

# Advanced Additive Manufacturing Method for SRF Cavities of Various Geometries

DOE Nuclear Physics STTR Grant: DE-SC0007666

*Presented by Marcos Ruelas  
on behalf of Pedro Frigola, PI*

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**STTR Collaborator:** University of Texas El Paso (UTEP) W.M. Keck Center for 3-D Innovation, El Paso, TX

**P. A. Norton, D. Espalin, S. M. Gaytan, J. Mireles, R.B. Wicker**

**STTR Subcontractor:** Thomas Jefferson National Accelerator Facility (JLab)- SRF Institute, Newport News, VA

**R.A. Rimmer, G. Ciovati, W. Clemens, P. Dhakal, F. Marhauser, J. Spradlin, S. Williams**

**T. Horn, O. Harrysson, H. West**

Department of Industrial and Systems Engineering  
North Carolina State University (NC State), Raleigh, NC

**A. Murokh, R. Agustsson, S. Boucher, L. Faillace, M. Ruelas**

RadiaBeam Technologies LLC, Santa Monica, CA

**DOE NP STTR Phase I/II Grant DE-SC0007666**

- RadiaBeam Technologies Overview
- AM Research History at RadiaBeam
- Overview of EBM AM Technology
- Goals and Relevance of Project
- Phase II Work

- Founded in 2004 as a spin-off from the UCLA Particle Beam Physics Laboratory
- Core mission is to provide well-engineered, high quality, cost-optimized accelerator systems and components, & develop novel accelerator technologies and applications
- ~50 employees, including 9 PhD scientists and 22 engineers
- Experience from US Labs, International Labs, Universities, and Industry
- Worldwide sales, service, and consulting

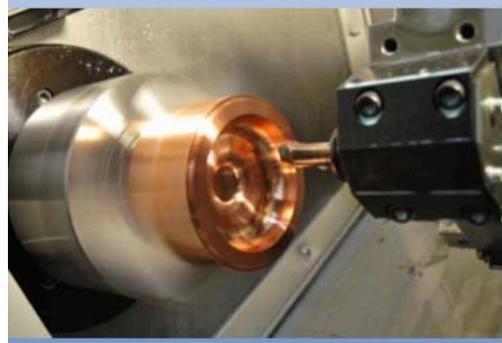
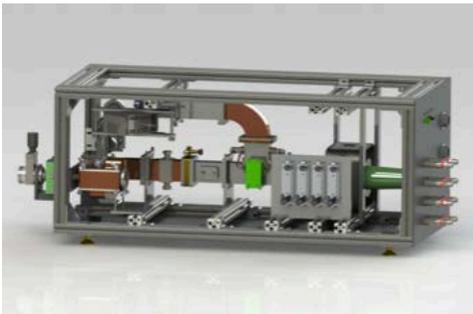
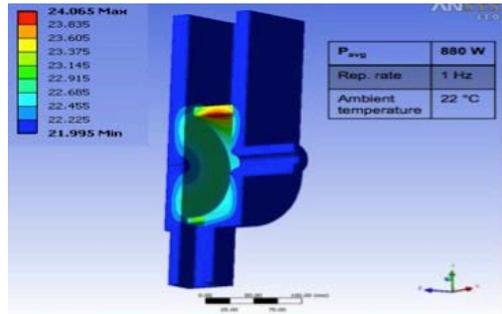


- Two Machine shops
- Magnetic measurements
- RF (cold) test area
- Hot test cell (up to 2 MeV)
- Optics area
- Chemical cleaning and Clean rooms
- Total of 16,000 sq. ft. space

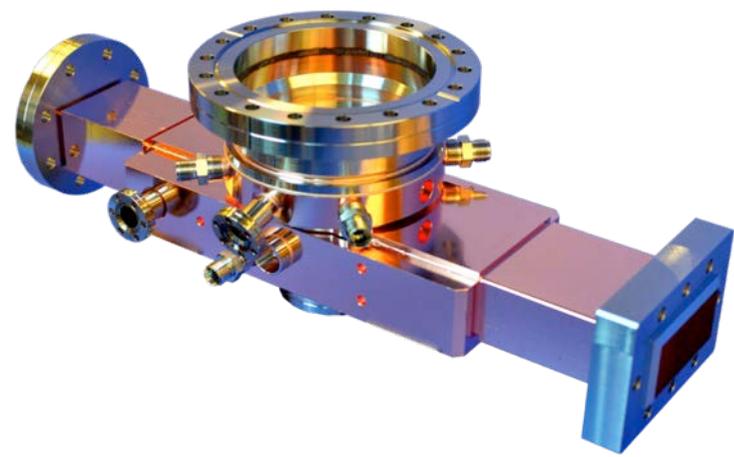


# Capabilities

- Design
- Engineering
- Fabrication
- Assembly
- Testing
- Installation
- Service



- Accelerator systems
  - Turnkey injectors
  - Transport lines
  - Industrial linacs
- Diagnostics
  - Beam profile monitors
  - Bunch length monitors
  - Charge, emittance, et cetera
- RF structures
  - RF photoinjectors
  - Bunchers
  - Linacs
  - Deflectors
- Magnet systems
  - Electromagnets
  - Permanent magnets
  - Systems (chicanes, final focus, spectrometers)



- Designed specifically for customer's application
- Wide variety of specs and options available
- Designed, built, delivered, and commissioned complete turnkey systems in < 9 months!



Application	Energy	Average Power
Field-deployable high-energy radiography	1-4 MeV	10 – 100 W
Cargo Inspection/Fixed-installation Radiography	4-9 MeV	100 – 1000 W
Oncology	4-20 MeV	100 – 1000 W
E-beam Sterilization/Processing	10 MeV	10 – 50 kW
X-ray Sterilization/Processing	7.5 MeV	20 – 200 kW

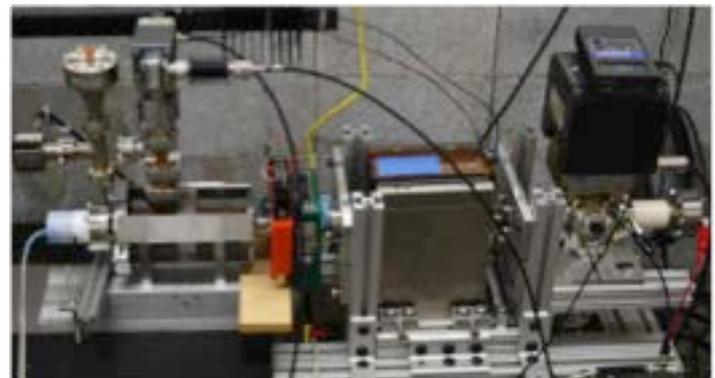
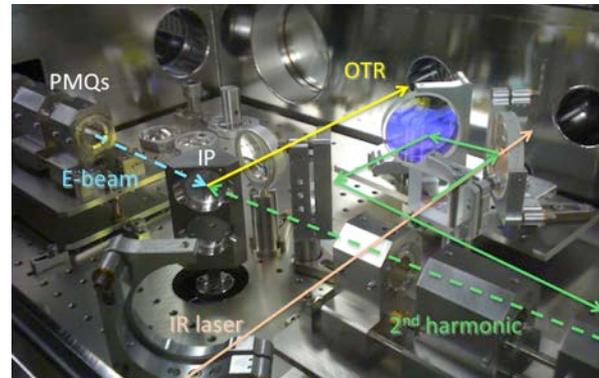
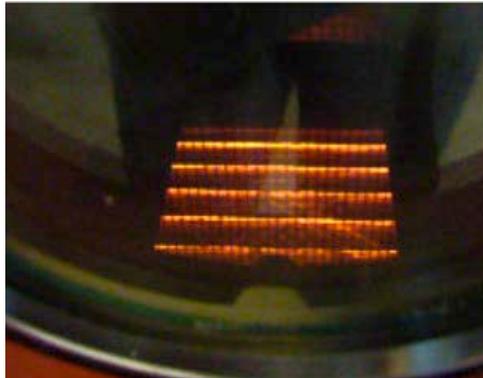
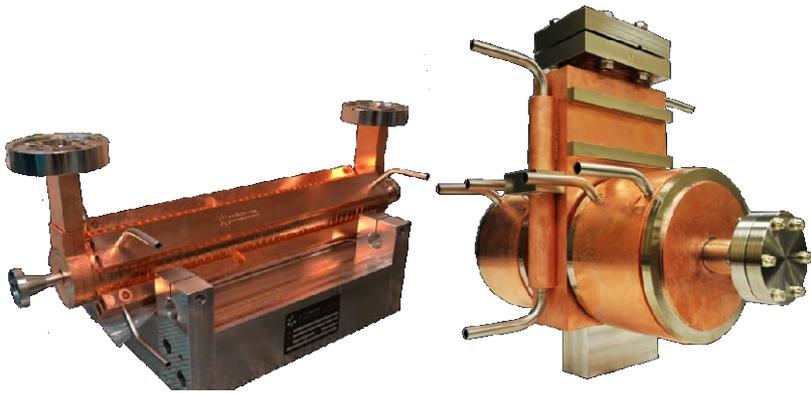
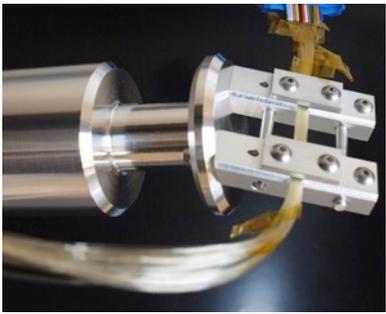


# Growing List of Customers



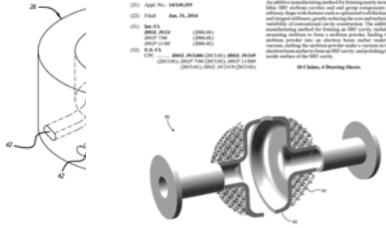
# Multiple Funding Agencies

SBIR, BAA, & commercial funded and self-funded R&D to develop new products and technical solutions



# Additive Manufacturing Development at RadiaBeam

- 2006 to present: DOE and DHS SBIR/STTR, as well as Internal R&D funded
  - Total of 7 Phase Is, and 4 Phase IIs
- Active collaboration with NC State, UTEP, JLab, UC Berkeley, LANL
- Developed accelerator designs and methods exploiting AM
  - NCRF accelerators (copper) : US Patent 7,411,361: *Method and apparatus for radio frequency cavity*
  - SRF accelerators (niobium) : **May 2015 awarded US Patent 9,023,765**; Joint patent with JLab - *Additive Manufacturing Method for SRF Components of Various Geometries*
  - Dissimilar metal joining (Inconel 718 to 316 SS): Applications in nuclear (fission and fusion) and concentrated solar power components (DOE Nuclear Energy Phase I/II (DE-SC0011826)
  - First to developed EBM AM process parameters for copper and niobium
  - *Fabricating Copper Components with Electron Beam Melting*, Advanced Materials & Processes, Vol. 172, Iss. 7, July 2014 (ASM International)
  - C. Terrazas t. al., *EBM Fabrication and Characterization of Reactor-Grade Niobium for Superconductor Applications*, Proceeding of Solid Freeform Fabrication Symposium, UT Austin, August 4-5, 2014
  - C. Terrazas, *Characterization of High-Purity Niobium Structures Fabricated using the Electron Beam Melting Process*, PhD Dissertation, UT El Paso, August, 2014



### Fabricating Copper Components with Electron Beam Melting

**R. Fripole**  
RadiaBeam  
Technologies LLC  
Santa Monica, Calif

**T.J. Hunt**  
**H.A. West**  
**R.L. Arman**  
**J.M. Ripstein**  
**FASMP**  
Center for Additive  
Manufacturing and  
Logistics  
North Carolina State  
University, Raleigh

**D.A. Ramirez**  
**L.E. Hunt, FASMP**  
**F. Medina**  
**R.B. Wicker**  
**E. Rodriguez**  
W.M. Keck Center  
for 3D Innovation  
University of Texas,  
El Paso

The ability to make components from copper and copper alloys via additive manufacturing is opening a range of novel applications.

Direct fabrication of fully dense metal structures using the electron beam melting (EBM) process developed by Anand AB, Sweden, has been successfully demonstrated for a wide range of materials including Ti-6Al-4V<sup>1,2,3,4</sup>, cobalt-chromium<sup>5,6</sup>, and nickel-base alloys<sup>7,8</sup>. A growing interest in additive manufacturing (AM) to build components from copper and copper alloys<sup>9,10</sup> is opening a variety of applications including novel radio frequency (RF) accelerating structures.

A critical issue for high average power, high brightness photostimulators—the technology of choice for generating high brightness electron beams used in many of today's linear accelerators—is efficient cooling. RadiaBeam Technologies is exploring the use of AM to fabricate complex RF photostimulators with geometries optimized for thermal management. Specially optimized internal cooling channels can be fabricated without the constraints typically associated with traditional manufacturing methods.

However, several properties of pure copper present significant processing challenges for direct metal AM. For one, pure copper has a relatively high thermal conductivity (801 W/m·K at 300K) which, while ideal for thermal management applications, rapidly conducts heat away from the melt area resulting in local thermal gradients. This can lead to laser coating, distortion, and ultimately melt and part failure. Additionally, copper's high density (8930 kg/m<sup>3</sup>) leads to powder removal and recovery. Particles also tend to agglomerate, reducing overall reliability and resulting powder deposition. Because Cu is sensitive to oxidation, great care must be taken in handling and storage before, during, and after part fabrication.

**Fabrication methods**

Initial experiments focused on developing viable parameters for processing copper using EBM. An Arcam model 512 at North Carolina State University and an Arcam model C12 at the University of Texas El Paso fabricated the samples shown here (representing EBM hardware as described elsewhere in detail<sup>11,12</sup>). A circular start plate made of virgin fine, high conductivity (99.99%) copper measuring approximately 130 x 10 mm landed on a 10-mm-thick bed of loose

copper powder was the build substrate. Initially, the electron beam was the start plate surface at high power and high speed, raising the plate temperature to 1000°C. For run times above maintenance of a relatively high temperature throughout the build process, reducing internal stresses caused by thermal gradients.

Processing each layer typically requires two separate parameter sets called doses, which contain all of the required process parameters, such as beam speed and power, and focus offset. The first step is preheating, which raises the powder temperature and causes it to lightly sinter together. The mechanical bond facilitates the next step, melting, which is conducted over sub-step contours and hatching. The contours step uses retreating, low currents and speed to trace the outline of each layer with a progressively melted easy called melt-back, which uses the high scan rate capabilities to jump between multiple locations on the contour, approximating multiple beams that are able to simultaneously maintain multiple full melt-pools. This approach improves surface finish compared to single-spot contouring while maintaining productivity. In the hatching step, beam current and speed are increased and the beam is rastered to fill the area between contours. With each layer the hatch direction is rotated 90° and spacing between hatch lines is offset by 600 μm.

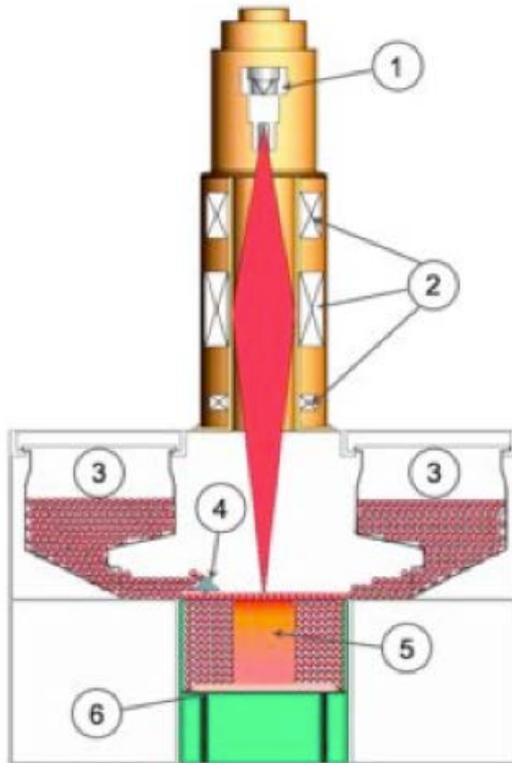
**EBM process parameters**

Preliminary efforts in parameter development focused on evaluating and optimizing powder material. Results from these manufacturers were obtained. Two high-purity 99.99% Cu powders (A and B) were examined in detail, while a third low-purity 99.95% Cu



- Electron Beam Melting Additive Manufacturing (EBM AM) is a fabrication process where parts are built by melting thin layers of metal powder
- An electron beam melts each layer to a geometry defined by a CAD model
- EBM AM parts are fully-dense, functional parts
- EBM AM advantages:
  - Cost/time savings
  - Excellent material properties
  - **Freedom in design**





## ARCAM A2 TECHNICAL DATA

Build tank volume	250x250x400 mm and 350x350x250 mm (W x D x H)
Maximum build size	200x200x350 mm and Ø 300x200 mm (W x D x H)
Model-to-Part accuracy, long range <sup>1</sup>	+/- 0.20 mm (3σ)
Model-to-Part accuracy, short range <sup>1</sup>	+/- 0.13 mm (3σ)
Surface finish (vertical & horizontal) <sup>2</sup>	Ra25/Ra35
Beam power	50–3500 W (continuously variable)
Beam spot size (FWHM)	0.2 mm – 1.0 mm (continuously variable)
EB scan speed	up to 8000 m/s
Build rate <sup>2</sup>	55/80 cm <sup>3</sup> /h (Ti6Al4V)
No. of Beam spots	1–100
Vacuum base pressure	<1 x 10 <sup>-4</sup> mBar
Power supply	3 x 400 V, 32 A, 7 kW
Size and weight	1850 x 900 x 2200 mm (W x D x H), 1420 kg
Process computer CAD interface	PC
CAD interface	Standard: STL
Network	Ethernet 10/100/1000
Certification	CE

<sup>1</sup> Long range: 100mm, Short range: 10mm, measured on Arcam Standard Test Part (ASTP).

<sup>2</sup> Measured on Arcam Standard Test Part (ASTP).

Settings optimized for fine surface quality/Settings optimized for high build speed.

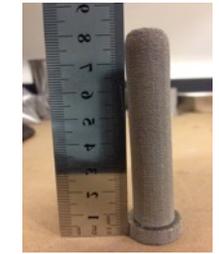
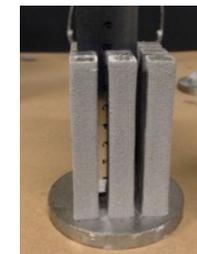
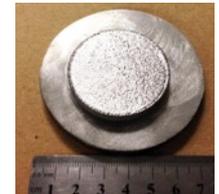
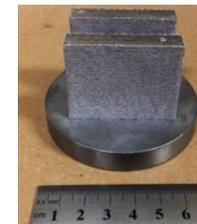
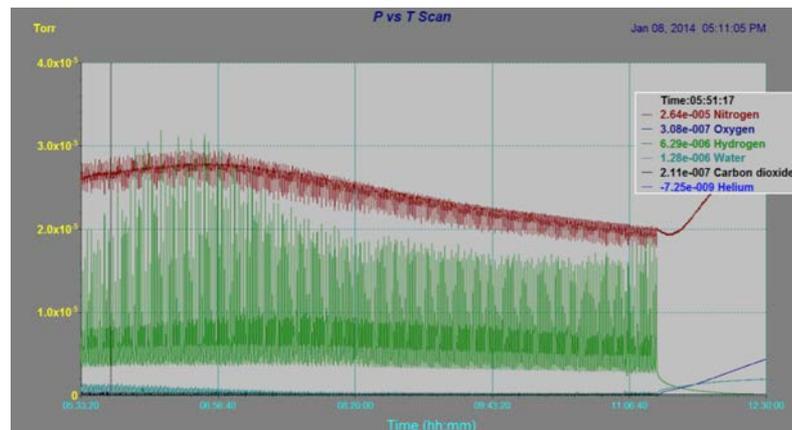
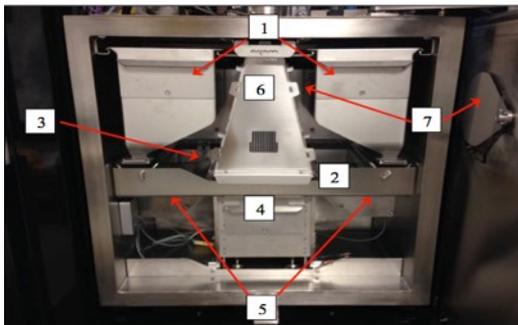
# Project Goals and Relevance

- **Project Goal:** Develop EBM AM for Nb, and experimentally validate SRF performance of prototype component(s)
- **DOE NP Relevance:** SRF cavities and ancillary components are a key technology for DOE NP (and others)
  - Reduce or eliminate joints in current designs
  - Integrated stiffeners for mitigation of: Lorentz force detuning, microphonics, pressure fluctuations
  - Realize truly novel designs – more physics driven, less manufacturing driven
    - Very thin walls (<1mm) with lattice supports
    - Integrate the helium vessel and cavity?



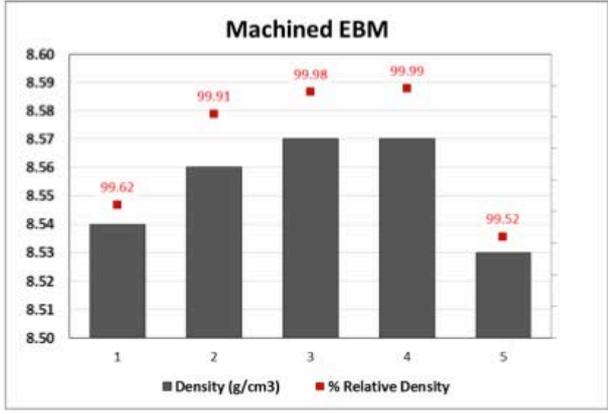
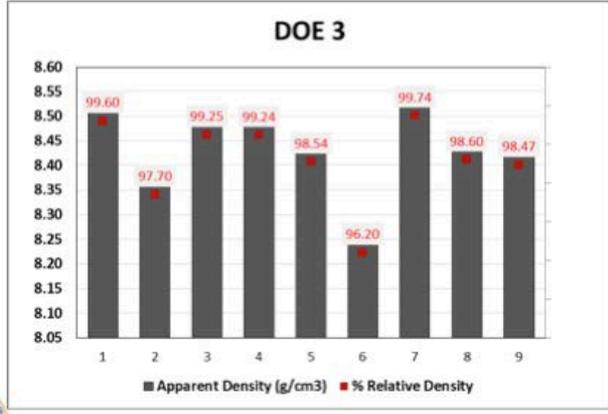
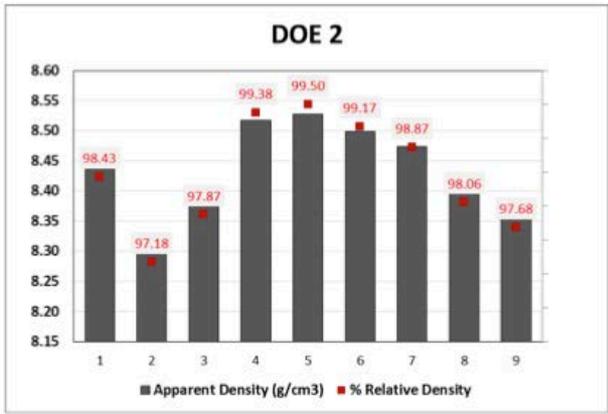
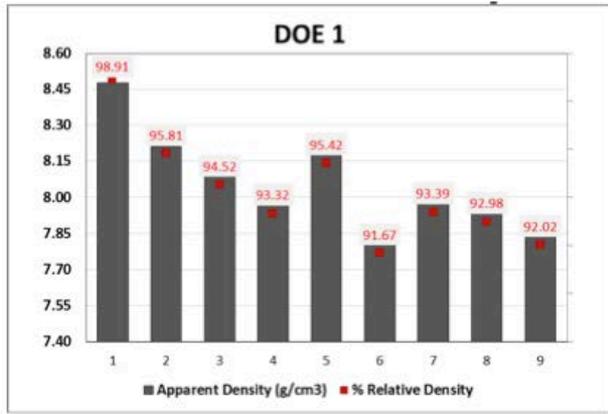
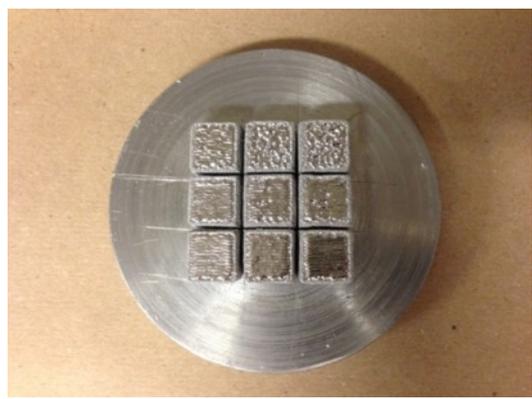
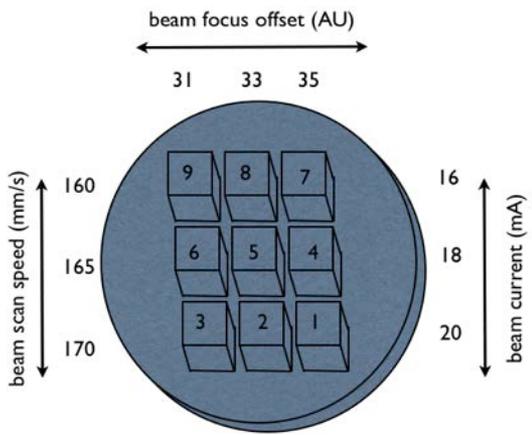
# Phase II EBM Process Optimization

- Year 1 concentrated on EBM process optimization
  - Feedstock powder
  - Hardware and software improvements to EBM machine
  - Fabrication of samples for material testing
- Year 2 focus on geometry optimization and SRF testing



# EBM Parameter Development

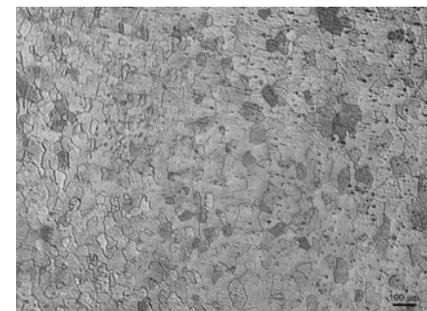
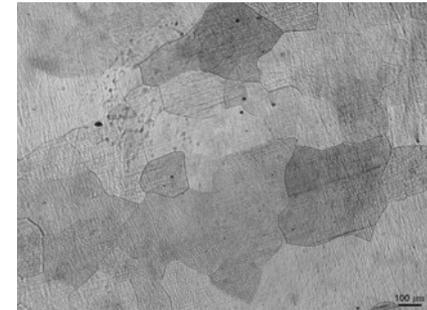
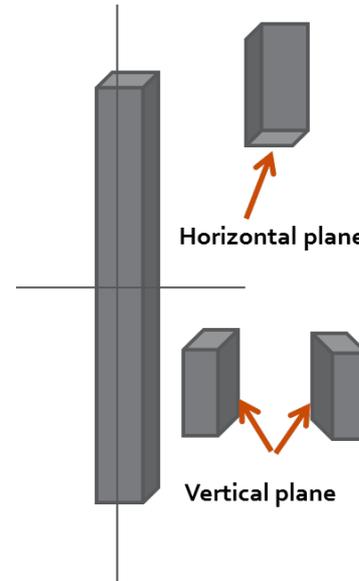
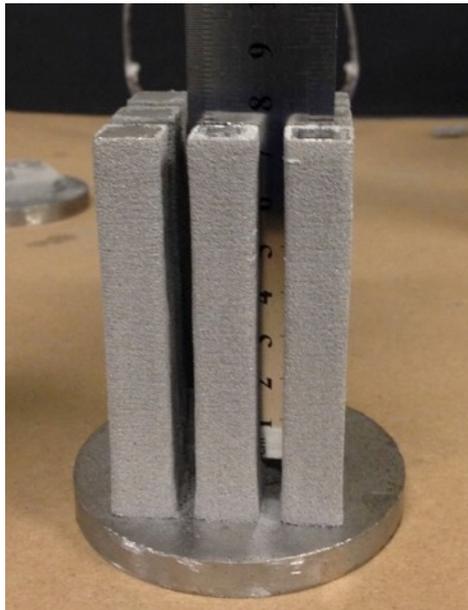
- Iterative Design of Experiment (DOE)
  - Improved as-EBM density > 8.55 g/cm<sup>3</sup> (from a 8.51 g/cm<sup>3</sup> in Phase I)



# Microstructure

- EBM bar samples

- Equiaxed grains in horizontal plane ( $\sim 250 \mu\text{m}$ )
- Elongated grains in vertical plane ( $\sim 20$  layers;  $\sim 1 \text{ mm}$ )



Wrought Nb;  
equiaxed grains in all  
directions

# Material Properties

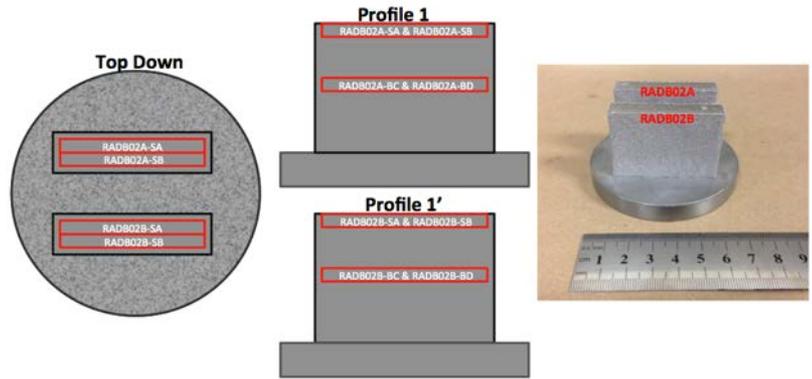


	EBM Ti6Al4V [16]	Wrought Ti6Al4V (ASTM F1472)	EBM Copper	Wrought C10100 Cu	EBM (reactor grade) Nb	Wrought Reactor Grade Nb
<b>Density</b>	>99.9%	-	8.84 g/cm <sup>3</sup>	8.90 g/cm <sup>3</sup>	8.55 g/cm <sup>3</sup>	8.57 g/cm <sup>3</sup>
<b>Electrical Conductivity @ 20° C</b>	-	-	97 % IACS	102 % IACS	-	-
<b>RRR</b>	-	-	-	-	19	40
<b>Thermal Conductivity</b>	-	-	390 W/m*K	391 W/m*K	50 W/m*K	53.7 W/m*K
<b>YS (Rp 0.2)</b>	950 MPa	860 MPa	76 MPa	69 MPa	135 MPa	110 MPa
<b>UTS (Rm)</b>	1020 MPa	930 MPa	172 MPa	220 MPa	225 MPa	226 MPa
<b>Elongation</b>	14 %	> 10%	-	-	35%	50%

[1] Arcam T64 Material Data Sheet, (<http://www.arcam.com/CommonResources/Files/www.arcam.com/Documents/EBM%20Materials/Arcam-Ti6Al4V-Titanium-Alloy.pdf>)

# RRR Measurements

- Performed at JLab SRF Institute using standard “4-probe method”
- Uniform SC properties
- $T_c \sim 9.1$  to  $9.2$  K, with sharp transitions
- As-EBM RRR  $\sim 17-18$  (roughly half of feedstock material)
- RRR  $\sim 44$  after BCP dip +800° C 3hr HV in Ti box



Sample ID	RRR	RRR $T_{Low}$	RRR $T_{High}$	$T_c$	$\Delta T_c$
RADB02A-SA 1	17	10	300	9.06	0.11
RADB02A-SA 2	17	10	300	9.19	0.05
RADB02A-SB 1	18	10	300	9.06	0.06
RADB02A-SB 2	18	10	300	9.21	0.09
RADB02A-BC 1	18	10	300	9.10	0.08
RADB02A-BD 1	17	10	300	9.12	0.11
RADB02A-BD 2	17	10	300	9.18	0.08
RADB02B-SA 1	17	10	300	9.05	0.06
RADB02B-SA 2	18	10	300	9.14	0.17
RADB02B-SB 1	17	10	300	9.07	0.09
RADB02B-SB 2	16	10	300	9.16	0.05
RADB02B-BC 1	18	10	300	9.05	0.12
RADB02B-BC 2	18	10	300	9.19	0.06
RADB02B-BD 1	17	10	300	9.04	0.14
RADB02B-BD 2	17	10	300	9.18	0.08

Sample	RRR by R/R	RRR Low Temperatur e (K)	RRR High Temperatur e (K)	$T_c$ (K)	Delta $T_c$ (K)
RADB02A-SB PA	44	10.4	300.0	9.15	0.08

# SRF Testing

- JLab TE011 cavity employs the removable probe as the center conductor in the coaxial resonator
  - Surface resistance
  - Quench field
  - Compare to wrought Nb
- Probe was EBMed and successfully leak checked
- Tested at JLab

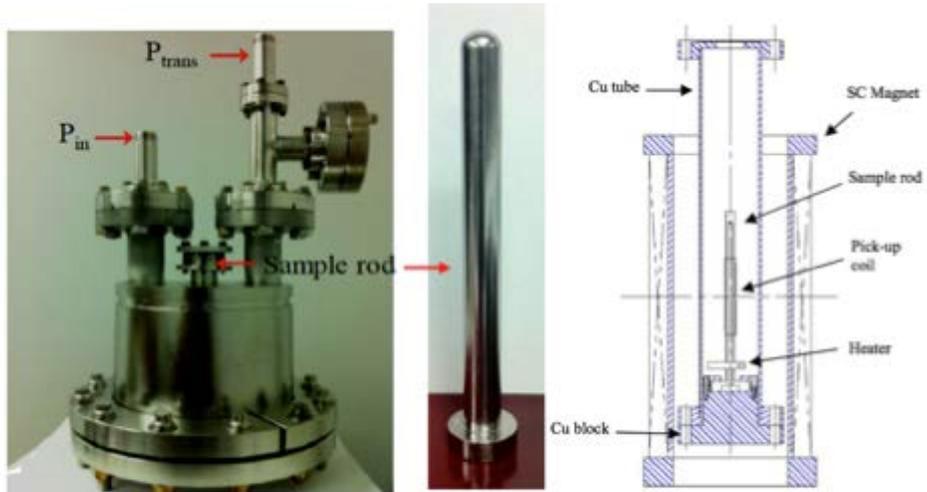
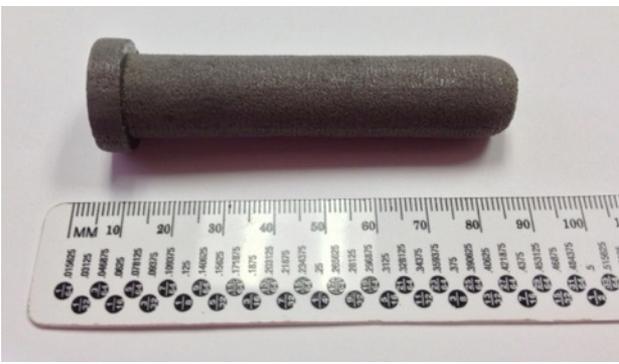
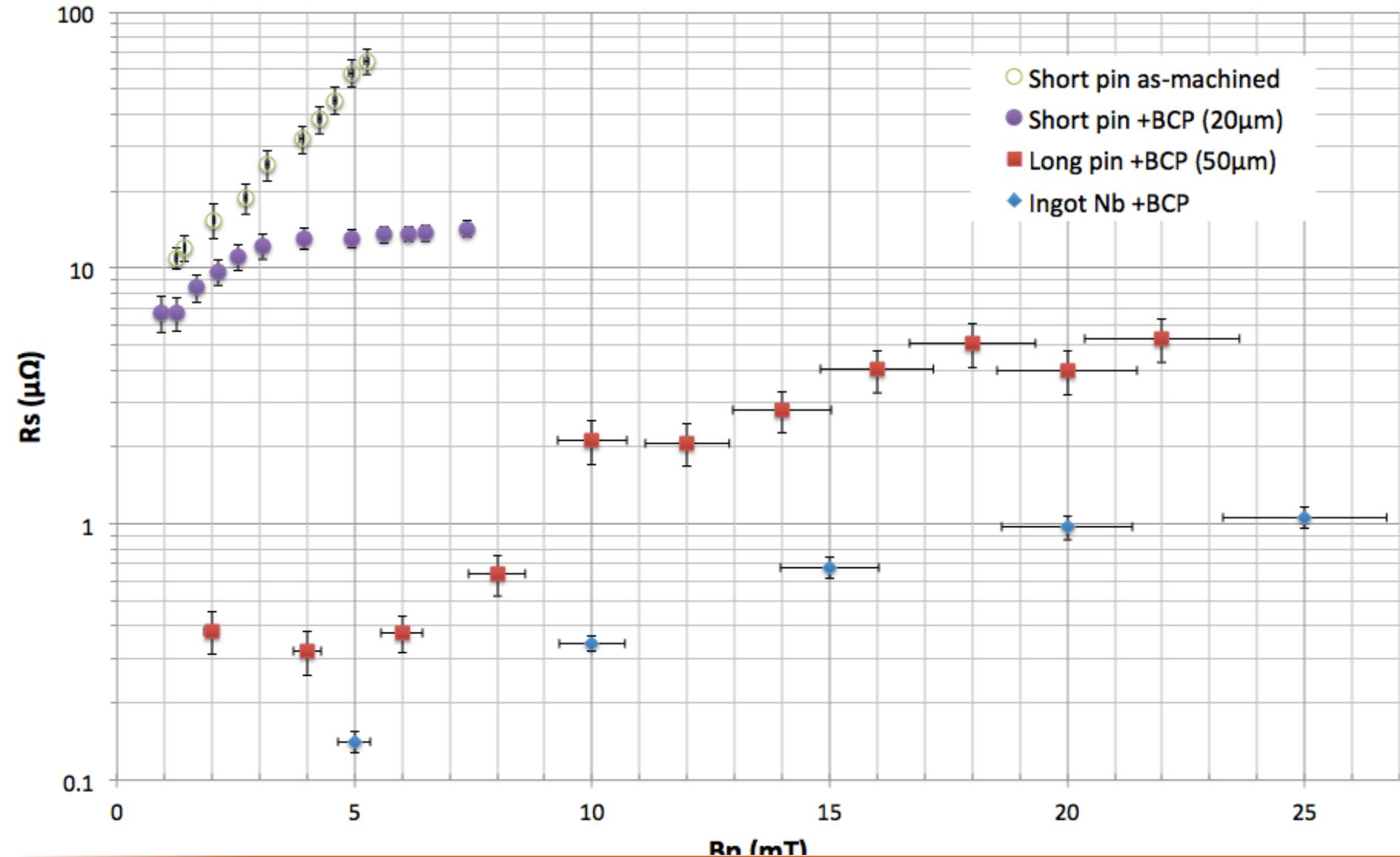


Figure 25: Photograph of the JLab TE011 cavity (Right), sample rod (Center), and system for measurement of superconducting properties (Left). [Courtesy of P. Dhakal, JLab.]



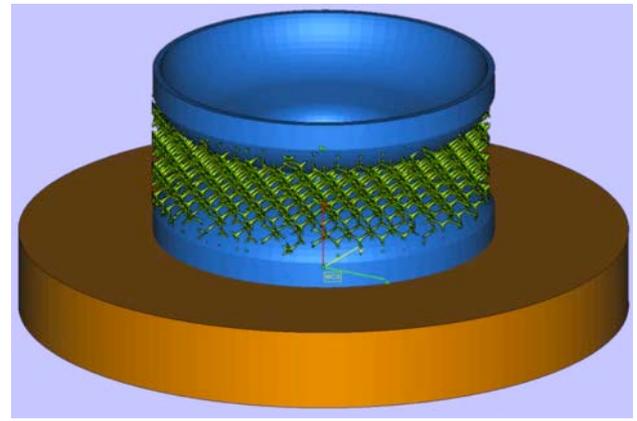
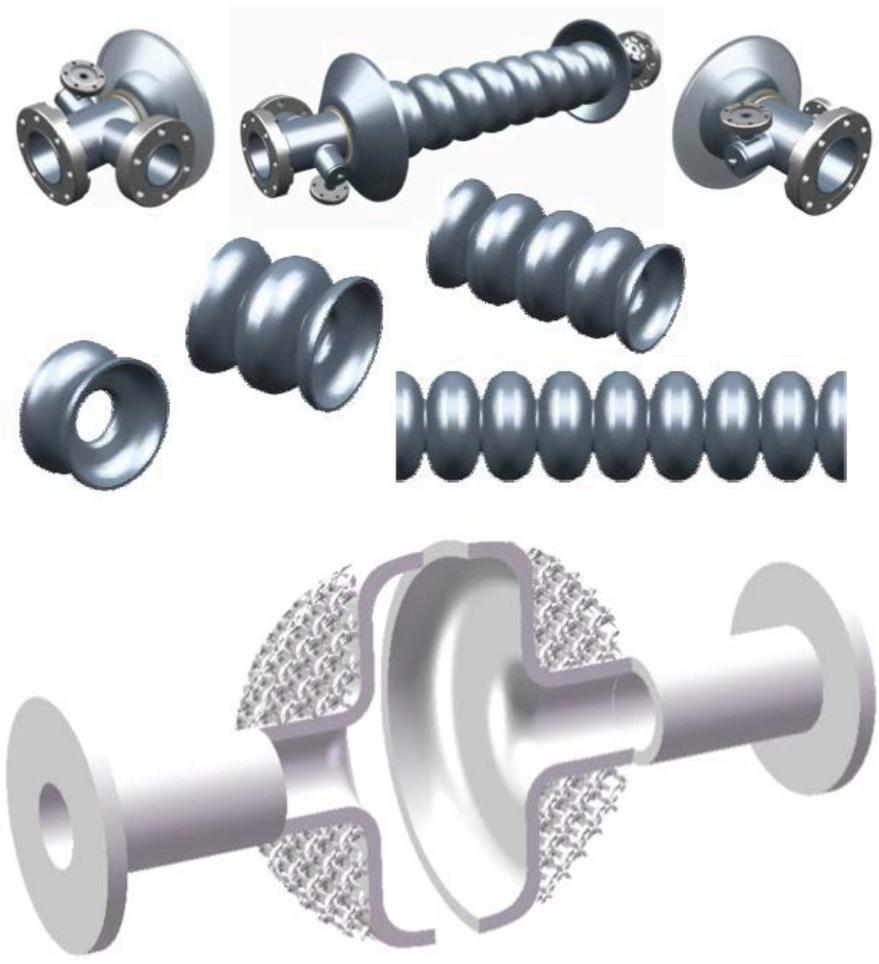
# TE011 Test Results

## TE011 Samples (f=3.585 GHz)



# EBM SRF Cavity Prototype Design

Fermilab: 3.9 GHz, 3<sup>rd</sup> Harmonic SRF Cavity Drawings – Rev. B  
2/8/2006



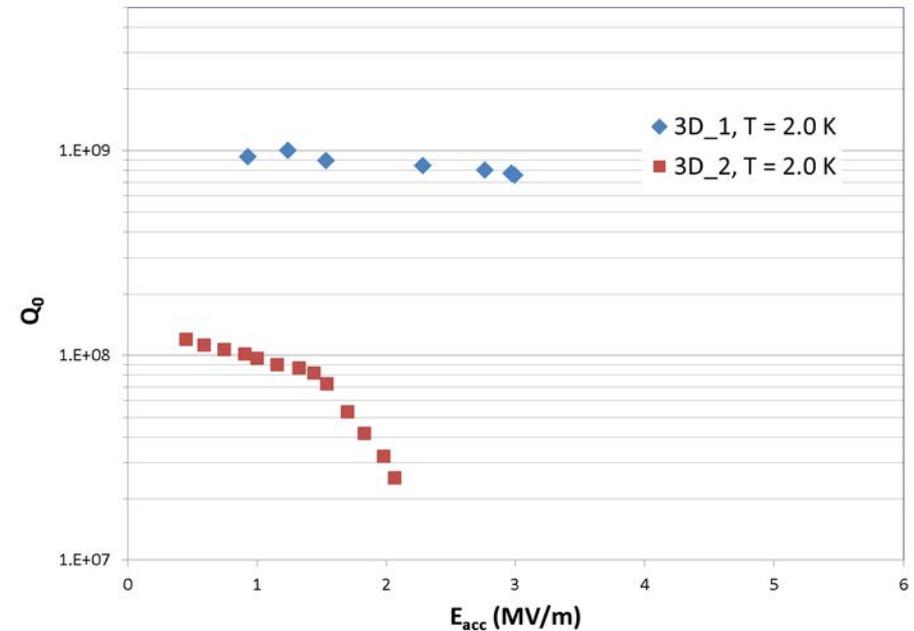
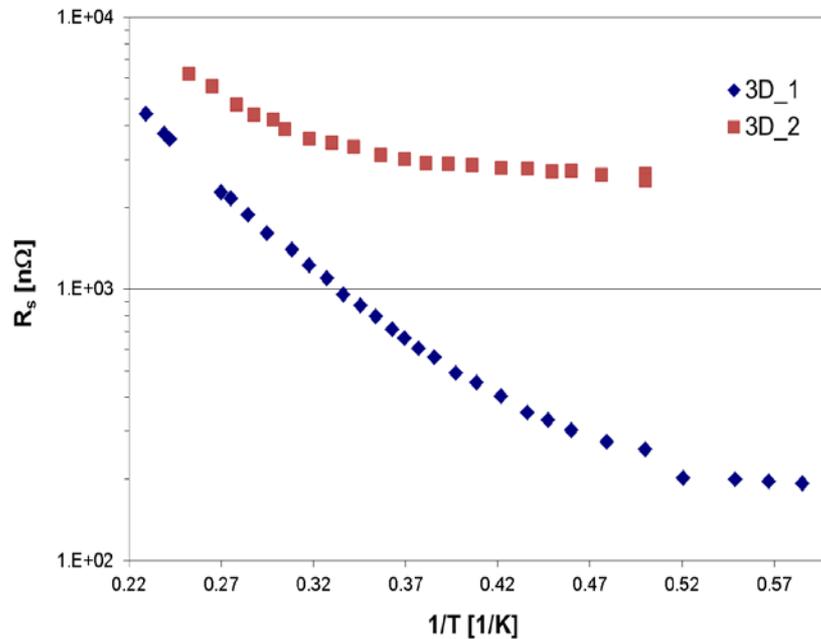
# Single cell cavity fabrication

- 3.8 GHz half-cells were AM using EBM technology
- RF surfaces were machined (turned), and half-cells were e-beam welded into two single-cell cavities
- 100 $\mu$ mBCP + annealing at 800 $^{\circ}$  C/3h + 20 $\mu$ m BCP



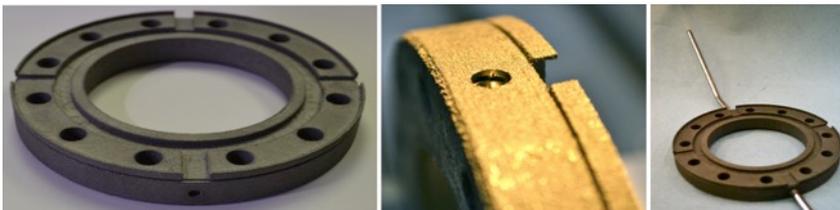
# SRF Test Results

- $Q_0$ ,  $E_{acc}$ , and  $H_{peak}$  low compare to wrought reactor grade cavity
- Encouraging results: Quench field corresponding to  $\sim 10$  mT



# Phase II +

- Develop commercial end-group components
- Improving as-EBM material quality
  - Focus on AM process parameters near SRF surface(s)
- Improve “near-net-shape” capability
  - Improve as-EBM surface roughness;  $\sim Ra\ 10\mu m$
  - Centripetal Barrel Polishing (CBP) + Electro polishing (EP)
- Partner with EBM platform manufacture to develop custom machine



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# Thank you!

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Questions?

# Extra slides

- Commercialized by ARCAM AB (Sweden) ~ 2000
- First machine sold in the US to NCSU in 2003
- Today ~ 100 machines in the US
- ~ 6 machines in academic institutions (2 at NCSU, 2 in UTEP)
- ORNL's MDF partner with Arcam in 2012



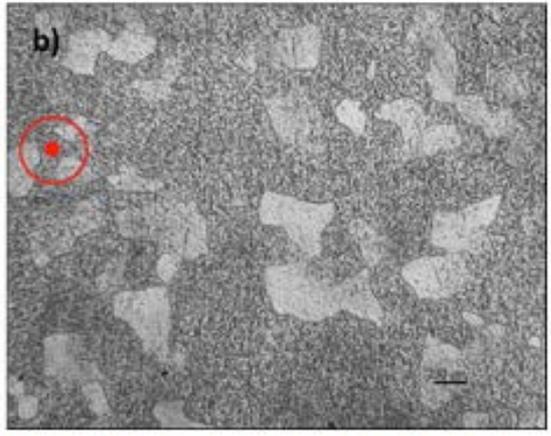
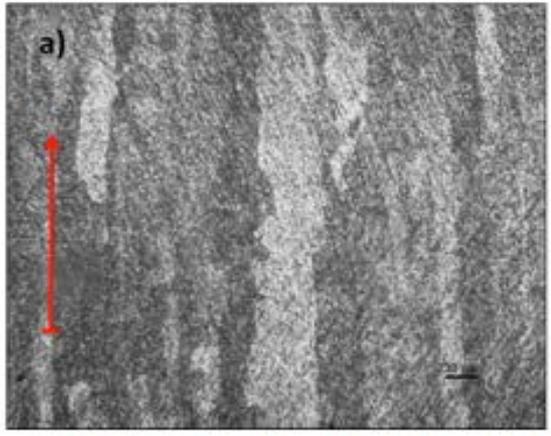
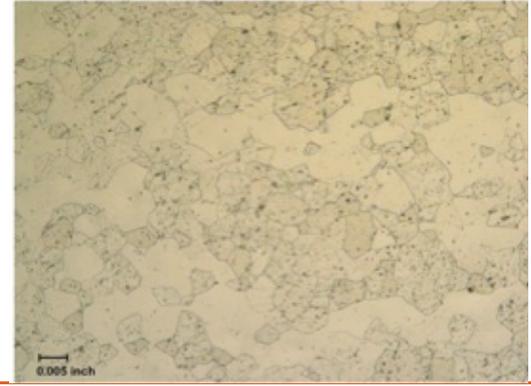
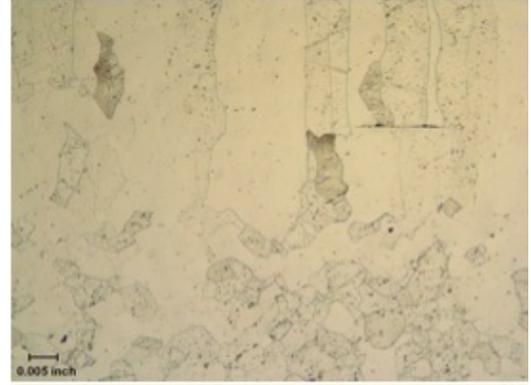
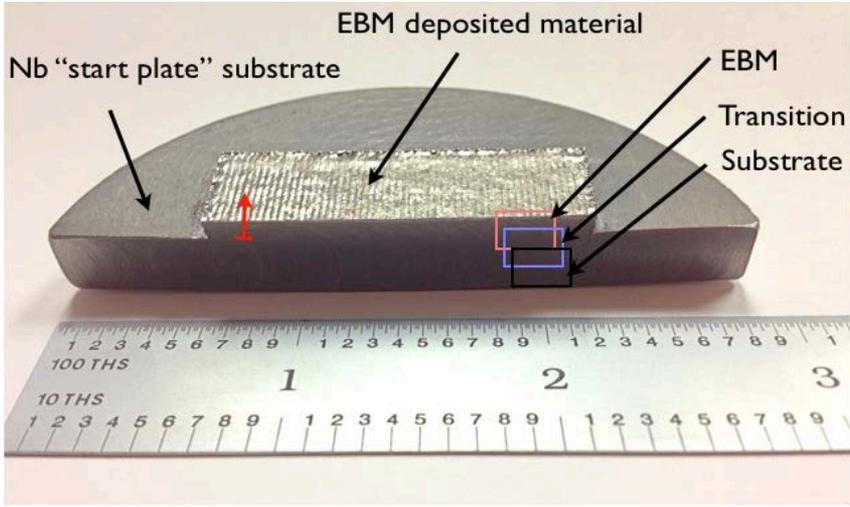
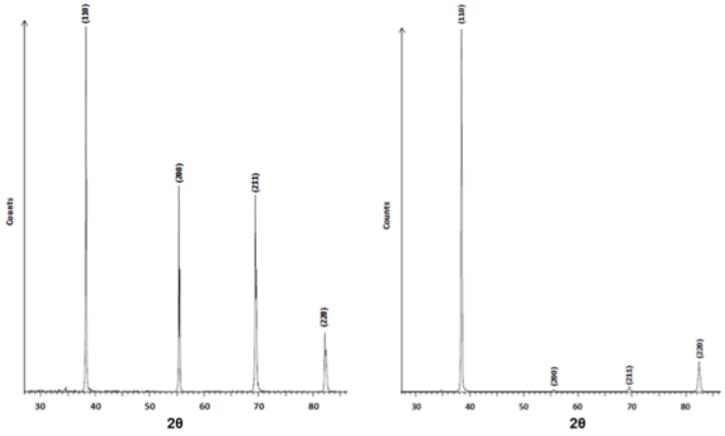


Figure 9: Vertical (a) and horizontal (b) micrographs of the EBM niobium showing elongated and irregular grains respectively, when etched with 1 part HF and 4 parts of HNO<sub>3</sub>. The arrow depicts the build direction, and the scale shown is 230 μm.



## Results – EBM purity (XRD)

- XRD revealed clean Nb spectra
  - BCC structure
  - $a = 0.33 \text{ nm}$



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	Feedstock Niobium (Reactor Grade - Type 1)	Phase-I EBM Niobium	Phase-II EBM Niobium
Density (g/cm <sup>3</sup> )	8.57	8.40 - 8.51	> 8.55
RRR	40 - 50	18-19	17-18
Thermal Conductivity (W/m*K)	53.7	-	50
YS (Rp 0.2) MPa	110	-	135
UTS (Rm) MPa	226	-	225
Elongation	50 %	-	35 %
Fatigue strength @ 600 MPa	-	-	In process
Vickers Hardness (GPa)	0.76 - 1.3	0.82 - 0.86	0.90 - 0.95