Industrial SRF Activities at RadiaBeam Technologies

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RadiaBeam

Company overview, products and capabilities

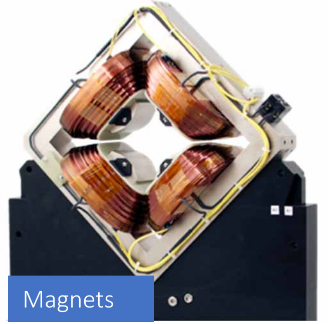
RadiaBeam Overview

- 50 employees
- 35,000 ft^2 headquarters in Santa Monica, CA

- Accelerator R&D, design, engineering, manufacturing and testing under one roof in a dynamic, small-business setting
- Products: accelerator components (RF structures, magnets, diagnostics), medical/industrial accelerator systems

Our Products and Capabilities

- Thousands of products delivered since 2004 with new products every year
- Mostly renowned for normal conducting RF

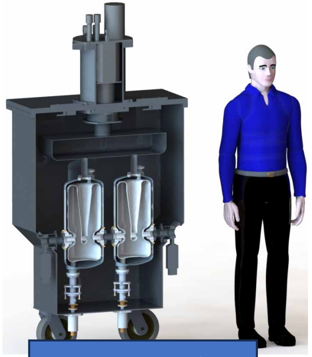


- Physics design and beam dynamics simulations
- RF and mechanical design/engineering
- Manufacturing/in-house machine shop
- Coil winding and epoxy encapsulation
- Precision magnetic testing
- Low-power and high-power RF testing
- Radiation bunkers with RF stations
- E-beam and X-ray measurement equipment

Our SRF Activities

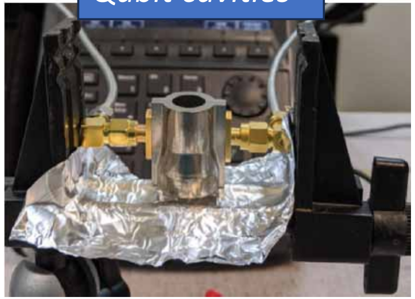
RadiaBeam

- RadiaBeam has recently engaged in SRF-related activities in collaboration with Universities and National Laboratories
  - Almost 100% supported via DOE SBIR program



Cryomodules

Qubit cavities



Accelerating cavities

U.S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

Fermilab

Jefferson Lab

THE UNIVERSITY OF CHICAGO

OHIO STATE

NC STATE UNIVERSITY

Stand-Alone Cryomodules

Stand-Alone Cryomodules

RadiaBeam

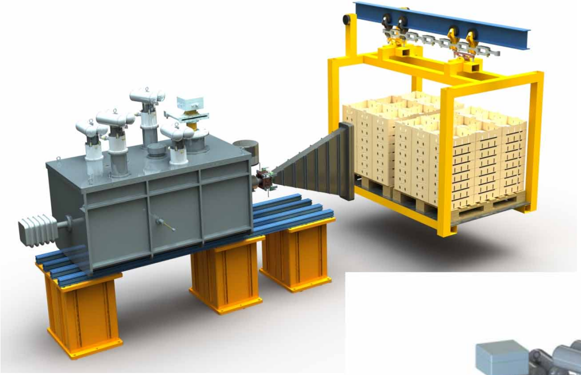
- SRF accelerators are very attractive for both industrial and research applications
  - Can produce high power CW beams
  - RF losses are negligible, so they require low peak RF power
  - Using higher cavity frequency by 2-4 times simultaneously with high-Q cavities, can be used to achieve a transformational reduction in cavity, cryomodule, subsystem costs
- Typically, SRF accelerators require a LHe refrigerator and complex piping to distribute liquid helium and nitrogen
  - This comes at a price of a very expensive production of LHe (~$10,000 per Watt)
  - Not many facilities have this
  - Many potential users can't afford such system
  - Building and maintaining SRF infrastructure is not an option for commercial devices
- There is an effort to build SRF cryomodules that can work without external cryogenic infrastructure

S.V. Kutsaev, "Advanced Technologies for Applied Particle Accelerators and Examples of Their Use (Review)", *Tech. Phys.* **66**(2), p. 161-195, 2021.

Deployable Conductively Cooled Cryostat

Fermilab

- A small mobile cryostat capable of running SRF cavities without a cryoplant
- The design accommodates a 4.5 cell 650 MHz Nb_3Sn Cavity
  - 10 MeV, 200 kW – 1 MW e-beam
  - 20 kW demosntration
- Utilizes 4 pulse tube cryocoolers from Cryomech each capable of 2.5W @ 4.2K and 50W @ 42K
  - Net capability is: 10W @ 4.2K and 200W @ 42K



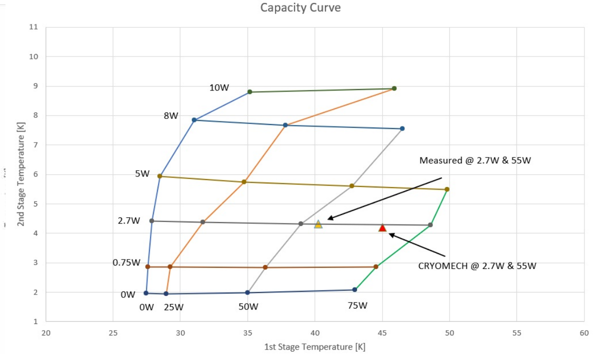
Cryomodule Envelope	
Width	*1m*
Height	*0.9m (Chamber) /1.45m (total)*
Length	*1.81m*

Cryomodule Expected Thermal Load	
Static @4.4K	*1.3 W*
Dynamic @4.4K	*≈7 W*
Thermal Shield @45K	*56 W*

Developed in collaboration with Fermilab's IARC team: Thomas Nicol, Charles Thangaraj, Christopher Edwards, Michael Henry

Current Status

- The procurement of all the cryostat parts and the UHV parts has concluded in June 2023
- Cryomech PT425 coldhead was characterized at RadiaBeam
- The cryostat and its constituent components are currently being received at FNAL in preparation for full assembly.
- We are planning to integrate the Cryomodule at IARC at Fermilab during July 2023 for a first test run in early August 2023.
- The chamber will be validated utilizing a single cell conductively cooled 650 MHz cavity provided by the IARC team at Fermilab.



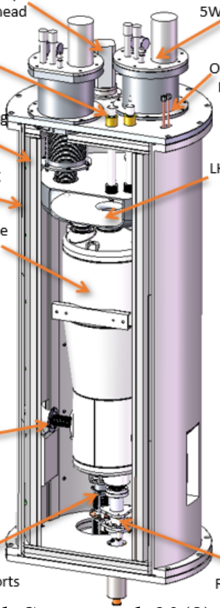
A. Schillaci et al, "Compact Cryomodule for Stand-Alone Accelerator", WEPWB086

ATLAS 72 MHz QWR

- Another project, funded by DOE NP in 2017, to design and build stand-alone cryomodules for ATLAS 72 MHz QWRs
  - Make a compact refrigerator that fits into a cryomodule
  - Compact LHe (4K) cryocoolers of only ~2W capacity existed
  - The cryocooler did not produce LHe (too long); it only removed enough heat to prevent boiling LHe
- RadiaBeam performed RF and engineering design/simulations

TABLE I
PARAMETERS OF THE STAND-ALONE ACCELERATOR SYSTEM

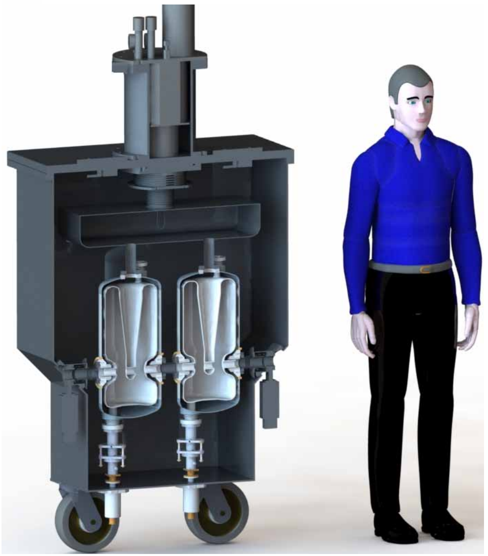
Parameter	Value
Dimensions	Ø40" x 88.5" Length
Frequency	72.75 MHz
Beta	0.07 – 0.12
Voltage per cavity	Up to 2.0 MV
Static 4.5 K load	1.94W
Dynamic 4.5K load	4.58W
Number of cryoheads	1-3
Cryogenic capacity	5-12W
Helium tank capacity	100 L



S.V. Kutsaev et al., "Design of Stand-Alone Cryomodule based on Superconducting Quarter-Wave Resonator", *IEEE Trans. Appl. Supercond.* **30**(8), 2020.

Nb3Sn 218 MHz QWR

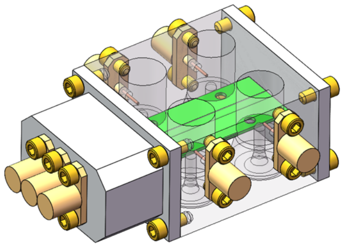
- Currently, we are collaborating with Argonne and Fermilab to develop and build a stand-alone cryomodule for 218 MHz Nb_3Sn QWR
- RadiaBeam activities
  - Performed engineering simulations (RF, thermal, mechanical)
  - Machined Nb and Nb-Ti parts for the cavity
  - Will build a slow-tuner for the cavity
  - Will commission a 10W cryocooler
  - Will design and build a cryomodule

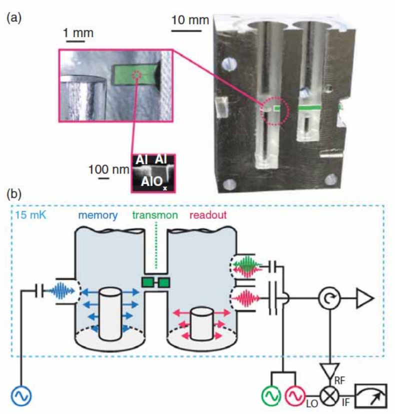


Qubit 3D Resonators

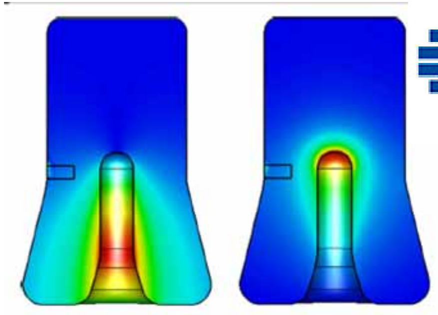
RadiaBeam's Quantum Projects

- In 2018, a collaboration between UChicago, Argonne, and Fermilab was established to develop a Nb 6 GHz qubit QWR
  - based on the Yale University concept of λ/4 Al resonator
  - allows *practical* coupling with a Josephson junction transmon
  - optimized shape with the increased G-factor
  - experience in building high-Q Nb resonators for accelerators
- 3 fabrication approaches were pursued at RadiaBeam
  - Machining
  - Additive manufacturing
  - Forming





M. Reagor, et al. Physical Review B 94.1 (2016): 014506.



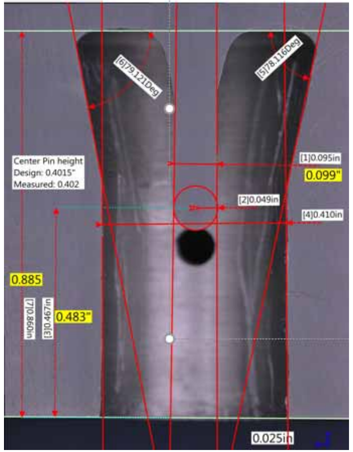
S. Kutsaev et al., Niobium quarter-wave resonator with the optimized shape for quantum information systems, *EPJ Quantum Technology* 7:1 (2020), 1-17.

A. Krasnok et al. "Advancements in Superconducting Microwave Cavities and Qubits for Quantum Information Systems", submitted to *Appl. Phys. Rev.* (2023): **arXiv:2304.09345**

Machining Niobium

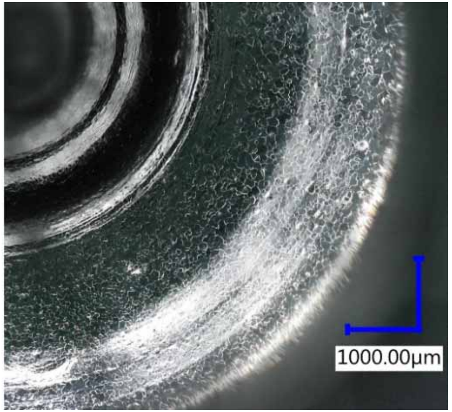
- Developed Nb machining capabilities at RadiaBeam
  - Machined 9 QWRs with the optimized shape
  - 2 niobium suppliers
  - Low f_0 spread: good machining accuracy
  - Theoretical room temp Q = 1190, measured 1074 ± 18: good finish

QWR	**vendor**	*f0 [MHz]*	*Q*
Nb_Q_3A	*Nb Tokyo*	*6047.8*	*1080*
Nb_Q_3B	*Nb Tokyo*	*6049.149*	*1084*
Nb_Q_3C	*Nb Tokyo*	*6068.076*	*1066*
Nb_Q_3D	*Nb Tokyo*	*6084.513*	*1096*
Nb_Q_3L	*Nb Ulvac*	*6048.167*	*1063*
Nb_Q_3M	*Nb Ulvac*	*6075.408*	*1092.1*
Nb_Q_3N	*Nb Ulvac*	*6061.252*	*1056*
Nb_Q_3O	*Nb Ulvac*	*6044.537*	*1090*
Nb_Q_3P	*Nb Ulvac*	*6044.69*	*1039*
		6058	**1074**
		14	**18**



Dimensional analysis of part in cross section

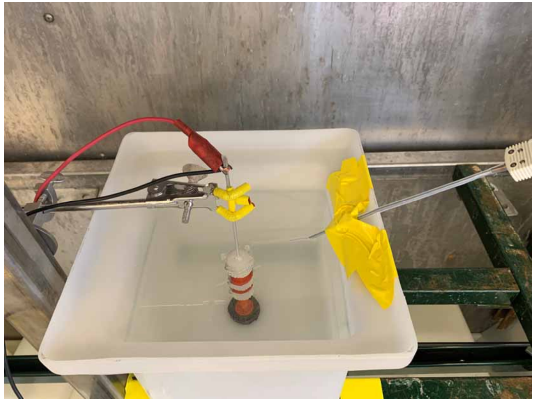
Etched niobium centerpin hemisphere

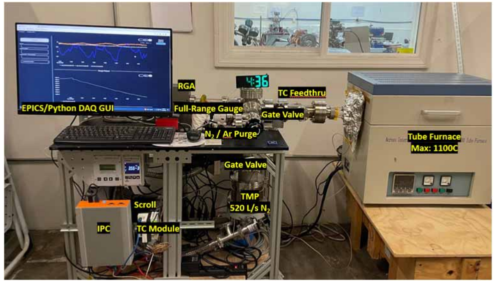


Etched niobium shorting plate

Post Processing

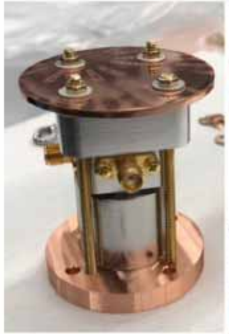
- Adapted best practices from SRF
  - Abrasive surface finishing
    - Bulk material removal + polishing
  - Buffered Chemical Polish
    - Bulk material removal
  - Diffusion-limited electropolishing
    - Improve surface finish
    - Remove mechanical damage layer
    - ANL DC: HF/H_2SO_4 Solution
    - Faraday technologies: Pulsed bi-polar EP: dilute H_2SO_4
  - High vacuum hydrogen outgassing
    - Remove interstitial H from chemistry
  - High pressure rinsing in class 100 clean room
  - 120°C/48Hr vacuum bake

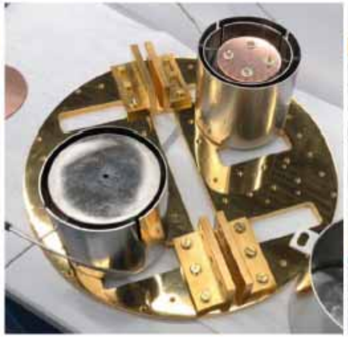


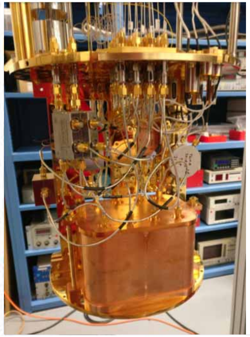


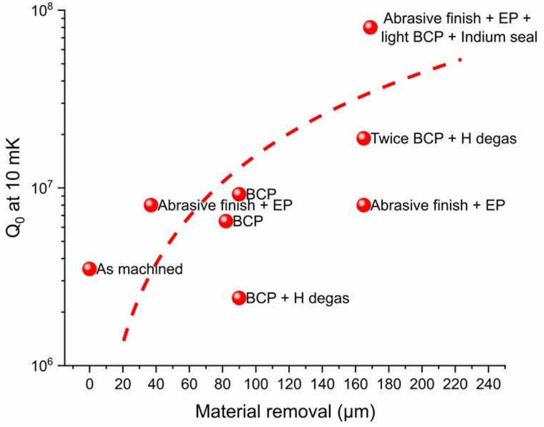
Cavity Testing

- 2019: Single cavity tested at 10 mK at UChicago (Q_0~1e6)
- 2020: 4 cavity cryogenic test stand (Q_0~2e7)
  - Magnetic shielding: μ-Metal, 2 layer, x5000 attenuation
  - IR shielding and absorption coating
  - 'Clean' assembly
- 2022: Indium-Sealed cavity @SFU Q0=8e7
- 2023: New Tests planned at SLAC





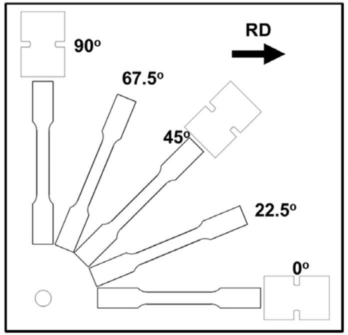




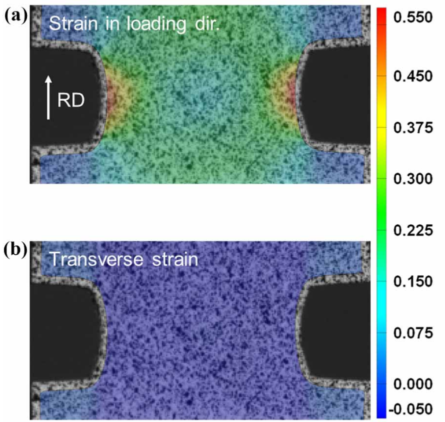
Forming Niobium

- Plasticity modelling and characterization of commercially-pure niobium (RRR = 60-70)
  - Calibration of FEA model: Uniaxial tension, strain-rate-jump, biaxial tension and disc compression

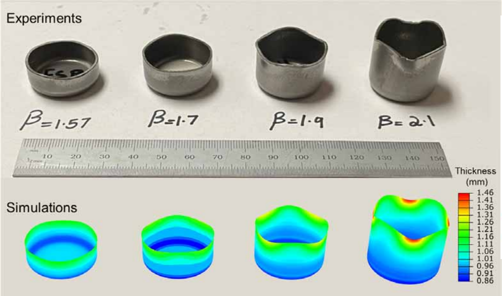
Material Microstructure



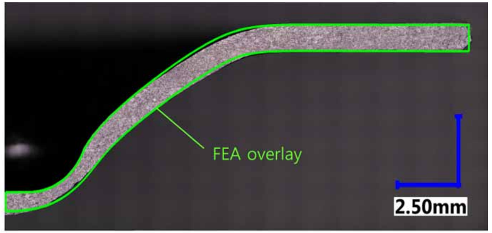
Sample Layout



Biaxial tension tests with 3D DIC imaging



Deep-drawn cups: Earing plastic anisotropy FEA model



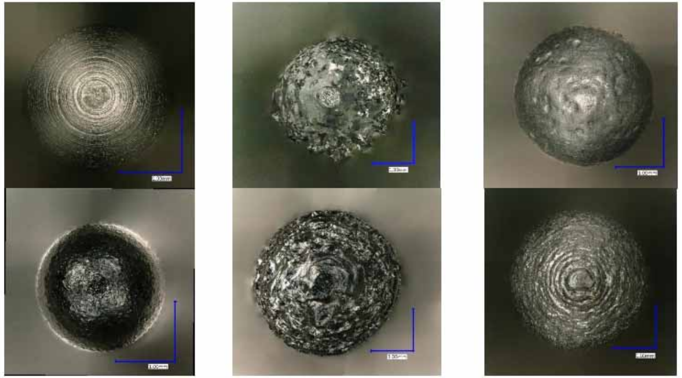
Cross section of local thinning versus FEA model

M. Kim, et al. "Mechanical behavior and forming of commercially-pure niobium sheet." *International Journal of Solids and Structures* 257 (2022): 111770.

Additive Manufacturing

- Metal additive manufacturing has reached high TRL in aero, medical & defense
  - Established alloys: cpTi, Al-Si-Mg
  - Emerging alloys: Nb (C103)
- Advantages:
  - Seamless 3D geometries without tool access limitations
  - Batch production with connecting channels

Machined *E-Beam AM* *Laser AM*



Nb *Nb* *Ti-64*

Nb	*Machined, as is*	*$3.5 \cdot 10^6$*
Nb	*EB-PBF, abrasive polish and etched*	*$1.6 \cdot 10^6$*
Nb	*EB-PBF, abrasive polish and etched*	*$1.2 \cdot 10^6$*
Ti64	*L-PBF, HIP, tumbled, etched (-10um)*	*$0.4 \cdot 10^6$*
Ti64	*L-PBF, HIP, etched (-10um)*	*$2.2 \cdot 10^6$*

P. Carriere et al., First cryogenic test results of 3D-printed resonators for quantum bits, *IOP Conf. Ser.: Mater. Sci. Eng*. 1241 012046, 2022
A. Riensche et al., "Application of Hybrid Laser Powder Bed Fusion Additive Manufacturing to Microwave Radio Frequency Quarter Wave Cavity Resonators", *Int. J. Adv. Manuf. Technol.* 10547, 2022.

RadiaBeam

Accelerating Cavities

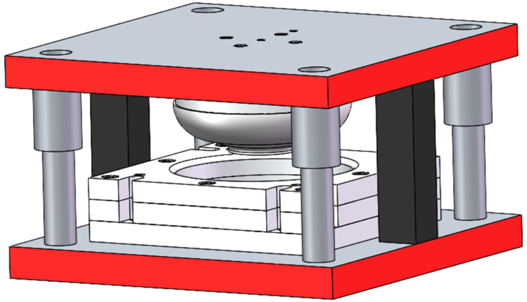
SRF cavity fabrication

- We are developing the technology, vendors, and collaborators to fabricate 1.3 GHz and 3 GHz Nb cavities.

<u>Ongoing activities:</u>

- In-house: Tooling and inspection, Weld joint machining, pre-weld BCP
- Outsourced: Forming – Ohio State University, EBW – Applied Fusion, CA
- Project consultants: John Rathke (AES), Ralf Edinger (PAVAC)
- Design and fabrication of deep drawing tooling for half-cells: punch + die + die set

300T Interlaken Servopress- Ohio State University

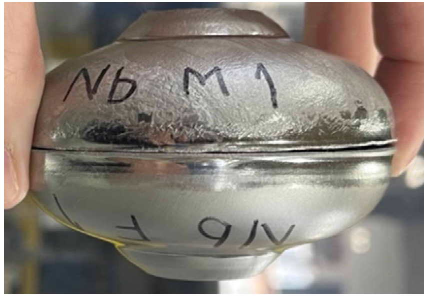


Deep drawing tooling

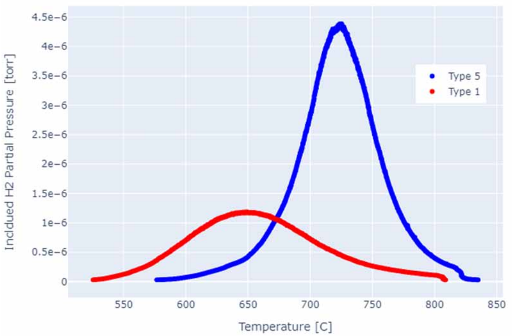
Niobium Forming

- Servopress forming of direct-sliced, medium grain high RRR niobium
  - Radiabeam, Jlab, Ohio State University, and ATI Wah Chang
- Comparative study with RRR and reactor grade, direct-forged ingot

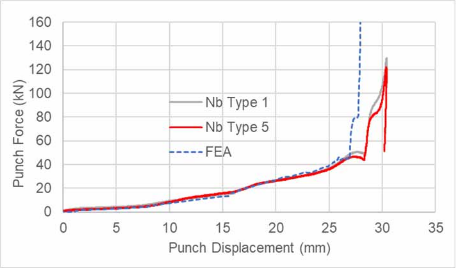
ATI direct forged, reactor-grade, medium grain Nb



3.9 GHz cavity



Post-BCP H vacuum desorption of MG and FG Nb



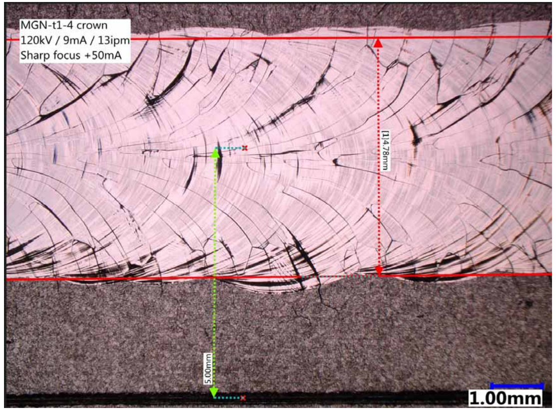
Deep drawing punch force/displacement curve versus FEA

MG and FG 3.9 GHz half cells

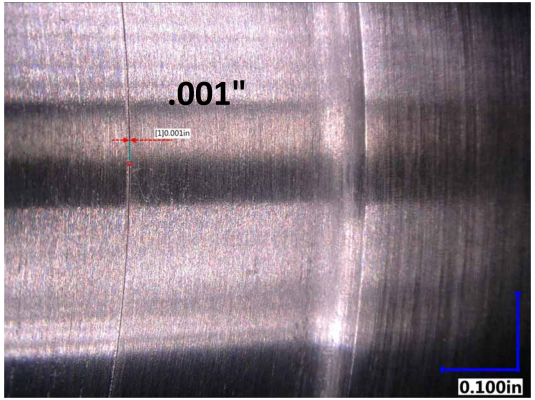
SRF cavity fabrication

Ongoing activities:

- Applied Fusion: x7 modern 150kV CNC probeam machines
  - Experienced: Semiconductor & Aerospace
  - State-of-the-art beam diagnostics and CNC control
- Bead-on-plate trials complete, radial weld trials of machined reactor-grade tube in-progress



Sample 4/5 gap, x30, within designed tolerances

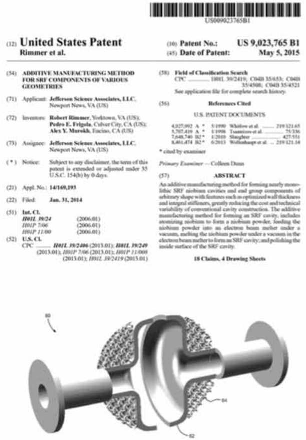


Additive-Manufactured Nb SRF Cavity

RadiaBeam

Jefferson Lab

- SRF R&D using AM (2009 to present)
  - US Patent 9,023,765: "Additive Manufacturing Method for SRF Components of Various Geometries"
- Two single cell 3.9 GHz niobium cavities fabricated in 2015
- Arcam EBM® (Electron Beam Melted) in halves, with post-machining (turning) of RF surfaces, and e-beam welded together at JLab.
- Tested at JLab, measured Q ~ 10e9 at ~ 3 MV/m



(12) United States Patent
Rimmer et al.

(10) Patent No.: US 9,023,765 B1
(45) Date of Patent: May 5, 2015

(54) ADDITIVE MANUFACTURING METHOD FOR SRF COMPONENTS OF VARIOUS GEOMETRIES

(71) Applicant: Jefferson Science Associates, LLC, Newport News, VA (US)

(72) Inventors: Robert Rimmer, Yorktown, VA (US); Pedro E. Frigola, Culver City, CA (US); Alex Y. Murokh, Encino, CA (US)

(73) Assignee: Jefferson Science Associates, LLC, Newport News, VA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: 14/169,193

(22) Filed: Jan. 31, 2014

(51) Int. Cl.

(58) Field of Classification Search
See application file for complete search history.

(56) References Cited

U.S. PATENT DOCUMENTS

* cited by examiner

Primary Examiner — Colleen Dunn

(57) ABSTRACT

An additive manufacturing method for forming nearly monolithic SRF niobium cavities and end group components of arbitrary shape with features such as optimized wall thickness and integral stiffeners, greatly reducing the cost and technical variability of conventional cavity construction. The additive manufacturing method for forming an SRF cavity, includes atomizing niobium to form a niobium powder, feeding the niobium powder into an electron beam melter under a vacuum, melting the niobium powder under a vacuum in the electron beam melter to form an SRF cavity; and polishing the inside surface of the SRF cavity.

18 Claims, 4 Drawing Sheets

P. Frigola et al. "Advance additive manufacturing method for SRF cavities of various geometries" *in Proc. SRF'15,* Whistler, BC, Canada (2015).

SRF Industrial Outlook and Conclusions

- Cavity Development and Fabrication
  - No present U.S. vendors for finished niobium cavities
  - Situation: AES out of business, Roark has some, but not all capabilities, European vendors costly/slow
- Thanks to DOE SBIR program + consulting from ANL, RadiaBeam developed in-house Nb machining capability
  - We machined 6 GHz QWRs, and Nb /NbTi parts for 218 MHz QWR
  - BCP and cavity baking capabilities were also developed for small scale cavities
  - EBW machine exists at RadiaBeam, but requires significant resources to become operational
- A new Phase IIB has been awarded to develop more SRF technology capabilities
  - Forming, welding, etc.
  - In discussions with FNAL, JLAB, ANL and other interested parties
- **In 2023 DOE introduced 70% cuts in the Office of Science SBIR programs**
  - This was historically the critical DOE program to support R&D activities by small businesses
  - These cuts affect RadiaBeam and other companies in the field, and may result in a major loss of capabilities and trained personnel within 1—2 years
  - Putting in question SRF perspectives at RadiaBeam and the ability of the US small businesses to remain a part of the accelerator community
- *We would like the community's feedback and ideas on how to support these new capabilities in this new environment*