Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Superconducting Quantum Materials and Systems Center

Anna Grassellino, SQMS Center Director
PAC 2022
23 June 2022

https://www.quantum.gov

https://science.osti.gov/Initiatives/QIS/QIS-Centers

H. R. 6227

(Bill Passed Dec 2018)

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

National Quantum Initiative Act

This bill directs the President to implement a National Quantum Initiative Program to, among other things, establish the goals and priorities for a 10-year plan to accelerate the development of quantum information science and technology applications.

The bill defines "quantum information science“ as the storage, transmission, manipulation, or measurement of information that is encoded in systems that can only be described by the laws of quantum physics.

The National Science and Technology Council shall establish a Subcommittee on Quantum Information Science, including membership from the National Institute of Standards and Technology (NIST) and the National Aeronautics and Space Administration (NASA), to guide program activities.

The President must establish a National Quantum Initiative Advisory Committee to advise the President and subcommittee on quantum information science and technology research and development.

NIST shall carry out specified quantum science activities and convene a workshop to discuss the development of a quantum information science and technology industry.

The National Science Foundation shall: carry out a basic research and education program on quantum information science and engineering, and award grants for the establishment of Multidisciplinary Centers for Quantum Research and Education.

The Department of Energy (DOE) shall carry out a basic research program on quantum information science. The Office of Science of DOE shall establish and operate National Quantum Information Science Research Centers to conduct basic research to accelerate scientific breakthroughs in quantum information science and technology.

SQMS

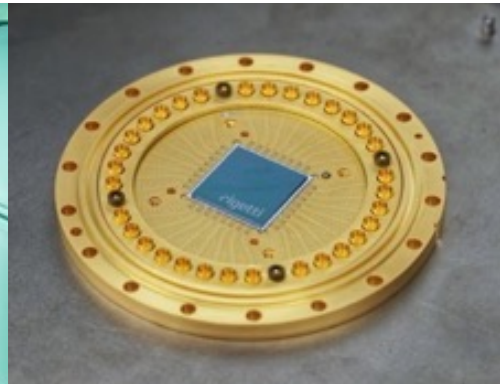
Led by FNAL, $115M
Awarded August 2020

Superconducting Quantum Materials and Systems Center

A DOE National Quantum Information Science Research Center

23 Institutions
> 350 Researchers
> 100 students/postdocs

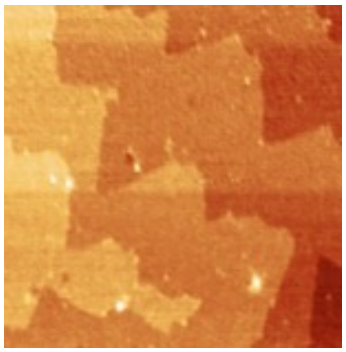
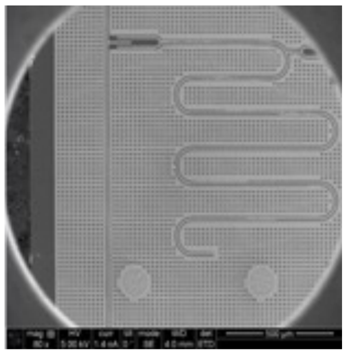
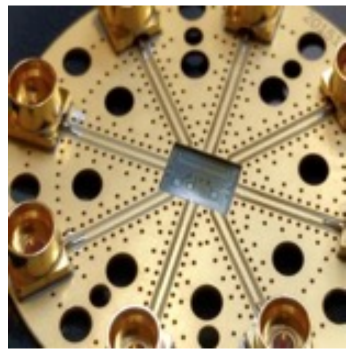
Fermilab · Northwestern University · rigetti · Ames Laboratory (Creating Materials & Energy Solutions, U.S. Department of Energy) · NASA Ames Research Center · NIST · INFN Istituto Nazionale di Fisica Nucleare · Stanford University · University of Illinois Urbana-Champaign · Rutgers · Università di Pisa · University of Colorado Boulder · Illinois Institute of Technology · Johns Hopkins University · Temple University · Colorado School of Mines · The University of Arizona · University of Minnesota · NYU · Goldman Sachs · Lockheed Martin · Janis · Unitary Fund

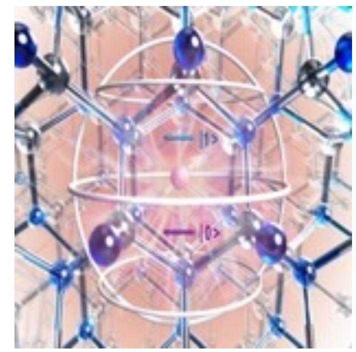
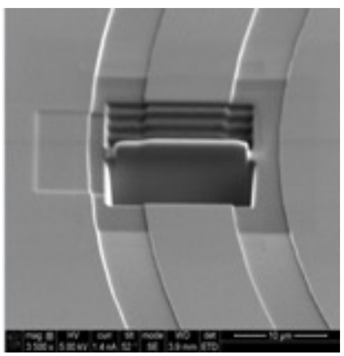


SQMS Mission Statement: “bring together the power of national labs, industry and academia to achieve transformational advances in the major cross-cutting challenge of understanding and eliminating **quantum decoherence** in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing."

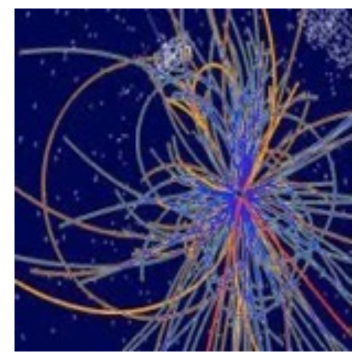
SQMS 10-year Roadmap: from material discovery to quantum advantage

Materials Discovery → High Coherence Devices → Systems Integration → New quantum computing and sensing platforms → Quantum Advantage

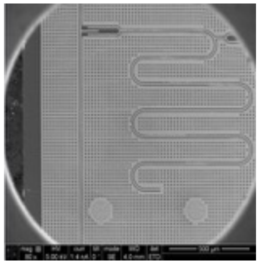




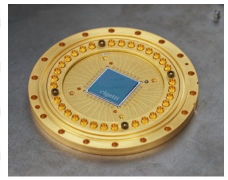
Potential for physics discovery lays at every step of the chain
Strong emphasis on benefit to HEP

Timeline of Major Activities

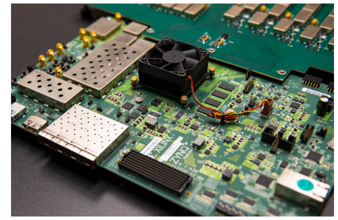
10+ qubits prototype



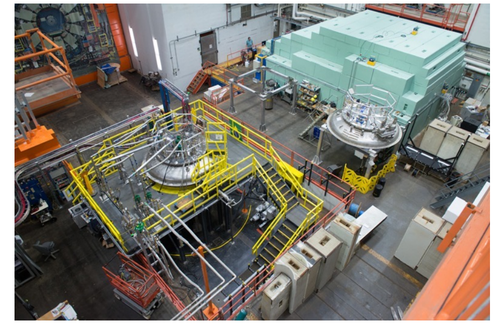
Transmon qubit improvement in coherence > 10



100+ qubits prototype



Electronics/optimal controls development/scale up



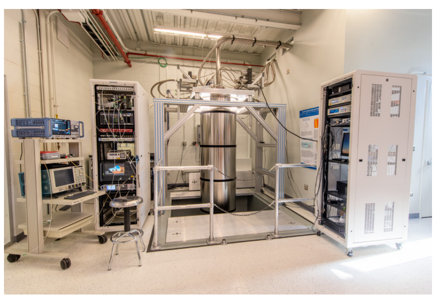
1000+ qubits prototype @ Colossal Fridge

2023
Mid Term DOE Center Technical Review

2025-6
Final Review and Center Renewal

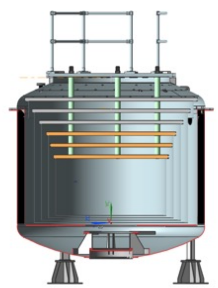
2028
Second Term mid term review

2031
Deployment of Quantum Facilities for National Research Program



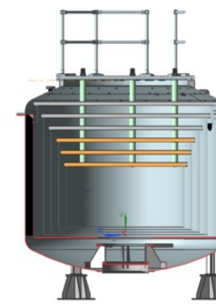
New testbeds commissioned

Quantum Sensors exploration for fundamental physics



Colossal fridge 50mK

Entangled multi-DR fridge system



Colossal fridge 10mK commissioned

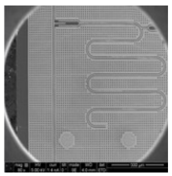
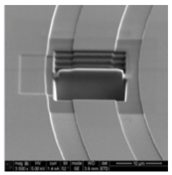
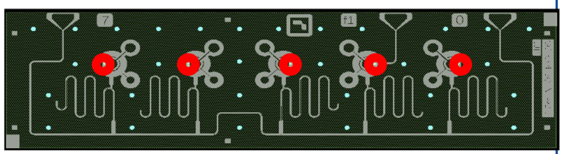
Fermilab

Superconducting Quantum Materials and Systems Center Y2 Highlights

>50 peer review and pre-prints in the past year; support > 100 students and postdocs;
>350 researchers from 23 institutions and > 100 different experiments across the center

Materials Research for Qubits

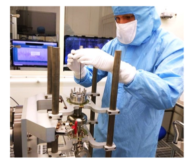
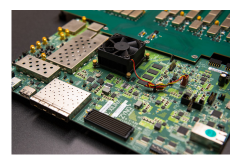
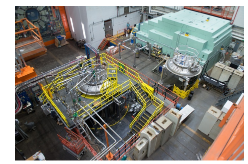
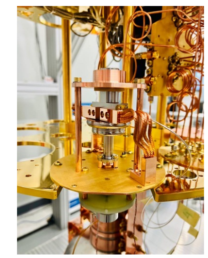
Launched multi-institutional study for material science studies towards understanding decoherence in qubits

Demonstrated: new defects and interfaces in qubits causing decoherence; new material/processes for high coherence qubits

Qubit Devices and Quantum processors

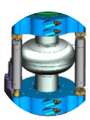
Multiple quantum devices experiments ongoing: 3D SRF cavities for quantum processors, round robin experiment for planar qubits; controls and electronics development for QPUs; record size fridge

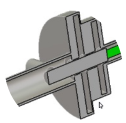
Demonstrated: record integrated cavity-qubit system for 3D quantum computing architecture

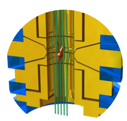
Quantum Sensing for fundamental physics

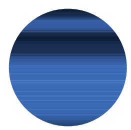
Multiple quantum sensing experiments ongoing: dark matter searches, precision measurements, gravitational wave studies


DarkSRF


Multimode Cavity Axion Search


Tunable Dark Photon Search

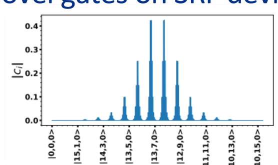

Single Particle Penning Trap

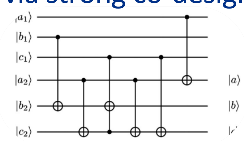

Gravitational Waves

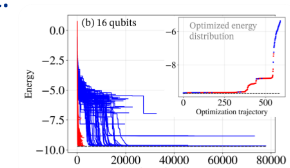
Demonstrated: most sensitive experiment for wavelike dark photons; world's record cavities quality factors for axion searches

Quantum Algorithms, Simulations, Applications

Algorithms for simulation of condensed matter/HEP theories. Engineering new and novel gates on SRF devices via strong co-design effort.


Scalar field theory simulations


Gauge theory simulations



Benchmarking condensed matter theories on real hardware

Demonstrated: new simulation algorithms for scalar field theories, gauge theories, new ways to manipulate photon states on SRF devices.

Building a diverse quantum workforce: > 40 new SQMS hires at Fermilab

SQMS Division at Fermilab formed and now has reached 50 employees
SQMS Center also supports hires in other divisions, Theory, APS-TD, FQI etc
SQMS Center supports ~ 50 FTE per week from >100 different employees at the lab

SQMS participates in the Snowmass effort:
QIS impacts all HEP areas – from science to technology (cosmic, precision, computing, accelerator, detector)

FERMILAB-PUB-22-260-SQMS

Quantum computing hardware for HEP algorithms and sensing

M. Sohaib Alam,[1,2] Sergey Belomestnykh,[3] Nicholas Bornman,[3] Gustavo Cancelo,[4] Yu-Chiu Chao,[3] Mattia Checchin,[3] Vinh San Dinh,[3,5,6] Anna Grassellino,[3] Erik J. Gustafson,[3,7] Roni Harnik,[3,7] Corey Rae Harrington McRae,[8,9] Ziwen Huang,[3] Keshav Kapoor,[3] Taeyoon Kim,[3,5,10] James B. Kowalkowski,[3] Matthew J. Kramer,[11] Yulia Krasnikova,[3] Prem Kumar,[3,12] Doga Murat Kurkcuoglu,[3] Henry Lamm,[3,7] Adam L. Lyon,[3] Despina Milathianaki,[13] Akshay Murthy,[3] Josh Mutus,[13] Ivan Nekrashevich,[3] JinSu Oh,[11] A. Barış Özgüler,[3] Gabriel Nathan Perdue,[3] Matthew Reagor,[13] Alexander Romanenko,[3] James A. Sauls,[3,5,10] Leandro Stefanazzi,[4] Norm M. Tubman,[14] Davide Venturelli,[1,2] Changqing Wang,[3] Xinyuan You,[3] David M. T. van Zanten,[3,*] Lin Zhou,[11] Shaojiang Zhu,[3] and Silvia Zorzetti[3,†]

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[12] *Center for Photonic Communication and Computing, ECE Department, Northwestern University, Evanston, IL 60208, USA*
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(Dated: May 2, 2022)

Quantum information science harnesses the principles of quantum mechanics to realize computational algorithms with complexities vastly intractable by current computer platforms. Typical applications range from quantum chemistry to optimization problems and also include simulations for high energy physics. The recent maturing of quantum hardware has triggered preliminary explorations by several institutions (including Fermilab) of quantum hardware capable of demonstrating quantum advantage in multiple domains, from quantum computing to communications, to sensing. The Superconducting Quantum Materials and Systems (SQMS) Center, led by Fermilab, is dedicated to providing breakthroughs in quantum computing and sensing, mediating quantum engineering and HEP based material science. The main goal of the Center is to deploy quantum systems with superior performance tailored to the algorithms used in high energy physics. In this Snowmass paper, we discuss the two most promising superconducting quantum architectures for HEP algorithms, i.e. three-level systems (qutrits) supported by transmon devices coupled to planar devices and multi-level systems (qudits with arbitrary N energy levels) supported by superconducting 3D cavities. For each architecture, we demonstrate exemplary HEP algorithms and identify the current challenges, ongoing work and future opportunities. Furthermore, we discuss the prospects and complexities of interconnecting the different architectures and individual computational nodes. Finally, we review several different strategies of error protection and correction and discuss their potential to improve the performance of the two architectures. This whitepaper seeks to reach out to the HEP community and drive progress in both HEP research and QIS hardware.

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

FERMILAB-PUB-22-150-SQMS-T

Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities

Asher Berlin,[2,1] Sergey Belomestnykh,[1,3,4] Diego Blas,[5,6] Daniil Frolov,[1] Anthony J. Brady,[7,1] Caterina Braggio,[8,9,1] Marcela Carena,[2,10,1] Raphael Cervantes,[1] Mattia Checchin,[1] Crispin Contreras-Martinez,[1,3] Raffaele Tito D'Agnolo,[11] Sebastian A. R. Ellis,[12] Grigory Eremeev,[1,3] Christina Gao,[13,2,1] Bianca Giaccone,[1] Anna Grassellino,[1,3] Roni Harnik,[1,2,*] Matthew Hollister,[1,3] Ryan Janish,[2,1] Yonatan Kahn,[13,1] Sergey Kazakov,[1,3] Doga Murat Kurkcuoglu,[14,1] Zhen Liu,[15,1] Andrei Lunin,[1] Alexander Netepenko,[1,3] Oleksandr Melnychuk,[1] Roman Pilipenko,[1,3] Yuriy Pischalnikov,[1,3] Sam Posen,[1,3,†] Alex Romanenko,[1,3] Jan Schütte-Engel,[13,1] Changqing Wang,[1] Vyacheslav Yakovlev,[1,3] Kevin Zhou,[16] Silvia Zorzetti,[1] and Quntao Zhuang[7,1,17]

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(Dated: March 25, 2022)

This is a Snowmass white paper on the utility of existing and future superconducting cavities to probe fundamental physics. Superconducting radio frequency (SRF) cavity technology has seen tremendous progress in the past decades, as a tool for accelerator science. With advances spearheaded by the SQMS center at Fermilab, they are now being brought to the quantum regime becoming a tool in quantum science thanks to the high degree of coherence. The same high quality factor can be leveraged in the search for new physics, including searches for new particles, dark matter, including the QCD axion, and gravitational waves. We survey some of the physics opportunities and the required directions of R&D. Given the already demonstrated integration of SRF cavities in large accelerator systems, this R&D may enable larger scale searches by dedicated experiments.

*Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)*

FERMILAB-PUB-22-241-SQMS-TD
April 5, 2022

Key directions for research and development of superconducting radio frequency cavities

ABSTRACT

Radio frequency superconductivity is a cornerstone technology for many future HEP particle accelerators and experiments from colliders to proton drivers for neutrino facilities to searches for dark matter. While the performance of superconducting RF (SRF) cavities has improved significantly over the last decades, and the SRF technology has enabled new applications, the proposed HEP facilities and experiments pose new challenges. To address these challenges, the field continues to generate new ideas and there seems to be a vast room for improvements. In this paper we discuss the key research directions that are aligned with and address the future HEP needs.

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

S. Belomestnykh[1,16], S. Posen[1] (**Editors**)

D. Bafia[1], S. Balachandran[12], M. Bertucci[10], A. Burrill[15], A. Cano[1], M. Checchin[1], G. Ciovati[19], L.D. Cooley[12], G. Dalla Lana Semione[9], J. Delayen[14,19], G. Eremeev[1], F. Furuta[1], F. Gerigk[5], B. Giaccone[1], D. Gonnella[15], A. Grassellino[1], A. Gurevich[14], W. Hillert[9], M. Iavarone[18], J. Knobloch[7,21], T. Kubo[11,17], W.-K. Kwok[2], R. Laxdal[20], P.J. Lee[12], M. Liepe[3], M. Martinello[1], O.S. Melnychuk[1], A. Nassiri[2], A. Netepenko[1], H. Padamsee[3,1], C. Pagani[10], R. Paparella[10], U. Pudasaini[19], C.E. Reece[19], D. Reschke[4], A. Romanenko[1], M. Ross[15], K. Saito[6], J. Sauls[13], D.N. Seidman[13], N. Solyak[1], Z. Sung[1], K. Umemori[11], A.-M. Valente-Feliciano[19], W. Venturini Delsolaro[5], N. Walker[4], H. Weise[4], U. Welp[2], M. Wenskat[9], G. Wu[1], X.X. Xi[18], V. Yakovlev[1], A. Yamamoto[11,5], J. Zasadzinski[8]

SQMS Year 1 DOE review and PEMP

- Management, Ecosystem, Instrumentation and Facilities review (3 of the 5 essential components)
- Excellent reviews, four recommendations

"The National QIS Research Centers program represents important multidisciplinary and multi- institutional investments in a priority initiative topic for the Office of Science, and we recognize and applaud the rapid progress in standing up these Centers"

- Priority and criticality of the initiative was reiterated by DOE at the 2022 ALP
- DOE expressed very positively on QIS becoming core competence at the lab
- Yearly PEMP Notable (Office of Science): Contribute to establishing the synergistic research program and deliver impactful science from the FNAL-led QIS Center, as measured by the FY 2022 trimester reports, annual report, common goals and milestones report, research publications and highlights, and participation in periodic conference calls.

September 13, 2021

Dr. Anna Grassellino
Director, SQMS
Fermi National Accelerator Laboratory

Dear Dr. Grassellino,

We extend our thanks to you and all others at the Superconducting Quantum Materials and Systems Center (SQMS) for your active participation in the National Quantum Information Science (QIS) Research Centers Management, Ecosystem Stewardship, and Instrumentation & Facilities Review that took place on July 12, 2021. We appreciate the considerable effort that went into developing review documentation, preparing and making presentations, and all other aspects of such complex reviews. Enclosed you will find the reviewers' comments from this review. Resulting analysis and guidance from the Office of Science (SC) are provided below in the body of this letter.

This was an initial review of the three essential components of your Center as identified above. SC informed the reviewers that the Centers had been in operation for less than a year, with activities initiated in September 2020. The stated overarching goal of the review was to demonstrate team science, focused and coordinated research activities, adaptive management, and adequate processes and resources to achieve the goals of the Center. Such a review early in the operational life of the Center affords a valuable opportunity to assess and refine the management approach, to confirm that activities are proceeding as planned, to identify both hurdles and good practices, and to communicate expectations and suggestions. SC wants to ensure that all the Centers are operated in an optimal way that takes full advantage of resources and the specifics of the working environment of each Center, to maximize scientific success and impact.

The National QIS Research Centers program represents important multidisciplinary and multi-institutional investments in a priority initiative topic for the Office of Science, and we recognize and applaud the rapid progress in standing up these Centers. While review findings and SC perspectives are summarized below, we encourage you to read and consider all reviewer comments. If you have any questions regarding individual comments, or the recommendations/action items below, please discuss them with me or with Dr. Tof Carim, the lead program manager for your Center. Note that each section of the findings and comments below begin with overall observations on the Centers collectively, followed by specific notes on SQMS.

Findings and Comments:

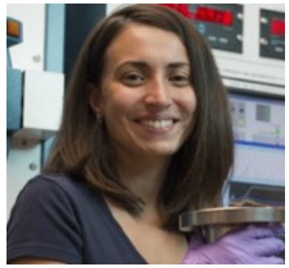
Management

Overall observations: Strong progress has been made in setting up the Centers, with robust structures and processes developed and implemented. Several particularly good practices were noted, including the implementation of a cross-center Chief Operating Officer Coordination Working Group and the use of formal management and tracking tools such as Jira, Confluence, and Microsoft Project. The absence of (or lack of description of) cybersecurity plans was noted. While the number and frequency of in-progress, planned, and proposed internal meetings was explained and justified by Centers, reviewers expressed concern about this becoming a bookkeeping exercise rather than one that adds value.

Fermilab

SQMS Core Management Group: top programmatic and institutional leadership

Dr. Anna Grassellino (FNAL)
Center Director



Prof. James Sauls
(Northwestern University)
Center Deputy Director

Dr. Matt Reagor (Rigetti)
Chief Technology Officer

Dr. Eleanor Rieffel (NASA Ames)
Chief Research Scientist

Dr. Matt Kramer (Ames Lab)
Chief Engineer

Dr. Stefano Lami (FNAL)
Chief Operating Officer

Dr. Alexander Romanenko
(FNAL) Technology Thrust
Leader

Dr. Roni Harnik
(FNAL)
Science Thrust
Leader

Rich Stanek (FNAL)
SQMS Deputy
Division Head

SQMS Advisory Board

Pat Dehmer

Sir Peter Knight

Hasan Padamsee

Alex King

Michael Hayduk

Eric Isaacs

John Saunders

Tommaso Calarco

Scientific and Technological Goals – quantum computing

Develop and deploy a prototype quantum computer at FNAL

Based on our own SRF technology for QIS

Explore and demonstrate advantage for HEP (and more)

The Computer and the Universe[1]

John Archibald Wheeler

Center for Theoretical Physics, The University of Texas at Austin, Austin, Texas 78712

Received May 7, 1981

"Computer science and basic physics mark two of the frontiers of the civilization of this age. One seeks to build complexity out of simplicity. The other tries to unravel complexity into simplicity. No one, it has been said, is better at taking a puzzle apart than the person who put it together and no one is better at putting a puzzle together than the one who took it apart"

SQMS processors performance goals compared to leading systems →

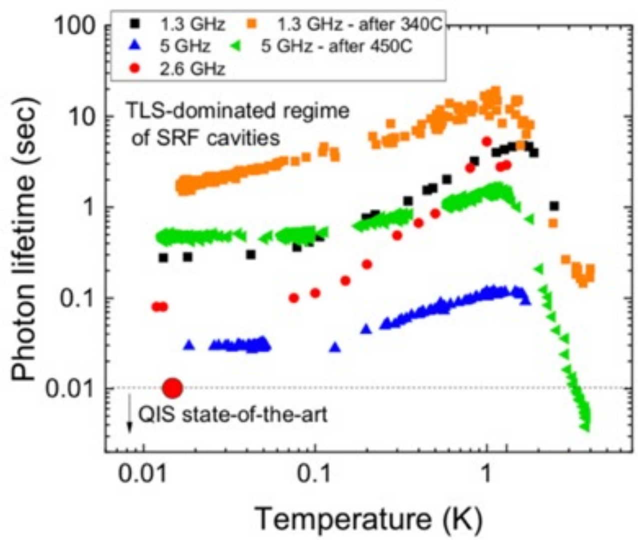
Processor metrics	Leading systems	Center prototypes (3 yr)		Center device goals (5 yr)	
		2D-Alpha (estimate)	SRF-Alpha (estimate)	SQMS-2D (estimate)	SQMS-3D (estimate)
Number of qubits	53	128	>100	256	>200
Connectivity graph (qubit:neighbors)	1:4	1:3	1:10	1:3	1:200
Qubit T_1 lifetime, μs (median)	70	200	400,000	400	1,000,000
Gate time, ns (median)	20	50	2000	40	100
Coherence/gate time ratio	1,000	4,000	20,000	10,000	10,000,000
Single qubit gate fidelity (%)	99.85	99.6	99.5	99.95	99.95
Two qubit gate fidelity (%)	99.65	99.2	99.5	99.9%	99.95
Achievable circuit depth (1/error)	300	100	200	1,000	2,000

SQMS key goals and estimated performance parameters.

Foundational Technological Strengths: SRF

- **The "perfect photon box"** – Einstein's dream closer than ever to reality
- Fermilab SRF group has demonstrated the world's record photon lifetime in quantum regime **with coherence up to 2 seconds**

A. Romanenko et al, Phys. Rev. Applied 13, 034032, 2020



Probing a quantum field in a photon box

J M Raimond[1], T Meunier[1], P Bertet[1], S Gleyzes[1], P Maioli[1], A Auffeves[1], G Nogues[1], M Brune[1] and S Haroche[1,2]

[1] Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France
[2] Collège de France, 11 place Marcelin Berthelot, F-75231 Paris Cedex 05, France

E-mail: jmr@lkb.ens.fr

Received 5 November 2004, in final form 8 December 2004
Published 25 April 2005
Online at stacks.iop.org/JPhysB/38/S535

Abstract

Einstein often performed thought experiments with 'photon boxes', storing fields for unlimited times. This is yet but a dream. We can nevertheless store quantum microwave fields in superconducting cavities for billions of periods. Using circular Rydberg atoms, it is possible to probe in a very detailed way the quantum state of these trapped fields. Cavity quantum electrodynamics tools can be used for a direct determination of the Husimi Q and Wigner quasi-probability distributions. They provide a very direct insight into the classical or non-classical nature of the field.

PHYSICAL REVIEW APPLIED **13**, 034032 (2020)

Three-Dimensional Superconducting Resonators at $T < 20$ mK with Photon Lifetimes up to $\tau = 2$ s

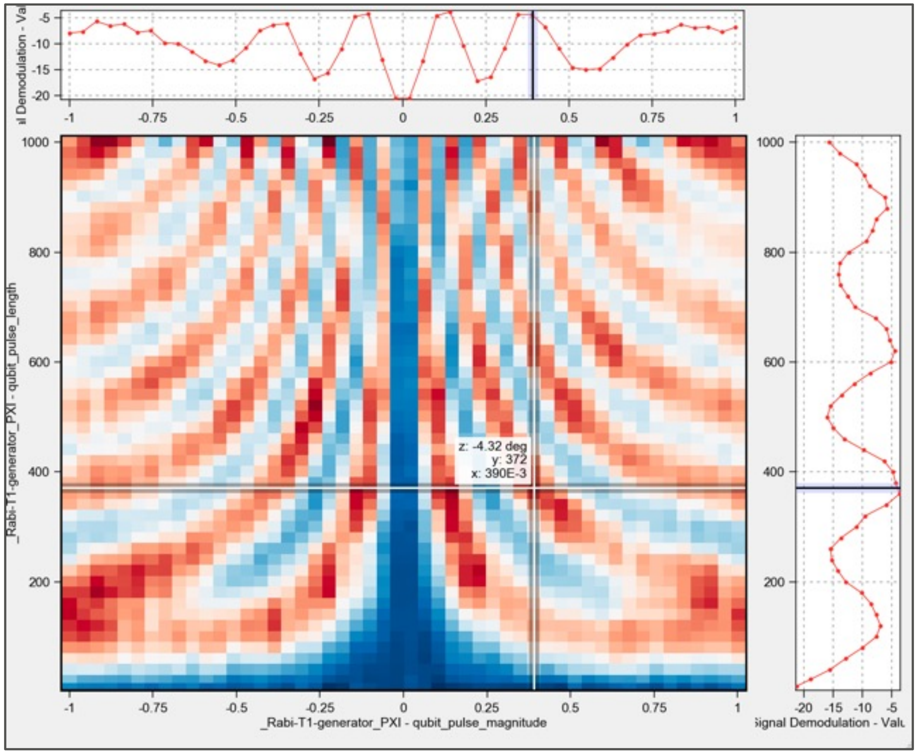
A. Romanenko,* R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, and A. Grassellino
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

(Received 23 December 2019; accepted 14 February 2020; published 12 March 2020)

Superconducting Quantum Material and Systems Center – Progress

- First observation in Fermilab quantum labs of Rabi oscillations of a transmon qubit coupled to an SRF cavity – the foundational building block of a quantum computer of 3D-based architecture
- Currently working on gates implementation

ONE nine cell SRF cavity + **ONE** transmon =
SQMS 100+ qubits processor



Oscillatory behavior (Rabi oscillation) of the qubit state in the SRF cavity alternating between ground and first excited state

Fermilab

Launched a multi-institutional qubits nanofab taskforce led by Fermilab experts

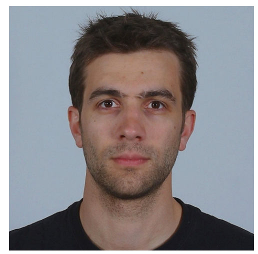
- Expertise in engineering performance of superconducting microwave devices, knowledge driven, based on material and SC physics characterization and understanding
- **SQMS adds a new core expertise to FNAL** – superconducting 2D quantum devices design, nanofabrication and test


Mustafa Bal
Scientist (FNAL)


Akshay Murthy
Scientist (FNAL)


Arpita Mitra
Postdoc (FNAL)


Francesco Crisa',
PhD student
(FNAL/IIT)

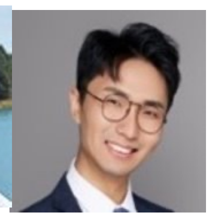

Florent Lecoq
Scientist (NIST)


Dominic Goronzy
Postdoc (NU)

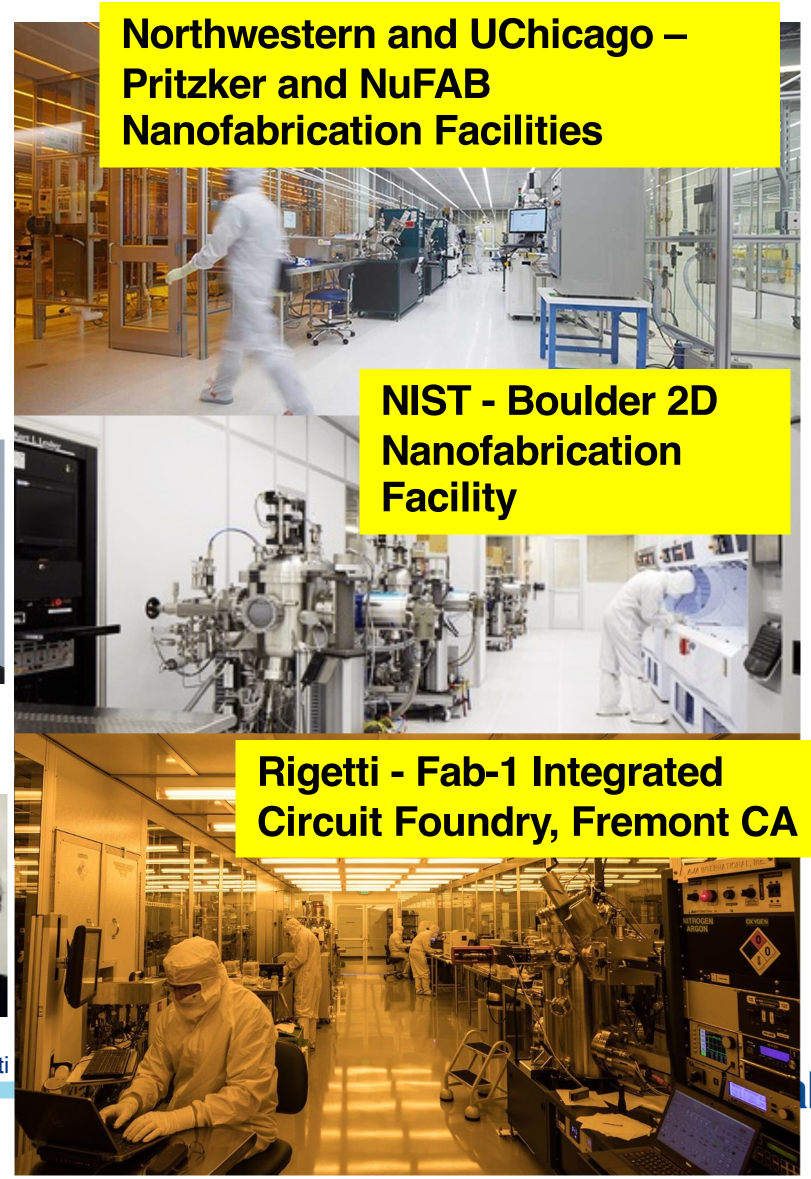

Carlos Torres
PhD student (NU)


Shaojiang Zhu
Scientist (FNAL)

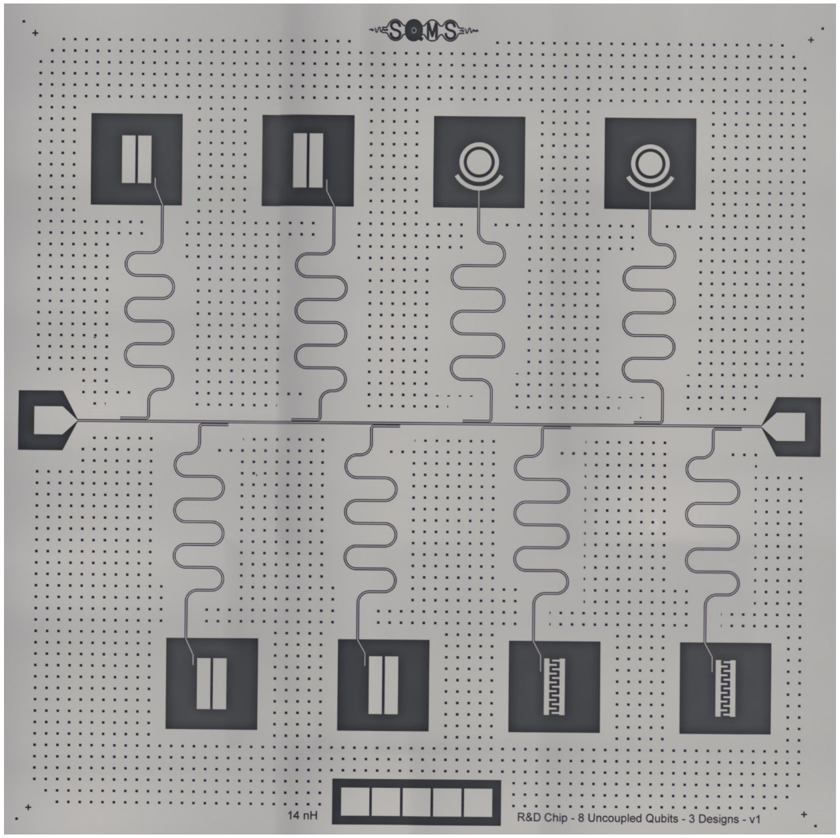

Xinyuan You
Postdoc (FNAL)


Ziwen Huang
Postdoc (FNAL)


Ella Lachman
Physicist, Rigetti



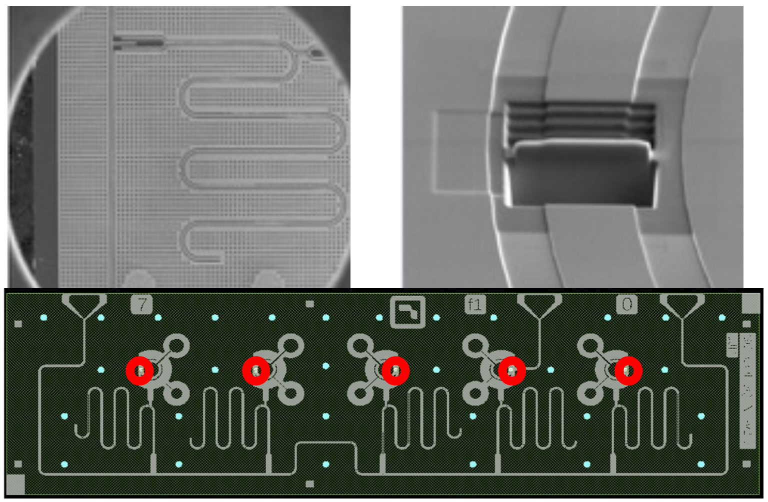
Our first Fermilab-made superconducting qubits chips!



Marching towards our first Fermilab/SQMS-made quantum processor

Launched the largest multi-institutional QIS materials and devices characterization effort

Dissecting and studying fragments of microwave performance characterized devices



Device Layout

- Leveraging DOE and SQMS academic partners user facilities capabilities
- Extending beyond-the-state-of-the-art via focused SQMS investments in upgrades e.g. for milliKelvin characterization

Cryogenic TEM, AFM, MFM

Cryo XRD, XRR

Cryogenic TOF-SIMS

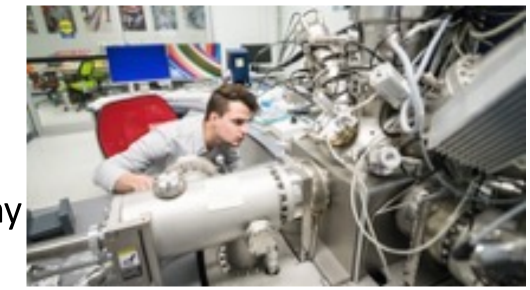
Atom Probe Tomography

THz spectroscopy

Magneto Optical Imaging

betaNMR, muSR

AMES LABORATORY | SIF SENSITIVE INSTRUMENT FACILITY



FNAL Material Science Lab

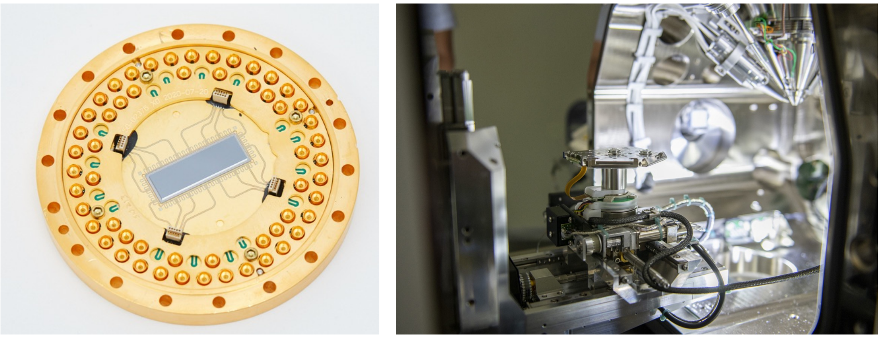
NUANCE Northwestern University Atomic and Nanoscale Characterization Experimental Center

ANL Advanced Photon Source

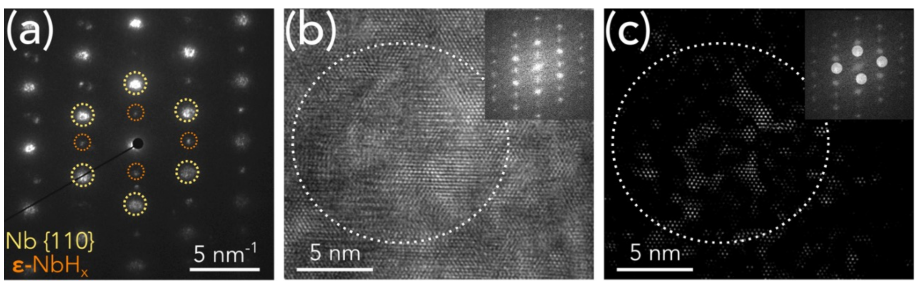
Northwestern | MRSEC MATERIALS RESEARCH SCIENCE AND ENGINEERING CENTER

TRIUMF

Discovery of niobium nano-hydride precipitates in superconducting transmon qubits



Lamellas of superconducting qubits from real Rigetti Computing processors are dissected via FIB-SEM at FNAL and studied for the first time via cryo-TEM



Cryogenic TEM, electron diffraction images of Rigetti 2D qubits , revealing the presence of hydrides precipitates in the niobium film at T=100K

Scientific achievement

First ever performed cryogenic microscopy studies of superconducting qubits lead to the discovery of the presence of hydride precipitates in the Rigetti Computing and other transmon qubit devices

Significance and Impact

Niobium nano-hydrides are poorly superconducting phases that can cause qubit device performance limitations and degradation over time and with subsequent cooldowns

Details

– Cryogenic AFM, electron diffraction and high-resolution transmission electron microscopy (TEM) analyses are performed on the Nb films at room temperature and cryogenic temperature (106 K)

– The results suggest the existence of two possible types of Nb hydride domains in Nb grains: (i) ~5 nm-sized Nb hydride domain with irregular shapes; (ii) 10s~100 of nm-sized distinct Nb hydride domains

– Pathways to mitigate the formation of the Nb hydrides are under study

J. Lee, Z. Sung, A. Murthy, M. Reagor, A. Grassellino, and A. Romanenko; https://arxiv.org/pdf/2108.10385.pdf

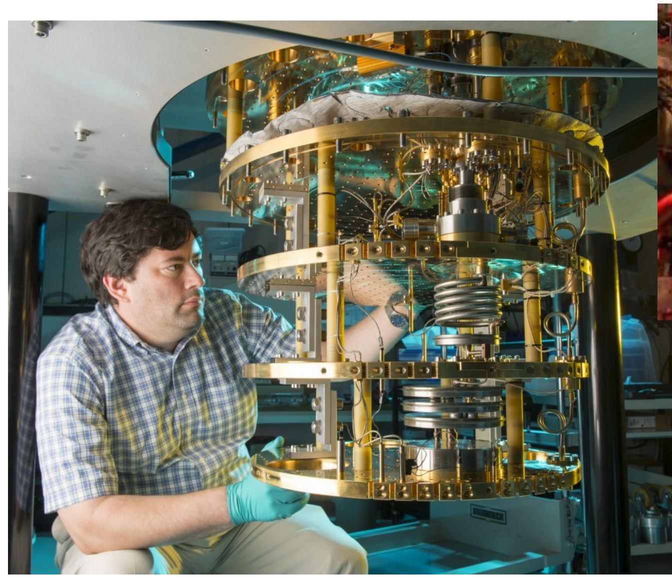
Work was performed at Fermi National Accelerator Laboratory material science lab and NUANCE user fac

U.S. DEPARTMENT OF ENERGY | Office of Science

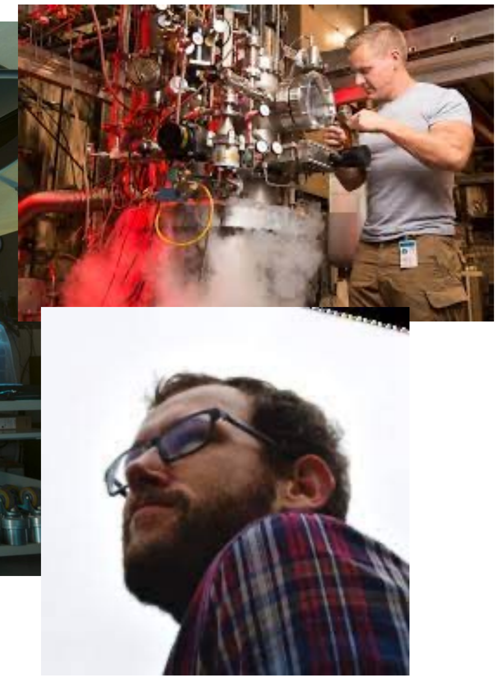
SQMS Fermilab rigetti

Foundational Strengths: large accelerators, R&D to large scale integration

Fermilab SQMS is constructing a world record sized DR capable of hosting thousands of qubits



M. Hollister, ultra low T cryogenics Department head in SQMS



Chris James and Grzegorz Tatkowski

Design of Colossus is well underway; internal review held with cryo experts to review technical progress, cost and schedule; exploring interest from companies like Oxford Instruments to co-develop platform

Scientific and Technological Goals – quantum sensing

Develop and deploy new quantum sensors at Fermilab

Push superconducting sensors at the frontier of coherence and frequency control technologies

From technology R&D to experimental prototypes, informing future large experiments

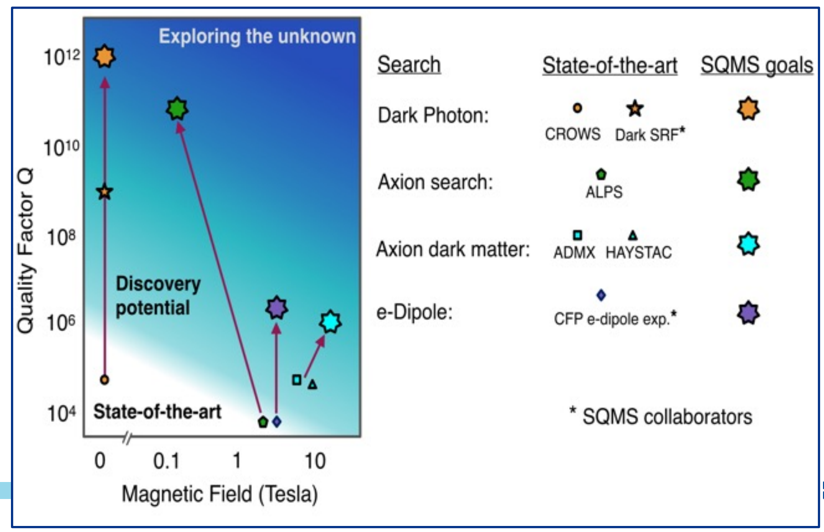
THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators Detector R&D Roadmap Process Group

Chapter 5

Quantum and Emerging Technologies Detectors

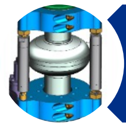
"The unprecedented sensitivity and precision of quantum systems enables the investigation of questions of fundamental concern to particle physics. These include the nature of dark matter, the existence of new forces, the earliest epochs of the universe at T >> 1TeV and the possible dynamics of dark energy, the possible existence of dark radiation and the cosmic neutrino background, the violation of fundamental symmetries, and even the nature of interaction and space-time at scales as high as $M_{Planck} \sim 10^{19}$ GeV"



Fermilab

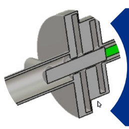
Physics and Sensing 5-year Roadmap

	Year 1	Year 2	Year 3	Year 4	Year 5

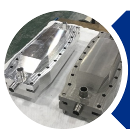


DarkSRF
- Measure in LHe, 1st DarkSRF publication
- Phase sensitive readout
- Implement in DR, quantum regime!
- Improve Q_0 towards 1e12

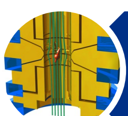
Multimode Cavity Axion Search
- Nonlinearity studies
- 2-cavity multimode design
- 2-cavity 1st test
- 2- and 3- mode 1-cavity design
- 2- and 3- mode 1-cavity 1st test



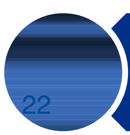
Tunable Dark Photon Search
- Design and fabricate cavity
- Trial runs, feedback
- Study heterodyne vs photon counting
- Data taking runs



High B-Field Axion Search
- Co-design w/ materials & devices
- Searches w/ best cavities and qubits
- Evaluate Nb_3Sn, NbTi Q_0 in high B
- Evaluate search w/ AC B-field

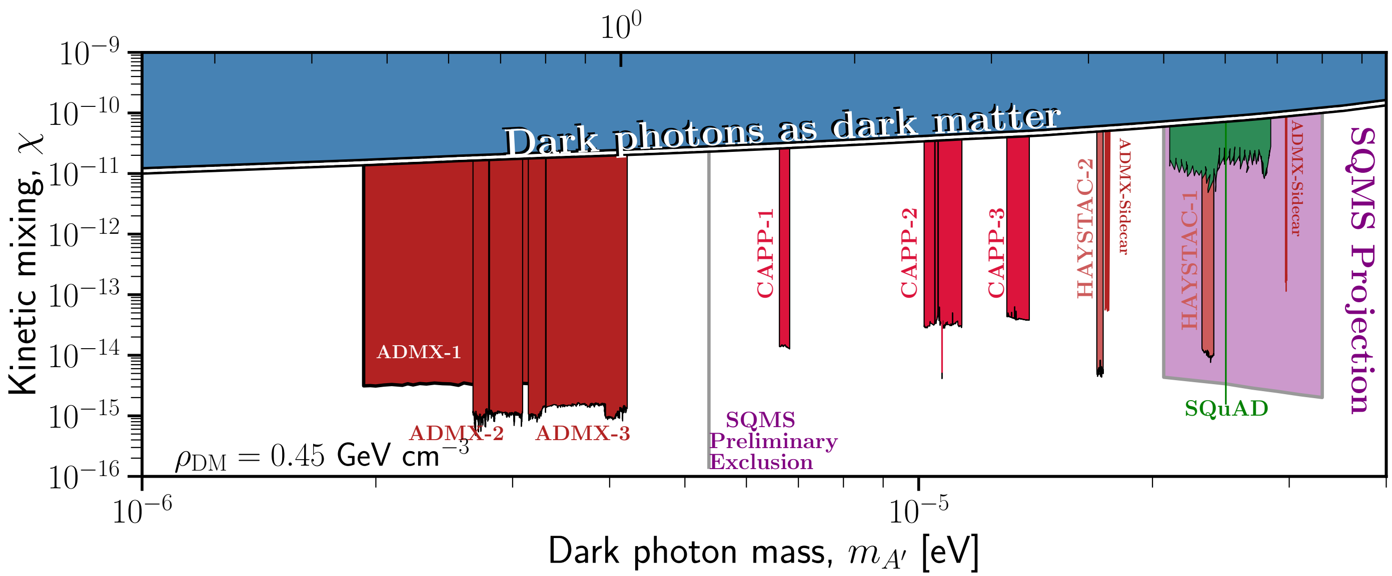


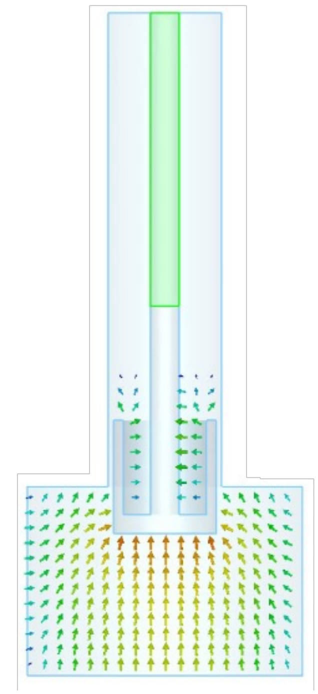
Single Particle Penning Trap
- Design high Q cavity geometry
- Testing optimized cavities/squids
- Prototype cavities & squids
- 1st next gen e- μ/μ_B measurements



Other Quantum Sensing Schemes
- Theory study of QIS for dark radiation detection, Quantum Sensor Network,
- Evaluate SRF cavities for gravitational wave detection, DM with traps.

Tuneable Cavity Dark Photon Dark Matter Search





Raphael Cervantes, SQMS Postdoc

- Dark photon search - similar to axion, but with no magnetic field
- **Just demonstrated the most sensitive experiment for wavelike dark photons.**
- By year 3: First results of 5-8 GHz dark photon search with unprecedented sensitivity using ultra-high Q cavities and superconducting qubits.

Theorists and Experimentalist working together to develop new experiments

- Axion-like particle search: Several concepts proposed by SQMS physicists.

2 modes ··· Static B field — signal mode

JHU: *Rajendran et al Phys.Rev.D 100 (2019)*

2 modes ··· spectator mode + signal mode

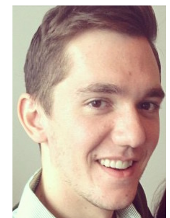
FNAL: Harnik and Gao (in prep)

2 modes ···· signal mode

UIUC: *Kahn et al. Phys. Rev. Lett.* 123 (2019)

R. Harnik

J. Sauls

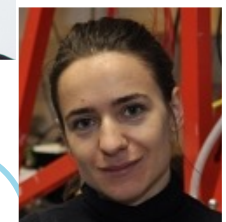


A. Berlin

Y. Kahn

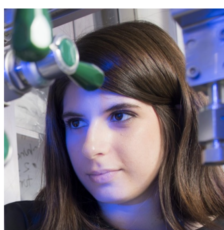
Theory

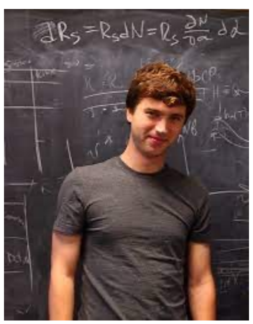
Options for mode setups + sensitivity



C. Braggio

B. Giaccone





A. Romanenko

Prototypes

Systems design, testing

(measure cross-talk, Q for various modes, readout)

co-design

Materials and Devices

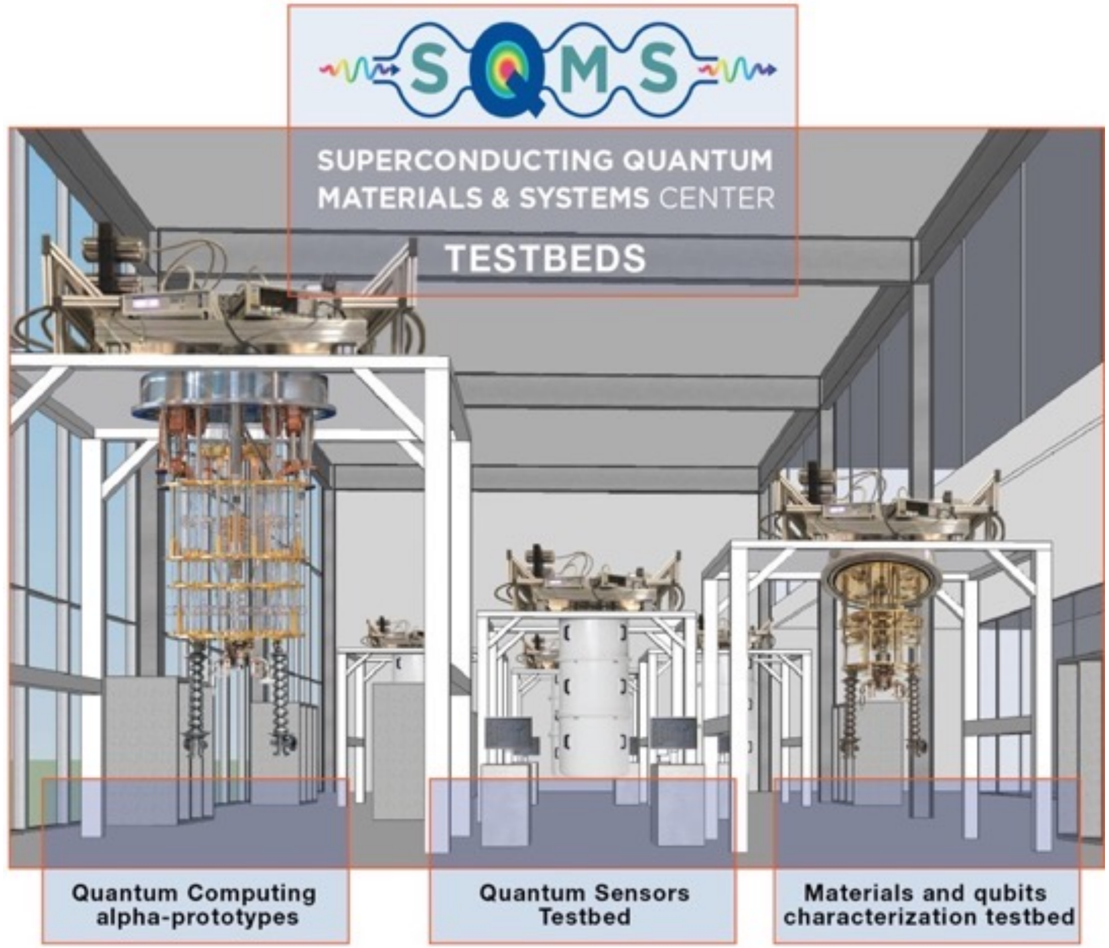
Improved Q, sensitivity, controls

S. Posen

SQMS 5-10 years quantum facilities progress

Developing and delivering tangible, unique platforms/instrumentation for QIS fabrication, computing and sensing:

- Foundries: New high-flexibility nanofabrication tools
- Materials testbeds: Qubits and quantum materials measurements in the most precise and sensitive environments
- Physics Testbeds: Platforms enabling new particle searches/sensing experiments
- Computing Testbeds: 2D and 3D-based quantum computer prototypes

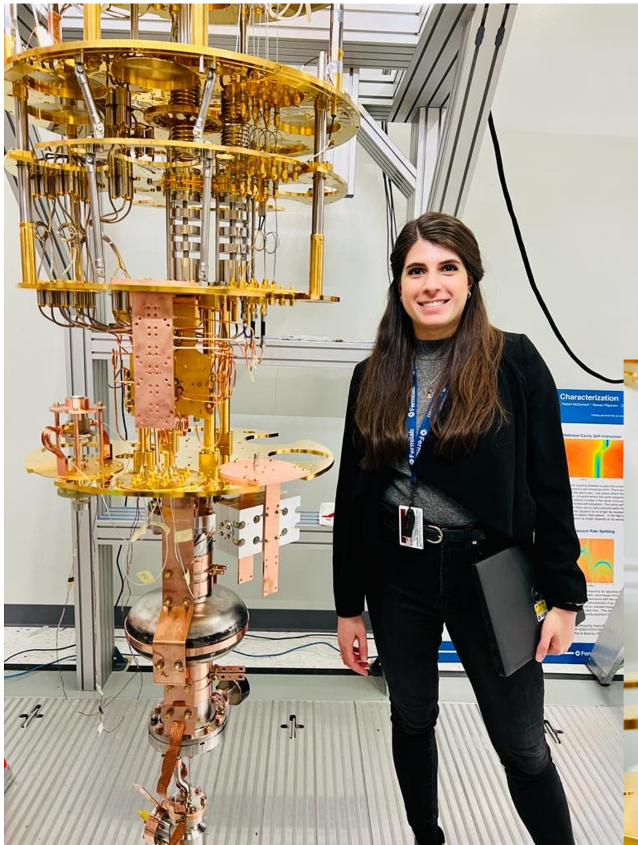


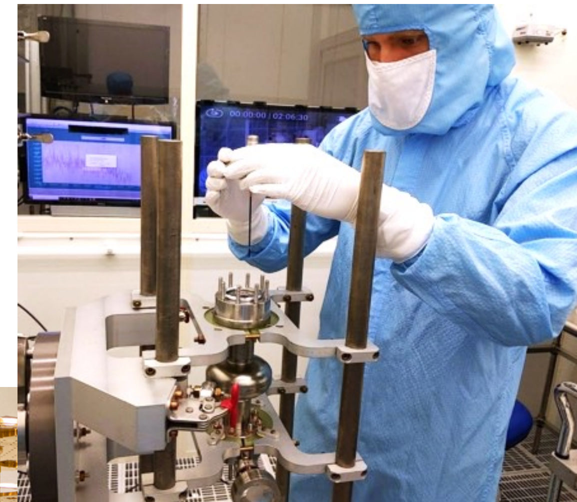
Quantum Facilities - 2021

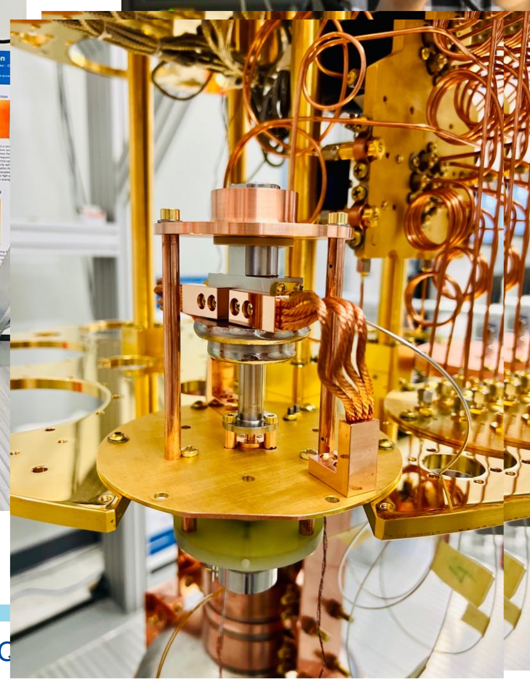
FNAL QCL-1 fully commissioned with two DRs, multiqubit controls and readout, piezo controls in DR

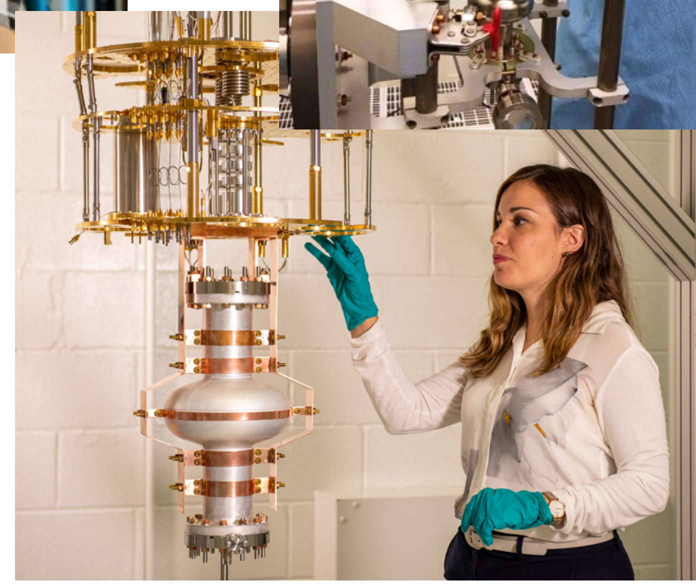
Quantum Facilities - 2021

QCL-1 fully commissioned with two DRs, multiqubit controls and readout, piezo controls in DR



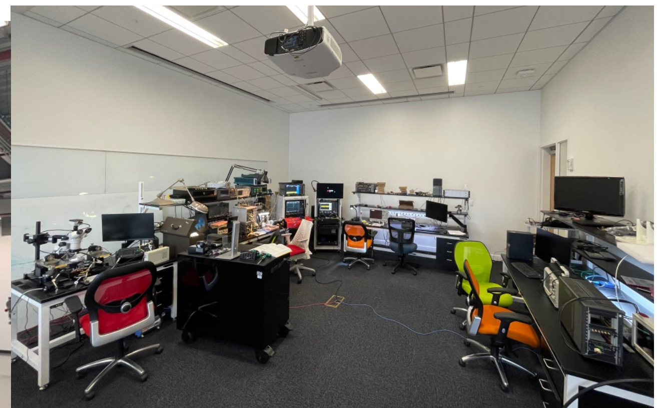


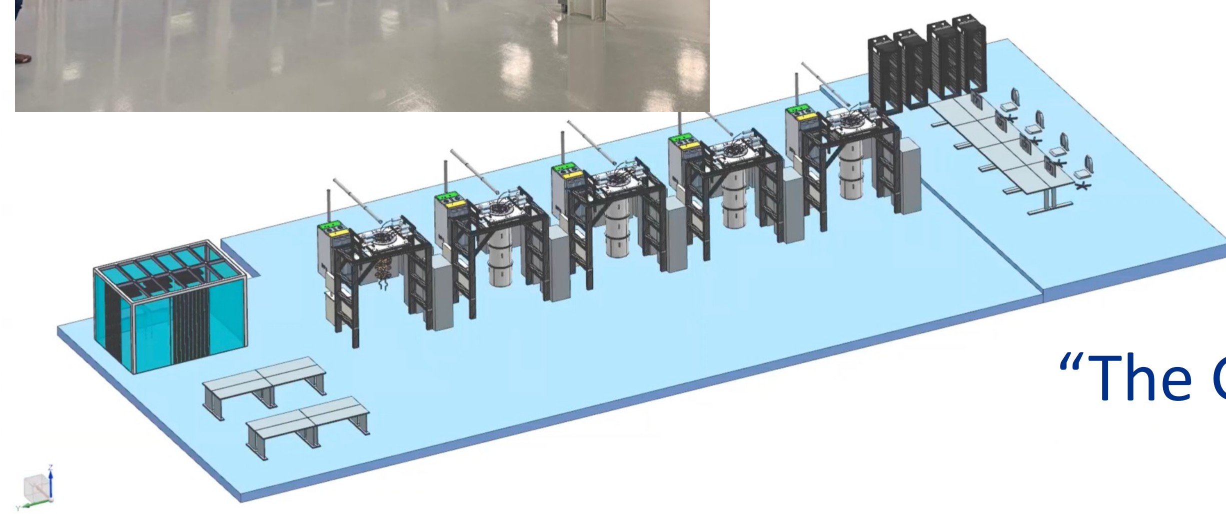




Quantum Facilities - 2023

QCL-2 and 3 will deploy an additional fleet of six dilution fridges, one with 9 Tesla magnet, hundreds of new cavities and qubits, controls for QIS experiments, with cavity/qubit preparation clean room area
Northwestern will deploy a new quantum testbed





On track with construction and procurement for commissioning in early 2023

“The Garage” @ the SQMS center

Conclusions

- SQMS making solid progress in all critical areas

  - Strong integration with HEP program in many areas, theory, cosmic, accelerator and detector technology; plan to further strengthen the connections in neutrinos, energy frontier and computing via presence of Fermilab leaders on SQMS ecosystem board and ad hoc workshops

- Progress in Workforce solid but requires constant attention and proactive approach
  - Retention an issue, center network and ecosystem helpful
  - Annual SQMS summer schools and internship (17 students this year), pipeline building and conversion
  - Overall initiative highly beneficial to attract top talent to Fermilab

- Exciting times for Fermilab; developing new scientific and technological research directions and capabilities which will have great impact on HEP and broadly the DOE Office of Science