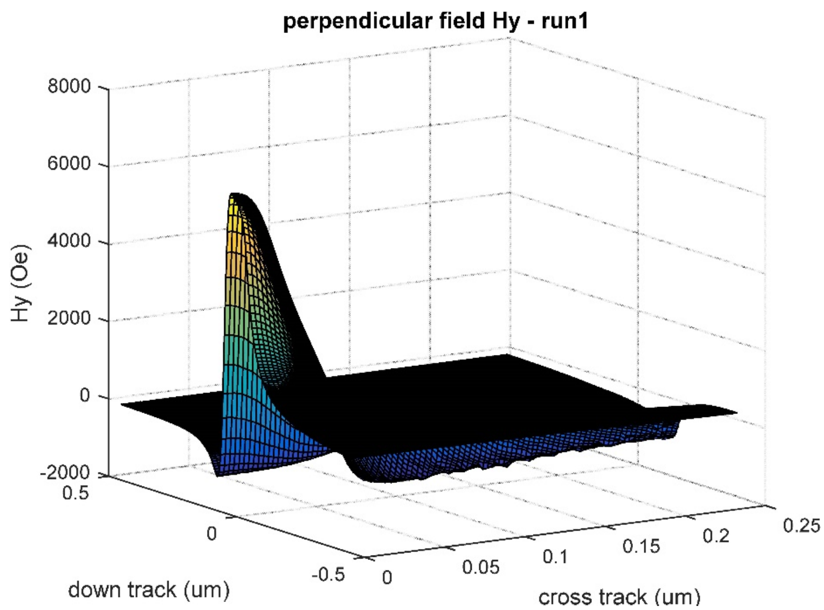

Figure3. Distribution of perpendicular field generated by the magnetic writer probe. Data provided to us by Seagate.

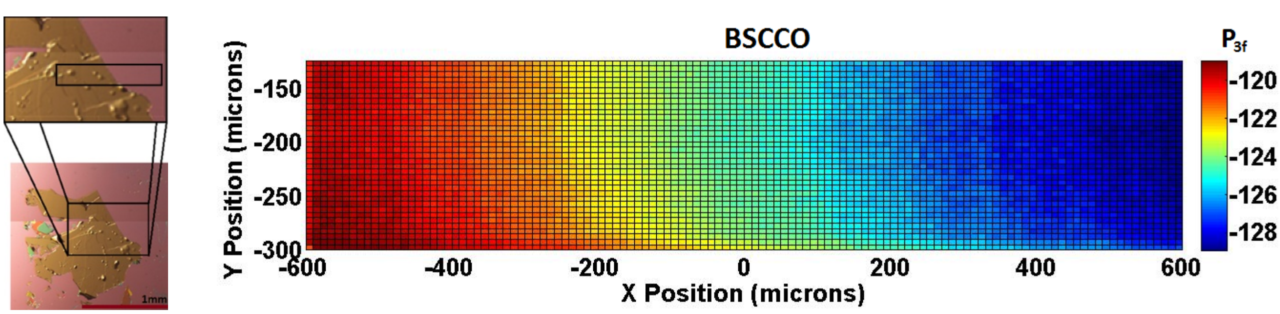

Figure4. (left) Microscope Image of measured BSCCO sample. The scanned area is shown by a black box. (Right) Scanned third harmonic power image of BSCCO sample at 89 K at -6 dBm applied field. The colorbar shows the 3rd Harmonic power in dBm.

b. What was accomplished under these goals?

1) We put together a new completely dry cryostat for cooling samples and experiments to temperatures below 2.7 K in a vacuum environment. The cooldown process for this new setup is fully automated in the sense that the user evacuates the system and starts the helium compressor and everything else is automatic (requiring no user intervention or control) down to the base temperature of the cryostat. The cryostat can operate in a continuous manner at base temperature for weeks or months at a time with minimal attention from the user and without consuming any cryogens or gases. This new setup significantly improves our efficiency to perform measurements and gives us the ability to collect vast amounts of measurement data with great reproducibility.

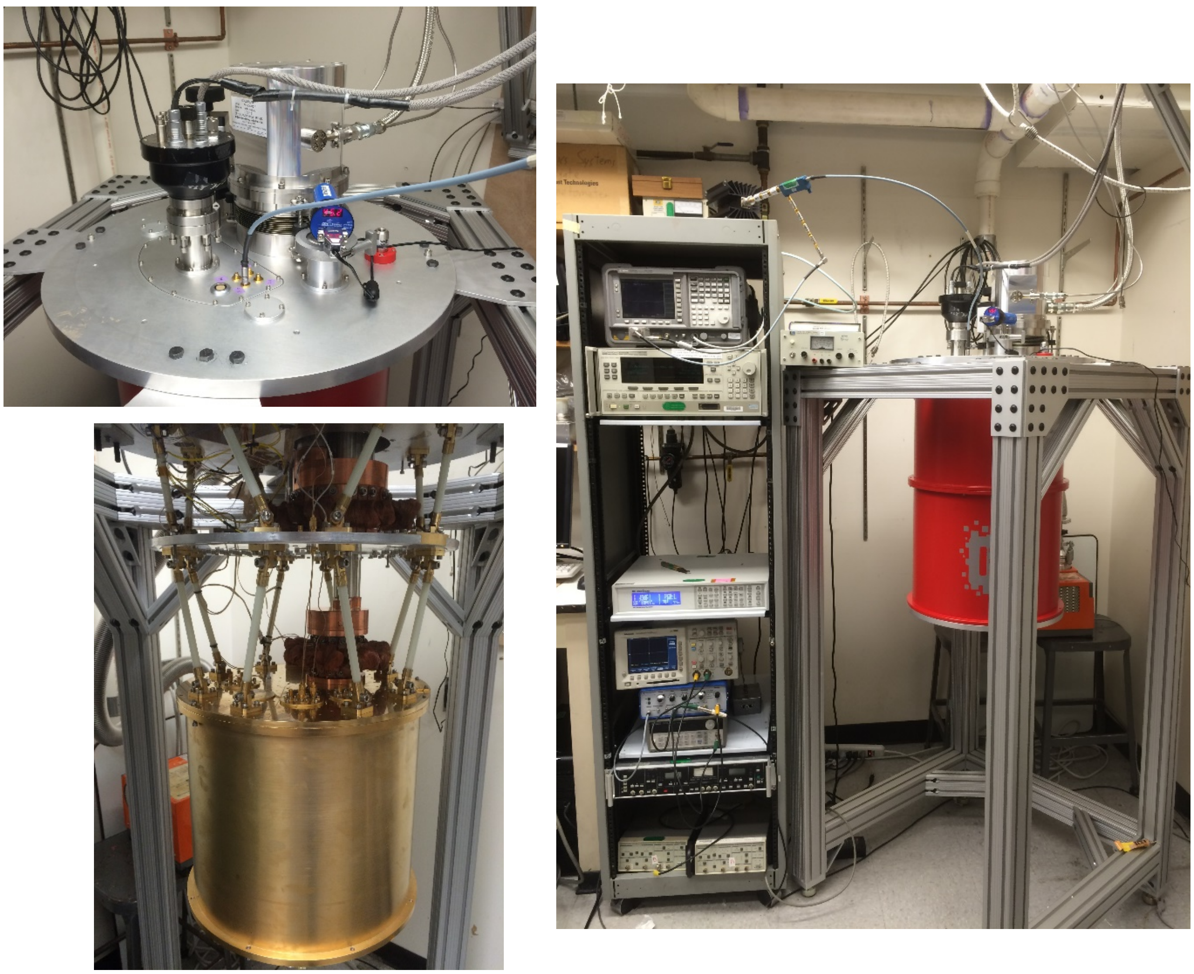

Figure 5. Our current measurement setup. Sample under test and magnetic probe are housed in inner can shown in the bottom left image.

2) We performed measurements on a wide variety of samples including:
   a. Bulk Nb "Dog Bone" Sample produced by T. Bieler (Michigan State University) mimicking SRF cavity production procedures,
   b. Nb on Copper film produced at CERN and provided by T. Junginger,

c. Nb on Copper films produced by O. Malyshev at ASTeC in the UK.

Our measurements revealed interesting periodicity in harmonic response as a function of applied field (Figure 6). This periodicity may be attributed to Josephson Junctions formed by weak links in grain boundaries. Further theoretical modeling and Comsol simulations are being performed to clearly understand this response.

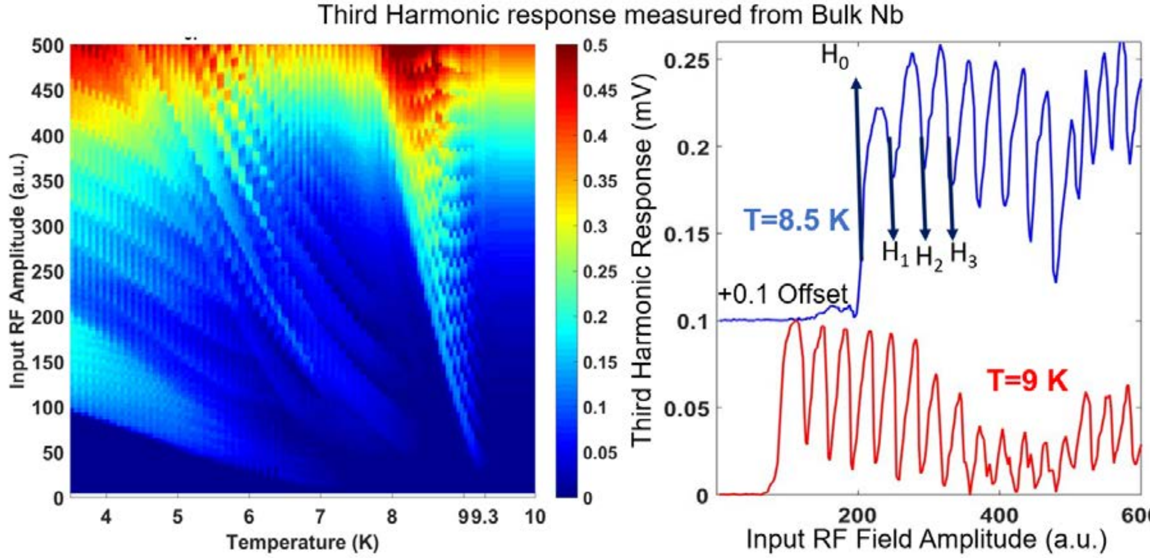

Figure6. (Left) 3rd Harmonic Response(color, linear scale) as a function of applied rf magnetic field (vertical axis, linear scale) and temperature. (Right) Line cuts along 8.5 K and 9 K temperatures. The 8.5 K data set is offset for clarity. We believe that the periodic structures are due to vortices entering SQUID loops on the surface of the sample.

3) A collaboration was started with Dr. Gianluigi Ciovati (Jefferson Lab) and Prof. Dr. Alexander V. Gurevich (Old Dominion University) to measure Nb residual surface resistance at mK temperatures. This measurement will be used to test several hypotheses regarding the origins of residual resistance in Nb SRF Cavities.
For this purpose we installed a full scale 2.2GHz SRF cavity inside our Dilution Refrigerator System with 7 mK base temperature. We reached a temperature of 110 mK on the equator of the cavity. Further efforts exist to go to even lower temperatures and the measure the Q and resonant frequency as a function of temperature and circulating rf power in the cavity.

Figure 7. The Jefferson Lab 2.2 GHz SRF Cavity mounted onto the Mixing Chamber plate (Coldest surface) of the UMD Dilution Fridge.

4) **We have investigated the surface impedance of a new superconducting material, Boron-doped diamond. We used the Parallel Plate Resonator technique to study the London penetration depth and surface resistance of various thin film samples and their temperature dependence. This measurement can reveal the pairing symmetry of an unknown or novel sample which is very important for newly proposed layered coatings in SRF cavities, for example. No d-wave superconductor should be used in SRF due to the linear dependence of the surface resistance with respect to temperature, and the high residual losses. The study was performed for several Boron-doped Diamond samples (see Fig. 8).**

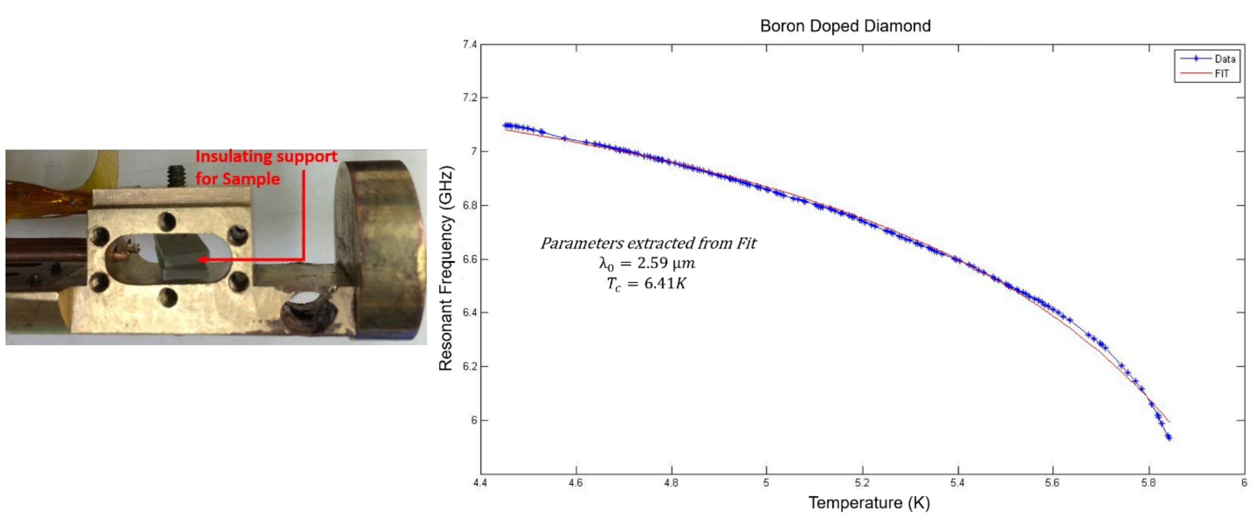

Figure 8. (Left) the parallel plate resonator (PPR) probe used to measure the surface impedance of superconducting thin films. (Right) PPR resonance frequency as a function of temperature. The value of the zero-temperature magnetic Penetration depth and transition temperature are extracted from this fit.

c. What opportunities for training and professional development has the project provided?

A Graduate student was trained in Cryogenics, Scanning Probe Microscopy and Numerical Simulations. During this project, this student completed the necessary steps to advance into Ph.D. Candidacy in Physics. The student also attended 4 conferences and 2 tutorials to be trained in Accelerator Science and Superconductivity.

Four undergraduate students were also exposed to research by the graduate student.

d. How have the results been disseminated to communities of interest?

We presented our findings in 5 conferences listed below:
1) 17th International Conference on RF Superconductivity, Sep 2015, Whistler, Canada
2) APS March Meeting, March 2016, Baltimore MD
3) 7th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity, July 2016, Jefferson Lab, Newport News VA
4) Applied Superconductivity Conference, Sep 2016, Denver CO
5) APS March Meeting, March 2017, New Orleans, LA

We also built collaborations and kept active contact with Leading experts in field including:
1) Prof. Dr. Alexander V. Gurevich - Old Dominion University
2) Dr. Gianluigi Ciovati - Old Dominion University/Jefferson Lab'
3) Prof. Dr. Xiaoxing Xi – Temple University
4) Dr. Oleg Malyshev - The Accelerator Science and Technology Centre (ASTeC) in the United Kingdom
5) Dr. Tobias Junginger - TRIUMF Canada's National Laboratory for Particle and Nuclear Physics, Vancouver

e. What do you plan to do during the next reporting period to accomplish the goals and objectives?

The goal for the next period is to get a new cryogenic scanning system to obtain spatially resolved images of Nb samples. We would also like to investigate the dependence of observed periodic response on probe height and position.
This will help us to better understand the data and the origin of nonlinearity and create definitive links between measured data and parameters relevant in SRF community.

3. PRODUCTS: Optional

What has the project produced?

a. Publications, conference papers, and presentations

i. Journal publications.

Tamin Tai, B. G. Ghamsari, T. Bieler, Steven M. Anlage, "**Nanoscale Nonlinear Radio Frequency Properties of Bulk Nb: Origins of Extrinsic Nonlinear Effects**," Phys. Rev. B **92**, 134513 (2015). pdf

Tamin Tai, Behnood Ghamsari, Jong-Hoon Kang, S. Lee, Chang-Beom Eom, Steven M. Anlage, "**Localized High Frequency Electrodynamic Behavior of an Optimally-doped $Ba(Fe_{1-x}Co_x)_2As_2$ Single Crystal film,**" Physica C **532**, 44-49 (2017). pdf

ii. Books or other non-periodical, one-time publications.

iii. Other publications, conference papers and presentations.

1) Poster at the 17th International Conference on RF Superconductivity, Sep 2015, Whistler, Canada
2) Oral presentation at APS March Meeting, March 2016, Baltimore MD
3) Oral presentation at 7th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity, July 2016, Jefferson Lab, Newport News VA
4) Oral presentation at Applied Superconductivity Conference, Sep 2016, Denver CO
5) Oral presentation at APS March Meeting, March 2017, New Orleans, LA

b. Website(s) or other Internet site(s)

1) http://anlage.umd.edu/AnlageNL%20Props%20of%20SCs_v2.htm
This websites outlines the goals of the project,, current status and relevant publications and announcements.
2) http://anlage.umd.edu/Anlage%20Linear%20Nonlinear%20Dielectric%20Props.htm
This website show the earlier version of this project and the work performed by older generation of graduate students.

c. Technologies or techniques

d. Inventions, patent applications, and/or licenses

e. Other products

Tamin Tai's Ph.D. thesis, "Measuring Electromagnetic Properties of Superconductors in High and Localized RF Magnetic Field" is available online at the following permanent link: http://hdl.handle.net/1903/14668

4. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS:

Who has been involved?

a. What individuals have worked on the project?

1. Name: Steven M. Anlage
2. Total Number of Months: 1
3. Project Role: PD/PI
4. Researcher Identifier: orcid.org/0000-0001-7850-9059
5. Contribution to Project: Prof. Anlage is PI and leader of this project.
6. State, U.S. territory, and/or country of residence: MD, U.S.A.
7. Collaborated with individual in foreign country: Yes
8. Country(ies) of foreign collaborator: UK, Canada, Germany
9. Travelled to foreign country: Yes
10. If traveled to foreign country(ies), duration of stay: 1 week

1. Name: Bakhrom Oripov
2. Total Number of Months: 38
3. Project Role: Graduate Student
4. Researcher Identifier: orcid.org/0000-0002-6626-2076
5. Contribution to Project: Mr. Oripov is employed as a main graduate researcher in this project as part of his Physics Doctoral Thesis.
6. State, U.S. territory, and/or country of residence: Tajikistan.
7. Collaborated with individual in foreign country: Yes
8. Country(ies) of foreign collaborator: Canada, UK
9. Travelled to foreign country: Yes
10. If traveled to foreign country(ies), duration of stay: 2 weeks

1. Name: Patrick Hemmer
2. Total Number of Months: 0 (unpaid undergraduate research student for 6 months)
3. Project Role: Undergraduate Student
5. Contribution to Project: Mr. Hemmer was involved in studying the background nonlinearity of the probe and its integration into new Cryostat
6. State, U.S. territory, and/or country of residence: Maryland, USA.
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: N/A
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay: N/A

1. Name: Eddie Chan
2. Total Number of Months: 0 (unpaid undergraduate research student for 6 months)
3. Project Role: Undergraduate Student
5. Contribution to Project: Mr. Chan performed HFSS simulations to calculate surface current distribution.
6. State, U.S. territory, and/or country of residence: Maryland, USA.
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: N/A
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay: N/A

1. Name: Benjamin Sela

2. Total Number of Months: 0 (unpaid undergraduate research student for 4 months)
3. Project Role: Undergraduate Student
5. Contribution to Project: Mr. Sela was involved in integration of Magnetic Writer Probe and Tuning Fork Sensor.
6. State, U.S. territory, and/or country of residence: Maryland, USA.
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: N/A
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay: N/A

b. Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

The previous Graduate Student Tamin Tai graduated with a Ph.D. degree in 2013, and a new student Bakhrom Oripov was hired as a Graduate Research Assistant.

c. What other organizations have been involved as partners?

1. Organization Name: **DOE Jefferson Labs**
2. Location of Organization: **Newport News, VA**
3. Partner's contribution to the project: **Providing insight and direction in terms of identifying key defects in SRF materials. Also provided a 2.2 GHz Nb cavity, as well as heat treatment of Nb samples.**
   i. Financial support; **NONE**
   ii. In-kind support **Provided a 2.2 GHz Nb cavity, as well as heat treatment of Nb samples.**
   iii. Facilities **N/A**
   iv. Collaborative research **Dr. Gigi Ciovati**
   v. Personnel exchanges **N/A**
   vi. Other **N/A**

d. Have other collaborators or contacts been involved?

1) **Prof. Dr. Alexander V. Gurevich - Old Dominion University, Virginia, USA**
2) **Dr. Gianluigi Ciovati - Old Dominion University/Jefferson Lab, Virginia, USA**
3) **Prof. Dr. Xiaoxing Xi – Temple University, Pennsylvania, USA**
4) **Dr. Oleg Malyshev - The Accelerator Science and Technology Centre (ASTeC), UK**
5) **Dr. Tobias Junginger - TRIUMF Canada's National Laboratory for Particle and Nuclear Physics, Vancouver, Canada**

5. IMPACT: Optional

What is the impact of the project? How has it contributed?

Over the years, this base of knowledge, techniques, people, and infrastructure is drawn upon again and again for application to commercial technology and the economy, to health and safety, to cost-efficient environmental protection, to the solution of social problems, to numerous other aspects of the public welfare, and to other fields of endeavor.

The taxpaying public and its representatives deserve a periodic assessment to show them how the investments they make benefit the nation. Through this reporting format, and especially this section, recipients provide that assessment and make the case for Federal funding of research and education.

Agencies use this information to assess how their research programs: increase the body of knowledge and techniques; enlarge the pool of people trained to develop that knowledge and techniques or put it to use; and improve the physical, institutional, and information resources that enable those people to get their training and perform their functions.

This component will be used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to: the development of the principal discipline(s) of the project; other disciplines; the development of human resources; teaching and educational experiences; physical, institutional, and information resources that form infrastructure; technology transfer (include transfer of results to entities in government or industry, adoption of new practices, or instances where research has led to the initiation of a startup company); society beyond science and technology; or foreign countries.

a. What was the impact on the development of the principal discipline(s) of the project?
"Nothing to Report."

b. What was the impact on other disciplines?
"Nothing to Report."

c. What was the impact on the development of human resources?
Two graduate students have been trained in RF accelerator science.

d. What was the impact on teaching and educational experiences?
Three undergraduate students were introduced to research activities through this grant.

e. What was the impact on physical, institutional, and information resources that form infrastructure?
"Nothing to Report."

f. What was the impact on technology transfer?
"Nothing to Report."

g. What was the impact on society beyond science and technology?
"Nothing to Report."

h. What percentage of the award's budget was spent in foreign country(ies)?

6. CHANGES/PROBLEMS: Optional

7. SPECIAL REPORTING REQUIREMENTS: Mandatory

N/A

8. BUDGETARY INFORMATION: Mandatory
N/A

9. PROJECT OUTCOMES: Optional