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14. ABSTRACT

The DURIP award provided funds for acquiring a cryogen-free adiabatic demagnetization refrigerator at Syracuse University. The new refrigerator has been installed and is now fully operational. The PI has intensive research efforts in the area of Quantum Information Science (QIS), including three ongoing projects with funding through the DoD, that are all benefitting greatly from the installation of this instrument in the PI's lab. The acquisition of this instrumentation has also enhanced ongoing research-related education associated with these projects. The students and postdoctoral researchers involved are part of cutting-edge efforts in QIS and superconducting device

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Report Title

Final Report: Acquisition of an Adiabatic Demagnetization Refrigerator for Quantum Information Science with Superconducting Circuits

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The DURIP award provided funds for acquiring a cryogen-free adiabatic demagnetization refrigerator at Syracuse University. The new refrigerator has been installed and is now fully operational. The PI has intensive research efforts in the area of Quantum Information Science (QIS), including three ongoing projects with funding through the DoD, that are all benefitting greatly from the installation of this instrument in the PI's lab. The acquisition of this instrumentation has also enhanced ongoing research-related education associated with these projects. The students and postdoctoral researchers involved are part of cutting-edge efforts in QIS and superconducting device technology, both critical areas of interest to the DoD.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

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TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

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TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Post Doctorates

NAME	PERCENT_SUPPORTED

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Total Number:

Names of Faculty Supported

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

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NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

The acquisition of the new refrigerator in the PI's lab has allowed for more rapid evaluation of new superconducting qubit designs. This has benefitted all of the PI's currently funded projects, including the IARPA and ARO-funded project in the MQCO program in which the PI collaborates closely with IBM.

Acquisition of an Adiabatic Demagnetization Refrigerator for Quantum Information Science with Superconducting Circuits (W911NF-14-1-0592)

Final Technical Report: November 2015

Britton Plourde (Syracuse University)

Following the receipt of the DURIP award from the ARO at the end of summer 2014, an order was placed with High Precision Devices (HPD) of Boulder, CO for the Adiabatic Demagnetization Refrigerator (ADR) requested in the original proposal. HPD has extensive experience making cryogenic equipment and is at the forefront of adiabatic demagnetization cooling technology. This ADR system was delivered at the end of December 2014, just before the winter holidays. In early 2015 the Plourde group worked closely with the Syracuse Physics machine shop to install the system in one of the low-temperature lab rooms of the Plourde research group in the Physics Department at Syracuse University (Fig. 1). Following the successful initial benchmarking tests of the performance of the new refrigerator, the Plourde group worked to add electrical feedthroughs and experimental wiring and microwave components for a wide variety of low-temperature microwave measurements of superconducting devices. As described in the original DURIP proposal from PI Plourde, the

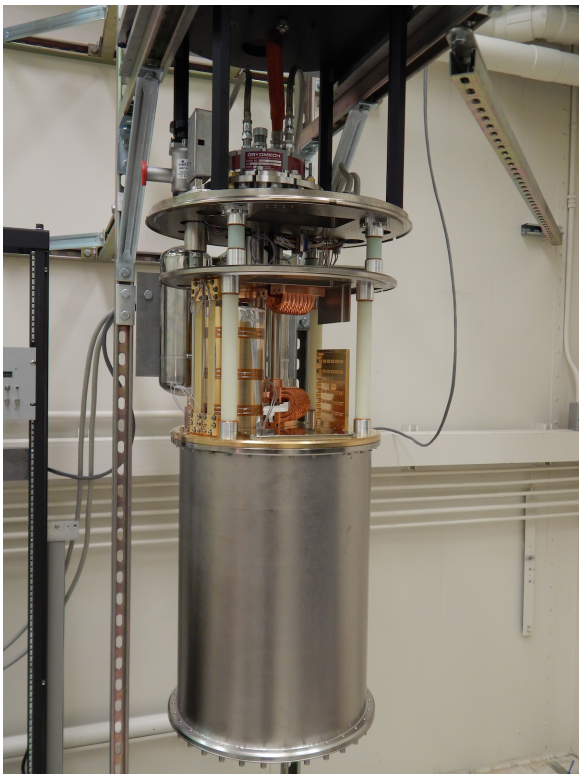

Figure 1: Photograph of ADR from High Precision Devices with vacuum jackets removed, installed in Plourde research lab at Syracuse University.

system is being used for the development of numerous superconducting devices for multiple research projects, including superconducting metamaterial structures for coupling to qubits [1] and Josephson photomultiplier circuits for photon-counting based qubit readout [2].

The new ADR is a Model 106 (Shasta) ADR Cryostat and has a pulse-tube cooler with temperature stages of 50 K and 3 K with sufficient cooling power for thermal anchoring of wiring and coaxial cables and mounting cryogenic semiconductor amplifiers. The final stage of the ADR can reach a base temperature of 50 mK. The experimental space that can be cooled to 50 mK is 13" in diameter and over 10" in height, thus providing substantial room for mounting a variety of samples, along with electrical filters and shielding. The pulse-tube cooler is cryogen free, thus removing the added cost and complication of supplying liquid cryogens associated with other low-temperature systems. The useful lifetime of the equipment is estimated to be 20 years.

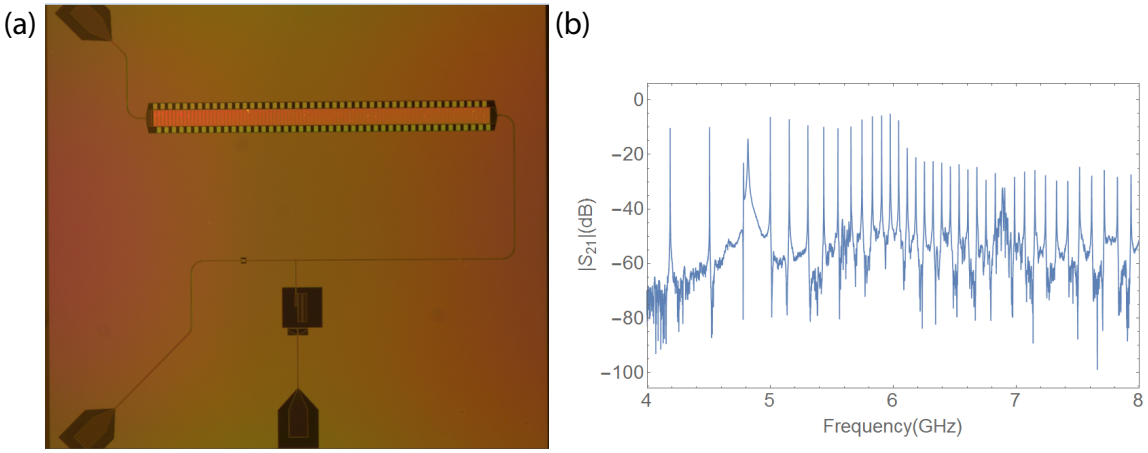

Figure 2: (a) Optical micrograph of Nb thin-film metamaterial circuit. (b) Low-temperature measurement of microwave transmission $S_{21}(f)$ of metamaterial circuit on ADR.

For our ARO-funded project in the quantum computing measurement program – *Scalable Readout of Superconducting Qubits with Novel Superconducting Amplifiers and Metamaterials* (W911NF-14-1-0080) – we have used the new ADR this year for characterizing new metamaterial designs [3] for experiments with superconducting transmon qubits coupled to metamaterials (Fig. 2). The rapid thermal cycle time for this system has been extremely helpful for important tests of these devices. In addition, we have had numerous cooldowns on the new ADR throughout this year for testing new qubit-cavity chips for implementing our photon-counting based qubit readout scheme.

We have also used the new ADR for multiple tests of single flux quantum (SFQ) circuits for exciting linear resonators as part of our new ARO-funded project with the University of Wisconsin – *Accurate Qubit Control with Single Flux Quantum Pulses* (W911NF-15-1-0248) – based on a new scheme for driving qubit rotations using SFQ circuits [4]. Our initial measurements on the new ADR for this project have involved measuring the current-voltage characteristics of SFQ-driver circuits with and without microwave excitation [Fig. 3(a)].

For our IARPA and ARO-funded project in the MQCO program led by IBM – *Surface-Code Multi-Qubit Functionality with Superconducting Qubits* (W911NF-10-1-0324) – we have

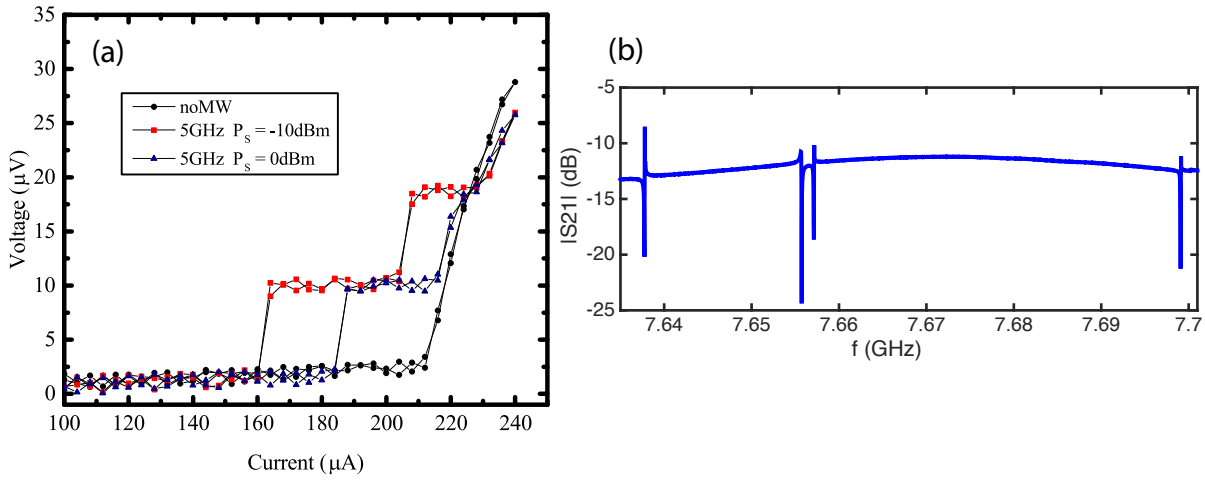

Figure 3: (a) Measurement of current-voltage characteristic with and without microwave excitation on new ADR for Nb-based SFQ-driver circuit for excitation of linear resonators. (b) Low-temperature measurement of microwave transmission $S_{21}(f)$ through Nb feedline showing four readout cavity resonances on multiplexed chip for investigating dephasing in asymmetric transmon qubits.

used the new ADR to characterize new designs of multiplexed qubit chips containing asymmetric transmon qubits [5] with different junction asymmetries [Fig. 3(b)]. This work is aimed at developing qubits with a reduced sensitivity to magnetic flux noise while having a small, but nonzero, range of frequency tunability.

The addition of this new low-temperature apparatus to the Plourde lab has enhanced the ongoing research-related education associated with the group's currently funded research projects. The students and postdoctoral researchers working on these projects are part of cutting-edge efforts in quantum information science (QIS), a critical area of interest to the DoD. Furthermore, the students and postdocs are also receiving extensive, hands-on training in superconducting device technology, another key area of interest to the DoD.

Bibliography

[1] D. J. Egger and F. K. Wilhelm. Multimode circuit quantum electrodynamics with hybrid metamaterial transmission lines. *Phys. Rev. Lett.*, 111:163601, Oct 2013.

[2] Luke C. G. Govia, Emily J. Pritchett, Canran Xu, B. L. T. Plourde, Maxim G. Vavilov, Frank K. Wilhelm, and R. McDermott. High-fidelity qubit measurement with a microwave-photon counter. *Phys. Rev. A*, 90:062307, 2014.

[3] B. L. T. Plourde, Haozhi Wang, Francisco Rouxinol, and M. D. LaHaye. Superconducting metamaterials and qubits. In *SPIE Sensing Technology+ Applications*, pages 95000M–95000M. International Society for Optics and Photonics, 2015.

[4] R. McDermott and M. G. Vavilov. Accurate qubit control with single flux quantum pulses. *Phys. Rev. Applied*, 2:014007, Jul 2014.

[5] J. D. Strand, Matthew Ware, Félix Beaudoin, T. A. Ohki, B. R. Johnson, Alexandre Blais, and B. L. T. Plourde. First-order sideband transitions with flux-driven asymmetric transmon qubits. *Phys. Rev. B*, 87(22):220505, 2013.