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

DOE Nuclear Physics SBIR/STTR Exchange Meeting Aug. 6-7, 2015

Acknowledgments

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DOE NP STTR Phase I/II Grant DE-SC0007666

Outline

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

Who We Are

- 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

Facilities

radiabeam TECHNOLOGIES

- 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

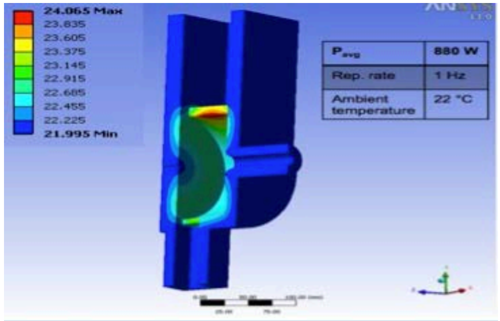


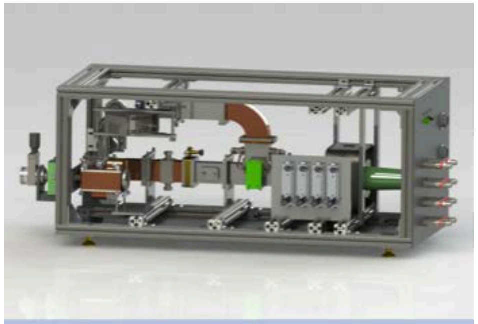
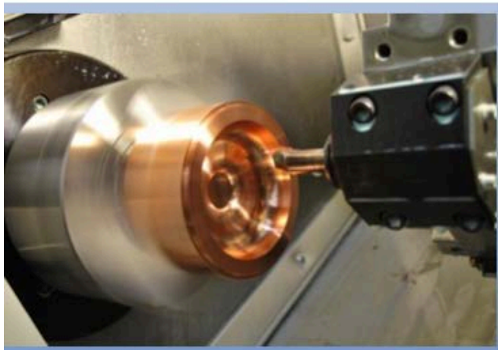



Capabilities

radiabeam TECHNOLOGIES

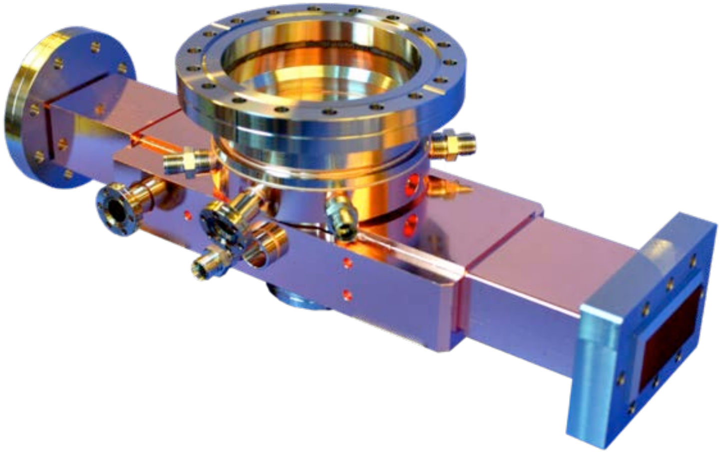
- Design
- Engineering
- Fabrication
- Assembly
- Testing
- Installation
- Service



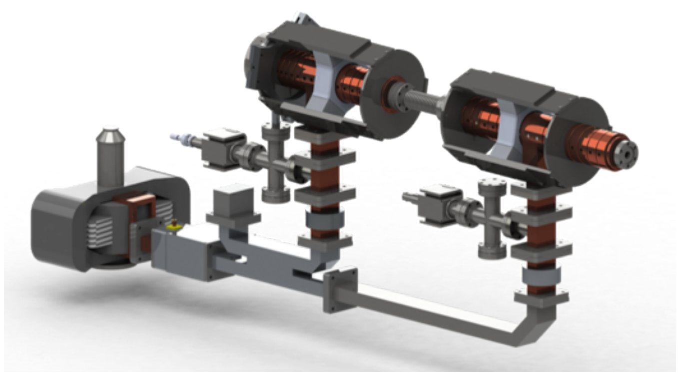

Products

- 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)



Accelerator Systems

- 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

radiabeam SYSTEMS

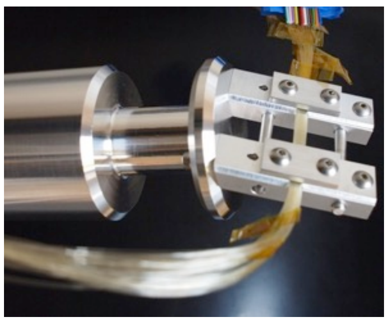
Growing List of Customers

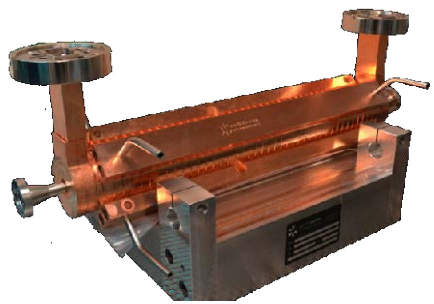
radiabeam TECHNOLOGIES

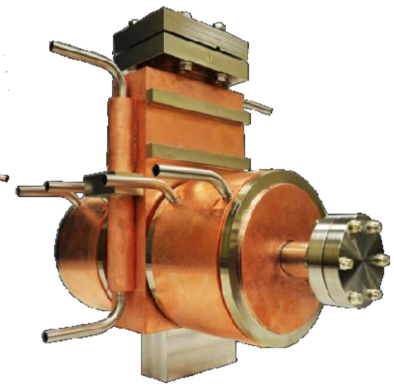
Argonne NATIONAL LABORATORY
CINEL
ISL
KAERI
iba
TeamBest Your True Partner
SPARKLE RADIOPHARMACEUTICALS
University of Colorado
CERN
University of Hawai'i Mānoa
NSRRC
University of Nebraska Lincoln
東京大学 THE UNIVERSITY OF TOKYO
NIOWAVE
Schlumberger
ACCURAY
Sterigenics
Fermilab
SIEMENS
Yale University
Lawrence Livermore National Laboratory
EUROTEK
Mizzou University of Missouri - Columbia
TRIUMF
excillum
BROOKHAVEN NATIONAL LABORATORY
UCLA
Kungl Tekniska Högskolan
TRAD Tests & radiations
Berkeley Lab
European Spallation Source
LNLS Laboratório Nacional de Luz Síncrotron
INFN Istituto Nazionale di Fisica Nucleare
Oak Ridge National Laboratory
Wright State University
Idaho Accelerator Center
Centre for Advanced Technology
PAL
Canadian Light Source / Centre canadien de rayonnement synchrotron
Ariel University
ENEA
Indiana University Bloomington
Sandia National Laboratories
CANDLE
Los Alamos National Laboratory
Wisconsin University of Wisconsin-Madison
Michigan
KIT Karlsruher Institut für Technologie
FERMI @elettra
SLAC National Accelerator Laboratory
MAX IV
SOLEIL Synchrotron
Vanderbilt University
Paul Scherrer Institut PSI

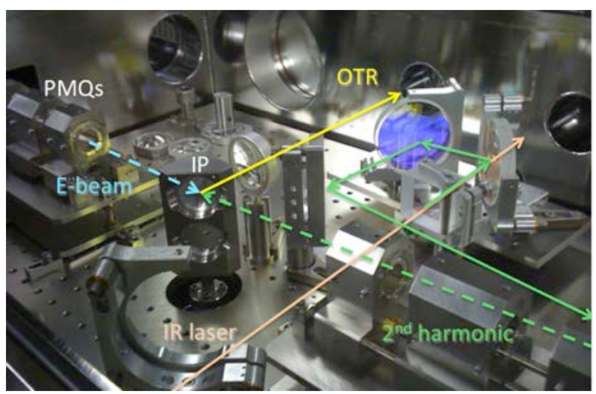
Multiple Funding Agencies

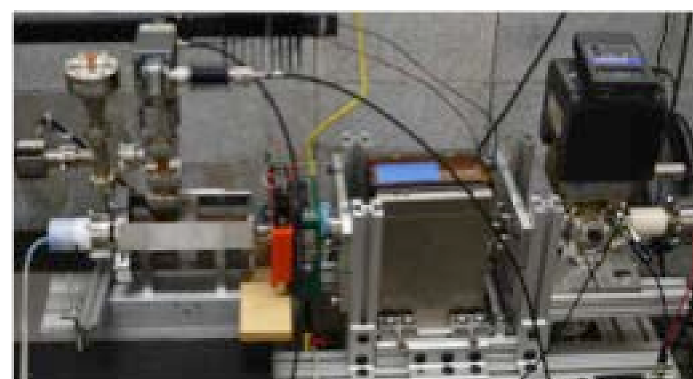
SBIR, BAA, &commercial funded and self-funded R&D to develop new products and technical solutions





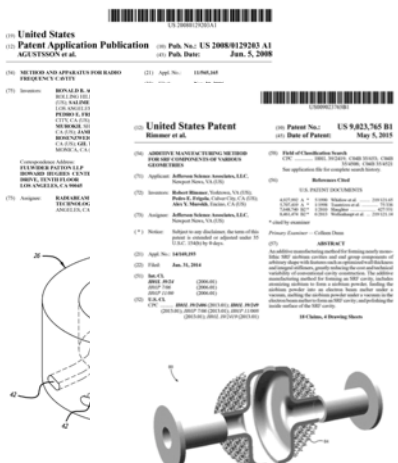






Additive Manufacturing Development at RadiaBeam

AM Development at RadiaBeam



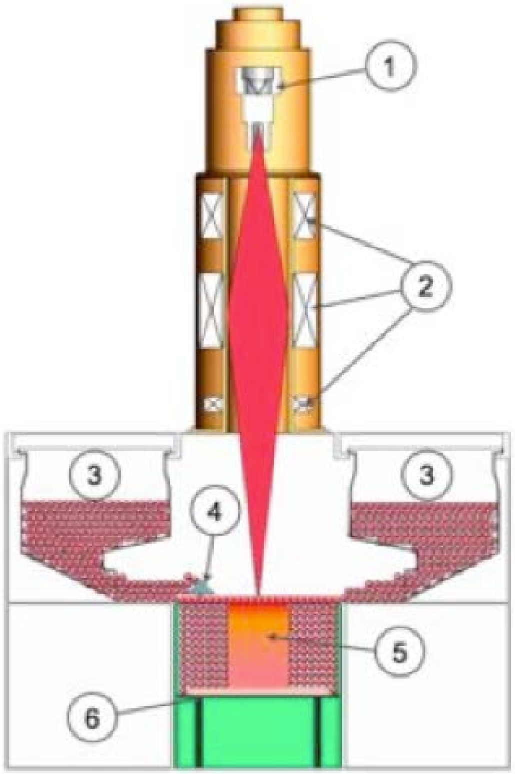

Fabricating Copper Components with Electron Beam Melting

- 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

ARCAM EBM® Additive Manufacturing

- Electron Beam Melting Additive Manufacturing (EBM AM) is a fabrication process were 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 EBM Overview



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 [1]	+/- 0.20 mm (3σ)
Model-to-Part accuracy, short range [1]	+/- 0.13 mm (3σ)
Surface finish (vertical & horizontal) [2]	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 [2]	55/80 cm^3/h (Ti6Al4V)
No. of Beam spots	1–100
Vacuum base pressure	$<1 \times 10^{-4}$ 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

[1] Long range: 100 mm, Short range: 10 mm, measured on Arcam Standard Test Part (ASTP).
[2] Measured on Arcam Standard Test Part (ASTP).
Settings optimized for fine surface quality/Settings optimized for high build speed.

Project Goals and Relevance

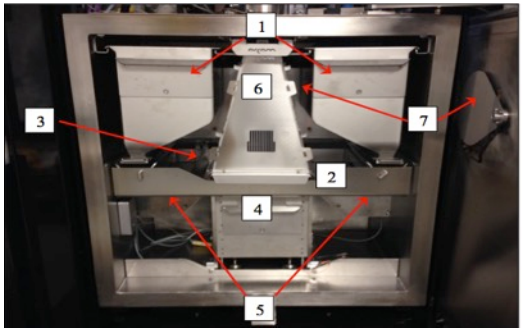
radiabeam TECHNOLOGIES

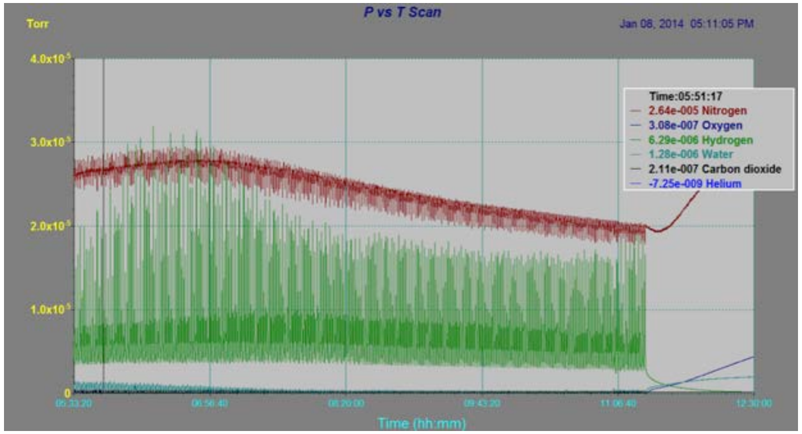
- **Project Goal**: Develop EBM AM for Nb, and experimentally validate SRF performance of prototype component(s)

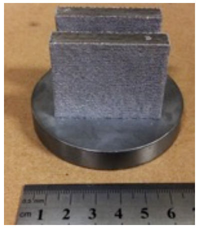
- **DOE NP Relevance**: SRF cavities and ancillary components are a key technology for DOE NP (and others)
  - Reduce or eliminate joints in current designs
  - Integrated stiffeners for mitigation of: Lorentz force detuning, microphonics, pressure fluctuations
  - Realize truly novel designs – more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

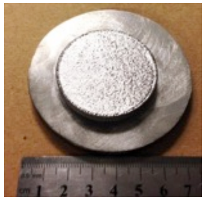
Phase II EBM Process Optimization

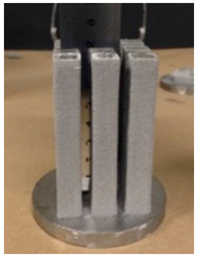
- Year 1 concentrated on EBM process optimization
  - Feedstock powder
  - Hardware and software improvements to EBM machine
  - Fabrication of samples for material testing
- Year 2 focus on geometry optimization and SRF testing

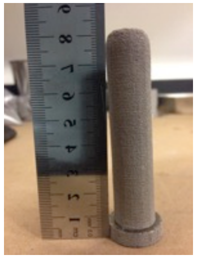






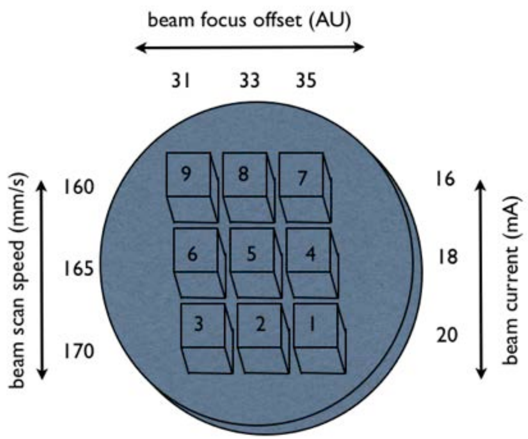


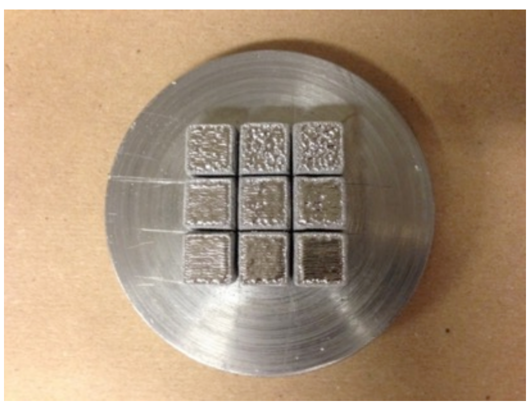


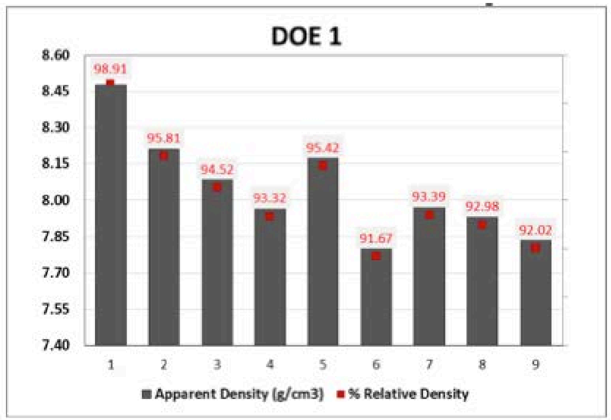


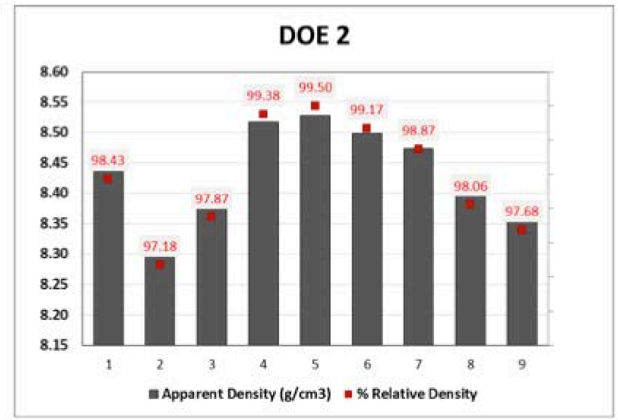
EBM Parameter Development

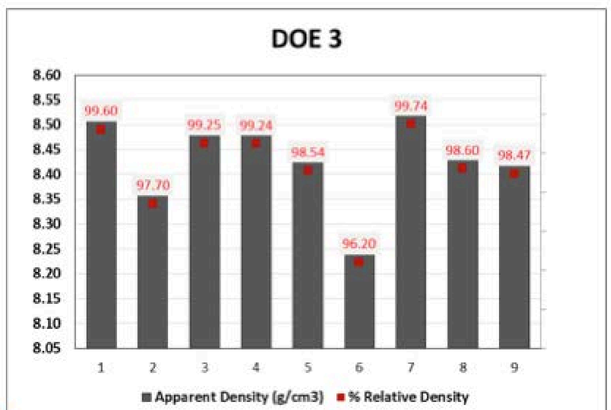
- Iterative Design of Experiment (DOE)
  - Improved as-EBM density > 8.55 g/cm3 (from a 8.51 g/cm3 in Phase I)

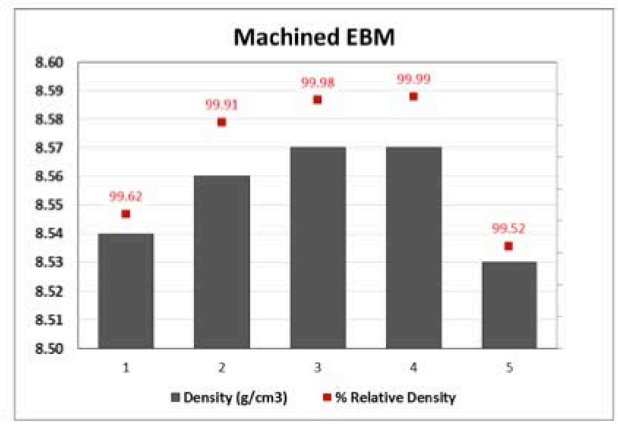






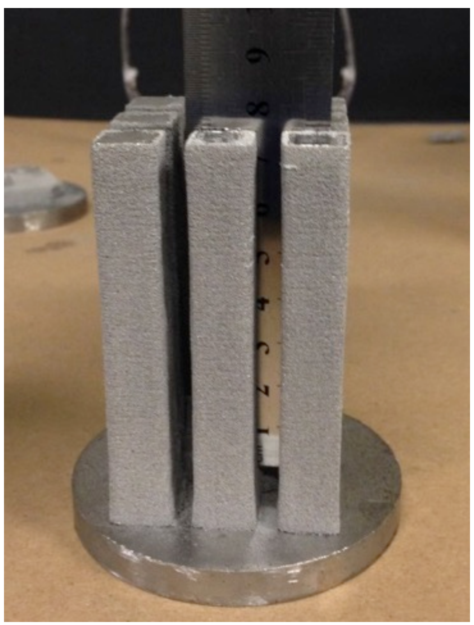


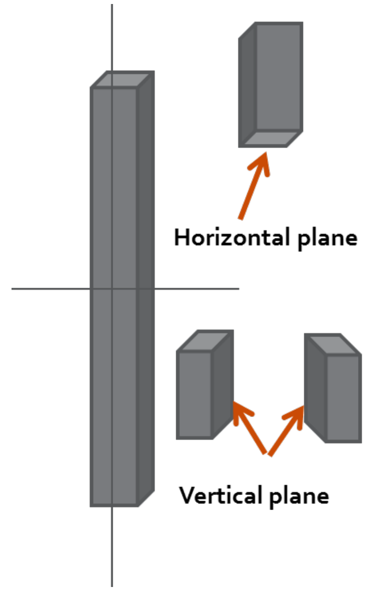


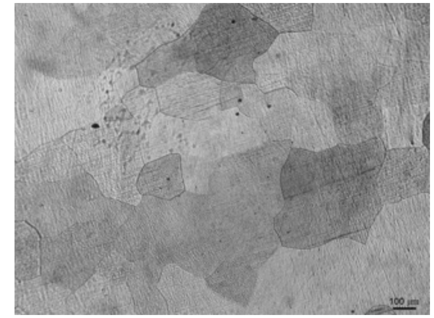


Microstructure

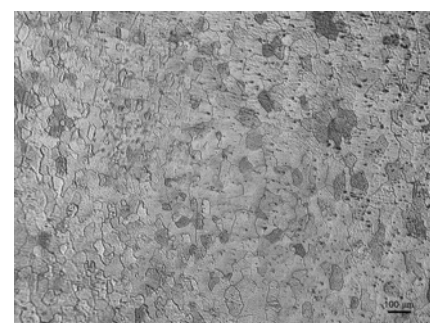
- EBM bar samples
  - Equiaxed grains in horizontal plane (~ 250 µm)
  - Elongated grains in vertical plane (~20 layers; ~1 mm)







Wrought Nb; equiaxed grains in all directions



Material Properties

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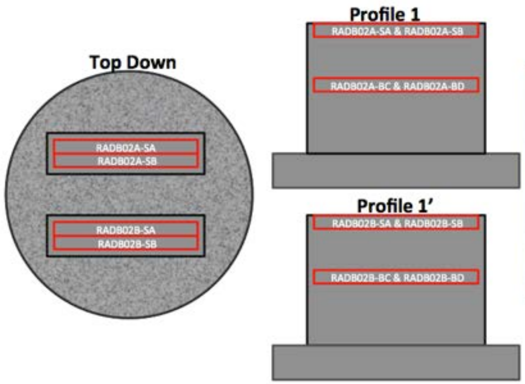
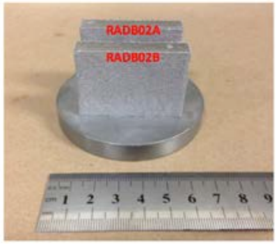
	EBM Ti6A14V [16]	Wrought Ti6A14V (ASTM F1472)	EBM Copper	Wrought C10100 Cu	EBM (reactor grade) Nb	Wrought Reactor Grade Nb
Density	>99.9%	–	8.84 g/cm³	8.90 g/cm³	8.55 g/cm³	8.57 g/cm³
Electrical Conductivity @ 20˚ C	–	–	97 % IACS	102 %IACS	–	–
RRR	–	–	–	–	19	40
Thermal Conductivity	–	–	390 W/m*K	391 W/m*K	50 W/m*K	53.7 W/m*K
YS (Rp 0.2)	950 MPa	860 MPa	76 MPa	69 MPa	135 MPa	110 MPa
UTS (Rm)	1020 MPa	930 MPa	172 MPa	220 MPa	225 MPa	226 MPa
Elongation	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
- Tc ~ 9.1 to 9.2 K, with sharp transitions
- As-EBM RRR ~ 17-18 (roughly half of feedstock material)
- RRR ~ 44 after BCP dip +800˚ C 3hr HV in Ti box





Sample ID	RRR	RRR T_{Low}	RRR T_{High}	T_c	ΔT_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 Temperature (K)	RRR High Temperature (K)	Tc (K)	Delta Tc (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

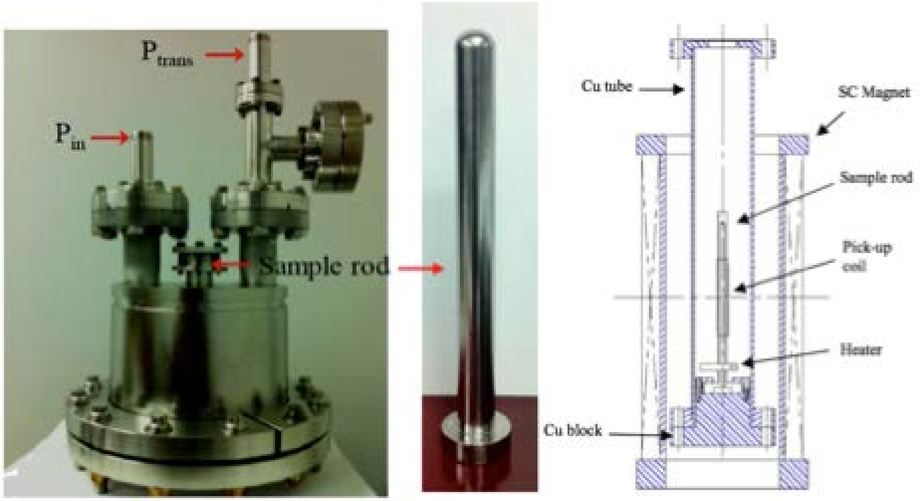
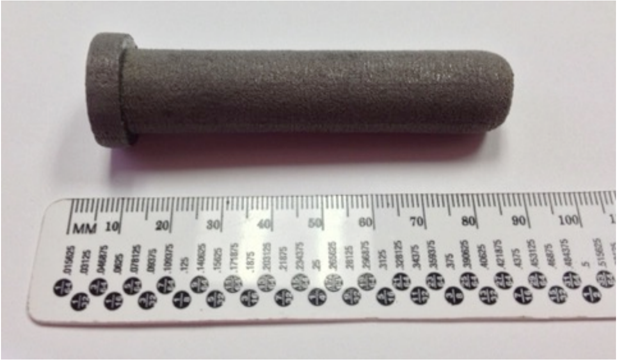
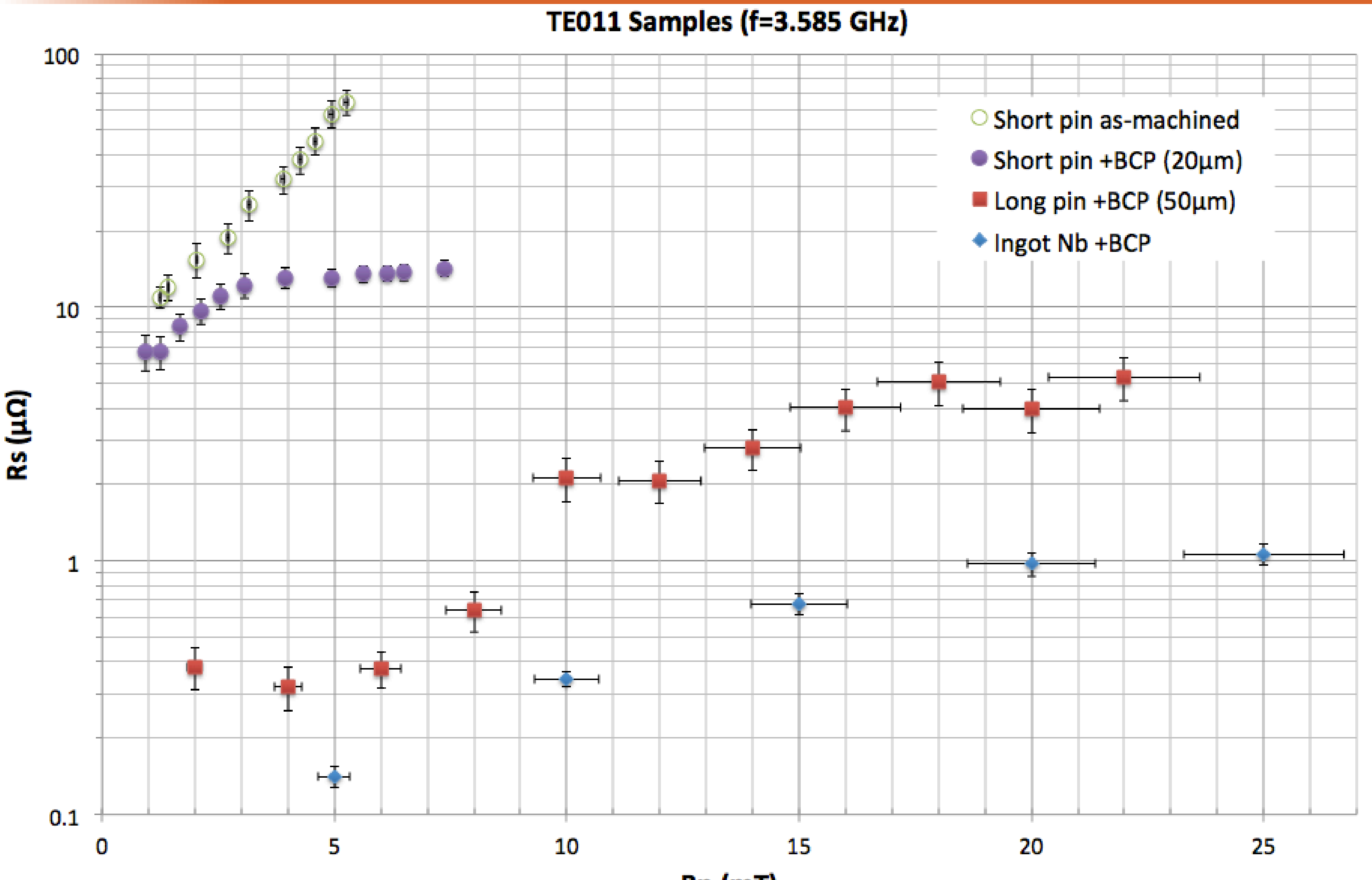


Figure 25: Photograph of the JLab TE011 cavity (Right), sample rod (Center), and system for measurement of superconducting properties (Left). [Courtesy of P. Dhakal, JLab.]



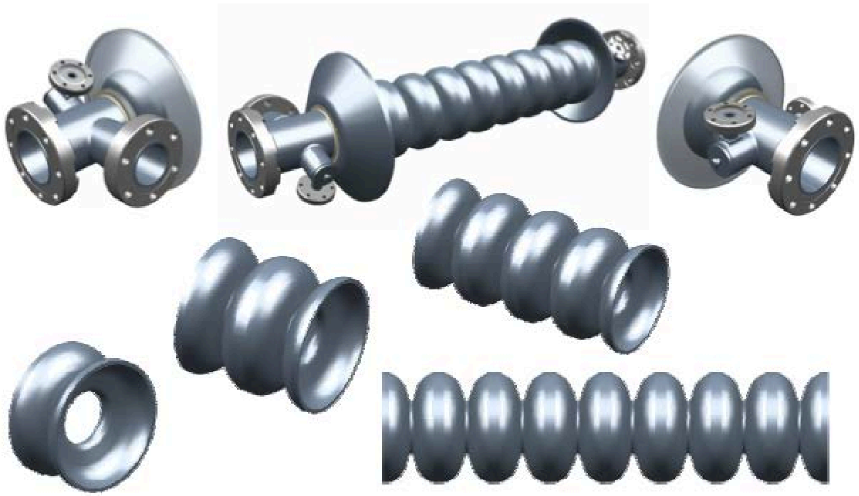
TE011 Test Results

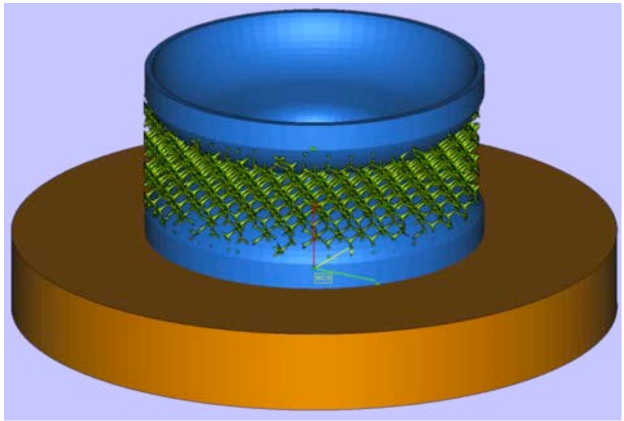


EBM SRF Cavity Prototype Design

radiabeam TECHNOLOGIES

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



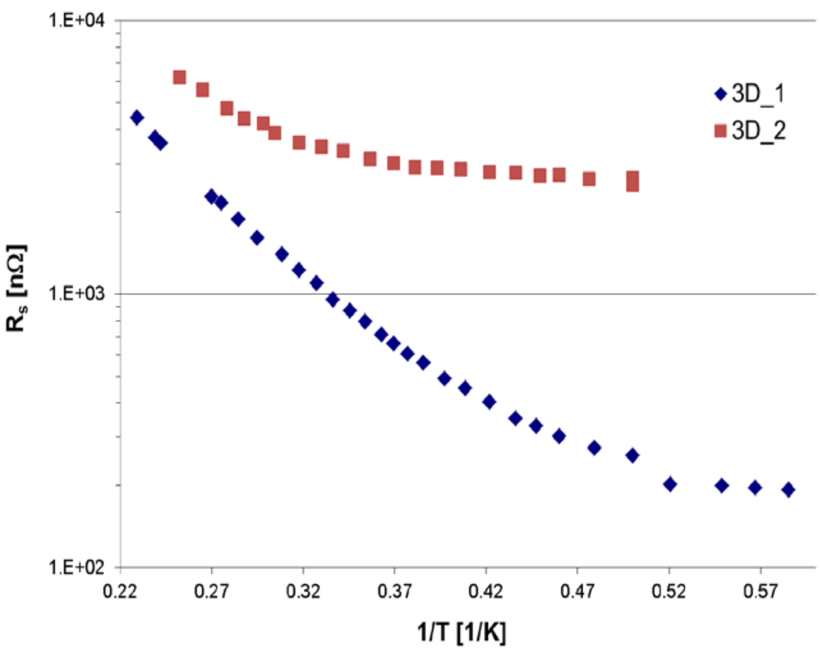


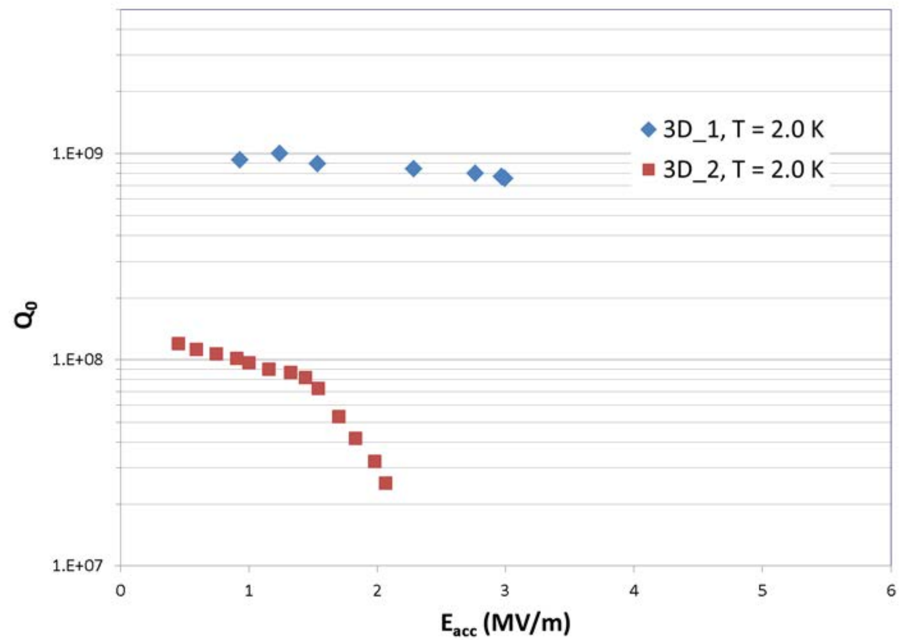
Single cell cavity fabrication

- 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
- 100µmBCP + annealing at 800˚ C/3h + 20µm BCP

SRF Test Results

- Qo, Eacc, and Hpeak low compare to wrought reactor grade cavity
- Encouraging results: Quench field corresponding to ~ 10 mT

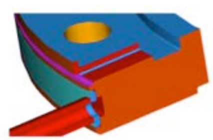
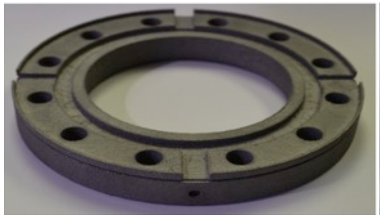


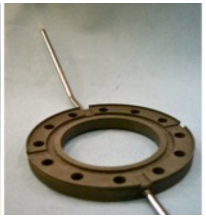


Phase II +

- 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; ~ Ra 10μm
  - Centripetal Barrel Polishing (CBP) + Electro polishing (EP)
- Partner with EBM platform manufacture to develop custom machine






Thank you!

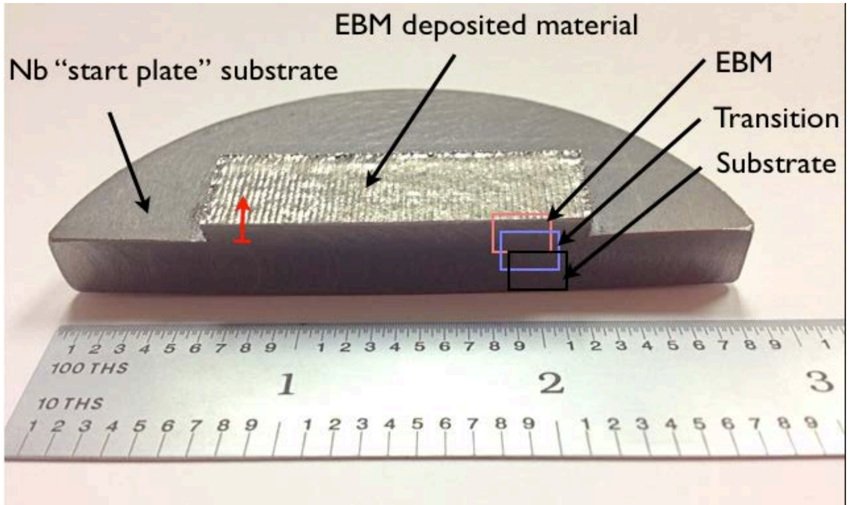
Questions?

Extra slides

ARCAM EBM Overview

- 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

Material testing



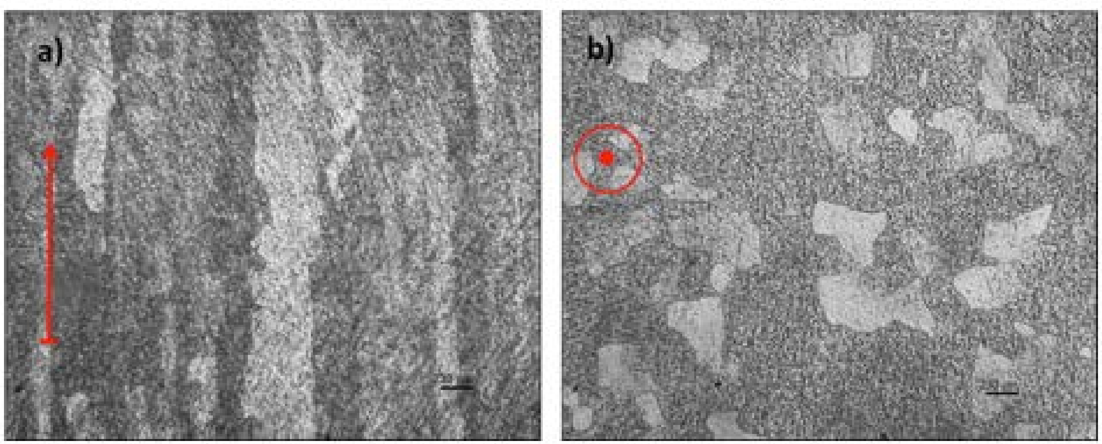
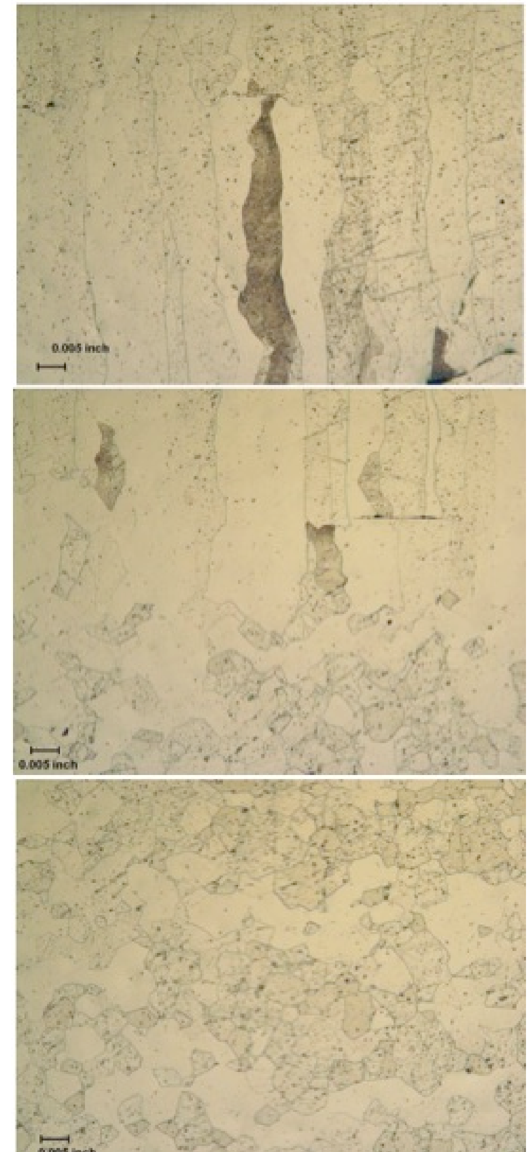
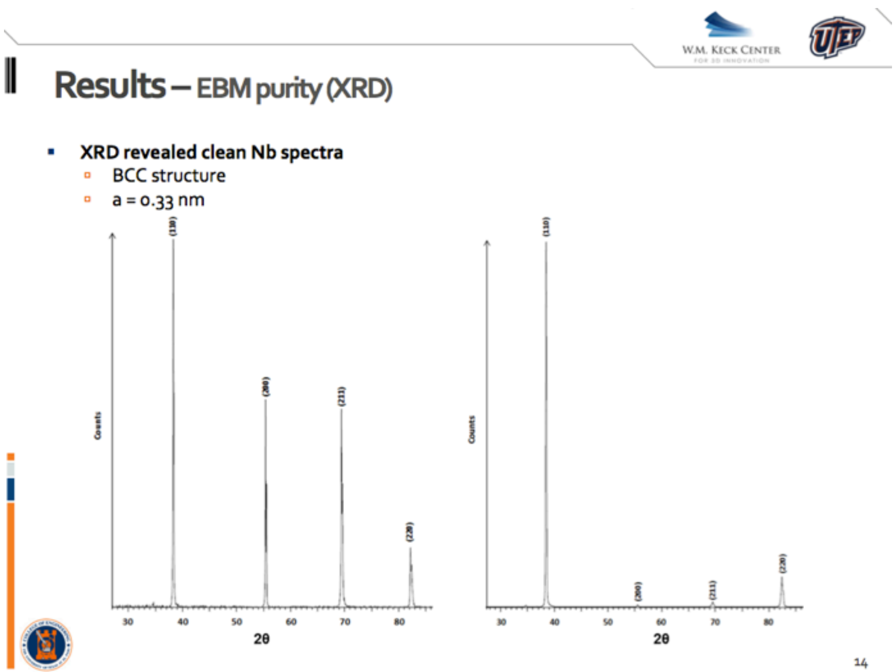


Figure 9: Vertical (a) and horizontal (b) micrographs of the EBM niobium showing elongated and irregular grains respectively, when etched with 1 part HF and 4 parts of HNO_3. The arrow depicts the build direction, and the scale shown is 230 µm.



Material testing



	Feedstock Niobium (Reactor Grade – Type 1)	Phase-I EBM Niobium	Phase-II EBM Niobium
Density (g/cm³)	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